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Performance of Epoxy Coated Rebars in Bridge Decks

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

FOREWORD

Epoxy coated rebar (ECR) was introduced in the mid 1970's as a means to minimize concrete deterioration caused by corrosion of the reinforcing steel and to extend the useful life of highway structures. This report summarizes the results of investigations performed by highway agencies in the United States and Canada, academia, and the Canadian Strategic Highway Research Program to evaluate the performance of ECR. A total of 92 bridge decks, 2 bridge barrier walls, and 1 noise barrier wall located in the States of California, Indiana, Kansas, Michigan, Minnesota, New York, Ohio, Pennsylvania, Virginia, West Virginia, and Wisconsin, and the provinces of Alberta, Nova Scotia, and Ontario were evaluated. The investigations consisted of a field and laboratory phase. The field phase primarily consisted of a visual examination of the decks, a chain drag for delaminations, the extraction of cores, and the taking of concrete powder samples. The laboratory phase primarily consisted of a visual examination and testing of the extracted cores and the ECR segment extracted with the core and the determination of chloride content in the concrete.

ECR has provided effective corrosion protection for up to 20 years of service with little or no maintenance or repair performed on the decks. No evidence of any significant premature concrete deterioration that could be attributed to corrosion of the ECR was found. No evidence of corrosion was found on 81 percent of extracted ECR segments. However, the ECR did not appear to perform as well when the concrete was cracked, the concrete cover was shallow, the concrete permeability was high, and the chloride concentration was high. Some ECR segments with a prolonged exposure to a moist environment experienced coating disbondment and softening. The number of defects in the epoxy coating and the amount of disbondment appear to influence the performance of ECR. The use of an adequate good quality concrete cover, adequate inspection, finishing, and curing of the concrete, and the proper manufacturing and handling of ECR complements the use of ECR in providing effective corrosion protection for concrete bridge decks.

This report will be of interest to materials and bridge engineers, reinforced concrete corrosion specialists, manufacturers of epoxy coated rebars, and those concerned with the performance of ECR in bridge decks.

Charles J. Nemmers, P.E.
Director, Office of Engineering Research
and Development

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16. Abstract

Epoxy coated rebar (ECR) was introduced in the mid 1970's as a means to minimize concrete deterioration caused by corrosion of the reinforcing steel and to extend the useful life of highway structures. This report summarizes the results of investigations performed by highway agencies in the United States and Canada, academia, and the Canadian Strategic Highway Research Program to evaluate the performance of ECR. A total of 92 bridge decks, two bridge barrier rails, and one noise barrier rail was evaluated in the States of California, Indiana, Kansas, Michigan, Minnesota, New York, Ohio, Pennsylvania, Virginia, West Virginia, and Wisconsin, and the provinces of Alberta, Nova Scotia, and Ontario.

The overall condition of the bridge decks was considered to be good. Deck cracking did not appear to be corrosion related. Very few of the decks had any delaminations or spalls associated with the ECR. Any delaminations or spalls that were associated with corrosion of ECR were small and generally in isolated locations.

No evidence of corrosion was found on 81 percent of the ECR segments extracted from the structures. The chloride concentrations at the rebar level were generally at or above the threshold to initiate corrosion in black steel. The ECR did not appear to perform as well when the concrete was cracked as when the concrete was not cracked. Corrosion was more severe on ECR segments extracted from locations of heavy cracking, shallow concrete cover, high concrete permeability, and high chloride concentrations. Coating disbondment and softening occurred as a result of prolonged exposure to a moist environment. The number of defects in the epoxy coating and the amount of disbondment appear to influence the performance of ECR.

ECR has provided effective corrosion protection for up to 20 years of service. Little or no maintenance or repair work has been performed on the decks. There was no evidence of any significant premature concrete deterioration that could be attributed to corrosion of the ECR. The use of adequate good quality concrete cover, adequate inspection, finishing, and curing of the concrete, and the proper manufacturing and handling of ECR complements the use of ECR in providing effective corrosion protection for concrete bridge decks.

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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		
in²	square inches	645.2	square millimeters	mm²
ft²	square feet	0.093	square meters	m²
yd²	square yards	0.836	square meters	m²
ac	acres	0.405	hectares	ha
mi²	square miles	2.59	square kilometers	km²
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft³	cubic feet	0.028	cubic meters	m³
yd³	cubic yards	0.765	cubic meters	m³
NOTE: Volumes greater than 1000 l shall be shown in m³.				
		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)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m²	cd/m²
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in²	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		
mm²	square millimeters	0.0016	square inches	in²
m²	square meters	10.764	square feet	ft²
m²	square meters	1.195	square yards	yd²
ha	hectares	2.47	acres	ac
km²	square kilometers	0.386	square miles	mi²
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m³	cubic meters	35.71	cubic feet	ft³
m³	cubic meters	1.307	cubic yards	yd³
		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)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m²	candela/m²	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/in²

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

(Revised September 1993)

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INTRODUCTION

The deterioration of reinforced concrete structures is a major problem. The cost of repairing or replacing deteriorated structures has become a major liability for highway agencies, estimated to be more than $20 billion and to be increasing at $500 million a year.[1] The primary cause of this deterioration is the corrosion of steel reinforcing bars due to chlorides. The two main sources of chlorides are deicing chemicals and sea water. The winter weather maintenance, bare pavement, policies of many highway agencies have resulted in extensive usage of salt-based deicing chemicals. The most common chemical used has been sodium chloride. Many bridges have also been built in coastal areas and are exposed to sea water.

The corrosion of steel reinforcing bars is an electrochemical process that requires a flow of electric current and several chemical reactions. The rate of corrosion is dependent on the availability of water, oxygen, and chloride ions, the ratio of steel surface area at the anode to that at the cathode, and the electrical resistivity of the concrete. The availability of oxygen is a function of its rate of diffusion through the concrete, which is affected by how saturated the concrete is with water. When totally submerged, the diffusion rate is slowed because the oxygen must diffuse through the pore water. When the concrete is dry, the oxygen can freely move through the pores. Alternating wet/dry cycles accelerates the corrosion process. Wet concrete has a lower resistivity than dry concrete due to the presence of water as an electrolyte.

Due to the high alkalinity of the concrete pore water, the steel reinforcing bars are passivated by an iron oxide film that protects the steel. Chloride ions reach the reinforcing steel by penetrating the concrete via the pore water and through cracks in the concrete. The chloride ions initiate corrosion by depassivating and/or penetrating the iron oxide film and reacting with iron to form a soluble iron-chloride complex.[2] When the iron-chloride complex diffuses away from the bar to an area with a higher pH and concentration of oxygen, it reacts with hydroxyl ions to form $Fe(OH)_2$, which frees the complexed chloride ions to continue the corrosion process, if the supply of available water and oxygen is adequate.[3]

The distribution of chlorides in a concrete bridge deck is not uniform. The chlorides typically enter the concrete from the top surface. The top mat of reinforcing steel is then exposed to higher concentrations of chlorides. The chlorides shift the potential of the top mat to a more negative (anodic) value. Since the potential of the bottom mat has a more positive (cathodic) value, the resulting difference in potentials sets up a galvanic type corrosion cell called a macrocell. An electric circuit is established. The concrete serves as the electrolyte and wire ties, metal chair supports, and steel bars serve as metallic conductors. Likewise the concentration of chlorides at the top mat is not uniform along the length of the steel bars due to the heterogeneity of the concrete and uneven deicer application. These differences in chloride concentrations establish anodes and cathodes on individual steel bars in the top mat and result in the formation of microcells.

The corrosion products resulting from the corrosion of steel reinforcing bars occupy a volume equal to three to six times the volume of the original steel. This increase in volume induces stresses in the concrete that result in cracks, delaminations, and spalls. This accelerates the corrosion process by providing an easy pathway for the water and chlorides to reach the steel.

Several measures have been developed and implemented to prevent the chloride-induced corrosion of steel reinforcing bars and the resulting deterioration. Some of the early measures used included lowering the water-cement ratio of the concrete and increasing the concrete cover over the steel reinforcing bars. Concrete permeability can also be reduced by the use of admixtures. Corrosion inhibitors are also being used. For most corrosion protection measures, the basic principle is to prevent the chloride ions from reacting with the steel surface and at the same time increase the time needed for the chloride ions to penetrate through the concrete cover. While these measures generally do not stop corrosion from eventually initiating, they do increase the service life of reinforced concrete structures by slowing the corrosion process.

Epoxy coated reinforcing steel (ECR) was introduced in the mid 1970's as a means to minimize concrete deterioration caused by corrosion of the reinforcing steel and to extend the useful life of highway structures. The epoxy coating is intended to prevent moisture and chlorides from reaching the surface of the reinforcing steel and reacting with the steel. It also serves to electrically isolate the steel to minimize the flow of corrosion current.

SUMMARY OF INDIVIDUAL REPORTS

This report summarizes the results of investigations performed by highway agencies in the United States and Canada, academia, and the Canadian Strategic Highway Research Program to evaluate the performance of ECR. Some of the evaluations were performed as part of early experimental applications of ECR and others as a result of new concerns about the effectiveness of ECR as a corrosion protection measure.

A total of 92 bridge decks, two bridge barrier walls, and one noise barrier wall located in the States of California, Indiana, Kansas, Michigan, Minnesota, New York, Ohio, Pennsylvania, Virginia, West Virginia, and Wisconsin, and the provinces of Alberta, Nova Scotia, and Ontario was evaluated. Bridge decks evaluated were constructed with ECR in only the top mat of reinforcing steel as well as in both the top and bottom mats of reinforcing steel. Numerous types of epoxy powders have been used in the structures evaluated: 3M Scotchkote 202, 213, and 214, Armstrong Epoxiplate R349 and R361, Dupont Flintflex 531-6080, and Cooks 270-A-009. At the time of the investigations the ECR had been in service for 3 to 20 years.

The investigations typically included field and laboratory evaluation phases. The field evaluation phases consisted of some or all of the following:

- A visual examination of the deck concrete for cracking, spalling, and patches.
- A chain drag to locate areas of delaminations.
- The use of a pachometer to determine the amount of concrete cover and to locate the top mat of reinforcing steel for concrete coring.
- Drilling for concrete powder samples for chloride content.
- Concrete coring to evaluate the quality of the concrete and for chloride content.
- Overall deck condition ratings.
- Half-cell potentials.
- Resistivity readings.
- Three-electrode linear polarization resistances to determine the rate of corrosion.

The laboratory evaluation phases consisted of some or all of the following:

- A visual examination of the concrete in the extracted cores.
- Measurement of concrete cover over the ECR in the extracted cores.

- An evaluation of the extracted ECR segments.
- Measurement of the epoxy coating thickness on the extracted ECR segments.
- Determination of total or water soluble chloride ion content in the concrete using the extracted cores or the concrete powder samples.
- Permeability of the concrete in the extracted cores.
- Determination of pH in the concrete adjacent to the ECR in the extracted cores.
- Compressive strength of the concrete in the extracted cores.
- Unit weight of concrete using the extracted cores.

CALIFORNIA

As a result of concerns about the effectiveness of ECR as a corrosion protection strategy, the State of California initiated an investigation to evaluate the performance of ECR in bridge decks. The investigation was conducted in 1992 on four of the oldest decks constructed using ECR. The results of this investigation are presented in an October 1995 draft report entitled "In Service Performance of Epoxy Coated Reinforcement In Bridge Decks."[4]

The four bridges selected are located in the mountain region of northern California. Two of the bridges have steel girder superstructures, were constructed in 1959, redecked in 1972 using bare reinforcing steel, and redecked again in 1982 using ECR. The other two bridges have concrete T-beam superstructures. One of the T-beam bridges was constructed in 1959, redecked in 1972 using bare reinforcing steel, and redecked again in 1984 using ECR. The other was constructed in 1960, redecked in 1972 using bare reinforcing steel, and redecked again in 1985 using ECR. At the time of the investigation the ECR had been in service for 7 to 10 years.

All four bridge decks evaluated were constructed with ECR in both the top and bottom mats of reinforcing steel. Epoxy powders used were Scotchkote 213 (in the T-beam bridges) and Scotchkote 214 (in the steel girder bridges) produced by the 3M Corporation. Table 1 contains a summary of background information for each of the bridges.

The investigation included a field and laboratory evaluation phase. The field evaluation phase consisted of the following:

- A visual examination of the concrete for cracking, spalling, and patches.
- A chain drag to locate areas of delaminations.
- The use of a pachometer to locate the top mat of reinforcing steel for concrete coring.
- Concrete coring to evaluate the quality of the concrete and for chloride content.

The laboratory evaluation phase consisted of the following:

- A visual examination of the concrete in the extracted cores.
- Measurement of concrete cover over the ECR in the extracted cores.
- An evaluation of the extracted ECR segments.
- Measurement of the epoxy coating thickness on the extracted ECR segments.
- Determination of total chloride content in the concrete using the extracted cores.

FINDINGS/DISCUSSION

The findings and discussion are based on the field evaluation of the bridge decks and the laboratory evaluation of cores taken from the decks. The results of the field evaluation for delaminations and the laboratory evaluations of the cores are contained in table 2. A summary of findings for each bridge is found in table 3.

Bridge Deck Condition

The decks were evaluated in the field for cracking, delaminations, and spalls. Since the Truckee River Bridge (17-13L) had been overlaid with asphalt, only a limited amount of field evaluation could be done on that bridge. The deck cracking in the other three bridges was in isolated areas and generally transverse in nature. In addition, some longitudinal cracking was found on the Truckee River Bridge (17-12L). No delaminations were detected in the Blue Canyon Undercrossing (19-115R). The other two bare concrete decks had delaminated areas of 0.3 and 1.9 m^2 (3 and 20 ft^2). Although approximately 0.4 m^2 (4 ft^2) of delaminated area was detected in the deck with the AC overlay (in the shoulders where the overlay is thinnest), it is possible other areas exist that could not be detected. No spalls were found on any of the decks.

Condition of Concrete Cores

A total of 32 cores was taken from the four bridge decks at cracks, delaminated areas, and non-cracked locations. Each of the cores were evaluated visually for extent of cracking. The extent of cracking was categorized as N, S, or H. The category, "N - No Cracks," indicated no visible cracks were observed in the concrete core. The category, "S - Shallow Cracks," indicated surface cracks did not reach the top mat of reinforcing steel. The category, "H - Heavy Cracks," indicated surface cracks extended to the top mat of reinforcing steel. Of the 32 cores, 17 were classified as having no cracks, 7 were classified as having shallow cracks, and 8 were classified as having heavy cracks. The cracks and the adjacent concrete in most of the cores showed little or no corrosion. A few cores showed slight staining of the concrete from corrosion products present at holidays and bare areas.

Depth of Concrete Cover

The depth of concrete cover over the top rebar was measured in each of the cores. Average concrete cover was found to be 41, 71, 58, and 107 mm (1.6, 2.8, 2.3, and 4.2 in) respectively for the four bridges as listed in table 3. The presence of uncoated shear connectors made it difficult to accurately locate the top mat of reinforcing steel and hence some of the cores may contain reinforcing steel from the bottom mat. This may explain the deep concrete cover in some of the cores and the high average concrete cover in the Blue Canyon Undercrossing.

Chloride Concentration

Total chloride content at the rebar level was determined using pulverized samples obtained from the concrete cores in accordance with California Test Method 404. Chloride profiles were also determined using selected cores taken from uncracked deck areas. All the average chloride concentrations at the rebar level were at or above the threshold level to initiate corrosion in black steel.

Epoxy Coating

ECR segments extracted from the cores were examined for visual defects in the coating (holidays), thickness of epoxy coating, and the blast profile on randomly selected bars. Of the 32 cores, 14 of the extracted ECR segments had visible evidence of holidays. None of the ECR segments appeared to have an excessive number of holidays. They ranged in size from small pinholes to a maximum area of about 6 by 10 mm (¼ by ⅜ in). The coating thickness and blast profiles were generally found to be acceptable under current Caltrans specifications.

Rebar Corrosion and Coating Disbondment

ECR segments extracted from the cores were examined for any coating disbondment and to determine the condition of the steel surface under the coating. Of the 32 cores, only 8 of the extracted ECR segments had experienced any corrosion. The ECR segments which experienced corrosion had visible holidays. The more heavily corroded ECR segments were from locations of relatively shallow concrete cover with high chloride concentrations. Coating disbondment was found on several ECR segments in both corroded and non-corroded areas. Except for one sample, visible holidays were present on all ECR segments that experienced coating disbondment.

<u>CA 1, Truckee River Bridge (17-12L)</u>

A total of seven cores was taken from this bridge deck. Three cores contained corroded ECR segments. All three cores had heavy cracks. The ECR segments in two of the cores experienced coating disbondment and corrosion over 100 percent of its surface area and had been exposed to very high chloride concentrations of 15.0 and 12.1 kg/m^3 (25.3 and 20.4 lb/yd^3). The

ECR segment in the third core experienced coating disbondment over 90 percent and corrosion over 85 percent of its surface area and had also been exposed to a very high chloride concentration of 9.7 kg/m^3 (16.4 lb/yd^3). All three ECR segments contained holidays. The concrete cover in all three cores was shallow: 25, 15, and 18 mm (1.0, 0.6, and 0.7 in). Except for a few isolated shallow pits at holidays, the corrosion was generally uniform. The underlying metal was discolored to black.

The ECR segment in the fourth core experienced coating disbondment over 32 percent of its surface area but no corrosion. This ECR segment contained holidays, was exposed to a relatively lower chloride concentration of only 5.1 kg/m^3 (8.6 lb/yd^3), and was from a core with shallow cracks.

The ECR segments in the other three cores did not experience any coating disbondment or corrosion on its surface. The ECR segments did not contain holidays, had been exposed to chloride concentrations of 0.4, 0.8, and 4.6 kg/m^3 (0.7, 1.4, and 7.7 lb/yd^3), and were from cores with no visible cracks.

CA 2, Truckee River Bridge (17-13L)

A total of 11 cores was taken from this bridge deck. Three cores contained corroded ECR segments but only a relatively small percentage of the rebars surface was corroded. Two of the cores did not have any visible cracks. The ECR segment in one of the uncracked cores experienced coating disbondment over 12 percent and corrosion over 3 percent of its surface area and had been exposed to a chloride concentration of 3.5 kg/m^3 (5.9 lb/yd^3). The ECR segment in the other uncracked core experienced coating disbondment over 3 percent and corrosion over 1 percent of its surface area and had been exposed to a chloride concentration of 4.3 kg/m^3 (7.3 lb/yd^3). The third core had shallow cracks. The ECR segment in this core experienced coating disbondment over 45 percent and corrosion over 6 percent of its surface area and had been exposed to a chloride concentration of 4.2 kg/m^3 (7.0 lb/yd^3). The corroded areas had only superficial discoloration at or near holidays with no corrosion products present.

The ECR segments in the fourth core experienced coating disbondment over 8 percent of its surface area and did not experience any corrosion on its surface area. It contained holidays, was exposed to a chloride concentration of 3.2 kg/m^3 (5.4 lb/yd^3), and was from a core with no visible cracks. The underlying metal was shiny.

The ECR segments in the other seven cores did not experience any coating disbondment or corrosion on its surface. All seven ECR segments did not contain holidays, had been exposed to chloride concentrations of 0.2, 0.6, 0.7, 0.9, 1.1, 1.2, and 1.5 kg/m^3 (0.4, 1.0, 1.2, 1.6, 1.8, 2.0 and 2.5 lb/yd^3), and were from cores with no visible cracks. Two of the ECR segments had been exposed to chloride concentrations below the threshold level to initiate corrosion in black steel.

CA 3. Kingvale Undercrossing (19-107R)

A total of eight cores was taken from this bridge deck. Two cores contained corroded ECR segments. Both cores had heavy cracks. The ECR segments in one of the cores experienced coating disbondment over 75 percent and corrosion over 21 percent of its surface area and had been exposed to a chloride concentration of 4.0 kg/m^3 (6.7 lb/yd^3). The ECR segment in the other core experienced coating disbondment over 75 percent and corrosion over 11 percent of its surface area and had also been exposed to a chloride concentration of 5.5 kg/m^3 (9.3 lb/yd^3). Both ECR segments contained holidays. Corrosion products present were dry and powdery.

The ECR segments in one of the cores experienced coating disbondment over 24 percent of its surface area and did not experience any corrosion on its surface area. It contained holidays, was exposed to a chloride concentration of 3.0 kg/m^3 (5.1 lb/yd^3), and was from a core with shallow cracks.

The ECR segments in five cores did not experience any coating disbondment or corrosion on its surface. Three of the ECR segments did not contain holidays and had been exposed to chloride concentrations of 1.1, 1.6, and 1.7 kg/m^3 (1.8, 2.7 and 2.8 lb/yd^3). The segment exposed to the highest concentration was from a core with no visible cracks and the other two segments were from cores with shallow cracks. The last two ECR segments contained holidays and had been exposed to chloride concentrations of 0.7 and 1.1 kg/m^3 (1.1 and 1.8 lb/yd^3). The segment exposed to the higher concentration was from a core with shallow cracks and the other segment was from a core with no visible cracks.

CA 4. Blue Canyon Undercrossing (19-115R)

A total of six cores was taken from this bridge deck. None of the cores contained corroded ECR segments. However, the ECR segments in two of the cores experienced coating disbondment over 75 and 45 percent of their surface area. The ECR segment with the 75 percent

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The overall condition of the bridge decks was considered to be good. Deck cracking did not appear to be corrosion related. Very few of the decks had any delaminations or spalls associated with the ECR. Any delaminations or spalls that were associated with corrosion of ECR were small and generally in isolated locations.

No evidence of corrosion was found on 81 percent of the ECR segments extracted from the structures. The chloride concentrations at the rebar level were generally at or above the threshold to initiate corrosion in black steel. The ECR did not appear to perform as well when the concrete was cracked as when the concrete was not cracked. Corrosion was more severe on ECR segments extracted from locations of heavy cracking, shallow concrete cover, high concrete permeability, and high chloride concentrations. Coating disbondment and softening occurred as a result of prolonged exposure to a moist environment. The number of defects in the epoxy coating and the amount of disbondment appear to influence the performance of ECR.

ECR has provided effective corrosion protection for up to 20 years of service. Little or no maintenance or repair work has been performed on the decks. There was no evidence of any significant premature concrete deterioration that could be attributed to corrosion of the ECR. The use of adequate good quality concrete cover, adequate inspection, finishing, and curing of the concrete, and the proper manufacturing and handling of ECR complements the use of ECR in providing effective corrosion protection for concrete bridge decks.

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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 yards	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)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°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	35.71	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)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°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 September 1993)

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INTRODUCTION

The deterioration of reinforced concrete structures is a major problem. The cost of repairing or replacing deteriorated structures has become a major liability for highway agencies, estimated to be more than $20 billion and to be increasing at $500 million a year.[1] The primary cause of this deterioration is the corrosion of steel reinforcing bars due to chlorides. The two main sources of chlorides are deicing chemicals and sea water. The winter weather maintenance, bare pavement, policies of many highway agencies have resulted in extensive usage of salt-based deicing chemicals. The most common chemical used has been sodium chloride. Many bridges have also been built in coastal areas and are exposed to sea water.

The corrosion of steel reinforcing bars is an electrochemical process that requires a flow of electric current and several chemical reactions. The rate of corrosion is dependent on the availability of water, oxygen, and chloride ions, the ratio of steel surface area at the anode to that at the cathode, and the electrical resistivity of the concrete. The availability of oxygen is a function of its rate of diffusion through the concrete, which is affected by how saturated the concrete is with water. When totally submerged, the diffusion rate is slowed because the oxygen must diffuse through the pore water. When the concrete is dry, the oxygen can freely move through the pores. Alternating wet/dry cycles accelerates the corrosion process. Wet concrete has a lower resistivity than dry concrete due to the presence of water as an electrolyte.

Due to the high alkalinity of the concrete pore water, the steel reinforcing bars are passivated by an iron oxide film that protects the steel. Chloride ions reach the reinforcing steel by penetrating the concrete via the pore water and through cracks in the concrete. The chloride ions initiate corrosion by depassivating and/or penetrating the iron oxide film and reacting with iron to form a soluble iron-chloride complex.[2] When the iron-chloride complex diffuses away from the bar to an area with a higher pH and concentration of oxygen, it reacts with hydroxyl ions to form $Fe(OH)_2$, which frees the complexed chloride ions to continue the corrosion process, if the supply of available water and oxygen is adequate.[3]

The distribution of chlorides in a concrete bridge deck is not uniform. The chlorides typically enter the concrete from the top surface. The top mat of reinforcing steel is then exposed to higher concentrations of chlorides. The chlorides shift the potential of the top mat to a more negative (anodic) value. Since the potential of the bottom mat has a more positive (cathodic) value, the resulting difference in potentials sets up a galvanic type corrosion cell called a macrocell. An electric circuit is established. The concrete serves as the electrolyte and wire ties, metal chair supports, and steel bars serve as metallic conductors. Likewise the concentration of chlorides at the top mat is not uniform along the length of the steel bars due to the heterogeneity of the concrete and uneven deicer application. These differences in chloride concentrations establish anodes and cathodes on individual steel bars in the top mat and result in the formation of microcells.

The corrosion products resulting from the corrosion of steel reinforcing bars occupy a volume equal to three to six times the volume of the original steel. This increase in volume induces stresses in the concrete that result in cracks, delaminations, and spalls. This accelerates the corrosion process by providing an easy pathway for the water and chlorides to reach the steel.

Several measures have been developed and implemented to prevent the chloride-induced corrosion of steel reinforcing bars and the resulting deterioration. Some of the early measures used included lowering the water-cement ratio of the concrete and increasing the concrete cover over the steel reinforcing bars. Concrete permeability can also be reduced by the use of admixtures. Corrosion inhibitors are also being used. For most corrosion protection measures, the basic principle is to prevent the chloride ions from reacting with the steel surface and at the same time increase the time needed for the chloride ions to penetrate through the concrete cover. While these measures generally do not stop corrosion from eventually initiating, they do increase the service life of reinforced concrete structures by slowing the corrosion process.

Epoxy coated reinforcing steel (ECR) was introduced in the mid 1970's as a means to minimize concrete deterioration caused by corrosion of the reinforcing steel and to extend the useful life of highway structures. The epoxy coating is intended to prevent moisture and chlorides from reaching the surface of the reinforcing steel and reacting with the steel. It also serves to electrically isolate the steel to minimize the flow of corrosion current.

SUMMARY OF INDIVIDUAL REPORTS

This report summarizes the results of investigations performed by highway agencies in the United States and Canada, academia, and the Canadian Strategic Highway Research Program to evaluate the performance of ECR. Some of the evaluations were performed as part of early experimental applications of ECR and others as a result of new concerns about the effectiveness of ECR as a corrosion protection measure.

A total of 92 bridge decks, two bridge barrier walls, and one noise barrier wall located in the States of California, Indiana, Kansas, Michigan, Minnesota, New York, Ohio, Pennsylvania, Virginia, West Virginia, and Wisconsin, and the provinces of Alberta, Nova Scotia, and Ontario was evaluated. Bridge decks evaluated were constructed with ECR in only the top mat of reinforcing steel as well as in both the top and bottom mats of reinforcing steel. Numerous types of epoxy powders have been used in the structures evaluated: 3M Scotchkote 202, 213, and 214, Armstrong Epoxiplate R349 and R361, Dupont Flintflex 531-6080, and Cooks 270-A-009. At the time of the investigations the ECR had been in service for 3 to 20 years.

The investigations typically included field and laboratory evaluation phases. The field evaluation phases consisted of some or all of the following:

- A visual examination of the deck concrete for cracking, spalling, and patches.
- A chain drag to locate areas of delaminations.
- The use of a pachometer to determine the amount of concrete cover and to locate the top mat of reinforcing steel for concrete coring.
- Drilling for concrete powder samples for chloride content.
- Concrete coring to evaluate the quality of the concrete and for chloride content.
- Overall deck condition ratings.
- Half-cell potentials.
- Resistivity readings.
- Three-electrode linear polarization resistances to determine the rate of corrosion.

The laboratory evaluation phases consisted of some or all of the following:

- A visual examination of the concrete in the extracted cores.
- Measurement of concrete cover over the ECR in the extracted cores.

- An evaluation of the extracted ECR segments.
- Measurement of the epoxy coating thickness on the extracted ECR segments.
- Determination of total or water soluble chloride ion content in the concrete using the extracted cores or the concrete powder samples.
- Permeability of the concrete in the extracted cores.
- Determination of pH in the concrete adjacent to the ECR in the extracted cores.
- Compressive strength of the concrete in the extracted cores.
- Unit weight of concrete using the extracted cores.

CALIFORNIA

As a result of concerns about the effectiveness of ECR as a corrosion protection strategy, the State of California initiated an investigation to evaluate the performance of ECR in bridge decks. The investigation was conducted in 1992 on four of the oldest decks constructed using ECR. The results of this investigation are presented in an October 1995 draft report entitled "In Service Performance of Epoxy Coated Reinforcement In Bridge Decks."[4]

The four bridges selected are located in the mountain region of northern California. Two of the bridges have steel girder superstructures, were constructed in 1959, redecked in 1972 using bare reinforcing steel, and redecked again in 1982 using ECR. The other two bridges have concrete T-beam superstructures. One of the T-beam bridges was constructed in 1959, redecked in 1972 using bare reinforcing steel, and redecked again in 1984 using ECR. The other was constructed in 1960, redecked in 1972 using bare reinforcing steel, and redecked again in 1985 using ECR. At the time of the investigation the ECR had been in service for 7 to 10 years.

All four bridge decks evaluated were constructed with ECR in both the top and bottom mats of reinforcing steel. Epoxy powders used were Scotchkote 213 (in the T-beam bridges) and Scotchkote 214 (in the steel girder bridges) produced by the 3M Corporation. Table 1 contains a summary of background information for each of the bridges.

The investigation included a field and laboratory evaluation phase. The field evaluation phase consisted of the following:

- A visual examination of the concrete for cracking, spalling, and patches.
- A chain drag to locate areas of delaminations.
- The use of a pachometer to locate the top mat of reinforcing steel for concrete coring.
- Concrete coring to evaluate the quality of the concrete and for chloride content.

The laboratory evaluation phase consisted of the following:

- A visual examination of the concrete in the extracted cores.
- Measurement of concrete cover over the ECR in the extracted cores.
- An evaluation of the extracted ECR segments.
- Measurement of the epoxy coating thickness on the extracted ECR segments.
- Determination of total chloride content in the concrete using the extracted cores.

FINDINGS/DISCUSSION

The findings and discussion are based on the field evaluation of the bridge decks and the laboratory evaluation of cores taken from the decks. The results of the field evaluation for delaminations and the laboratory evaluations of the cores are contained in table 2. A summary of findings for each bridge is found in table 3.

Bridge Deck Condition

The decks were evaluated in the field for cracking, delaminations, and spalls. Since the Truckee River Bridge (17-13L) had been overlaid with asphalt, only a limited amount of field evaluation could be done on that bridge. The deck cracking in the other three bridges was in isolated areas and generally transverse in nature. In addition, some longitudinal cracking was found on the Truckee River Bridge (17-12L). No delaminations were detected in the Blue Canyon Undercrossing (19-115R). The other two bare concrete decks had delaminated areas of 0.3 and 1.9 m^2 (3 and 20 ft^2). Although approximately 0.4 m^2 (4 ft^2) of delaminated area was detected in the deck with the AC overlay (in the shoulders where the overlay is thinnest), it is possible other areas exist that could not be detected. No spalls were found on any of the decks.

Condition of Concrete Cores

A total of 32 cores was taken from the four bridge decks at cracks, delaminated areas, and non-cracked locations. Each of the cores were evaluated visually for extent of cracking. The extent of cracking was categorized as N, S, or H. The category, "N - No Cracks," indicated no visible cracks were observed in the concrete core. The category, "S - Shallow Cracks," indicated surface cracks did not reach the top mat of reinforcing steel. The category, "H - Heavy Cracks," indicated surface cracks extended to the top mat of reinforcing steel. Of the 32 cores, 17 were classified as having no cracks, 7 were classified as having shallow cracks, and 8 were classified as having heavy cracks. The cracks and the adjacent concrete in most of the cores showed little or no corrosion. A few cores showed slight staining of the concrete from corrosion products present at holidays and bare areas.

Depth of Concrete Cover

The depth of concrete cover over the top rebar was measured in each of the cores. Average concrete cover was found to be 41, 71, 58, and 107 mm (1.6, 2.8, 2.3, and 4.2 in) respectively for the four bridges as listed in table 3. The presence of uncoated shear connectors made it difficult to accurately locate the top mat of reinforcing steel and hence some of the cores may contain reinforcing steel from the bottom mat. This may explain the deep concrete cover in some of the cores and the high average concrete cover in the Blue Canyon Undercrossing.

Chloride Concentration

Total chloride content at the rebar level was determined using pulverized samples obtained from the concrete cores in accordance with California Test Method 404. Chloride profiles were also determined using selected cores taken from uncracked deck areas. All the average chloride concentrations at the rebar level were at or above the threshold level to initiate corrosion in black steel.

Epoxy Coating

ECR segments extracted from the cores were examined for visual defects in the coating (holidays), thickness of epoxy coating, and the blast profile on randomly selected bars. Of the 32 cores, 14 of the extracted ECR segments had visible evidence of holidays. None of the ECR segments appeared to have an excessive number of holidays. They ranged in size from small pinholes to a maximum area of about 6 by 10 mm (¼ by ⅜ in). The coating thickness and blast profiles were generally found to be acceptable under current Caltrans specifications.

Rebar Corrosion and Coating Disbondment

ECR segments extracted from the cores were examined for any coating disbondment and to determine the condition of the steel surface under the coating. Of the 32 cores, only 8 of the extracted ECR segments had experienced any corrosion. The ECR segments which experienced corrosion had visible holidays. The more heavily corroded ECR segments were from locations of relatively shallow concrete cover with high chloride concentrations. Coating disbondment was found on several ECR segments in both corroded and non-corroded areas. Except for one sample, visible holidays were present on all ECR segments that experienced coating disbondment.

<u>CA 1, Truckee River Bridge (17-12L)</u>

A total of seven cores was taken from this bridge deck. Three cores contained corroded ECR segments. All three cores had heavy cracks. The ECR segments in two of the cores experienced coating disbondment and corrosion over 100 percent of its surface area and had been exposed to very high chloride concentrations of 15.0 and 12.1 kg/m^3 (25.3 and 20.4 lb/yd^3). The

ECR segment in the third core experienced coating disbondment over 90 percent and corrosion over 85 percent of its surface area and had also been exposed to a very high chloride concentration of 9.7 kg/m^3 (16.4 lb/yd^3). All three ECR segments contained holidays. The concrete cover in all three cores was shallow: 25, 15, and 18 mm (1.0, 0.6, and 0.7 in). Except for a few isolated shallow pits at holidays, the corrosion was generally uniform. The underlying metal was discolored to black.

The ECR segment in the fourth core experienced coating disbondment over 32 percent of its surface area but no corrosion. This ECR segment contained holidays, was exposed to a relatively lower chloride concentration of only 5.1 kg/m^3 (8.6 lb/yd^3), and was from a core with shallow cracks.

The ECR segments in the other three cores did not experience any coating disbondment or corrosion on its surface. The ECR segments did not contain holidays, had been exposed to chloride concentrations of 0.4, 0.8, and 4.6 kg/m^3 (0.7, 1.4, and 7.7 lb/yd^3), and were from cores with no visible cracks.

<u>CA 2, Truckee River Bridge (17-13L)</u>

A total of 11 cores was taken from this bridge deck. Three cores contained corroded ECR segments but only a relatively small percentage of the rebars surface was corroded. Two of the cores did not have any visible cracks. The ECR segment in one of the uncracked cores experienced coating disbondment over 12 percent and corrosion over 3 percent of its surface area and had been exposed to a chloride concentration of 3.5 kg/m^3 (5.9 lb/yd^3). The ECR segment in the other uncracked core experienced coating disbondment over 3 percent and corrosion over 1 percent of its surface area and had been exposed to a chloride concentration of 4.3 kg/m^3 (7.3 lb/yd^3). The third core had shallow cracks. The ECR segment in this core experienced coating disbondment over 45 percent and corrosion over 6 percent of its surface area and had been exposed to a chloride concentration of 4.2 kg/m^3 (7.0 lb/yd^3). The corroded areas had only superficial discoloration at or near holidays with no corrosion products present.

The ECR segments in the fourth core experienced coating disbondment over 8 percent of its surface area and did not experience any corrosion on its surface area. It contained holidays, was exposed to a chloride concentration of 3.2 kg/m^3 (5.4 lb/yd^3), and was from a core with no visible cracks. The underlying metal was shiny.

The ECR segments in the other seven cores did not experience any coating disbondment or corrosion on its surface. All seven ECR segments did not contain holidays, had been exposed to chloride concentrations of 0.2, 0.6, 0.7, 0.9, 1.1, 1.2, and 1.5 kg/m^3 (0.4, 1.0, 1.2, 1.6, 1.8, 2.0 and 2.5 lb/yd^3), and were from cores with no visible cracks. Two of the ECR segments had been exposed to chloride concentrations below the threshold level to initiate corrosion in black steel.

CA 3. Kingvale Undercrossing (19-107R)

A total of eight cores was taken from this bridge deck. Two cores contained corroded ECR segments. Both cores had heavy cracks. The ECR segments in one of the cores experienced coating disbondment over 75 percent and corrosion over 21 percent of its surface area and had been exposed to a chloride concentration of 4.0 kg/m^3 (6.7 lb/yd^3). The ECR segment in the other core experienced coating disbondment over 75 percent and corrosion over 11 percent of its surface area and had also been exposed to a chloride concentration of 5.5 kg/m^3 (9.3 lb/yd^3). Both ECR segments contained holidays. Corrosion products present were dry and powdery.

The ECR segments in one of the cores experienced coating disbondment over 24 percent of its surface area and did not experience any corrosion on its surface area. It contained holidays, was exposed to a chloride concentration of 3.0 kg/m^3 (5.1 lb/yd^3), and was from a core with shallow cracks.

The ECR segments in five cores did not experience any coating disbondment or corrosion on its surface. Three of the ECR segments did not contain holidays and had been exposed to chloride concentrations of 1.1, 1.6, and 1.7 kg/m^3 (1.8, 2.7 and 2.8 lb/yd^3). The segment exposed to the highest concentration was from a core with no visible cracks and the other two segments were from cores with shallow cracks. The last two ECR segments contained holidays and had been exposed to chloride concentrations of 0.7 and 1.1 kg/m^3 (1.1 and 1.8 lb/yd^3). The segment exposed to the higher concentration was from a core with shallow cracks and the other segment was from a core with no visible cracks.

CA 4. Blue Canyon Undercrossing (19-115R)

A total of six cores was taken from this bridge deck. None of the cores contained corroded ECR segments. However, the ECR segments in two of the cores experienced coating disbondment over 75 and 45 percent of their surface area. The ECR segment with the 75 percent disbonded area did not contained holidays, was exposed to a very low chloride concentration of 0.4 kg/m^3 (0.6 lb/yd^3), and was from a core with no visible cracks. The ECR segment with the 45 percent disbonded area contained holidays, was also exposed to a relatively low chloride concentration of 1.1 kg/m^3 (1.8 lb/yd^3), and was from a core with heavy cracks.

The ECR segments in the other two cores did not experience any coating disbondment or corrosion on its surface. Both segments did not contain holidays and had been exposed to low chloride concentrations of 0.7 and 0.9 kg/m^3 (1.2 and 1.6 lb/yd^3). The ECR segment exposed to the higher chloride concentration was from a core with shallow cracks and the other ECR segment was from a core with no visible cracks.

COMMENTS

Some comments on the results and findings of this investigation of four bridge decks constructed with ECR in California are:

- Based on the dates of original construction and first redecking, it appears that the use of bare reinforcing steel only provided 10 to 12 years of service life. It is possible that shallow concrete cover and a lower quality of concrete were contributing factors.
- Corrosion on the extracted ECR segments was determined to be minor in most of the extracted cores.
- Coating disbondment occurred at both corroded and non-corroded areas and was generally detected at visible holidays.
- High chloride concentrations, up to 4.6 kg/m^3 (7.7 lb/yd^3) did not initiate corrosion when there were no defects (holidays) in the coating, indicating that non-damaged epoxy coatings provide an adequate barrier to chlorides.
- Corrosion on the extracted ECR segments was more severe at locations of heavy cracking, shallow concrete cover, 15 to 25 mm (0.6 to 1.0 in), and high chloride concentrations 9.7 to 15.0 kg/m^3 (16.4 to 25.3 lb/yd^3). These ECR segments also had more epoxy coating disbondment and invariably holidays were present. Moisture/water may be present at the rebar level for a considerable length of time at cracks and shallow concrete cover locations to provide a necessary ingredient for the severe corrosion observed.

- Deck cracking did not appear to be related to corrosion of ECR. Deck cracking does appear to accelerate the corrosion process by giving chlorides and moisture easy and direct access to the ECR.
- ECR has provided effective corrosion protection for the 7 to 10 years of service with no maintenance and repair work done on the decks.

Table 1 - Bridge Decks with Epoxy Coated Rebar in California

No.	Bridge Name and Number	Bridge Type	Year Built	Year Redecked with Bare Steel	Year Redecked with ECR	Age of ECR (years)	Epoxy Powder	Mat
CA 1	Truckee River Bridge (17-12L)	Steel Girder	1959	1971	1982	10	Scotchkote 214	Both
CA 2	Truckee River Bridge (17-13L)	Steel Girder	1959	1971	1982	10	Scotchkote 214	Both
CA 3	Kingvale Undercrossing (19-107R)	T-Beam	1959	1972	1984	8	Scotchkote 213	Both
CA 4	Blue Canyon Undercrossing (19-115R)	T-Beam	1960	1972	1985	7	Scotchkote 213	Both

Table 2 - Evaluation Results for Bridge Decks with Epoxy Coated Rebar in California

No.	Delaminations (ft^2)	Epoxy Powder	Mat	Age (years)	Coating Thickness (mil)	Holidays	Disbondment (percent)	Corrosion (percent)	Clear Cover (in)	Cl^- Content[1] (lb/yd^3)	Concrete Cracking[1]
CA 1	3	Scotchkote 214	Both	10	6.3	Yes	100	100	1.0	25.3	H
					6.4	Yes	90	85	0.7	16.4	H
					7.2	No	0	0	2.4	1.4	N
					7.8	No	0	0	1.9	7.7	N
					6.8	Yes	32	0	2.6	8.6	S
					9.4	No	0	0	2.6	0.7	N
					6.5	Yes	100	100	0.6	20.4	H
CA 2	4	Scotchkote 214	Both	10	7.0	No	0	0	2.4	1.2	N
					7.7	Yes	3	1	1.6	7.3	N
					7.5	No	0	0	5.6	0.4	N
					7.4	No	0	0	2.5	1.6	N
					11.5	No	0	0	2.4	2.0	N
					8.1	Yes	12	3	2.6	5.9	N
					9.5	No	0	0	2.3	1.8	N
					8.5	No	0	0	2.6	2.5	N
					7.8	Yes	45	6	2.6	7.0	S
					6.0	Yes	8	0	3.4	5.4	N
					8.6	No	0	0	2.9	1.0	N
CA 3	20	Scotchkote 213	Both	8	10.0	Yes	75	21	2.3	6.7	H
					7.0	No	0	0	2.1	2.8	N
					8.7	Yes	0	0	2.0	1.1	N
					7.8	Yes	24	0	2.6	5.1	S
					8.2	Yes	75	11	2.3	9.3	H
					6.4	Yes	0	0	2.4	1.8	S
					6.7	No	0	0	2.4	2.7	S
					6.2	No	0	0	2.3	1.8	S
CA 4	0	Scotchkote 213	Both	7	11.9	No	0	0	5.3	0.8	H
					7.8	Yes	45	0	3.0	1.8	H
					8.2	No	75	0	4.5	0.6	N
					8.7	No	0	0	2.8	1.2	N
					14.3	No	0	0	5.0	1.6	S
					8.2	No	0	0	4.5	1.1	H

1 ft^2 = 0.0929 m^2, 1 mil = 0.0254 mm = 25.4 μm, 1 inch = 25.4 mm, 1 lb/yd^3 = 0.6 kg/m^3

1. Total chloride content at rebar level.
2. N = No Cracks - No visible cracks were observed in the concrete core.
   S = Shallow Cracks - Surface cracks did not reach the top mat.
   H = Heavy Cracks - Surface cracks extended to top mat.

Table 3 - Summary of Findings for Bridge Decks with Epoxy Coated Rebar in California

No.	Delaminations (ft^2)	Epoxy Powder	Mat	Age (years)	Average Coating Thickness (mil)	No. of ECR Segments Holidays		Average Disbondment (percent)	Average Corrosion (percent)	Average Concrete Cover (in)	Average Cl^- Content[1] (lb/yd^3)	No. of Cores Concrete Cracking[2]		
						Yes	No					N	S	H
CA 1	3	Scotchkote 214	Both	10	7.2	4	3	46	41	1.6	11.5	3	1	3
CA 2	4	Scotchkote 214	Both	10	8.1	4	7	6	1	2.8	3.3	10	1	0
CA 3	20	Scotchkote 213	Both	8	8.0	5	3	24	4	2.3	3.9	2	4	2
CA 4	0	Scotchkote 213	Both	7	9.8	1	5	20	0	4.2	1.2	2	1	3

1 ft^2 = 0.0929 m^2, 1 mil = 0.0254 mm = 25.4 μm, 1 inch = 25.4 mm, 1 lb/yd^3 = 0.6 kg/m^3

1. Total chloride content at rebar level.
2. N = No Cracks - No visible cracks were observed in the concrete core.
   S = Shallow Cracks - Surface cracks did not reach the top mat.
   H = Heavy Cracks - Surface cracks extended to top mat.

INDIANA

As a result of concerns about the effectiveness of ECR as a corrosion protection strategy, the State of Indiana initiated a study to evaluate the performance of ECR in concrete bridge decks and slabs. The study was conducted on six bridge decks and slabs constructed using ECR. The results of this study are presented in an August 1995 report entitled "Behavior of Concrete Bridge Decks and Slabs Reinforced with Epoxy-Coated Steel."[5]

The bridges included in the study are located throughout Indiana and were selected to represent various environmental conditions, traffic, and severity of deicer exposure. The first bridge constructed with epoxy coated reinforcing steel in Indiana was also included. The bridge types included in the study are continuous steel girder, continuous steel box girder, continuous prestressed concrete girder, and continuous concrete slab. Five of the decks evaluated were constructed with ECR in both the top and bottom mats of reinforcing steel and the remaining deck was constructed with ECR in only the top mat of reinforcing steel. The epoxy powders used are unknown. At the time of the study the ECR had been in service for 8 to 17 years. Table 4 contains a summary of background information for each of the bridges.

The investigation included a field and laboratory evaluation phase. The field evaluation phase consisted of the following:

- A visual examination of the deck concrete for cracking, spalling, and patches.
- A chain drag to locate areas of delaminations.
- The use of an R-meter to determine the amount of concrete cover and to locate the top mat of reinforcing steel.
- Detailed mapping of delaminations, spalls, and crack patterns.
- Drilling for concrete powder samples for chloride content.
- Concrete coring to evaluate the quality of the concrete.

The laboratory evaluation phase consisted of the following:

- A visual examination of the extracted ECR segments.
- Measurements of concrete cover over the ECR in the extracted cores.
- Compressive strength of the concrete in the extracted cores.
- Unit weight of concrete using the extracted cores.

- Determination of total chloride content in the concrete using the concrete powder samples.

FINDINGS/DISCUSSION

The findings and discussion are based on the field evaluation of the bridge decks and the laboratory evaluation of cores taken from the decks. The results of the laboratory evaluations of the cores are contained in table 5. A summary of findings for each bridge is found in table 6.

Bridge Deck Condition

The decks were evaluated in the field for cracking, delaminations, and spalls. A crack comparator card was used to estimate crack widths. Maximum crack widths ranged from 0.6 to 1.5 mm (0.025 to 0.060 in).

IN 1, Bridge No. 40-49-7032, US 40, Marion County

The deck cracking in this bridge is fairly extensive and transverse in nature. The maximum crack width is estimated to be 0.8 mm (0.030 in). No delaminations or spalls are indicated by the maps contained in the published report.

IN 2, Bridge No. 20-71-6538, US 2, St Joseph County

The deck cracking in this bridge consists of a minor amount of random cracks with no preferred orientation. The maximum crack width is estimated to be 0.6 mm (0.025 in). Some spalling on this deck was indicated by the maps contained in the published report.

IN 3, Bridge No. 31-50-2540, US 31, Marshall County

The deck cracking in this bridge consists of a fair amount of transverse crack distributed throughout the deck area. The maximum crack width is estimated to be 0.8 mm (0.030 in). No delaminations or spalls are indicated by the maps contained in the published report.

IN 4, Bridge No. 7-03-6797, SR 7, Bartholomew County

The deck cracking in this bridge is concentrated at the pier locations and is transverse in nature. Some longitudinal cracks were also found. The maximum crack width is estimated to be 0.9 mm (0.035 in). No delaminations or spalls are indicated by the maps contained in the published report.

IN 5, Bridge No. 912-45-6599, SR 912, Lake County

The deck cracking in this bridge is primarily longitudinal in nature. The widths of the two widest longitudinal cracks are estimated to be 0.6 mm (0.025 in) for one and from 0.6 to 1.5 mm (0.025 to 0.060 in) for the other. Two wide transverse cracks are present and are estimated to be 0.8 and 1.3 mm (0.030 and 0.050 in) in width. The maximum width of all the cracks found is the 1.5 mm (0.060 inch) longitudinal crack. A large spall or delaminated area was indicated by the maps contained in the published report and is located where a longitudinal and transverse crack intersect.

IN 6, Bridge No. 7-40-6527, SR 7, Jennings County

The deck cracking in this bridge is primarily longitudinal in nature and is concentrated along the centerline of the bridge. A very minor amount of transverse cracking was found. The maximum crack width is estimated to be 1.3 mm (0.050 in). Some scaling, spalling, delaminations, and a considerable amount of popouts were found on this bridge. The spalling and delamination was concentrated in one span near the railing as indicated by the maps contained in the published report. The popouts were confined to a different span.

Concrete Cores

A total of 50 cores was taken from the six decks. The cores were tested for concrete compressive strength and unit weight. The average concrete compressive strength based on tests of the 152-mm (6-inch) diameter cores ranged from 37.9 to 51.6 MPa (5495 psi to 7483 psi). The average unit weight ranged from 2327.5 to 2481.3 kg/m^3 (145.3 lb/ft^3 to 154.9 lb/ft^3).

Depth of Concrete Cover

The depth of concrete cover over the top bar was measured in each of the cores. Average concrete cover was found to be 61, 82, 62, 97, 74, and 77 mm (2.40, 3.21, 2.44, 3.82, 2.92, and 3.02 in) respectively for the six bridges as listed in table 6.

Chloride Concentration

The total chloride content at the rebar level was determined using concrete powder samples obtained from holes drilled in the decks. Chloride concentrations were determined at four depths: 0 - 25 mm (0 - 1 in), 25 - 51 mm (1 - 2 in), 51 - 76 mm (2 - 3 in), and 76 - 102 mm (3 - 4 in). Except for one bridge, the average chloride concentrations at the rebar level, 51 to 76 mm (2 - 3 in), were at or above the threshold level to initiate corrosion in black steel. Although the chloride concentration at the rebar level, 76 to 102 mm (3 - 4 in), in Bridge No. 7-03-6797, SR 7 in Bartholomew County, was below the threshold level, it was approaching it. In addition, the concrete cover in this bridge was more than the other five and therefore more time is needed for the chlorides to penetrate the concrete cover and reach the rebar level.

Rebar Corrosion and Coating Disbondment

ECR segments extracted from the cores were also examined for any coating disbondment and to determine the condition of the steel surface under the coating. None of the ECR segments showed any signs of corrosion or debonding of the epoxy coating. It was difficult to strip the coatings with a knife. Some segments were mechanically stripped of their coating and no signs of underfilm corrosion were found.

COMMENTS

Some comments on the results and findings of this study of six bridge decks constructed with ECR in Indiana are:

- The ECR segments extracted from the concrete cores showed no signs of corrosion or coating disbondment and had been exposed to chloride concentrations up to 3.0 kg/m^3 (5.0 lb/yd^3).
- The chloride concentrations at the rebar level for five of the six bridges was at or above the corrosion threshold for black steel. The chloride concentration at the rebar level in the sixth bridge was approaching the threshold level.
- The use of an adequate good quality concrete cover, adequate inspection, finishing, and curing of the concrete, and the proper manufacturing and handling of ECR complement the use of ECR in providing effective corrosion protection for concrete bridge decks.
- The combination of adequate concrete cover and ECR has provided good corrosion protection for the 8 to 17 years of service with no maintenance or repair work done on the decks.

Table 4 - Bridge Decks with Epoxy Coated Rebar in Indiana

No.	Bridge Number	Location	Year Built	Age (years)	Superstructure	Maximum Span (Ft)	Epoxy Powder	Mat
IN 1	40-49-7032	US 40 Marion County	1985	8	Continuous composite steel box girder	206	Unknown	Both
IN 2	20-71-6538	US 2 St. Joseph County	1983	10	Continuous composite prestressed concrete girder	90	Unknown	Both
IN 3	31-50-2540	US 31 Marshall County	1980	13	Continuous composite welded steel girder	62	Unknown	Both
IN 4	7-03-6797	SR 7 Bartholomew County	1985	8	Continuous concrete slab	46	Unknown	Top
IN 5	912-45-6599	SR 912 Lake County	1980	13	Continuous composite steel girder	64.5	Unknown	Both
IN 6	7-40-6527	SR 7 Jennings County	1976	17	Continuous prestressed concrete girder	73.75	Unknown	Both

1 foot = 0.3048 m

Table 5 - Evaluation Results for Bridge Decks with Epoxy Coated Rebar in Indiana

No.	Epoxy Powder	Mat	Age (years)	Span	Minimum Compressive Strength (psi)	Unit Weight (lb/ft^3)	Concrete Cover (in)	Cl^- Content[1] (lb/yd^3)				
								Span	Level			
									0-1 in	1-2 in	2-3 in	3-4 in
IN 1	Unknown	Both	8	I	6080	145.4	2.70	I	6.74	2.55	1.17	1.08
				I	6320	148.1	2.20	I	4.14	0.87	0.77	0.92
				I	3770	144.3	2.40	II	4.59	0.97	1.25	1.09
				II	6100	146.1	2.20	II	3.91	1.19	0.98	1.23
				II	4930	142.5	2.40	III	9.09	1.97	1.36	1.14
				II	7290	150.0	3.00	III	9.33	3.34	0.90	1.31
				IV	6330	149.3	2.80	IV	12.28	6.40	2.47	0.61
				IV	6330	149.2	3.00	IV	2.24	1.08	1.26	1.69
				IV	6570	147.0	1.60	V	3.48	2.38	1.34	0.91
				IV	6110	144.3	2.20	V	7.87	1.15	1.18	1.45
				V	5100	144.5	2.70	VI	3.56	1.22	1.50	0.95
				V	7020	147.1	2.50	VI	3.88	2.98	3.60	1.79
				VI	6210	142.4	2.00					
				VI	6370	145.7	1.90					
IN 2	Unknown	Both	10	B	8280	152.3	1.60	B	20.86	7.85	4.03	4.50
				B	8460	152.8	3.30	B	12.49	5.34	1.84	2.10
				C	7030	149.9	3.00	C	11.25	4.20	3.14	3.02
				C	7970	152.1	3.80	C	14.68	6.19	3.51	3.54
				D	8040	148.3	3.30	C	14.84	8.88	4.66	8.24
				D	7540	151.0	3.60	D	11.74	4.71	3.40	3.11
				E	6780	152.0	4.30	D	14.40	8.61	5.61	4.21
				E	5760	151.2	2.80	E	15.90	10.82	4.71	4.06
								E	11.45	7.36	2.71	2.97
IN 3	Unknown	Both	13	A	5990	148.8	2.50	A	25.56	14.66	6.36	2.63
				B	7160	151.0	2.60	A	18.71	7.84	1.85	1.32
				B	6190	148.3	2.30	B	23.12	12.00	1.71	1.26
				C	7370	151.0	2.80	B	1.91	8.06	1.88	1.01
				C	5910	145.6	2.00	B	20.6	10.61	4.04	2.17
								C	19.27	16.77	5.63	1.82
								C	15.15	15.12	0.99	1.03

Table 5 - Evaluation Results for Bridge Decks with Epoxy Coated Rebar in Indiana (continued)

No.	Epoxy Powder	Mat	Age (years)	Span	Minimum Compressive Strength (psi)	Unit Weight (lb/ft^3)	Concrete Cover (in)	Cl^- Content[1] (lb/yd^3)				
								Span	Level			
									0-1 in	1-2 in	2-3 in	3-4 in
IN 4	Unknown	Top	8	1	7430	153.5	3.80	1	5.17	1.38	0.92	0.70
				1	5310	155.8	3.80	1	5.54	1.71	0.68	0.72
				2	6970	165.5	4.00	2	7.70	2.40	1.26	0.85
				2	6650	158.0	3.80	2	6.62	2.18	0.79	0.70
				2	6490	157.6	4.00	3	7.88	2.44	0.81	0.70
				3	6820	149.3	3.50	3	9.90	6.61	2.09	1.13
				3	6780	144.9	-					
IN 5	Unknown	Both	13	1	5740	146.0	3.50	1	16.41	6.32	4.08	3.65
				1	4910	146.4	3.00	1	15.91	8.39	3.94	2.57
				2	4780	143.6	2.00	2	9.85	4.06	2.01	2.11
				2	6270	142.8	-	2	11.01	4.17	2.89	3.10
				3	5620	147.5	2.80	3	11.62	3.39	4.27	2.53
				3	6730	145.2	3.30	3	7.84	2.97	2.42	2.83
IN 6	Unknown	Both	17	0-1	4760	147.3	2.90	0-1	21.51	7.38	4.55	2.06
				0-1	5040	145.4	3.80	0-1	22.07	6.93	3.46	1.80
				0-1	4770	147.4	2.70	0-1	15.31	8.81	4.62	3.39
				0-1	5050	147.6	3.10	1-2	12.21	5.18	2.76	1.72
				1-2	6540	150.3	3.20	1-2	6.32	-	-	4.31
				1-2	4780	150.0	2.90	2-3	12.89	12.47	6.47	3.03
				1-2	7180	151.3	2.60	2-3	14.37	-	7.92	4.22
				2-3	5150	149.6	2.70	2-3	16.05	10.19	5.13	1.43
				2-3	5820	150.3	2.90					
				2-3	5860	148.7	3.40					

1 psi = 0.0069 Mpa, 1 lb/ft^3 = 16.0185 kg/m^3, 1 inch = 25.4 mm, 1 lb/yd^3 = 0.6 kg/m^3

1. Total chloride content.

Table 6 - Summary of Findings for Bridge Decks with Epoxy Coated Rebar in Indiana

No.	Epoxy Powder	Mat	Age (years)	Average Core Strength (psi)	Average Calculated Cylinder Strength (psi)	Average Unit Weight (lb/ft^3)	Average Concrete Cover (in)	Average Cl^- Content[1] (lb/yd^3)				Maximum Crack Width (in)
								Level				
								0-1 in	1-2 in	2-3 in	3-4 in	
IN 1	Unknown	Both	8	6038	5132	146.1	2.40	5.93	2.17	1.48	1.18	0.030
IN 2	Unknown	Both	10	7483	6360	151.2	3.21	14.18	7.11	3.73	3.97	0.025
IN 3	Unknown	Both	13	6524	5545	148.9	2.44	17.76	12.15	3.21	1.61	0.030
IN 4	Unknown	Top	8	6636	5640	154.9	3.82	7.14	2.79	1.09	0.80	0.035
IN 5	Unknown	Both	13	5675	4824	145.3	2.92	12.11	4.88	3.27	2.80	0.060
IN 6	Unknown	Both	17	5495	4670	148.8	3.02	15.09	8.49	4.99	2.75	0.050

1 psi = 0.0069 Mpa, 1 lb/ft^3 = 16.0185 kg/m^3, 1 inch = 25.4 mm, 1 lb/yd^3 = 0.6 kg/m^3

1. Total chloride content

In order to extend the useful life of reinforced concrete bridge decks, the State of Kansas implemented the use of ECR as a corrosion protection strategy. As a result of concerns about the effectiveness of ECR as a corrosion protection strategy, several evaluations of the performance of ECR in bridge decks have been performed. The results of these preliminary evaluations are documented in an October 1993 memorandum on epoxy coated reinforcing steel in Kansas and summary tables presented at the American Society for Testing and Materials Workshop on ECR held in Denver, Colorado.[6,7]

The first bridge decks using ECR as a corrosion protection measure were constructed in 1977. These initial bridges were constructed with only ECR as the corrosion protection strategy. Most bridges are now being constructed with both ECR and a low permeability, good quality concrete deck overlay. The deck overlays commonly used are dense concrete, latex modified concrete, and silica fume concrete.

FINDINGS/DISCUSSION

The findings and discussion are based on the deck condition ratings given by the bridge inspectors and the field evaluation of three bridge decks. A summary of deck condition ratings is contained in table 7.

Bridge Deck Condition

When bridge decks are inspected as part of routine periodic bridge inspections, a numeric condition rating is assigned. The rating scale ranges from one to eight. A rating of eight indicates a deck with no significant defects. A rating of one indicates a critical condition with the facility closed to traffic. A rating of six or less would indicate a problem with the reinforcing steel. Of the 213 bridges constructed with only ECR as the corrosion protection strategy, 212 were rated as a 7 or 8. The remaining bridge deck was rated as a 6. The deck distress in this bridge consisted of shallow spalls with a maximum diameter of 102 mm (4 in) and transverse cracking. No reinforcing steel was visible in the shallow spall locations.

An analysis of the most recent deck condition ratings for 757 bridges built using ECR between 1977 and 1994 was performed in 1995. Only six decks were rated as a 6, with probable evidence of deterioration associated with problems with the reinforcing steel. Five of these were built between 1980 and 1984. All of the oldest bridges constructed with ECR are rated seven and eight, good condition with minor or no concrete deterioration.

The northbound and southbound bridges on US-75 over Lower Silver Lake Road were surveyed in detail for cracking, delaminations, and spalls in 1988 after 10 years of service. Minor deck cracking was observed and it was transverse in nature. Approximately 0.1 m^2 (11 ft^2) of delaminations were detected in the northbound bridge. No delaminations were detected in the southbound bridge.

Rebar Corrosion

ECR segments extracted from two bridge decks were examined to determine the condition of the ECR. These were the northbound US 75 bridge over Lower Silver Lake Road, built in 1978 and the K-192 bridge over Dawson Creek, built in 1977. Both ECR segments were found to be equivalent to new condition. However, the chloride concentrations at the rebar level were below the threshold level to initiate corrosion in black steel. The chloride concentration in the Lower Silver Lake Road bridge deck was approximately 0.4 kg/m^3 (0.75 lb/yd^3). The chloride concentration in the Dawson Creek bridge deck was approximately 0.2 kg/m^3 (0.34 lb/yd^3).

COMMENTS

Some comments on the results and findings of the evaluations of bridge decks constructed with ECR in Kansas are:

- No corrosion was found on the two extracted ECR samples.
- Only 6 out of the 757 (1 percent) bridge decks constructed with ECR have any concrete deterioration that may be associated with corrosion of the reinforcing steel.
- The two surveyed bridges had insufficient chloride levels to initiate corrosion.
- ECR has provided effective corrosion protection for up to 16 years of service with no deck problems. A detailed field survey, including a chloride analysis, is required to determine long term performance of ECR.

Table 7 - Deck Condition Ratings for Decks with Epoxy Coated Rebar in Kansas									
Year Built	Age (years)	Condition Rating							
		6		7		8		6 - 8	
		Number	Percent	Number	Percent	Number	Percent	Number	Percent
1977-79	15-17	0	0	67	75	22	25	89	100
1980-84	10-14	5	5	129	69	49	26	183	100
1985-89	5-9	1	1	77	38	124	61	202	100
1990-94	0-4	0	0	66	23	217	77	283	100
Overall	0-17	6	1	339	45	412	54	757	100

In order to evaluate the effectiveness of ECR as a corrosion protection strategy for reinforced concrete bridge decks the State of Michigan constructed three experimental decks. An evaluation of the experimental decks was done in 1988 and 1991. As a result of new concerns about the effectiveness of ECR as a corrosion protection strategy, nine additional decks were evaluated in 1992. The results of these evaluations are presented in a March 1995 draft report entitled "A Comparison of The Corrosion Performance of Uncoated, and Epoxy Coated Reinforcing Steel in Concrete Bridge Decks."[8]

The bridges evaluated in the study were built between 1976 and 1982 and include some of the older bridge decks constructed using ECR. At the time of the investigations the ECR had been in service for 10 to 15 years. The experimental decks were constructed with ECR in both the top and bottom mats of reinforcing steel in spans 2 and 3. One span was constructed with bare steel, one span was constructed with galvanized steel and each of the remaining two spans was constructed with ECR coated with different epoxy powders. Of the nine additional decks evaluated, five were constructed with ECR in only the top mat of reinforcing steel and four were constructed with ECR in both the top and bottom mats of reinforcing steel. Epoxy powders used in the experimental decks were 3M Scotchkote 202, Dupont Flintflex 531-6080, and Cooks 270-A-009. Some unknown brown and green color epoxy powders were used in eight of the nine additional decks. The remaining deck, MI 12, used a Scotchkote epoxy powder.

The investigation included a field and laboratory evaluation phase. The field evaluation phase consisted of the following:

- A visual examination of the deck concrete for cracking, spalling, and patches.
- Use of a mechanical device developed by MDOT and hammer or chain drag to locate areas of delaminations.
- Concrete coring to evaluate the quality of the concrete and for chloride content.

The laboratory evaluation phase consisted of the following:

- A visual examination of the concrete in the extracted cores.
- Measurement of concrete cover over the ECR in the extracted cores.
- An evaluation of the extracted ECR segments.

- Determination of total chloride ion content in the concrete using the extracted cores.

FINDINGS/DISCUSSION

The findings and discussion are based on the field evaluation of the bridge decks and the laboratory evaluation of cores taken from the decks in 1991 and 1992. The results of the laboratory evaluations of the cores are contained in table 8. A summary of findings for each bridge is found in table 9. The experimental decks are identified as MI 1 to MI 3 and the additional decks are identified as MI 4 to MI 12.

Bridge Deck Condition

The decks were evaluated in the field for cracking, delaminations, and spalls. Except for a small area (less than 1 percent of the deck area) in span 2 of the Curtis Road bridge, no spalls or delaminations were detected. The following description of deck cracking in the experimental decks is based on the maps presented in the draft report. Deck cracking in the Curtis Road bridge is fairly widespread and transverse in nature. Deck cracking in the Napier Road bridge is fairly minimal and random in nature. The deck cracking in the Post Road bridge is minimal and transverse in nature. A description of the condition of the additional decks evaluated is not given in the draft report.

The three experimental decks carry lightly traveled routes over heavily traveled routes. Since significantly more deicers are used on the heavily traveled routes under the experimental decks, it was decided to evaluate the underside of these decks. No evidence of unusual cracking or spalling due to corrosion of the bottom mat of reinforcing steel was found.

Condition of Concrete Cores

A total of 49 cores was taken in 1991 and 1992 from the 12 bridge decks at cracks and random locations. Each of the cores were visually evaluated for extent of cracking. The presence of vertical and horizontal cracks, and if vertical cracks extended to the top mat of reinforcing steel was noted. Of the 49 cores, 28 (57 percent) did not have any vertical or horizontal cracking. Only one core had vertical and horizontal cracking and the vertical crack in this core extended below the top mat of reinforcing steel. The remaining cores did not have any horizontal cracking but did have vertical cracks. The vertical cracks in 2 (4 percent) cores extended below the top mat, in 10 (21 percent) cores did not extent to the top mat, and in 8 (16 percent) cores were surface cracks.

Depth of Concrete Cover

The depth of concrete cover was measured in each of the cores. Average concrete cover measured in the cores ranged from 56 to 93 mm (2.20 to 3.65 in).

Chloride Concentration

Total chloride content at the rebar level was determined using powder samples obtained from the concrete cores. Except for the Napier Road bridge, all the average total chloride concentrations at the rebar level were at or above the threshold level to initiate corrosion in black steel.

Epoxy Coating, Rebar Corrosion, and Coating Disbondment

ECR segments extracted from the cores were examined for any coating disbondment and to determine the condition of the steel surface under the coating and the extent of corrosion. The extent of corrosion was ranked on a scale from 1 to 6. A rating of 1 indicates no visible corrosion. A rating of 2 indicates some very minor amount of corrosion on the bar deformations. A rating of 3 indicates the presence of corrosion on the bar surface. The remaining ratings indicate progressively more severe corrosion with possible section loss with a rating of 6 which indicating extensive corrosion with loss of section. The worst condition ranking of all of the extracted ECR segments was a ranking of 3. Of the 47 ECR segments extracted in 1991 and 1992, 37 (79 percent) had no visible corrosion, 3 (6 percent) had a minor amount of corrosion on the bar deformations, and 7 (15 percent) had corrosion present on the bar surface. The epoxy coatings on ECR segments extracted from cores taken from the experimental decks and which contained moist concrete were easily removed by hand with the use of a fingernail.

The thickness of the epoxy coating on the ECR used in the experimental decks was measured at the time of construction. The specification limits for the epoxy thickness at that time were 127 to 229 µm (5 to 9 mil). The thickness in one of the experimental deck spans was not measured. The average thicknesses in the remaining spans were 178, 119, 170, 155, and 157 µm (7.0, 4.7, 6.7, 6.1, and 6.2 mil). All but one of these averages is within allowable limits. However, the overall range of measured thickness for all five spans was from 38 to 381 µm (1.5 to 15.0 mil) with minimum thicknesses within individual spans being 51, 51, 38, 64, and 64 µm (2.0, 2.0, 1.5, 2.5, and 2.5 mil). Therefore, it would appear that a fair number may be below the minimum thickness specified. It also appears that a fair number may be above the maximum thickness specified. Since the thickness of the epoxy coating on extracted ECR segments was not reported, if it was even measured, a relationship between insufficient coating thickness and any corrosion can not be established.

COMMENTS

Some comments on the results and findings from this investigation of 12 bridge decks constructed with ECR in Michigan are:

- The coatings did not adhere well to the ECR segments extracted from cores taken in the experimental decks. Exposed sections of coatings on ECR segments extracted from moist concrete could easily be removed.
- Of the seven ECR segments extracted from cores taken in the experimental decks five had no visible corrosion. Four of these segments were from cores taken in locations with cracks and had been exposed to chloride concentrations up to 4.1 kg/m^3 (6.9 lb/yd^3).
- Of the 31 ECR segments extracted from cores taken in the decks with only the top mat of reinforcing steel epoxy coated, 24 had no visible corrosion. Most of these segments were from cores taken in locations with no cracks and had been exposed to chloride concentrations at or above the threshold level, up to 1.7 kg/m^3 (2.9 lb/yd^3).
- Of the eight ECR segments extracted from cores taken in the decks with both the top and bottom mats of reinforcing steel epoxy coated, seven had no visible corrosion. All of these segments were from cores taken in locations with cracks and had been exposed to chloride concentrations up to 3.4 kg/m^3 (5.8 lb/yd^3).
- A comparison of the performance of ECR in the decks with only the top mat of reinforcing steel epoxy coated with that of ECR in decks with both the top and bottom mat of reinforcing steel epoxy coated suggests superior performance when both mats are epoxy coated. However, the decks with both mats epoxy coated are about 5 years younger and it may be too soon to verify any improved performance.
- ECR has provided effective corrosion protection for the 10 to 15 years of service with no signs of deterioration of the concrete deck due to corrosion of the reinforcing steel.

Table 8 - Evaluation Results for Bridge Decks with Epoxy Coated Rebar in Michigan

No.	Location	Year Built	Age (years)	Epoxy Powder	Mat	Span	Reinforcement Condition[1] (ranking)	Clear Cover (in)	Cl^- Content[2] (lb/yd^3)	Concrete Cracking[3] (Vertical/ Horizontal)	Spalls and Delaminations (percent)
MI 1	Curtis Road	1976	15	Scotchkote 202	Both	2	1	3.25	6.0	Yes/No[6]	<1
							1	2.50	7.7	Yes/No[6]	
				Flintflex 531-6080	Both	3	3	3.00	10.8	Yes/No	0
MI 2	Napier Road	1976	15	Scotchkote 202	Both	2	1	2.40	0.2	Yes/No[6]	0
				Flintflex 531-6080	Both	3	NR	2.80[4]	0.3[4]	NR	0
MI 3	Post Road	1976	15	Scotchkote 202	Both	2	1	3.60	3.0	No/No	0
							1	2.65	4.2	Yes/No[6]	
				Cooks 270-A-009	Both	3	3	2.20	7.3	Yes/Yes[7]	0
MI 4	US 31 Over Muskegon River	1977	15	Brown Color	Top	1	NR	3.00[5]	0.8	No/No	0
							2	3.00[5]	3.0	Yes/No	
							3	3.00[5]	7.0	Yes/No	
						2	3	3.00[5]	6.2	No/No	0
						3	2	3.00[5]	4.6	Yes/No	0
							NR	3.00[5]	1.3	No/No	
MI 5	M99 Over Grand River	1978	14	Green Color	Top	1	3	3.00[5]	1.5	No/No	0
							1	3.00[5]	1.1	No/No	
							1	3.00[5]	2.2	No/No	
						2	1	3.00[5]	1.3	No/No	0
							1	3.00[5]	1.1	No/No	
						3	1	3.00[5]	1.0	No/No	0
							1	3.00[5]	1.4	No/No	
MI 6	I475 Under Leith Street	1977	15	Green Color	Top	1	3	3.00[5]	6.1	Yes/No	0
							1	3.00[5]	0.9	No/No	
						2	3	3.00[5]	3.8	Yes/No	0
							1	3.00[5]	1.2	No/No	
						3	1	3.00[5]	4.6	Yes/No	0
							1	3.00[5]	0.9	No/No	

Table 8 - Evaluation Results for Bridge Decks with Epoxy Coated Rebar in Michigan (continued)

No.	Location	Year Built	Age (years)	Epoxy Powder	Mat	Span	Reinforcement Condition[1] (ranking)	Clear Cover (in)	Cl^- Content[2] (lb/yd^3)	Concrete Cracking[3] (Vertical/ Horizontal)	Spalls and Delaminations (percent)
MI 7	M37 Over Calvin College Service Road	1978	14	Brown Color	Top	1	1	3.00[5]	1.4	No/No	0
							1	3.00[5]	0.9	No/No	
							1	3.00[5]	0.9	No/No	
							1	3.00[5]	0.9	No/No	
							1	3.00[5]	1.0	No/No	
							1	3.00[5]	1.1	No/No	
MI 8	I475 Under Saginaw Street	1977	15	Green Color	Top	1	1	3.00[5]	2.6	No/No	0
							1	3.00[5]	0.9	No/No	
						2	1	3.00[5]	1.1	No/No	0
							1	3.00[5]	0.9	No/No	
						3	1	3.00[5]	1.2	No/No	0
							1	3.00[5]	0.9	No/No	
						4	1	3.00[5]	1.3	No/No	0
							1	3.00[5]	0.9	No/No	
MI 9	M29 Over Belle River	1982	10	Green Color	Both	1	1	3.80	6.6	Yes/No[6]	0
							1	3.80	5.9	Yes/No	
						3	1	3.30	2.4	Yes/No[6]	0
MI 10	M19 Over I69	1982	10	Brown Color	Both	1	1	3.70	4.1	Yes/No[6]	0
						2	1	3.60	3.4	Yes/No[6]	0
MI 11	I94 (EB) Exit Ramp Over Pelham Road	1982	10	Brown Color	Both	1	1	3.00[5]	3.0	Yes/No[7]	0
							2	3.25[5]	2.2	Yes(P)/No[7]	
MI 12	US12 (Business Rte.) Over US12	1982	10	Scotchkote	Both	1	1	3.00	6.5	Yes/No[6]	0
						3	1	3.00	5.1	Yes/No[6]	0

1 inch = 25.4 mm, 1 lb/yd^3 = 0.6 kg/m^3

1. Condition ranked on a scale from 1 (no visible corrosion) to 6 (major corrosion). NR - No data reported.
2. Total chloride content.
3. In cores, P, when used, indicates cracking perpendicular to top mat. NR - No data reported.
4. Data at 12 years of age.
5. Clear cover not available, depth of Cl^- content instead.
6. Vertical crack does not extend to top mat.
7. Vertical crack extends below top mat.

Table 9 - Summary of Findings for Bridge Decks with Epoxy Coated Rebar in Michigan														
No.	Age (years)	Epoxy Powder	Mat	No. of ECR Segments By Reinforcement Condition			Average Clear Cover (in)	Average Cl^- Content[2] (lb/yd^3)	No. of Cores By Concrete Cracking					Spalls and Delaminations (percent)
				Ranking[1]					Vertical/Horizontal					
				1	2	3			Yes/ Yes[4]	Yes/ No	Yes/ No[3]	Yes/ No[4]	No/ No	
MI 1	15	Scotchkote 202	Both	2	0	0	2.88	6.9	0	0	2	0	0	<1
		Flintflex 531-6080	Both	0	0	1	3.00	10.8	0	1	0	0	0	0
MI 2	15	Scotchkote 202	Both	1	0	0	2.40	0.2	0	0	1	0	0	0
		Flintflex 531-6080	Both	0	0	0	2.80[5]	0.3[5]	0	0	0	0	0	0
MI 3	15	Scotchkote 202	Both	2	0	0	3.13	3.6	0	0	1	0	1	0
		Cooks 270-A-009	Both	0	0	1	2.20	7.3	1	0	0	0	0	0
MI 4	15	Brown Color	Top	0	2	2	3.00[6]	3.8	0	3	0	0	3	0
MI 5	14	Green Color	Top	6	0	1	3.00[6]	1.4	0	0	0	0	7	0
MI 6	15	Green Color	Top	4	0	2	3.00[6]	2.9	0	3	0	0	3	0
MI 7	14	Brown Color	Top	6	0	0	3.00[6]	1.0	0	0	0	0	6	0
MI 8	15	Green Color	Top	8	0	0	3.00[6]	1.2	0	0	0	0	8	0
MI 9	10	Green Color	Both	3	0	0	3.63	5.0	0	1	2	0	0	0
MI 10	10	Brown Color	Both	2	0	0	3.65	3.8	0	0	2	0	0	0
MI 11	10	Brown Color	Both	1	1	0	3.13[6]	2.6	0	0	0	2[7]	0	0
MI 12	10	Scotchkote	Both	2	0	0	3.00	5.8	0	0	2	0	0	0

1 inch = 25.4 mm, 1 lb/yd^3 = 0.6 kg/m^3

1. Condition ranked on a scale from 1 (no visible corrosion) to 6 (major corrosion).
2. Total chloride content.
3. Vertical crack does not extend to top mat.
4. Vertical crack extends below top mat.
5. Data at 12 years of age.
6. Clear cover not available, depth of Cl^- content instead.
7. In one core cracking was perpendicular to top mat.

MINNESOTA

As a result of concerns about the effectiveness of ECR as a corrosion protection strategy, the State of Minnesota initiated an investigation to evaluate the performance of ECR in bridge decks. The investigation was conducted in 1992 on 11 bridge decks constructed using ECR. The results of this investigation are presented in an April 1994 report entitled "Field Examination of Epoxy Coated Rebars In Concrete Bridge Decks."[9]

Ten of the bridges selected are located on I-35E south of St. Paul and were built in the late 1970's. In addition, one other bridge built in 1974 and located in Inner Grove Heights was selected since it is the first bridge deck built with ECR in Minnesota. The structure types are steel girders and prestressed concrete girders. At the time of the investigation the ECR had been in service for about 15 to 20 years. All the bridge decks evaluated were constructed with ECR in only the top mat of reinforcing steel.

The investigation included a field and laboratory evaluation phase. The field evaluation phase consisted of a visual examination of the deck concrete for cracks and concrete coring. The laboratory evaluation phase consisted of a visual examination of the extracted concrete cores.

FINDINGS/DISCUSSION

The findings and discussion are based on the field evaluation of the bridge decks and the laboratory evaluation of cores.

Bridge Deck Condition

The decks were evaluated in the field for cracking. The decks on the prestressed concrete girder bridges had a few hairline cracks. The decks on the steel girder bridges had numerous transverse cracks. The first bridge deck built with ECR showed no apparent signs of distress.

Concrete Cores and Rebar Corrosion

A total of 10 cores, 1 from each deck, was taken from 10 of the decks at cracked locations. The first bridge deck built with ECR was not cored. ECR segments extracted from the cores were examined for any coating disbondment and to determine the condition of the steel surface under the coating. One of the cores was taken in the original portion of a bridge that had been widened and contained an uncoated reinforcing bar. This uncoated rebar had a considerable amount of corrosion product and an apparent loss of section. Of the remaining nine cores with ECR segments, only one segment showed any signs of corrosion. An area on the bar of about 25.4 mm (1 in) in length was covered with rust. Removal of the rust revealed an area of approximately ⅛ inch in diameter with corrosion concurrent with a holiday in the epoxy coating.

COMMENTS

Some comments on the results and findings of this investigation of 11 bridge decks constructed with ECR in Minnesota are:

- None of the decks had any delaminations and/or spalls.
- None of the decks had any cracks due to corrosion of ECR.
- Significant corrosion of ECR was not discovered in any of the bridges.
- ECR has provided effective corrosion protection for the 10 to 20 years of service. No signs of distress were found in the first bridge deck built with ECR after 20 years of service.

NEW YORK

As a result of concerns about the effectiveness of ECR as a corrosion protection strategy, the State of New York initiated an investigation to evaluate the performance of ECR in bridge decks. The investigation was conducted in 1990 on 14 of the older decks constructed using ECR. The results of this investigation are presented in a June 1992 report entitled "In-Service Performance of Epoxy-Coated Steel Reinforcement in Bridge Decks."[10]

The structures included in the study are located throughout New York State and were selected to represent a "worst case." All of the bridges selected were known to have deck surface distress. At the time of the investigation the ECR had been in service for 7 to 12 years.

All 14 bridge decks evaluated were constructed with ECR in only the top mat of reinforcing steel. Epoxy powders used were 3M Scotchkote 213, 3M Scotchkote 214, and Armstrong Epoxiplate R349. Table 10 contains a summary of background information for each of the bridges.

The investigation included a field and laboratory evaluation phase. The field evaluation phase consisted of the following:

- A visual examination of the deck concrete for cracking, spalling, and patches.
- A chain drag to locate areas of delaminations.
- Limited use of a pachometer to determine the amount of concrete cover.
- Concrete coring to evaluate the quality of the concrete and for chloride content.

The laboratory evaluation phase consisted of the following:

- A visual examination of the concrete in the extracted cores.
- Measurement of concrete cover over the ECR in the extracted cores.
- An evaluation of the extracted ECR segments.
- Measurement of the epoxy coating thickness on the extracted ECR segments.
- Determination of total chloride ion content in the concrete using the extracted cores.
- Determination of pH in the concrete adjacent to the ECR in the extracted cores.

FINDINGS/DISCUSSION

The findings and discussion are based on the field evaluation of the bridge decks and the laboratory evaluation of cores taken from the decks. The results of the laboratory evaluations of the cores are contained in table 11. A summary of findings for each bridge is found in table 12.

Bridge Deck Condition

The decks were evaluated in the field for cracking, delaminations, and spalls. Deck cracking was generally transverse and extended over the width of the travel lane. Only one delamination was detected in a 9 year old deck (Bridge Number 1070700, NY 9). The area of this delamination was 0.2 m^2 (2 ft^2). A core taken at this location showed the delamination was not at the reinforcing steel level and therefore was not related to bar corrosion. No spalls were found on any of the decks.

Condition of Concrete Cores

A total of 54 cores was taken from the 14 bridge decks at cracks, delaminations, patches, and areas with no surface distress. Each of the cores were visually evaluated for extent of cracking. The extent of cracking was categorized as N, S, or D. The category, "N - No Crack," indicated no visible cracks were observed in the concrete core. The category, "S - Shallow Crack," indicated a surface crack did not reach the top mat of reinforcing steel. The category, "D - Deep Crack," indicated a surface crack extended to the top mat of reinforcing steel. Of the 54 cores, 24 (44 percent) were classified as having no cracks, 10 (19 percent) were classified as having shallow cracks, and 20 (37 percent) were classified as having deep cracks.

Depth of Concrete Cover

The depth of concrete cover was measured in each of the cores. Average concrete cover measured in the 54 cores was 73 mm (2.873 in) and ranged from 41 to 108 mm (1.625 to 4.250 in).

Chloride Concentration and pH Level

Total chloride content at the rebar level was determined using powder samples obtained from the concrete cores. The average chloride concentrations at the rebar level for 11 of the bridges were at or above the threshold level to initiate corrosion in black steel. They are NY 1, 4 through 7, and 9 through 14 as identified in table 12. The chloride contents reported here in kilograms per cubic metre (pounds per cubic yard) are converted from the values in the New York report (ppm) using a concrete weight of 2400 kg/m^3 (4000 lb/yd^3, conversion factor of 0.004). The pH levels ranged from 11.7 to 12.0 and averaged 12.0.

Epoxy Coating

The thickness of epoxy coating on each of the ECR segments extracted from the cores was measured in a minimum of four locations. The average coating thickness of all 54 segments was 228 μm (8.99 mil) and ranged from 127 to 349 μm (5.00 to 13.75 mil). Although all of the segments met the specification for minimum thickness, 127 μm (5 mil), the specification for the maximum thickness, 229 μm (9 mil), was exceeded on 20 segments.

Rebar Corrosion and Coating Disbondment

ECR segments extracted from the cores were also examined for any coating disbondment and to determine the extent of corrosion. The extent of corrosion was described as N, R, or B. The description, "N - Negligible Corrosion," indicated no corrosion or any spots of corrosion on the body of the bar were less than 6 by 6 mm (¼ by ¼ in). The category, "R - Rib Corrosion," indicated corrosion limited to the ribs of the bar and any spots of corrosion on the body of the bar were less than 6 by 6 mm (¼ by ¼ in). The category, "B - Bar Corrosion," indicated corrosion on the ribs and one or more areas on the body of the bar were greater than 6 by 6 mm (¼ by ¼ in). Of the 54 segments, 35 (65 percent) had negligible corrosion, 16 samples (30 percent) had rib corrosion, and only 3 (5 percent) had bar corrosion. The areas of corrosion were normally found on the top or sides of bars exposed to deck cracks. The severity of corrosion was superficial and none of the segments showed complete coating deterioration or had pits or loss of steel section. The epoxy coating adjacent to corroded areas had not been undercut.

<u>NY 1, 1000530, Route 3, Le Ray</u>

A total of two cores was taken from this bridge deck. ECR segments in both cores had rib corrosion and had been exposed to chloride concentrations of 0 and 2.6 kg/m^3 (0 and 4.3 lb/yd^3). Both cores had a deep crack. For the ECR segment not exposed to chlorides, the rib corrosion may have been present at the time of construction.

<u>NY 2, 1000540, Route 3, Rutland</u>

One core was taken from this bridge deck. The ECR segment in the core had no corrosion. However, it also had not yet been exposed to any chlorides. The core did not have any visible cracks.

<u>NY 3, 1017600, Route 23, Davenport</u>

A total of six cores was taken from this bridge deck. ECR segments in the cores had no corrosion and had been exposed to chloride concentrations at or below the threshold level, 0, 0, 0.1, 0.2, 0.9, and 1.0 kg/m^3 (0, 0, 0.1, 0.3, 1.6, and 1.7 lb/yd^3). Four of the cores did not have any visible cracks, one core had a shallow crack, and one core had a deep crack.

NY 4, 1027060, Route 55, Neversink

A total of nine cores was taken from this bridge deck. The ECR segment in one core had bar corrosion and had been exposed to a chloride concentration of 6.8 kg/m^3 (11.4 lb/yd^3). This core had a deep crack. The ECR segment in three cores had rib corrosion and had been exposed to chloride concentrations of 1.8, 2.7, and 3.9 kg/m^3 (3.1, 4.6, and 6.6 lb/yd^3). These cores each had a deep crack. The remaining five ECR segments had no corrosion and had been exposed to chloride concentrations of 1.2, 2.2, 2.6, 2.7, and 3.8 kg/m^3 (2.1, 3.7, 4.4, 4.6, and 6.4 lb/yd^3). These cores each had one of the three crack conditions.

NY 5, 1040070, Route 200, Harford

A total of three cores was taken from this bridge deck. The ECR segment in two cores had rib corrosion and had been exposed to chloride concentrations of 3.6 and 4.4 kg/m^3 (6.0 and 7.4 lb/yd^3). The core with the lower chloride content had a deep crack and the other had a shallow crack. The ECR segment in one core had no corrosion and had been exposed to a chloride concentration of 0.5 kg/m^3 (0.9 lb/yd^3). This core did not have any visible cracks.

NY 6, 1040080, Route 200, Harford

A total of two cores was taken from this bridge deck. The ECR segments in both cores had no corrosion and had been exposed to chloride concentrations were 5.8 and 7.6 kg/m^3 (9.7 and 12.8 lb/yd^3). The cores did not have any visible cracks. The ECR segment exposed to the higher chloride concentration also had shallow concrete cover, 41 mm (1.625 in).

NY 7, 1052020, Route 365, Barneveld

A total of two cores was taken from this bridge deck. The ECR segments in both cores had no corrosion and had been exposed to chloride concentrations of 2.9 and 7.3 kg/m^3 (4.9 and 12.3 lb/yd^3). The core with the higher chloride content did not have any visible cracks and the other core had a deep crack.

NY 8, 1069800, Ramp, Rome

A total of two cores was taken from this bridge deck. The ECR segments in both cores had no corrosion and had been exposed to chloride concentrations below the threshold value, 0.2

and 0.5 kg/m^3 (0.4 and 0.9 lb/yd^3). The core with the higher chloride content did not have any visible cracks and the other core had a shallow crack.

NY 9, 1070700, Route 88I, Duanesburg

A total of two cores was taken from this bridge deck. The ECR segment in one core had bar corrosion and had been exposed to a chloride concentration of 6.2 kg/m^3 (10.4 lb/yd^3). The ECR segment in the other core had rib corrosion and had been exposed to a chloride concentrations of 4.3 kg/m^3 (7.3 lb/yd^3). Both cores had a deep crack .

NY 10, 107086C, Route 787I, Troy

A total of two cores was taken from this bridge deck. The ECR segment in one core had rib corrosion and had been exposed to a chloride concentration of 2.0 kg/m^3 (3.3 lb/yd^3). This core had a deep crack. The ECR segment in the other core had no corrosion and had been exposed to a chloride concentration of 0.9 kg/m^3 (1.6 lb/yd^3). This core did not have any visible cracks.

NY 11, 1071010, Main, Oneonta

A total of seven cores was taken from this bridge deck. The ECR segment in one core had bar corrosion and had been exposed to a chloride concentration of 2.4 kg/m^3 (4.0 lb/yd^3). The ECR segment in two cores had rib corrosion and had been exposed to chloride concentrations of 0.7 and 3.0 kg/m^3 (1.1 and 5.0 lb/yd^3). These three cores each had a deep crack. The remaining four ECR segments had no corrosion and had been exposed to chloride concentrations below the threshold level for black steel, 0.2, 0.2, 0.5, and 0.5 kg/m^3 (0.3, 0.4, 0.9 and 0.9 lb/yd^3). Three of these cores did not have any visible cracks and the other core had a shallow crack.

NY 12, 1071111, Route 390I, Avon

A total of nine cores was taken from this bridge deck. The ECR segment in four cores had rib corrosion crack and had been exposed to chloride concentrations of 3.4, 3.9, 4.5, and 5.7 kg/m^3 (5.7, 6.6, 7.6, and 9.6 lb/yd^3). The core with the lowest chloride content had a shallow crack and the other cores each had a deep crack. The remaining five ECR segments had no corrosion and had been exposed to chloride concentrations of 0.4, 0.9, 1.4, 3.0, and 3.7 kg/m^3 (0.6, 1.6, 2.4, 5.1, and 6.3 lb/yd^3). The two cores with the lowest chloride contents did not have any visible cracks and the other cores each had a shallow crack.

NY 13, 1072300, Conn, Islip

A total of three cores was taken from this bridge deck. The ECR segment in one core had rib corrosion and had been exposed to a chloride concentration of 2.3 kg/m^3 (3.9 lb/yd^3). This core had a deep crack. The ECR segments in the other cores had no corrosion and had not yet been exposed to chlorides. These cores did not have any visible cracks.

NY 14, 3312170, Route 23, Cincinnatus

A total of four cores was taken from this bridge deck. The ECR segment in all four cores had no corrosion and had been exposed to chloride concentrations of 1.0, 1.2, 1.4, and 4.2 kg/m^3 (1.7, 2.1, 2.3, and 7.1 lb/yd^3). The core with the lowest chloride content had a shallow crack and other cores did not have any visible cracks.

COMMENTS

Some comments on the results and findings from this investigation of 14 bridge decks constructed with ECR in New York are:

- Coating deterioration and loss of steel section was not found on any of the ECR segments.
- Bar corrosion was found on only 3 of the 54 extracted ECR segments. All three of these segments were from cores taken in locations with deep cracks and had been exposed to high chloride concentrations up to 6.8 kg/m^3 (11.4 lb/yd^3). Corrosion products were not sufficient to crack the concrete or cause any other deterioration.
- A significant number of ECR segments had rib corrosion and had been exposed to a variable chloride concentration from zero to as high as 5.7 kg/m^3 (9.6 lb/yd^3). It appears that some of the rib corrosion in some of the ECR segments may have been present at the time of construction. Corrosion had not progressed away from the corroded area. No coating undercutting or disbondment was found in these ECR segments.
- There was more corrosion activity on ECR segments extracted from cores taken at locations where the deck was cracked. It appears that the epoxy coating did not perform well when the concrete was cracked. The cracks provide the chlorides and moisture an easy and direct access to the ECR as opposed to the normal diffusion process through sound concrete.
- Even with high chloride concentrations up to 7.6 kg/m^3 (12.8 lb/yd^3), only negligible

corrosion was found on ECR segments extracted from cores taken in uncracked locations. The lack of cracks appears to hinder the corrosion process.

- ECR has provided effective corrosion protection for the 7 to 12 years of service, corrosion was not a problem in any of the decks evaluated.

Table 10 - Bridge Decks with Epoxy Coated Rear in New York

No.	Bridge Number	Route	City, Town, Village	Year Built or Reconstructed with ECR	Age (years)	No. of Spans	Length (ft)	Epoxy Powder	Mat
NY 1	1000530	3	Le Ray	1983[2]	7	2	167	Scotchkote 214	Top
NY 2	1000540	3	Rutland	1983[2]	7	3	224	Scotchkote 214	Top
NY 3	1017600	23	Davenport	1979[1]	11	2	218	Scotchkote 213	Top
NY 4	1027060	55	Neversink	1978[2]	12	6	283	Scotchkote 213	Top
NY 5	1040070	200	Harford	1979[2]	11	1	84	Scotchkote 213	Top
NY 6	1040080	200	Harford	1979[2]	11	1	38	Scotchkote 213	Top
NY 7	1052020	365	Barneveld	1979[2]	11	1	62	Scotchkote 213	Top
NY 8	1069800	Ramp	Rome	1980[1]	10	1	100	Armstrong R349	Top
NY 9	1070700	88I	Duanesburg	1981[1]	9	2	298	Scotchkote 213	Top
NY 10	107086C	787I	Troy	1981[1]	9	7	1093	Armstrong R349	Top
NY 11	1071010	Main	Oneonta	1979[1]	11	3	341	Scotchkote 213	Top
NY 12	1071111	390I	Avon	1980[1]	10	4	863	Scotchkote 213	Top
NY 13	1072300	Conn	Islip	1983[1]	7	3	269	Scotchkote 214	Top
NY 14	3312170	23	Cincinnatus	1981[1]	9	2	187	Armstrong R349	Top

1 foot = 0.3048 m

1. Year built.
2. Year reconstructed.

Table 11 - Evaluation Results for Bridge Decks with Epoxy Coated Rebar in New York											
No.	Epoxy Powder	Mat	Age (years)	Span	Coating Thickness (mil)	Extent of Corrosion[1]	Condition[2]	Concrete Cover (in)	Cl⁻ Content[3]		pH
									(ppm)	(lb/yd^3)	
NY 1	Scotchkote 214	Top	7	1	7.00	R	D	4.000	0	0	12.0
				1	7.90	R	D	2.500	1070	4.3	12.0
NY 2	Scotchkote 214	Top	7	1	6.50	N	N	2.250	0	0	12.1
NY 3	Scotchkote 213	Top	11	1	5.75	N	N	2.000	392	1.6	12.0
				1	9.25	N	D	2.250	428	1.7	11.9
				1	8.00	N	S	2.750	71	0.3	12.0
				2	8.50	N	N	2.750	36	0.1	11.8
				2	8.75	N	N	3.250	0	0	11.9
				2	8.50	N	N	3.250	0	0	11.9
NY 4	Scotchkote 213	Top	12	1	12.00	R	D	3.000	785	3.1	11.8
				1	7.50	N	N	2.375	1606	6.4	11.9
				1	9.00	R	D	3.000	1641	6.6	11.7
				2	13.75	N	N	3.250	928	3.7	11.8
				2	10.50	B	D	2.375	2854	11.4	11.8
				2	8.75	N	D	3.125	1142	4.6	11.9
				3	7.25	N	S	3.000	1106	4.4	11.9
				3	8.25	R	D	3.000	1142	4.6	11.9
				3	5.00	N	N	3.000	535	2.1	11.9
NY 5	Scotchkote 213	Top	11	1	9.50	R	D	2.750	1499	6.0	12.1
				1	11.25	N	N	2.000	214	0.9	11.9
				1	7.00	R	S	2.250	1855	7.4	11.9
NY 6	Scotchkote 213	Top	11	1	13.00	N	N	1.625	3211	12.8	11.9
				1	11.25	N	N	2.375	2426	9.7	12.0
NY 7	Scotchkote 213	Top	11	1	8.75	N	N	2.000	3068	12.3	11.9
				1	8.75	N	D	2.125	1213	4.9	12.0
NY 8	Armstrong R349	Top	10	1	7.75	N	N	2.000	214	0.9	12.1
				1	9.25	N	S	2.000	103	0.4	12.0
NY 9	Scotchkote 213	Top	9	1	10.25	B	D	3.000	2605	10.4	12.0
				2	12.00	R	D	2.250	1820	7.3	12.1
NY 10	Armstrong R349	Top	9	1	8.49	N	N	2.875	392	1.6	11.8
				2	7.65	R	D	3.250	821	3.3	11.9

Table 11 - Evaluation Results for Bridge Decks with Epoxy Coated Rebar in New York (continued)

No.	Epoxy Powder	Mat	Age (years)	Span	Coating Thickness (mil)	Extent of Corrosion[1]	Condition[2]	Concrete Cover (in)	Cl^- Content[3] (ppm)	Cl^- Content[3] (lb/yd^3)	pH
NY 11	Scotchkote 213	Top	11	1	12.50	B	D	4.250	999	4.0	12.0
				1	9.75	N	N	4.000	107	0.4	12.0
				2	12.25	N	N	3.375	71	0.3	12.0
				2	10.75	N	S	4.250	214	0.9	12..0
				3	8.50	R	D	4.250	285	1.1	11.9
				3	8.50	N	N	3.750	214	0.9	11.9
				3	11.50	R	D	4.250	1249	5.0	12.0
NY 12	Scotchkote 213	Top	10	1	8.80	R	D	3.250	1891	7.6	12.0
				1	7.90	R	D	3.125	2391	9.6	12.0
				2	7.70	R	S	3.500	1427	5.7	12.1
				3	7.30	R	D	3.000	1641	6.6	12.2
				3	7.00	N	N	2.250	392	1.6	12.0
				3	7.40	N	S	3.250	607	2.4	12.0
				4	8.90	N	S	3.000	1570	6.3	12.1
				4	8.90	N	N	2.625	143	0.6	12.0
				4	7.60	N	S	3.375	1284	5.1	12.1
NY 13	Scotchkote 214	Top	7	1	5.80	R	D	3.375	963	3.9	12.0
				1	7.30	N	N	2.875	0	0	11.8
				2	6.90	N	N	3.250	0	0	12.1
NY 14	Armstrong R349	Top	9	1	11.25	N	S	2.000	428	1.7	12.0
				1	11.25	N	N	2.375	571	2.3	12.0
				2	9.75	N	N	2.375	535	2.1	11.9
				2	10.75	N	N	1.750	1784	7.1	12.0

1 mil = 0.0254 mm = 25.4 μm, 1 inch = 25.4 mm, 1 lb/yd^3 = 0.6 kg/m^3

1. N - Negligible Corrosion, no corrosion or any spots of corrosion on the body of the bar were less than ¼ in by ¼ in.
   R - Rib Corrosion, corrosion limited to the ribs of the bar and any spots of corrosion on the body of the bar were less than ¼ in by ¼ in.
   B - Bar Corrosion , indicated corrosion on the ribs and one or more areas on the body of the bar were greater than ¼ in by ¼ in.
2. N - No Crack, no visible cracks were observed in the concrete core.
   S - Shallow Crack, surface crack did not reach the top mat of reinforcing steel.
   D - Deep Crack, surface crack extended to the top mat of reinforcing steel.
3. Total chloride content.

Table 12 - Summary of Findings for Bridge Decks with Epoxy Coated Rebar in New York

No.	Epoxy Powder	Mat	Age (years)	Average Coating Thickness (mil)	Number of ECR Segments Extent of Corrosion[1]			Number of Cores Condition[2]			Average Concrete Cover (in)	Average Cl^- Content[3]		Average pH
					N	R	B	N	S	D		(ppm)	(lb/yd^3)	
NY 1	Scotchkote 214	Top	7	7.45	0	2	0	0	0	2	3.25	535	2.1	12.0
NY 2	Scotchkote 214	Top	7	6.50	1	0	0	1	0	0	2.25	0	0	12.1
NY 3	Scotchkote 213	Top	11	8.13	6	0	0	4	1	1	2.71	155	0.6	11.9
NY 4	Scotchkote 213	Top	12	9.11	5	3	1	3	1	5	2.90	1304	5.2	11.8
NY 5	Scotchkote 213	Top	11	9.25	1	2	0	1	1	1	2.33	1189	4.8	12.0
NY 6	Scotchkote 213	Top	11	12.13	2	0	0	2	0	0	2.00	2819	11.3	12.0
NY 7	Scotchkote 213	Top	11	8.75	2	0	0	1	0	1	2.06	2141	8.6	12.0
NY 8	Armstrong R349	Top	10	8.50	2	0	0	1	1	0	2.00	159	0.6	12.1
NY 9	Scotchkote 213	Top	9	11.13	0	1	1	0	0	2	2.63	2213	8.9	12.1
NY 10	Armstrong R349	Top	9	8.07	1	1	0	1	0	1	3.06	607	2.4	11.9
NY 11	Scotchkote 213	Top	11	10.54	4	2	1	3	1	3	4.02	448	1.8	12.0
NY 12	Scotchkote 213	Top	10	7.94	5	4	0	2	4	3	3.04	1261	5.0	12.1
NY 13	Scotchkote 214	Top	7	6.67	2	1	0	2	0	1	3.17	321	1.3	12.0
NY 14	Armstrong R349	Top	9	10.75	4	0	0	3	1	0	2.13	830	3.3	12.0

1 mil = 0.0254 mm = 25.4 μm, 1 inch = 25.4 mm, 1 lb/yd^3 = 0.6 kg/m^3

1. N - Negligible Corrosion, no corrosion or any spots of corrosion on the body of the bar were less than ¼ in by ¼ in.
   R - Rib Corrosion, corrosion limited to the ribs of the bar and any spots of corrosion on the body of the bar were less than ¼ in by ¼ in.
   B - Bar Corrosion , indicated corrosion on the ribs and one or more areas on the body of the bar were greater than ¼ in by ¼ in.
2. N - No Crack, no visible cracks were observed in the concrete core.
   S - Shallow Crack, surface crack did not reach the top mat of reinforcing steel.
   D - Deep Crack, surface crack extended to the top mat of reinforcing steel.
3. Total chloride content.

PENNSYLVANIA

In order to extend the useful life of reinforced concrete bridge decks the State of Pennsylvania implemented the use of ECR as a corrosion protection strategy. Two separate evaluations of the performance of ECR in bridge decks have been performed.

The first evaluation was done in 1984 and included 11 bridge decks. The results of this evaluation are presented in a August 1985 report entitled "Evaluation of Epoxy Coated Reinforcing Steel in Eight Year Old Bridge Decks."(11) The structures in this study are located throughout Pennsylvania and include some of the oldest bridge decks constructed using ECR. The structure types evaluated are steel girders, prestressed concrete girders, and spread box beams. At the time of this investigation the ECR had been in service for about 6 to 10 years.

All 11 bridge decks evaluated were constructed with ECR in probably only the top mat of reinforcing steel. The epoxy powders used are unknown. Table 13 contains a summary of background information for each of the bridges.

This investigation included a field and laboratory evaluation phase. The field evaluation phase consisted of the following:

- A visual examination of the deck concrete for cracking, spalling, and patches.
- A chain drag supplemented with hammer soundings to locate areas of delaminations.
- Limited use of a pachometer to determine the amount of concrete cover.
- Drilling for concrete powder samples for chloride content.

The laboratory evaluation phase consisted of the determination of total chloride content in the concrete using the concrete powder samples.

Although the visual examination of the deck concrete was performed on all 11 bridges, the remainder of the field evaluation phase and the laboratory phase was performed on only 2 of the bridges.

The second evaluation was done in 1986 and included four additional bridge decks. The results of this evaluation are presented in a July 1988 report entitled "Bridge Deck Protective Systems."(12) The structures in this study are located throughout Pennsylvania and also included the first bridge deck constructed using ECR in the United States. At the time of this investigation the ECR had been in service for about 6 to 10 years.

This investigation included a field and laboratory evaluation phase. The field evaluation phase consisted of the following:

- A visual examination of the deck concrete for cracking, spalling, and patches.
- A chain drag to locate areas of delaminations.
- Limited use of a pachometer to determine the amount of concrete cover.
- Concrete coring to evaluate the quality of the concrete and for chloride content.
- Overall deck condition ratings.
- Half-cell potentials.

The laboratory evaluation phase consisted of the following:

- A visual examination of the concrete in the extracted cores.
- Measurement of concrete cover over the ECR in the extracted cores.
- An evaluation of the extracted ECR segment.
- Measurement of the epoxy coating thickness on the extracted ECR segments.
- Determination of water soluble chloride ion content in the concrete using the extracted cores.
- Permeability of the concrete in the extracted cores.

FINDINGS/DISCUSSION

The findings and discussion are based on the field evaluation of the bridge decks and the laboratory evaluation of cores taken from the decks for both investigations. The results of the laboratory evaluations of the cores taken from the bridge decks in the first study are contained in table 14. The results of the field evaluations and the laboratory evaluation of the cores taken from the bridge decks in the second study are contained in table 15.

Bridge Deck Condition

The decks were evaluated in the field for cracking, delaminations, and spalls. For the decks in the first study, no deck cracking, spalling, or patching was identified. For the decks in the second study, two delaminations were detected (Bridge Number LR 1010-D1, PA 13 and Bridge Number LR 1021-8, PA 15). The delamination in PA 13 was associated with an expansion joint. The extent of delamination in PA 15 was not reported. An overall bridge deck rating was also given to the decks in the second study. This rating is the bridge deck condition rating described in the Pennsylvania DOT Structural Inventory Record System Bridge Inspection Manual. The condition ratings and criteria used are the same as those found in the 1979 Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges published by the Federal Highway Administration. The values given to the decks are 7, 8, 7, and 6 respectively for the bridges as listed in table 15 and indicate light to moderate deterioration.

Depth of Concrete Cover

For two of the bridges in the first study, the depth of concrete cover was measured using a pachometer. The average concrete cover measured in the deck was 61 and 66 mm (2.41 and 2.59 in). For the bridges in the second study, the depth of concrete cover was measured in each of the cores. Average concrete cover measured was 64, 59, 83, and 60 mm (2.53, 2.34, 3.28, and 2.36 in) respectively for the four bridges as listed in table 15.

Concrete Permeability

Rapid permeability tests were performed on two cores taken from each deck in the second study. The average permeabilities were 3758, 3668, 4945, and 8100 coulombs respectively for the four bridges as listed in table 15.

Chloride Concentration

For two of the bridges in the first study, total chloride content was determined using concrete powder samples from holes drilled in the deck and at three depths: 6 to 9 mm (¼ to ¾ in), 9 to 44 mm (¾ to 1¾ in), and 44 to 57 mm (1¾ to 2¼ in). For the bridges in the second study, the water soluble chloride content at the rebar level was determined using powder samples obtained from the concrete cores. The average chloride concentrations at the rebar level for two of the six bridges were at or above the threshold level to initiate corrosion in black steel. They are PA 13 and 15 as identified in table 15.

Epoxy Coating

The thickness of epoxy coating was measured on three ECR segments extracted from cores taken from each of the four decks in the second study. The average coating thickness of all 12 samples was 234 μm (9.2 mil) and ranged from 107 to 447 μm (4.2 to 17.6 mil). Although only one of the segments did not meet the specification for minimum thickness, 127 μm (5 mil), the specification for the maximum thickness, 229 μm (9 mil), was exceeded on six samples. These were the specification requirements in effect at the time of construction.

Rebar Visual Ratings

ECR segments extracted from the cores taken in the second study were visually inspected to compare condition and assess performance. A numeric rating system was used which combined rebar condition and apparent corrosion. The range of ratings is from 0.0, very poor condition and very severe corrosion, to 5.0, new condition and no corrosion. The ratings given by five different inspectors were averaged together to yield a rating for each ECR segment. The average of all visual ratings were 4.8, 4.6, 4.6, and 4.3 respectively for the four bridges as listed in table 15. These ratings indicate rebars in excellent condition with no corrosion. One ECR segment was rated 1.6 and had been exposed to a chloride concentration of 4.0 kg/m^3 (6.7 lb/yd^3). The report did not indicate which bridge this segment was extracted from. It appears that a coating deficiency contributed to this condition as other segments were rated as almost new and had been exposed to comparable chloride concentrations.

Half-cell Potentials

Half-cell potentials for the bridges in the second study were taken on bars that were specially instrumented during construction. Since the use of half cell potentials as a criterion to determine the probability of active corrosion occurring is intended for use with black reinforcing steel, the standard interpretation of the results from tests with ECR may not be valid. Nevertheless, using the standard interpretation of the half-cell potentials for black steel applied to ECR, the average half-cell readings obtained were in the uncertain range.

COMMENTS

Some comments on the results and findings of these two investigations of 15 bridge decks constructed with ECR in Pennsylvania are:

- The average of all the visual rebar rating for the four bridges investigated in the second evaluation was 4.6 which is close to 5 indicating new condition and no corrosion.
- For the bridge deck with a condition rating of 6, the average concrete permeability was 8100 coulombs and the chloride concentration was 2.6 kg/m^3 (4.3 lb/yd^3). The high permeability indicates a poor quality of concrete with a greater probability of retaining water/moisture at the rebar level. Under these conditions, the average rebar rating was 4.3, which is somewhat lower than the other three bridge decks.

- One rebar segment exposed to a chloride concentration of 4.0 kg/m^3 (6.7 lb/yd^3) had a lower average rebar rating of 1.6.
- Even with high average chloride concentrations, up to 2.6 kg/m^3 (4.3 lb/yd^3), the ECR segments were generally rated in excellent condition.
- Some of the decks investigated had not been in service very long and chloride levels were still below the threshold level to initiate corrosion in black steel. For these bridges it may be too soon to determine the effectiveness of ECR. The State of Pennsylvania is planning to perform another detailed field survey which will provide a better understanding of the role of ECR as part of a cost effective corrosion protection system.
- ECR has provided effective corrosion protection for the 6 to 12 years of service with so signs of deterioration of the concrete deck due to corrosion of the reinforcing steel.

Table 13 - Bridge Decks with Epoxy Coated Rebar in Pennsylvania - 1

No.	Bridge ID Number	County	Year Built	Age (years)	Superstructure	Span Lengths (Ft)	Epoxy Powder	Mat
PA 1	03581000103002049592	Tioga	1974	10	Steel Girders	87	Unknown	Top?
PA 2	03411001073000093114	Lycoming	1975	9	Prestressed I Beams	41-101-50	Unknown	Top?
PA 3	03411001073000093211	Lycoming	1975	9	Prestressed I Beams	50-101-41	Unknown	Top?
PA 4	03411001073000069725	Lycoming	1976	8	Prestressed I Beams	60-68-36	Unknown	Top?
PA 5	03411001073000069791	Lycoming	1976	8	Prestressed I Beams	56-90-36	Unknown	Top?
PA 6	03411001073000061803	Lycoming	1976	8	Prestressed I Beams	36-105-42	Unknown	Top?
PA 7	03411001073000061967	Lycoming	1976	8	Prestressed I Beams	42-105-36	Unknown	Top?
PA 8	03411001073000067128	Lycoming	1976	8	Steel Girders	41-112-50	Unknown	Top?
PA 9	05062006143000013185	Berks	1978	6	Prestressed I Beams	50-50-64	Unknown	Top?
PA 10	05062006143000013788	Berks	1978	6	Prestressed I Beams	35-100-34	Unknown	Top?
PA 11	05061000784000017711	Berks	1978	6	Spread Box Beams	42-107-38	Unknown	Top?

1 foot = 0.3048 m

Table 14 - Evaluation Results for Bridge Decks with Epoxy Coated Rebar in Pennsylvania - 1

No.	Epoxy Powder	Mat	Age (years)	Average Depth of Reinforcing Steel (in)	Cl⁻ Content[1] (lb/yd³) Depth ½ in	1¼ in	2 in	Delaminated Area (ft²)	Percent Delaminated
PA 2	Unknown	Top?	9	2.41	9.5	4.3	0.9	0	0.0
					6.9	1.1	0.0		
					7.8	2.5	0.4		
PA 3	Unknown	Top?	9	2.29	12.7	4.1	0.9	0	0.0
					8.7	1.4	0.0		
					7.4	1.4	0.9		

1 inch = 25.4 mm, 1 lb/yd^3 = 0.6 kg/m^3, 1 ft^2 = 0.0929 m^2

1. Total chloride content.

Table 15- Summary of Findings for Bridge Decks with Epoxy Coated Rebar in Pennsylvania - 2

No.	Location	Year Built	Epoxy Powder	Mat	Age (years)	Average Depth to Rebar Center (in)	Rebar Rating	Average Half-cell Potentials (volts)	Average Cl^- Content[1] (lb/yd^3)	Average Permeability (coulombs)	Number of Delaminations	Overall Deck Rating
PA 12	LR 1044-A04 Clinton Co.	1976	Unknown	?	10	2.53	4.8	0.31	0.20	3758	0	7
PA 13	LR 1010-D1 Montgomery Co.	1974	Flintflex 531-6080	Both	12	2.34	4.6	0.33	1.59	3668	1 (Exp. Jt.)	8
PA 14	LR 1005-N2A Dauphin Co.	1975	Unknown	?	11	3.28	4.6	0.26	0.46	4945	0	7
PA 15	LR 1021-8 Allegheny Co.	1976	Scotchkote 202	Top	10	2.36	4.3	0.26	4.30	8100	1	6

1 inch = 25.4 mm, 1 $lb/yd^3 = 0.6\ kg/m^3$

1. Water soluble chloride content.

VIRGINIA

In order to evaluate the effectiveness of ECR as a corrosion protection strategy for reinforced concrete bridge decks the State of Virginia constructed two test decks. An initial evaluation was done at the time of construction and additional evaluations were done in 1987 and 1990. As a result of new concerns about the effectiveness of ECR as a corrosion protection strategy, the two decks were visually inspected again in 1993. The results of these evaluations are presented in a July 1993 report entitled "Evaluation of Epoxy-Coated Reinforcing Steel."[13]

The test decks are on parallel bridges located on I - 77 in Carroll County. The bridges are continuous steel beam structures built in 1977. At the time of the evaluations the ECR had been in service for 10 and 13 years. The bridge decks were constructed with ECR in both the top and bottom mats of reinforcing steel. Epoxy powder used was Scotchkote 202 produced by the 3M Corporation.

The investigation included a field and laboratory evaluation phase. The field evaluation phase consisted of the following:

- A visual examination of the deck concrete for cracking, spalling, and patches.
- A chain drag to locate areas of delaminations.
- The use of a pachometer to measure the concrete cover.
- Drilling concrete powder samples for chloride content.
- Concrete coring to evaluate the quality of the concrete.
- Resistivity readings.
- Half-cell potentials.
- Three-electrode linear polarization resistances to determine the rate of corrosion.

The laboratory evaluation phase consisted of the following:

- A visual examination of the extracted concrete cores.
- Measurement of concrete cover over the ECR in the extracted cores.
- An evaluation of the extracted ECR samples.
- Determination of total chloride content in the concrete using the concrete powder samples.

FINDINGS/DISCUSSION

The findings and discussion are based on the field evaluation of the bridge decks and the laboratory evaluation of cores taken from the decks. The results of the field evaluation for delaminations and the laboratory evaluations of the cores are contained in table 16. A summary of findings for each bridge is found in table 17.

Bridge Deck Condition

The decks were evaluated in the field for cracking, delaminations, and spalls. Pattern and transverse cracking was widespread in both decks. Deck cracking was first noted after only 2 years of service and since then has progressed in severity and extent. This type of cracking is common on continuous span bridges and is not related to corrosion of the reinforcing steel. No delaminations were found in either of the decks. The visual inspection done in 1993 found no changes in the condition of the decks.

Condition of Concrete Cores

A total of four cores was taken in 1990 from the two bridge decks at both cracked and non-cracked locations. The cores taken at cracks in the deck were heavily stained with material from the roadway surface. These cores readily separated at the cracks.

Depth of Concrete Cover

The depth of concrete cover over the top rebar was measured in the field with a pachometer and in each of the extracted cores. Concrete cover as measured in the extracted cores ranged from 70 to 73 mm (2.75 to 2.88 in) with an average of 70 mm (2.75 in). The values measured in the cores were slightly higher than those indicated by the pachometer survey.

Chloride Concentration

Powder samples obtained from holes drilled in the deck were used to determine total chloride contents at three depths: 25 to 38 mm (1 to 1.5 in), 38 to 51 mm (1.5 to 2 in), and 51 to 64 mm (2 to 2.5 in). Six samples were taken in 1987 and eight samples were taken in 1990. All the average chloride concentrations near the rebar level, in both 1987 and 1990, were at or above the threshold level to initiate corrosion in black steel.

Epoxy Coating

An evaluation of the ECR at the time of construction showed that the coating did not meet the requirements of Virginia's special provisions in their ECR specification. Visual inspections and resistivity testing at that time revealed numerous holidays and flaws in the coating and indicated the field repairs with liquid epoxy was ineffective.

Rebar Corrosion and Coating Disbondment

ECR segments extracted from the four cores were examined for any coating disbondment and to determine the condition of the steel surface under the coating. Although there was no indication of rust on any of the bars, some corrosion could have occurred under the epoxy film. The epoxy coatings remained tightly bonded to the steel and could only be removed with a knife. After the coatings were removed, the exposed steel surfaces had a dull, dark gray appearance instead of the white metal appearance as required in the specifications in effect at the time of construction. Since the actual condition of the steel surface prior to coating was not recorded, no comparison can be made.

Other Corrosion Tests

Other tests and evaluations performed included half-cell potentials and three-electrode linear polarization resistance. Half-cell potentials were taken on bars that were specially instrumented during construction. Since the use of half cell potentials as a criterion to determine the probability of active corrosion occurring is intended for use with black reinforcing steel, the standard interpretation of the results from tests with ECR may not be valid. Nevertheless, the standard interpretation of the half-cell potentials for black steel applied to ECR indicated three areas of possible active corrosion and some locations with readings in the uncertain range. However, the three-electrode linear polarization resistance measurements indicated the absence of active corrosion.

COMMENTS

Some comments on the results and findings of this investigation of the first two bridge decks constructed with ECR in Virginia are:

- ECR has provided adequate corrosion protection even in areas with chloride concentrations up to 2.0 kg/m^3 (3.29 lb/yd^3) above the chloride threshold level for initiating corrosion in black steel. These high chloride areas are at transverse cracks.
- There were no indications of significant corrosion or coating disbondment even though the initial condition of the coating was poor. Numerous holidays and bare areas were present.

- The use of ECR in combination with adequate concrete cover has provided effective corrosion protection for over 13 years of service with so signs of deterioration of the concrete deck due to corrosion of the reinforcing steel.

Table 16 - Evaluation Results for Bridge Decks with Epoxy Coated Rebar in Virginia

No.	Location	Epoxy Powder	Mat	Year Built	Age (years)	Cl^- Content[1] (lb/yd^3)			Core Location	Delaminations
						Depth (in)				
						1 - 1.5	1.5 - 2	2 - 2.5		
VA 1	I77 (NB) over SR 620	Scotchkote 202	Both	1977	10	-	-	0.10	Uncracked concrete	None
						-	-	0.90	Transverse crack	
						-	-	3.29	Transverse crack[2]	
					13	0.62	0.47	0.40	Uncracked concrete	
						3.16	2.14	1.22	Uncracked concrete	
						3.38	2.16	1.20	Uncracked concrete	
						3.01	2.34	2.08	Transverse crack	
						2.63	2.68	2.55	Transverse crack	
VA 2	I77 (SB) over SR 620	Scotchkote 202	Both	1977	10	-	-	0.42	Uncracked concrete	None
						-	-	0.75	Uncracked concrete	
						-	-	2.98	Transverse crack	
					13	1.00	0.60	0.56	Uncracked concrete	
						0.92	0.47	0.42	Uncracked concrete	
						2.63	2.77	2.59	Transverse crack	
						3.09	2.85	2.23	Transverse crack	

1 inch = 25.4 mm, 1 lb/yd^3 = 0.6 kg/m^3

1. Total chloride content.
2. Crack had penetrated full depth of the slab.

Table 17 - Summary of Findings for Bridge Decks with Epoxy Coated Rebar in Virginia

No.	Epoxy Powder	Mat	Age (years)	Average Cl^- Content[1] (lb/yd^3)			Delaminations
				Depth (in)			
				1 - 1.5	1.5 - 2	2 - 2.5	
VA 1	Scotchkote 202	Both	10	-	-	1.43	None
			13	2.56	1.96	1.49	
VA 2	Scotchkote 202	Both	10	-	-	1.38	None
			13	1.91	1.67	1.45	

1 inch = 25.4 mm, 1 lb/yd^3 = 0.6 kg/m^3

1. Total chloride content.

WEST VIRGINIA

In order to extend the useful life of reinforced concrete bridge decks the State of West Virginia implemented the use of ECR as a corrosion protection strategy. An evaluation of the performance of ECR in fourteen bridge decks constructed using ECR was performed in 1993. The results of this evaluation are presented in a January 1994 report entitled "Evaluation of Bridge Decks Using Epoxy Coated Reinforcement."[(14)]

The bridges included in this evaluation represent the initial efforts at using ECR in West Virginia. Table 18 contains a summary of background information for each of the bridges. At the time of the evaluation the ECR had been in service for 17 to 19 years.

The investigation included a field and laboratory evaluation phase. The field evaluation phase consisted of the following:

- A visual examination of the deck concrete for cracking, spalling, and patches.
- A chain drag to locate areas of delaminations.
- Drilling for concrete powder samples for chloride content.

The laboratory evaluation phase consisted of the determination of chloride content in the concrete using the concrete powder samples.

FINDINGS/DISCUSSION

The findings and discussion are based on the field evaluation of the bridge decks and the chloride content in selected decks. The results of the field evaluation for delaminations, cracking, spalls, and patches and the chloride contents are contained in table 19.

Bridge Deck Condition

The decks were evaluated in the field for cracking, delaminations, spalls, and patches. Most of the decks surveyed had transverse cracking on the top surface. These cracks are not believed to be associated with corrosion induced distress. A relatively minor amount of delaminations were found. Only one spalled area associated with a delamination was found. No patching was found. Overall, little or no concrete deterioration due to corrosion of the reinforcing steel was found.

WV 1, Bridge No. 2930, Industrial Bridge - Clarksburg

The deck cracking in this bridge consisted of partial to full width transverse cracks. Five delaminations were detected in this deck. Four of the delaminations were approximately 0.1, 0.1, 0.1, and 0.6 m^2 (1, 1, 1, and 6 ft^2) in area. The fifth delamination was approximately 0.6 m (2 ft) wide, extended over the width of both lanes and was centered on a construction joint. The total area of all five delaminations was approximately 3.7 m^2 (40 ft^2). No delaminations were associated with any of the cracks.

WV 2, Bridge No. 2953, US 19 - Adamson St. Bridge - Clarksburg

The deck cracking in this bridge consisted of one full width transverse crack. No other cracks or spalls were found. In addition, no delaminations were detected.

WV 3, Bridge No. 2776, Co. 37 - Buffalo Creek

No deck cracking, spalling, or patching was found on this deck. No delaminations were detected in the traffic lanes and most of the shoulders. Approximately one fourth of the shoulders could not be examined due to a large buildup of debris.

WV 4, Bridge No. 2771, WV 20 - Hinton Bridge

The deck cracking in this bridge consisted of light transverse cracks over approximately half of the deck surface. No delaminations were detected.

WV 5, Bridge No. 2665, Rt 2 Bridge - Huntington

The deck cracking in this bridge consisted of widespread transverse cracks. No spalling or patching was found. The only delamination detected was a small one associated with an expansion dam. No delaminations associated with the reinforcing steel were detected.

WV 6, Bridge No. 2673, I-79 Overhead Bridge - Charleston

A low number of cracks (~12) was found on this deck. The only delaminations detected were those associated with the expansion dam at each end of the bridge and the first construction joint in from each end.

WV 7, Bridge No. 2655, US 52 Bridge - Kermit

No deck cracking, spalling, or patching was found on this deck. In addition, no delaminations were detected.

WV 8, Bridge No. 2847, US 52 - McDowell County

No apparent deficiencies were found on this deck. One delamination of approximately 0.1

m^2 (1 ft^2) in size was detected.

WV 9, Bridge No. 2975, WV 37 - East Lynn Bridge

The deck cracking in this bridge consisted of typical full width transverse cracks. Three small circular spalled areas, 13 to 19 mm (½ to ¾ in) deep, were found. No delaminations associated with the reinforcing steel were detected.

WV 10, Bridge No. 2768, Co. 37 - Buffalo Creek

No deck cracking, spalling, or patching was found on this deck. No delaminations were detected in the traffic lanes and most of the shoulders. Approximately one fourth of the shoulders could not be examined due to a large buildup of debris.

WV 11, Bridge No. 2672, I-79 Mainline Bridge - Charleston (north)

WV 12, Bridge No. 2672, I-79 Mainline Bridge - Charleston (south)

The deck cracking in these bridges consisted of a typical amount of transverse cracks. No delaminations associated with the reinforcing steel were detected in either deck.

WV 13, Bridge No. 2668, I-79 Big Sandy Bridge - Charleston (north)

WV 14, Bridge No. 2668, I-79 Big Sandy Bridge - Charleston (south)

The deck cracking in these bridges consisted of a higher number of transverse cracks in the traffic lanes only. No delaminations were detected in the southbound bridge. A delaminated area of approximately 0.1 m^2 (1 ft^2) in size was detected in the northbound bridge. A popout, approximately 51 mm (2 in) deep, is associated with this delamination.

Chloride Concentration

The total chloride content was determined using powder samples obtained from holes drilled in the decks. The average chloride concentrations for the concrete located between 12 mm (½ in) below the deck surface and the rebar level were reported. Only four of the surveyed decks were sampled for chloride content due to inclement weather. For the bridges sampled, all the average chloride concentrations were at or above the threshold level to initiate corrosion in black steel.

COMMENTS

Some comments on the results and findings of this evaluation of 14 bridge decks constructed with ECR in West Virginia:

- Bridge number 2930 (Industrial Bridge - Clarksburg) was built in 1974 and at 19 years of service life had a total of approximately 3.7 m^2 (40 ft^2) of delaminated area out of a total deck area of 1653.6 m^2 (17,800 ft^2), approximately 0.25 percent of the deck area. The largest of these delaminations was approximately 0.6 m (2 ft) wide, extended over the width of both lanes, and was centered on a construction joint. Chloride contents are not available for this deck and the report does not indicate if the delaminations are corrosion induced. The State of West Virginia indicated in their report that based on their previous experience a typical deck of the same design but with black steel would have more delaminations (5 to 20 percent of the deck area being common).
- Two other bridges had 0.2 m^2 (2 ft^2) of delaminated area out of a total deck area of 4022.6 m^2 (43,300 ft^2) which indicates a good performance by the ECR. The chloride concentration in one of the decks is 2.0 kg/m^3 (3.3 lb/yd^3), above the corrosion threshold.
- Although the use of ECR did not necessarily reduce deck cracking, deterioration of the deck concrete resulting from any corrosion of reinforcing steel was greatly reduced, if not eliminated, with the use of ECR.
- ECR has provided effective corrosion protection for the 17 to 19 years of service with no maintenance or repair work done on the decks.

Table 18 - Bridge Decks with Epoxy Coated Rebar in West Virginia

No.	Bridge Number	Location	Year Built	Age (years)	Deck Area (ft^2)	Length (ft)	Epoxy Powder	Mat
WV 1	2930	Industrial Bridge - Clarksburg	1974	19	17800	557	Unknown	?
WV 2	2953	Adamson St. Bridge - Clarksburg	1975	18	9000	300	Unknown	?
WV 3	2776	Buffalo Creek	1975	18	6200	136	Unknown	?
WV 4	2771	Hinton Bridge	1976	17	41600	1300	Unknown	?
WV 5	2665	Rt 2 Bridge - Huntington	1976	17	21000	584	Unknown	?
WV 6	2673	Overhead Bridge - Charleston	1975	18	17000	400	Unknown	?
WV 7	2655	Rt 52 Bridge - Kermit	1976	17	17000	445	Unknown	?
WV 8	2847	Rt 52 - McDowell County	1976	17	4100	130	Unknown	?
WV 9	2975	East Lynn Bridge	1976	17	5160	172	Unknown	?
WV 10	2768	Buffalo Creek	1976	17	5300	116	Unknown	?
WV 11	2672	Mainline - Charleston (north)	1976	17	7000	?	Unknown	?
WV 12	2672	Mainline - Charleston (south)	1976	17	7000	?	Unknown	?
WV 13	2668	Big Sandy Bridge - Charleston (north)	1976	17	39200	980	Unknown	?
WV 14	2668	Big Sandy Bridge - Charleston (south)	1976	17	39200	980	Unknown	?

1 foot = 0.3048 m, 1 ft^2 = 0.0929 m^2

Table 19 - Summary of Findings for Bridge Decks with Epoxy Coated Rebar in West Virginia

No.	Epoxy Powder	Mat	Age (years)	Average Cl^- Content[1] (lb/yd³)	Delaminated Area (ft²)	Percent Delaminated	Observed Deterioration		
							Transverse Cracking	Spalls	Patches
WV 1	Unknown	?	19	NT	40	0.225	Light, full-width and partial-width	NR	NR
WV 2	Unknown	?	18	NT	None	0.000	Only one, full width	NR	NR
WV 3	Unknown	?	18	NT	None	0.000	None	None	None
WV 4	Unknown	?	17	5.3	None	0.000	Light, less than half of the deck	NR	NR
WV 5	Unknown	?	17	2.4	None	0.000	Most of the deck	None	None
WV 6	Unknown	?	18	NT	None[2]	0.000	Extremely low number	NR	NR
WV 7	Unknown	?	17	NT	None	0.000	None	None	None
WV 8	Unknown	?	17	NT	1	0.024	None	None	None
WV 9	Unknown	?	17	NT	None	0.000	Full width of deck	Three small circular areas ½ to ¾ in deep	NR
WV 10	Unknown	?	17	NT	None	0.000	None	None	None
WV 11	Unknown	?	17	NT	None	0.000	Normal amount	NR	NR
WV 12	Unknown	?	17	NT	None	0.000	Normal amount	NR	NR
WV 13	Unknown	?	17	3.3	1	0.002	More in traffic lanes	2 inch deep popout at delamination	NR
WV 14	Unknown	?	17	2.1	None	0.000	More in traffic lanes	NR	NR

1 inch = 25.4 mm, 1 ft² = 0.0929 m², 1 lb/yd³ = 0.6 kg/m³

1. Total chloride content between ½ inch below the deck surface and the rebar level, NT - Not tested
2. Delaminations found were associated with the expansion dam devices and construction joints at each end of bridge.
3. NR - Not reported, report did not indicate the presence or absence of spalls or patches

As a result of concerns about the effectiveness of ECR as a corrosion protection strategy, the Providence of Ontario initiated an investigation to evaluate the performance of ECR. This evaluation was conducted in 1988 on two of the first barrier walls constructed using ECR. The results of this investigation are presented in a December 1989 report entitled "Field Investigation of Epoxy-Coated Steel Reinforcement."[15] To further understand the effectiveness of ECR as a corrosion protection strategy, the Providence of Ontario initiated a more extensive investigation to evaluate the performance of ECR in reinforced concrete structures. This investigation is currently in progress and only preliminary results are available.[16]

The structures included in the first study were selected to represent a "worst case." The locations selected were thought to have some of the highest concentration of chlorides at the level of the reinforcing steel. In addition, since all bridge decks are waterproofed, only barrier walls (parapets) were considered. The barrier walls evaluated were constructed in 1979 and had been in service for 9 years when the investigation was conducted. Epoxy powder used was Armstrong Epoxiplate R361.

The first investigation included a field and laboratory evaluation phase. The field evaluation phase consisted of the following:

- A visual examination of the concrete for cracking, spalling, and patches.
- Concrete coring to evaluate the quality of the concrete and for chloride content.
- Half-cell potentials.
- Three-electrode linear polarization resistances to determine the rate of corrosion.
- Electrical continuity.

The laboratory evaluation phase consisted of the following:

- A visual examination of the concrete in the extracted cores.
- An evaluation of the extracted ECR segments.
- Determination of total chloride content in the concrete using the extracted cores.

FINDINGS/DISCUSSION

The findings and discussion are based on the field evaluation of the barrier walls and the laboratory evaluation of cores taken from the walls. The results of the field evaluation for cracks, spalls, and delaminations and the laboratory evaluations of the cores from the first investigation are contained in table 20. The results of the adhesion tests for ECR segments extracted from cores taken as part of the second investigation are contained in table 21.

Concrete Condition

The barrier walls in the first study were evaluated in the field for cracking and signs of deterioration of the concrete resulting from corrosion of the reinforcing steel.

N-W Ramp over Joshua Creek

The cracking in these barrier walls consisted of scattered pattern cracking along with a few major vertical cracks. There was only minor evidence of premature corrosion induced concrete deterioration.

Eglinton Avenue UP Hwy 403

The cracking in these barrier walls consisted of pattern cracking and some vertical cracks. There was no evidence of serious premature corrosion induced concrete deterioration. There was also no visual evidence of any active corrosion.

The second investigation evaluated 12 bridges built with water proof membranes between 1978 and 1992. These structures were examined for signs of concrete distress and were surveyed for delaminations. Except for small spalls in one barrier wall the remainder were all in good condition.

Chloride Concentration

Acid soluble chloride profiles were determined using pulverized samples obtained from the concrete cores. All the chloride concentrations at the rebar level were at or above the threshold level to initiate corrosion in black steel. The chloride contents reported here in kilograms per cubic metre (pounds per cubic yard) are converted from the values in the Ontario report (percent chloride by mass of concrete) using a concrete weight of 2400 kg/m^3 (4000 lb/yd^3).

Epoxy Coating

ECR segments extracted from the cores were examined for visual defects in the coating (holidays) and thickness of epoxy coating. The condition of the epoxy coating on ECR segments from the barrier wall of Joshua Creek Bridge was very good and no noticeable deficiencies were noted. A small bare area was found on one of the ECR segments from the barrier wall of

Eglinton Avenue bridge. This was on the hook portion of a vertical bar. Although a few coating thickness measurements were below the minimum required thickness, the coating thickness was generally found to be within specification requirements.

Rebar Corrosion and Coating Disbondment

ECR segments extracted from the cores were examined for any coating disbondment and to determine the condition of the steel surface under the coating. None of the ECR segments from the Joshua Creek barrier wall showed evidence of any corrosion or coating disbondment. One of the ECR segments from the Eglinton Avenue barrier wall had some minor surface corrosion at a bare area on the bar. There was no corrosion or pitting under the coating adjacent to the bare area. None of the remaining ECR segments from this wall showed any evidence of corrosion.

There was evidence of isolated locations with poor bond between the epoxy coating and the ribs of the rebars. The coating could be removed at these locations with a knife. However, the coating on the body of the bar could not be removed by a knife after scoring a cross into the coating. Some damage to the epoxy coating on the ribs was found. This damage occurred during handling and placement of the rebar during construction.

The rebars in portion of the Eglinton Avenue barrier wall were exposed by mechanically removing the concrete cover. The overall condition of the ECR was good. The only location where corrosion was found was on a hairpin stirrup at the top of the wall. The corrosion was confined to a small bare area. The coating appears to have been damaged during construction.

In the second investigation, cores were taken from the 12 bridges in exposed concrete components: barrier walls, end dams, sidewalks, and decks built without water proofing. The extracted ECR segments were tested for adhesion of the epoxy coating to the steel surface. The adhesion of the epoxy coating decreased with passage of time. The adhesion is rated using a scale of 1, 3, and 5. A rating of 1 indicates a well adhered coating that can not be lifted from the steel substrate. A rating of 3 indicates the coating can be pried up from the substrate in small pieces, but can not be peeled off easily. A rating of 5 indicates the coating can be easily peeled off from the substrate and leaves no residue behind. Of the ECR segments extracted from structures built in 1979 and 1980, 73 percent had adhesion ratings of 3 and 5. Of the ECR segments extracted from structures built between 1982 and 1985, 40 percent had adhesion ratings of 3 and 5. Of the

ECR segments extracted from structures built in 1990, only 12 percent had adhesion ratings of 3 and 5. It appears that adhesion of the epoxy coating decreases with time as ECR segments extracted from bridges with the longest service life have exhibited the most adhesion loss.

Half Cell Potentials

Half-cell potentials were taken on the barrier walls evaluated in the first study. Since the use of half cell potentials as a criterion to determine the probability of active corrosion occurring is intended for use with black reinforcing steel, the standard interpretation of the results from tests with ECR may not be valid. Nevertheless, the standard interpretation of the half-cell potentials for black steel applied to ECR indicated areas of possible active corrosion and yet no evidence of corrosion activity was found on the Joshua Creek bridge.

Electrical Continuity

The electrical continuity tests was performed to give an indication of the condition and adequacy of the epoxy coating. Since the epoxy coating is not electrically conductive, crossing or overlapping bars should be electrically discontinuous. All of the rebars in the Joshua Creek barrier wall were found to be electrically discontinuous. Except for electrical continuity between two vertical rebars and the intersecting horizontal rebars, all of the remaining vertical rebars in the Eglinton Avenue barrier wall were electrically discontinuous. The electrical continuity indicates inadequate coatings on these rebars.

Rate of Corrosion

The rate of corrosion measurement was performed on rebars in both barrier walls. This test is usually referred to as the three-electrode linear polarization method. The results for many of the rebars were erratic and polarization resistances could not be calculated. The reading which indicated the most corrosion activity was for the bar which was experiencing active corrosion. The results for the other tested rebars imply little corrosion activity which is confirmed by visual examination.

COMMENTS

Some comments on the results and findings of these investigations of barrier walls and other structures constructed with ECR in Ontario are:

- Except for localized corrosion on one vertical bar, there was no evidence of corrosion on the ECR.

- The bond between the epoxy coating and the steel substrate in the ECR segments in the first study was generally good.
- The number of defects in the epoxy coating and the amount of disbondment influence the performance of ECR.
- Adhesion of the epoxy coating to the steel substrate decreases with time.
- ECR has provided adequate corrosion protection even in areas with chloride concentrations, up to 3.8 kg/m^3 (6.4 lb/yd^3) well above the chloride threshold level for initiating corrosion in black steel.

Table 20 - Summary of Findings for Bridge Barrier Walls with Epoxy Coated Rebar in Ontario

No.	Site No.	Location	Year Built	Age (years)	Epoxy Powder	Cl^- Content[1]		Observed Deterioration
						(%)	(lb/yd^3)	
ON 1	100140B	N-W ramp over Joshua Creek	1979	9	Unknown	~0.03	~1.2	A few major vertical cracks, scattered pattern cracking, only minor evidence of premature concrete deterioration
ON 2	240319	Eglinton Avenue UP, Hwy 403	1979	9	Armstrong R361	0.12 to 0.16	4.0 to 6.4	Appeared sound, some vertical cracks, pattern cracking, no evidence of serious premature concrete deterioration, no visual evidence of ongoing corrosion activity.

$1\ lb/yd^3 = 0.6\ kg/m^3$

1. Total chloride content at the level of the reinforcing steel.

Table 21 - Summary of Adhesion Ratings for Structures with Epoxy Coated Rebar in Ontario[1]

Source of ECR	Year Built	Age (years)	Percent of ECR Segments		
			Adhesion Rating		
			1	3	5
Inservice structures	1979 - 80	12 - 15	27	28	45
Inservice structures	1982 - 85	7 - 10	60	15	25
Inservice structures	1990	2	88	6	6

1. Cores taken from 11 barrier walls, 3 sidewalks, 6 end dams, and 2 exposed concrete bridge decks

As a result of concerns about the effectiveness of ECR as a corrosion protection strategy, the Canadian Strategic Highway Research Program (C-SHRP) initiated an investigation to evaluate the performance of ECR in reinforced concrete highway structures. The investigation was conducted in 1990 and 1991 on various types of structures constructed using ECR. The results of this investigation are presented in an December 1992 report entitled "Effectiveness of Epoxy Coated Reinforcing Steel - Final Report."[17]

A total of 19 structures was evaluated in this investigation. The structures were located in the United States and Canada and included 17 bridge decks, one noise wall, and one barrier wall. Some of the structures were previously evaluated in other investigations and the results of those investigations are summarized elsewhere in this report. Even though these structures have been previously evaluated, they are included here since this investigation was generally performed at a different time, i.e. several years later. At the time of the investigation the ECR had been in service for 3 to 16 years.

Of the 17 bridge decks evaluated, 15 were constructed with ECR in only the top mat of reinforcing steel and one was constructed with ECR in both the top and bottom mats of reinforcing steel. The remaining deck was constructed with ECR, but it is not known if only the top mat or both mats of reinforcing steel were epoxy coated. The noise wall and barrier wall were constructed with ECR. Epoxy powders used were 3M Scotchkote 202 and 213, Armstrong Epoxiplate R349 and R361, Dupont Flintflex 531-6080, and some unknown brown and green color types. Table 22 contains a summary of background information for each of the structures.

The investigation included a field and laboratory evaluation phase. The field evaluation phase consisted of the following:

- A visual examination of the concrete for cracking, spalling, and patches.
- A chain drag to locate areas of delaminations.
- Concrete coring to evaluate the quality of the concrete and for chloride content.

The laboratory evaluation phase consisted of the following:

- A visual examination of the concrete in the extracted cores.
- Measurement of concrete cover over the ECR in the extracted cores.

- Unit weight of concrete using the extracted cores.
- Absorption of concrete using the extracted cores.
- Determination of pH in the concrete adjacent to the ECR in the extracted cores.
- Determination of water soluble chloride content in the concrete using the extracted cores.
- Permeability of the concrete in the extracted cores.
- An evaluation of the extracted ECR segments.
- Measurement of the epoxy coating thickness on the extracted ECR segments.

FINDINGS/DISCUSSION

The findings and discussion are based on the field evaluation of the bridge decks, bridge barrier walls, and noise wall and the laboratory evaluation of cores taken from the structures. The results of the field evaluation for delaminations and the laboratory evaluations of ECR segments extracted from the cores are contained in table 23. The results of the laboratory evaluations of concrete properties for the cores are contained in table 24.

Bridge Deck and Structure Condition

The decks, barrier walls, and noise wall were evaluated in the field for cracking, delaminations, and spalls. The field evaluations were generally performed by personnel of the State or Province where the structure was located.

C1, Alberta Bridge Deck #79411N, CPR Overhead, Hwy 21 NB, Akenside

Deck cracking in this bridge consisted of numerous wide cracks which were predominantly longitudinal in nature. No delaminations were detected.

C2, Alberta Bridge Deck #229N, Vermillion River, Hwy 16, Vegerville

Deck cracking in this bridge consisted of a few cracks which were predominantly longitudinal in nature. The deck also had aggregate popouts present. Some delaminations were detected. However, they were due to a lack of bond between the concrete deck and the precast concrete girders and not corrosion induced. Some deck repairs were done in 1987. What these repairs consisted of was not described in the report.

C3, Nova Scotia Bridge Deck #89-024, Middle River, Hwy 104, New Glasgow

The deck on this bridge is waterproofed and has an asphalt overlay. The sidewalk is not waterproofed and therefore it was the only part of the deck that was evaluated. No delaminations were detected in the sidewalk.

C4. Nova Scotia Bridge Deck #88-032, Little Narrows

The deck on this bridge had not been waterproofed as of the time of this investigation. The deck had not yet been exposed to any road deicers and is located in a cold marine environment. One of the cores taken from this structure was on a wide crack in the sidewalk.

C5. Ontario Noise Barrier Wall, Keele St. and Hwy 401 WB

This noise wall consists of precast concrete panels. The panels erected closest to the roadway surface, 0.9 to 1.8 m (3 to 6 ft) above ground, have experienced cracking, rust staining, and spalling.

C6. Ontario Bridge Barrier Walls, Site 240319

These barrier walls were previously evaluated by Ontario (see ON 2). Cracking in these barrier walls consisted of scattered pattern cracking and some vertical cracks. No evidence of premature concrete deterioration due to corrosion or other damage was found.

C7. Virginia Bridge Deck #2030, I-66 WB, Relocated Rte. 55, Fauquier County

C8. Virginia Bridge Deck #2031, I-66 EB, Relocated Rte. 55, Fauquier County

The deck cracking in this bridge consisted of severe transverse and random cracks. No delaminations were detected in either deck. Significant delaminations and spalling were noted in the parapets which were constructed with bare steel. At the time of the field evaluation, no repair work had been done on either of these decks.

C9. Virginia Bridge Deck #2045, I-64 WB, Rte. 629, Rockbridge County

The deck cracking in this bridge consisted of minor cracking. One small delamination was detected. A core taken at this location verified that the delamination was not related to the ECR.

C10. Wisconsin Bridge Deck #B67-170, US-16 EB, C.T.H. "E", Waukesha County

No delaminations were detected in this bridge deck. The presence or absence of deck cracks was not noted in the C-SHRP report.

C11. Wisconsin Bridge Deck #B40-475, Airport Spur, South 13th St., Milwaukee County

Deck cracking in this bridge consisted of transverse cracks. A limited delimanination survey (near locations of cores) detected no delaminations.

C12. Pennsylvania Bridge Deck #LR1010/D1, I-476 NB, Schuylkill River, Montgomery County

This bridge was constructed with ECR in 4 of its 15 spans. The deck in those spans contained a significant amount of patching. The cause of the distress which resulted in the patching could not be determined. No delaminations were detected in the spans constructed with ECR. This deck was previously evaluated by Pennsylvania (see PA 13). This evaluation was done about 4 years before the C-SHRP evaluation. The first evaluation detected a delamination associated with an expansion joint.

C13. Pennsylvania Bridge Deck #LR1021/8, I-79 SB, Turnpike, Allegheny County

No significant deck cracking was found. No delaminations were detected in this investigation. This deck was also previously evaluated by Pennsylvania (see PA15). The first evaluation detected a delamination. The extent of delamination was not reported.

C14. New York Bridge Deck #BIN 3312170, Cortland

The deck cracking in this bridge consisted of wide cracks which were transverse in nature. No delaminations were detected. This deck was also evaluated by New York (see NY 14).

C15. New York Bridge Deck #BIN 1070700, Albany

The deck cracking in this bridge consisted of several wide cracks, 1.6 to 3.2 mm (one-sixteenth to one-eight of an inch), and numerous hairline cracks which were all transverse in nature. Some of the wide cracks showed rust stains. One delamination of about 0.2 m^2 (2 ft^2) in size was detected. This deck was also evaluated by New York (see NY 9).

C16. New York Bridge Deck #BIN 107086C, Troy

The deck cracking in this bridge consisted of several hairline cracks which were transverse in nature. No delaminations were detected. This deck was also evaluated by New York (see NY 10).

C17. Ohio Bridge Deck #HAM-275-1080R, I-74 & I-275, Harrison Rd., Hamilton County

A description of the condition of this deck was not available. However, all of the cores taken from this deck were in good condition.

C18. Ohio Bridge Deck #MAH-680-0705, South Ave., Mahoning County

The deck cracking in this bridge consisted of minor cracks which covered less than five percent of the deck area. Delaminations totaling less than one percent of the deck area were detected.

C19. Ohio Bridge Deck #CUY-480-0832N, I-480, Cuyahoga County

No deck cracking was observed in this bridge. No delaminations were detected.

Condition of Concrete Cores

Concrete cores were taken from the structures at cracks, delaminated areas, and non-cracked locations. The cores were provided by the State or Province where the structure was located. All of the cores were visually evaluated by the authors of the C-SHRP report for condition of the concrete. The cores taken from 8 of the 19 structures were not cracked. For cores taken from nine of the structures, one out of seven, one out of six, one out of seven, three out of six, an unspecified number out of eight, three out of six, two out of six, four out of seven, and five out of eight were cracked. All six of the cores from the remaining structure were cracked.

Some of the cores were tested for concrete absorption and unit weight. The average unit weight ranged from 1901.5 to 2258.6 kg/m^3 (3205 to 3807 lb/yd^3 or 119 to 141 lb/ft^3). Absorption ranged from 4.53 to 9.93 percent.

Depth of Concrete Cover

The depth of concrete cover over the top rebar was measured in each of the cores. Average concrete cover ranged from 14 to 93 mm (0.56 to 3.67 in). For most of the structures the average concrete cover was in the 51 to 76 mm (2 to 3 in) range.

Concrete Permeability

Rapid permeability tests were performed on two cores taken from each structure. The average permeabilities ranged from 955 coulombs (very low) to 22 722 coulombs (very high). Most of the average permeabilities were in the low to moderate range.

Chloride Concentration and pH Level

The water soluble chloride content at the rebar level was determined using pulverized samples obtained from the concrete cores. The average chloride concentrations at the rebar level in 8 of the 19 structures (C5, C10, C12 through C18) were at or above the threshold level to initiate corrosion in black steel. The pH levels at the rebar level ranged from 9.5 to 11.0.

Epoxy Coating

ECR segments extracted from the cores were examined for visual defects in the coating (holidays, bare areas, and mashed areas) and the thickness of epoxy coating was measured. Mashed areas are places where the epoxy coating thickness is reduced but is still intact. The number of visual defects on each ECR segment was converted to a number of defects per metre (per foot). All of the ECR segments contained visible defects: holidays, bare areas, mashed areas, or a combination of two or more of these. The average number of defects was 39 holidays per meter (12 per foot), 26 bare areas per meter (8 per foot), and 10 mashed areas per meter (3 per foot). The average epoxy coating thickness for all the ECR segments was 229 μm (9 mil) and ranged from 127 to 356 μm (5 to 14 mil).

Rebar Corrosion and Coating Disbondment

ECR segments extracted from the cores were examined for any coating disbondment and to determine the condition of the steel surface under the coating. The condition of the extracted ECR segments was generally good. For segments exhibiting corrosion, the severity varied from minor rust staining to significant corrosion and complete loss of the coating. These ECR segments were from cracked cores more than 8 years old and the staining and corrosion was at crack locations. The most severe corrosion was found on ECR segments from cracked cores and exposed to high chloride levels. The extent of coating disbondment was determined using the dry knife adhesion test. A rating scale of 1, 3, and 5 was used. A rating of 1 indicated a very well bonded coating. A rating of 3 indicated a coating which is somewhat easy to remove. A rating of 5 indicated a coating which is easy to remove or totally disbonded. Of the 44 tests performed on ECR segments from the 19 structures, 54 percent were rated a 1, 14 percent were rated a 3, and 32 percent were rated a 5. The coatings on more than half of the ECR segments still had good adhesion.

COMMENTS

Some comments on the results and findings of this investigation of bridge decks, barrier walls, and a noise wall constructed with ECR:

- All of the extracted ECR segments contained defects: holidays, bare areas, mashed areas, or a combination of one or more of these.
- Corrosion on the extracted ECR segments was determined to be minor in most of the extracted cores. However, the chloride levels at the rebar level in these cores were at or below the threshold level to initiate corrosion in black steel.
- Corrosion on the extracted ECR segments was more severe at a location of heavy cracking, shallow concrete cover, 15 mm, (0.58 in), and high chloride concentration, 9.4

kg/m^3 (15.8 lb/yd^3). This ECR segment was extracted from a noise barrier wall panel. This was the only structure which had significant corrosion induced concrete distress. Moisture/water may be present at the rebar level for a considerable length of time at cracks and shallow concrete cover locations to provide a necessary ingredient for the corrosion observed. The concrete in this barrier wall was also very permeable (21 293 and 22 722 coulombs). The cracks also give chlorides and moisture easy and direct access to the ECR. A typical bridge deck does not have such a low concrete cover and/or highly permeable concrete.

- Coating disbondment and softening occurred as a result of prolonged exposure to a moist environment. However, approximately 54 percent of the extracted ECR segments still had good adhesion of the epoxy coating.
- None of the bridge decks had any significant delaminations except for C 18, Bridge Number MAH-680-0705, in Ohio. The level of deck cracking and delaminations was considered to be minor by Ohio DOT personnel.
- ECR has provided effective corrosion protection for the 3 to 16 years of service, corrosion was not a significant problem in any of the decks evaluated. There was no evidence of any premature concrete deterioration that could be attributed to corrosion of the ECR. Some of the cores were intentionally taken at locations representing a "worst case." Therefore, these cores may not be representative or indicative of the overall performance that can be obtained from ECR.

Table 22 - Structures with Epoxy Coated Rebar Evaluated in C-SHRP

No.	State or Province	Structure Identification	Structure Location	Year Built	Age (years)	Epoxy Powder	Mat
C 1	Alberta	Bridge, 79-441	Akenside	1984	7	Scotchkote 213	Top
C 2	Alberta	Bridge, 229	Vegerville	1983	8	Scotchkote 213	Top
C 3	Nova Scotia	Bridge, 89-024	New Glasgow	1988	3	Scotchkote 213	Top
C 4	Nova Scotia	Bridge, 88-032	Little Narrows	1988	3	Scotchkote 213	Top
C 5	Ontario	Noise Barrier Wall Panels	Highway 401	1981	10	Scotchkote 213	All
C 6	Ontario	Barrier Wall, Site 240319	Highway 403	1979	12	Armstrong R361	All
C 7	Virginia	Bridge, 2030 (WBL)	Fauquier County	1978	12	Brown Color	Top
C 8	Virginia	Bridge, 2031 (EBL)	Fauquier County	1978	12	Brown Color	Top
C 9	Virginia	Bridge, 2045 (WBL)	Rockbridge County	1978	12	Green Color	Top
C 10	Wisconsin	Bridge, B67-170	Waukesha County	1976	14	Scotchkote	Top
C 11	Wisconsin	Bridge, B40-475	Milwaukee County	1977	13	Scotchkote	Top
C 12	Pennsylvania	Bridge, LR 1010/D1	Montgomery County	1974	16	Flintflex 6080	Both
C 13	Pennsylvania	Bridge, LR 1021/8	Allegheny County	1976	14	Scotchkote 202	Top
C 14	New York	Bridge, 3312170	Cortland	1981	9	Armstrong R349	Top
C 15	New York	Bridge, 1070700	Albany	1981	9	Scotchkote 213	Top
C 16	New York	Bridge, 107086C	Troy	1981	9	Armstrong R349	Top
C 17	Ohio	Bridge, HAM-275-1080R	Hamilton County	1977	13	Scotchkote	Top
C 18	Ohio	Bridge, MAH-680-0705	Mahoning County	1974	16	Scotchkote 202	?
C 19	Ohio	Bridge, CUY-480-0832N	Cuyahoga County	1979	11	Brown Color	Top

Table 23 - Evaluation Results and Coated Rebar Properties for Structures with Epoxy Coated Rebar Evaluated in C-SHRP

No.	Epoxy Powder	Mat	Age (years)	Structure Delaminations	Rebar Size	Gage Coating Thickness (mil)	Holidays	Bare Areas	Mashed Areas	Underfilm Contamination (percent)	Condition of Extracted Steel
							Number per foot				
C 1	Scotchkote 213	Top	7	None	20M	7.2	15	12	3	35	No Corrosion
					15M	5.6	9	9	0		No Corrosion
C 2	Scotchkote 213	Top	8	None	15M	7.5	6	6	6	15	No Corrosion
C 3	Scotchkote 213	Top	3	None[2]	15M	11.3	0	3	6	35	No Corrosion
C 4	Scotchkote 213	Top	3	None	25M	8.5	0	3	0	35	No Corrosion
					20M	9.1	0	6	6		
					15M	8.0	6	12	0		
C 5	Scotchkote 213	All	10	Yes	10M	8.3	3	18	0	40	No Corrosion
					10M	8.2	9[3]	0[3]	18[3]	15	One Significant Corrosion
C 6	Armstrong R361	All	12	None	15M	9.2	0	39	3	25	No Corrosion
C 7	Brown Color	Top	12	None	#5	8.2	3	12	3	30	No Corrosion
					#4	5.1	>64	0	0		
C 8	Brown Color	Top	12	None	#5	12.3	6	6	12	45	No Corrosion
					#4	5.3	>64	3	0		
C 9	Green Color	Top	12	None	#5	10.9	3	9	6	40	No Corrosion
C 10	Scotchkote	Top	14	None	#6	10.4	9	6	3	20	No Corrosion
					#5	9.1	3	9	6		
C 11	Scotchkote	Top	13	None[4]	#7	9.3	6	6	3	10	No Corrosion
					#6	11.1	3	3	0		
C 12	Flintflex 6080	Both	16	None[5]	#5	5.7	>64	12	0	15	No Corrosion
C 13	Scotchkote 202	Top	14	None	#5	10.5	6	6	3	20	No Corrosion
					#5	13.6	6	3	0		
					#4	9.2	>64	6	0		
C 14	Armstrong R349	Top	9	None	#5	11.5	3	6	3	70	Some Corrosion
C 15	Scotchkote 213	Top	9	$2\ ft^2$	#5	14.3	3	3	0	20	Significant Corrosion
C 16	Armstrong R349	Top	9		#5	10.6	9	15	0	70	Some Corrosion
C 17	Scotchkote	Top	13	?	#4	7.4	6	9	0	50	Some Corrosion
					#6	6.2	6	9	0		
C 18	Scotchkote 202	?	16	<1%	#6	8.4	0	3	6	15	Some Corrosion
C 19	Brown Color	Top	11	None	#6	10.6	0	6	3	10	No Corrosion
					#7	10.2	0	6	3	10	No Corrosion

1 mil = 0.0254 mm = 25.4 µm, 1 defect/foot = 3.3 defects/m

1. No delaminations in concrete. There are some hollow sounding areas near construction joints where concrete overlay had debonded from precast beams.
2. Survey done on sidewalk where there is not any membrane or asphalt overlay.
3. Holidays, bare areas, and mashed areas not measured on one bar due to significant corrosion.
4. Spot survey near core locations and cracks.
5. Deck patching also.

Table 24 - Evaluation Results of Concrete Properties for Structures with Epoxy Coated Rebar Evaluated in C-SHRP

No.	Epoxy Powder	Mat	Age (years)	Clear Cover (in)	Unit Weight (lb/yd^3)	Absorption (percent)	Cl^- Content[1] (lb/yd^3)	Average Rapid Permeability Test (Coulombs)	Trace pH	Visual Condition of Cores
C 1	Scotchkote 213	Top	7	2.83	3362	8.41	0.17	2694 - Moderate	11.0	3 of 6 Cracked
C 2	Scotchkote 213	Top	8	2.77	3465	6.89	0.31	1842 - Low	11.0	? Of 8 Cracked
C 3	Scotchkote 213	Top	3	3.67	3345	9.83	0.36	5424 - High	10.0	3 of 6 Cracked
C 4	Scotchkote 213	Top	3	3.02	3205	9.93	0.24	4629 - High	10.0	1 of 7 Cracked
C 5	Scotchkote 213	All	10	0.56	3767	8.63	11.01	21293 - Very High	11.0	? Cores Not Cracked
				0.58	3778	7.54	15.77	22722 - Very High	11.0	? Cores Not Cracked
C 6	Armstrong R361	All	12	1.50	3804	4.96	0.29	Not reported	11.0	2 Cores Not Cracked
C 7	Brown Color	Top	12	2.94	3797	7.84	0.82	2085 - Moderate	11.0	6 Cores Not Cracked
C 8	Brown Color	Top	12	2.71	3628	8.77	0.52	2626 - Moderate	11.0	7 Cores Not Cracked
C 9	Green Color	Top	12	2.85	3620	7.55	0.57	3142 - Moderate	11.0	7 Cores Not Cracked
C 10	Scotchkote	Top	14	2.40	3807	4.53	1.59	1024 - Low	10.0	? Cores Not Cracked
C 11	Scotchkote	Top	13	2.84	3761	6.75	0.83	2600 - Moderate	10.0	7 Cores Not Cracked
C 12	Flintflex 6080	Both	16	1.98	3696	6.04	1.04	1556[2] - Low	11.0	6 Cores Not Cracked
C 13	Scotchkote 202	Top	14	2.00	3596	8.04	8.06	4193 - High	11.0	1 of 7 Cracked
C 14	Armstrong R349	Top	9	2.00	3659	6.50	2.12	1349 - Low	10.5	2 of 6 Cracked
C 15	Scotchkote 213	Top	9	2.25	3596	7.78	0.61 to 11.07	2936 - Moderate	9.5	4 of 7 Cracked
C 16	Armstrong R349	Top	9	2.81	3680	7.59	6.87	Not reported	10.0	6 of 6 Cracked
C 17	Scotchkote	Top	13	2.75	3751	5.83	1.87	955 - Very Low	10.5	6 Cores Not Cracked
C 18	Scotchkote 202	?	16	2.23	3630	7.97	2.85	3704 - Moderate	11.0	5 of 8 Cracked
C 19	Brown Color	Top	11	2.75	3567	8.83	0.56	2319 - Moderate	11.0	6 Cores Not Cracked

1 inch = 25.4 mm, 1 lb/yd^3 = 0.6 kg/m^3

1. Water soluble content, baseline content not deducted.
2. Result is from a single test, others are the average of two tests.

CLEVELAND, OHIO

In order to extend the useful life of reinforced concrete bridge decks the State of Ohio implemented the use of ECR as a corrosion protection strategy. Initially only the top mat of reinforcing steel was epoxy coated. Recent inspections of these decks revealed a significant amount of concrete cracking and spalling on the bottom side of some of the decks. As a result of this finding a detailed investigation of three of these decks was initiated in late 1995. This investigation is currently in progress. A visual inspection of one deck was performed in early 1995 by personnel from the State and FHWA.

FINDINGS/DISCUSSION

The findings and discussion are based on the visual inspection of the one bridge deck. The bridge is located in Cleveland Ohio and carries I-480 over Fitch Road, Bridge No. CUY-480-283. It was built in 1979. The use of a high cement content in the deck concrete mix resulted in a deck cracking problem.

Bridge Deck Condition

The 1994 bridge inspection report for this bridge identified deterioration of the deck concrete. The deterioration identified includes leaching, cracks, 2.3 m^2 (25 ft^2) of spalls, and 0.3 m^2 (3 ft^2) of scaling. The depth of scaling is up to 19 mm (¾ in).

The 1995 visual inspection revealed a significant amount of cracking, corrosion, and spalling on the underside of the deck. Approximately 1 percent of the bottom deck surface had already spalled and spalling continues to occur. The corrosion is taking place only at the uncoated bottom mat of reinforcing steel. No cracking, spalling, or rust was visible on the top surface of the deck. This indicates that the ECR in the top mat of reinforcing steel may have tolerated a chloride ion concentration much above the corrosion threshold. Normally the chloride concentration at the top mat (epoxy coated) would be higher than at the bottom mat (black steel) due to the application of deicers on the top deck surface. The chloride concentrations in the two concrete samples taken from the bottom surface of the deck at the spalled/rusted locations were in the range of 5.9 to 11.9 kg/m^3 (10 to 20 lb/yd^3). One of the goals of the detailed investigation is to determine the chloride profiles to accurately evaluate the performance of ECR. Based on limited data from two chloride analyses at the bottom mat level, it is likely that the average chloride level at the top mat, ECR, will be higher than 5.9 kg/m^3 (10 lb/yd^3).

SUMMARY OF FINDINGS AND DISCUSSION

The summary of findings and discussion are based on the field evaluations of the structures and the laboratory evaluation of cores taken from the various structures. A summary of the overall condition of the structures and the condition of ECR segments extracted from the cores is contained in table 25.

Overall Condition of Structures

A total of 92 bridge decks, 2 bridge barrier walls (parapets), and 1 noise barrier wall was evaluated in the field for cracking, delaminations, and spalls. Overall the structures were generally found to be in good condition. Concrete deterioration was generally in isolated areas and often not related to corrosion of the ECR.

The extent of deck cracking ranged from very little or none to extensive. Cracking, when present, was generally transverse in nature. Deck cracking was not thought to be a result of any corrosion of ECR. The cracking in the bridge barrier walls consisted of scattered pattern cracking with some vertical cracks. The noise barrier wall consists of precast concrete panels and the panels that are closest to the roadway surface were cracked the most.

Very few spalls or delaminations were found. Delaminations were detected in only 10 of the bridge decks. Approximately half of these delaminations were small, 0.1 m^2 (1 ft^2) in size. The others varied from 0.3 m^2 (3 ft^2) to approximately 2.8 m^2 (30 ft^2) in size. Several other detected delaminations were associated with expansion devices (uncoated metal) and not due to any corrosion of ECR. The precast concrete panels in the noise barrier wall that are closest to the roadway exhibited rust staining and spalling.

Depth of Concrete Cover

The depth of concrete cover over the top rebar was measured in each of the cores. Average concrete cover was generally found to be adequate, at least 51 mm (2 in). However, some instances of inadequate concrete cover were found. In these instances chloride concentrations were usually higher and the concrete was typically cracked. As a result, the probability of corrosion occurring is enhanced.

Chloride Concentration

Most investigators determined the total chloride (acid soluble) content at the rebar level or chloride profiles. The concrete samples were either obtained from the concrete cores or from holes drilled into the concrete. In most cases the average chloride concentrations at the rebar level were at or above the threshold level to initiate corrosion in black steel.

The total chloride concentration was determined in 40 bridge decks. The average chloride concentration of all these decks was 2.2 kg/m^3 (3.7 lb/yd^3). The chloride concentration was greater than or equal to 0.6 kg/m^3 (1.0 lb/yd^3) in 33 (83 percent) of these decks and was greater than or equal to 1.2 kg/m^3 (2.0 lb/yd^3) in 24 (60 percent) of these decks. In addition, the chloride concentration was greater than or equal to 3.0 kg/m^3 (5.0 lb/yd^3) in 11 (28 percent) decks with the highest concentration being 6.8 kg/m^3 (11.5 lb/yd^3).

The water soluble chloride concentration was determined in 16 other bridge decks. The average chloride concentration of all these decks was 0.7 kg/m^3 (1.1 lb/yd^3). The chloride concentration was greater than or equal to 0.6 kg/m^3 (1.0 lb/yd^3) in 5 (31 percent) of these decks and was greater than or equal to 1.2 kg/m^3 (2.0 lb/yd^3) in 2 (13 percent) of these decks. None of these decks had chloride concentrations greater than 3.0 kg/m^3 (5.0 lb/yd^3) with the highest concentration being 2.6 kg/m^3 (4.3 lb/yd^3).

Epoxy Coating

Some of the ECR segments extracted from the cores were examined for visual defects in the coating (holidays), thickness of epoxy coating, and the blast profile on selected bars. Most if not all of the segments that were examined contained holidays or bare areas. The thickness of the coatings was generally within the limits specified at the time of construction. In most of the instances when the coating thickness did not meet specifications it exceeded the upper limit. The blast profiles which were evaluated were found to have met applicable specifications.

Rebar Corrosion and Coating Disbondment

ECR segments extracted from the cores were examined to determine the condition of the steel surface under the coating. Approximately 212 different ECR segments were examined. This total does not include ECR segments evaluated in the C-SHRP study from the five bridge decks and one barrier wall that were previously evaluated by others. It also does not include ECR segments from Pennsylvania as that report did not indicate how many segments were examined. For the majority of ECR segments no corrosion was present.

Approximately 202 ECR segments were extracted from bridge decks. Out of these segments, 162 (81 percent) did not have any corrosion present. For some of the remaining segments which exhibited evidence of corrosion, the corrosion may have been present at the time of construction since chloride contents at the time of the evaluation were below the initiation threshold. Only four ECR segments (2 percent) were reported as having experienced significant corrosion. The areas of corrosion were typically at locations of visible holidays or bare areas. The more heavily corroded ECR segments were also from locations of relatively shallow concrete cover with high chloride concentrations.

Ten ECR segments were extracted from the barrier and noise walls. Out of these segments, eight (80 percent) did not have any corrosion present. Only one ECR segment (10 percent) was reported as having experienced significant corrosion. The areas of corrosion were typically at locations of visible holidays or bare areas. The more heavily corroded ECR segment was also from a location of very shallow concrete cover, highly permeable concrete, and with high chloride concentration.

Some ECR segments extracted from the cores were also examined for any coating disbondment. The extent of coating disbondment varied and was found in both corroded and noncorroded areas. Visible holidays were generally present on ECR segments that experienced coating disbondment. In most cases the coating was generally still bonded to the steel surface. California reported coating disbondment on 12 ECR segments (out of 32 total) in both corroded and noncorroded areas. Except for one segment, visible holidays were present on all ECR segments that experienced coating disbondment. The extent of coating disbondment varied from 3 to 100 percent of the rebar surface with six segments having coating disbondment of more than 75 percent of its surface. Indiana reported no ECR segments showed any signs of debonding of the epoxy coating. The coatings were difficult to strip with a knife. Some segments were mechanically stripped of their coating in order to examine for underside of film. Michigan reported the epoxy coatings on ECR segments extracted from the experimental decks and with moist concrete were easily removed by hand with the use of a fingernail. Virginia reported the epoxy coatings remained tightly bonded to the steel and could only be removed with a knife.

The results of two separate investigations done in Ontario were reported. In the first investigation two barrier walls were evaluated. None of the ECR segments in one of the barrier walls showed evidence of any coating disbondment. There was evidence of isolated locations in the second wall with poor bond between the epoxy coating and the ribs of the rebars where the coating could be removed with a knife. However, the coating on the body of the bar could not be removed by a knife after scoring a cross into the coating.

In a second investigation, ECR segments were extracted from 12 bridges in exposed concrete components: barrier walls, end dams, sidewalks, and decks built without water proofing. The extracted ECR segments were tested for adhesion of the epoxy coating to the steel surface. Of the ECR segments extracted from structures built in 1979 and 1980, 27 percent had a well adhered coating that could not be lifted from the steel substrate. Of the ECR segments extracted from structures built between 1982 and 1985, 60 percent had a well adhered. Of the ECR segments extracted from structures built in 1990, 88 percent had a well adhered coating. It appears that adhesion of the epoxy coating decreases with time as ECR segments extracted from bridges with the longest service life exhibited the most adhesion loss.

In the C-SHRP study the extent of coating disbondment was determined using the dry knife adhesion test. Of the 44 tests performed on ECR segments from the 19 structures, 54 percent had a very well bonded coating, 14 percent had a coating which is somewhat easy to remove, and 32 percent had a coating which is easy to remove or totally disbonded. The coatings on slightly more than half of the ECR segments still had good adhesion.

Table 25 - Summary of Findings for Structures with Epoxy Coated Rebar

No.	Age (years)	Epoxy Powder	Mat	Condition of Extracted Steel	Average Cl^- Content[1] (lb/yd^3)	Overall Condition of Structure	Comments
CA 1	10	Scotchkote 214	Both	3 segments with significant corrosion, 4 segments with no corrosion	11.5 (t)	Isolated transverse cracking, some longitudinal cracking, no spalls, delaminated area of 3 ft^2	High ave. Cl^- above corrosion threshold and no indication if delamination due to corrosion of ECR. For segments with significant corrosion ave. Cl^- = 20.7 lb/yd^3, ave. cover = 0.7 in and holidays present. For segments with no corrosion ave. Cl^- = 5.1 lb/yd^3.
CA 2	10	Scotchkote 214	Both	3 segments with minor corrosion, 8 segments with no corrosion	3.3 (t)	Overlaid with asphalt, delaminated area of 4 ft^2 detected	Ave. Cl^- above corrosion threshold and no indication if delamination due to corrosion of ECR. For segments with minor corrosion ave. Cl^- = 6.7 lb/yd^3 and holidays present. For segments with no corrosion ave. Cl^- = 2.0 lb/yd^3.
CA 3	8	Scotchkote 213	Both	2 segments with some corrosion, 6 segments with no corrosion	3.9 (t)	Isolated transverse cracking, no spalls, delaminated area of 20 ft^2	Ave. Cl^- above corrosion threshold and no indication if delamination due to corrosion of ECR. For segments with some corrosion ave. Cl^- = 8.0 lb/yd^3 and holidays present. For segments with no corrosion ave. Cl^- = 2.6 lb/yd^3.
CA 4	7	Scotchkote 213	Both	6 segments with no corrosion	1.2 (t)	Extensive transverse cracking, no spalls or delaminations	Cl^- at corrosion threshold but no corrosion or evidence of corrosion induced concrete deterioration.
IN 1	8	Unknown	Both	14 segments with no corrosion	1.5 (t)	Extensive transverse cracking, no spalls or delaminations.	Cl^- above corrosion threshold but no corrosion or evidence of corroson induced concrete deterioration.
IN 2	10	Unknown	Both	8 segments with no corrosion	4.0 (t)	Minor random cracking, some spalling.	Cl^- above corrosion threshold but no corrosion or evidence spalling due to corroson of ECR.
IN 3	13	Unknown	Both	5 segments with no corrosion	3.2 (t)	Widespread transverse cracking, no spalls or delaminations.	Cl^- above corrosion threshold but no corrosion or evidence of corroson induced concrete deterioration.

1 inch = 25.4 mm, 1 lb/yd^3 = 0.6 kg/m^3 1 ft^2 = 0.0929 m^2

1. (t) - total or acid soluble chloride content, (w) - water soluble chloride content, NT - not tested

Table 25 - Summary of Findings for Structures with Epoxy Coated Rebar (continued)

No.	Age (years)	Epoxy Powder	Mat	Condition of Extracted Steel	Average Cl^- Content[1] (lb/yd^3)	Overall Condition of Structure	Comments
IN 4	8	Unknown	Top	6 segments with no corrosion	0.8 (t)	Transverse cracking at piers, some longitudinal cracking, no spalls or delaminations.	Cl^- below corrosion threshold and no corrosion or evidence of corroson induced concrete deterioration.
IN 5	13	Unknown	Both	5 segments with no corrosion	3.3 (t)	Longitudinal cracking, two wide transverse cracks, one large spall or delamination	Cl^- above corrosion threshold but no corrosion or indication if spall/delamination due to corroson of ECR
IN 6	17	Unknown	Both	10 segments with no corrosion	5.0 (t)	Longitudinal cracking, minor transverse cracking, some scaling, considerable popouts, spalling and delaminations in one span only	Cl^- above corrosion threshold but no corrosion or indication if spalling and delaminations due to corroson of ECR
MI 1	15	Scotchkote 202	Both	2 segments with no corrosion	6.9 (t)	Widespread transverse cracking, no spalls, one small delamination (< 1% deck area)	Cl^- above corrosion threshold but no corrosion or indication if delamination due to corroson of ECR
	15	Flintflex 531-6080	Both	1 segment with corrosion on bar surface	10.8 (t)	Widespread transverse cracking, no spalls or delaminations	High Cl^- above corrosion threshold, some corrosion, but no evidence of corroson induced concrete deterioration.
MI 2	15	Scotchkote 202	Both	1 segment with no corrosion	0.2 (t)	Minimal transverse cracking, no spalls or delaminations	Cl^- below corrosion threshold and no corrosion or evidence of corroson induced concrete deterioration.
	12	Flintflex 531-6080	Both	No segments examained	0.3 (t)	Minimal transverse cracking, no spalls or delaminations	Cl^- below corrosion threshold and no evidence of corroson induced concrete deterioration.
MI 3	15	Scotchkote 202	Both	2 segments with no corrosion	3.6 (t)	Minimal random cracking, no spalls or delaminations	Cl^- above corrosion threshold but no corrosion or evidence of corroson induced concrete deterioration.
	15	Cooks 270-A-009	Both	1 segment with corrosion on bar surface	7.3 (t)	Minimal random cracking, no spalls or delaminations	Cl^- above corrosion threshold, some corrosion, but no evidence of corroson induced concrete deterioration.

Table 25 - Summary of Findings for Structures with Epoxy Coated Rebar (continued)

No.	Age (years)	Epoxy Powder	Mat	Condition of Extracted Steel	Average Cl^- Content[1] (lb/yd^3)	Overall Condition of Structure	Comments
MI 4	15	Brown color	Top	2 segments with minor corrosion, 3 segments with corrosion on bar surface	3.8 (t)	Overall condition not reported, 3 cores not cracked, 3 cores with vert. cracks	Cl^- above corrosion threshold, some corrosion, but no evidence of corroson induced concrete deterioration. For segments with bar corrosion ave. Cl^- = 6.6 lb/yd^3. For segments with minor corrosion ave. Cl^- = 3.8 lb/yd^3.
MI 5	14	Green color	Top	6 segments with no corrosion, 1 segment with corrosion on bar surface	1.4 (t)	Overall condition not reported, 7 cores not cracked	Cl^- above corrosion threshold, some corrosion on only 1 of 7 segments, and no evidence of corroson induced concrete deterioration.
MI 6	15	Green color	Top	4 segments with no corrosion, 2 segments with corrosion on bar surface	2.9 (t)	Overall condition not reported, 3 cores not cracked, 3 cores with vert. cracks	Cl^- above corrosion threshold, some corrosion on only 2 of 6 segments, no evidence of corroson induced concrete deterioration. For segments with bar corrosion ave. Cl^- = 5.0 lb/yd^3. For segments with no corrosion ave. Cl^- = 1.4 lb/yd^3.
MI 7	14	Brown color	Top	6 segments with no corrosion	1.0 (t)	Overall condition not reported, 6 cores not cracked	Cl^- near corrosion threshold and no corrosion or evidence of corroson induced concrete deterioration.
MI 8	15	Green color	Top	8 segments with no corrosion	1.2 (t)	Overall condition not reported, 8 cores not cracked	Cl^- near corrosion threshold and no corrosion or evidence of corroson induced concrete deterioration.
MI 9	10	Green color	Both	3 segments with no corrosion	5.0 (t)	Overall condition not reported, 3 cores with vert. cracks	Cl^- above corrosion threshold but no corrosion or evidence of corroson induced concrete deterioration.
MI 10	10	Brown color	Both	2 segments with no corrosion	3.8 (t)	Overall condition not reported, 2 cores with vert. cracks	Cl^- above corrosion threshold but no corrosion or evidence of corroson induced concrete deterioration.

Table 25 - Summary of Findings for Structures with Epoxy Coated Rebar (continued)

No.	Age (years)	Epoxy Powder	Mat	Condition of Extracted Steel	Average Cl^- Content[1] (lb/yd^3)	Overall Condition of Structure	Comments
MI 11	10	Brown color	Both	1 segment with no corrosion, 2 segments with minor corrosion	2.6 (t)	Overall condition not reported, 2 cores with vert. cracks extending below top mat	Cl^- above corrosion threshold with some minor corrosion but no evidence of corroson induced concrete deterioration.
MI 12	10	Scotchkote	Both	2 segments with no corrosion	5.8 (t)	Overall condition not reported, 2 cores with vert. cracks	Cl^- above corrosion threshold but no corrosion or evidence of corroson induced concrete deterioration.
NY 1	7	Scotchkote 214	Top	2 segments with corrosion on rebar ribs	2.1 (t)	Transverse cracks over width of travel lanes, no delaminations or spalls.	Cl^- above corrosion threshold with some corrosion on rebar ribs but no evidence of corroson induced concrete deterioration. Rib corrosion on one segment from a core with no Cl^- may have been present at time of construction.
NY 2	7	Scotchkote 214	Top	1 segment with no corrosion	0 (t)	Transverse cracks over width of travel lanes, no delaminations or spalls.	Zero chlorides and no corrosion or evidence of corrosion induced concrete deterioration.
NY 3	11	Scotchkote 213	Top	6 segments with no corrosion	0.6 (t)	Transverse cracks over width of travel lanes, no delaminations or spalls.	Cl^- below corrosion threshold and no corrosion or evidence of corroson induced concrete deterioration.
NY 4	12	Scotchkote 213	Top	1 segment with corrosion on bar surface, 3 segments with rib corrosion, and 5 segments with no corrosion	5.2 (t)	Transverse cracks over width of travel lanes, no delaminations or spalls.	Cl^- above corrosion threshold with some corrosion on 4 of 5 segments but no evidence of corrosion induced concrete deterioration. For segments with bar corrosion Cl^- = 11.4 lb/yd^3. For segments with rib corrosion ave. Cl^- = 4.8 lb/yd^3. For segments with no corrosion ave. Cl^- = 4.2 lb/yd^3.
NY 5	11	Scotchkote 213	Top	2 segments with rib corrosion and 1 segment with no corrosion	4.8 (t)	Transverse cracks over width of travel lanes, no delaminations or spalls.	Cl^- above corrosion threshold with some corrosion on 2 of 3 segments but no evidence of corrosion induced concrete deterioration. For segments with rib corrosion ave. Cl^- = 6.7 lb/yd^3. For segment with no corrosion Cl^- = 0.9 lb/yd^3.

Table 25 - Summary of Findings for Structures with Epoxy Coated Rebar (continued)

No.	Age (years)	Epoxy Powder	Mat	Condition of Extracted Steel	Average Cl^- Content[1] (lb/yd^3)	Overall Condition of Structure	Comments
NY 6	11	Scotchkote 213	Top	2 segments with no corrosion	11.3 (t)	Transverse cracks over width of travel lanes, no delaminations or spalls.	High Cl^- above corrosion threshold but no corrosion or evidence of corroson induced concrete deterioration.
NY 7	11	Scotchkote 213	Top	2 segments with no corrosion	8.6 (t)	Transverse cracks over width of travel lanes, no delaminations or spalls.	Cl^- above corrosion threshold but no corrosion or evidence of corroson induced concrete deterioration.
NY 8	10	Armstrong R349	Top	2 segments with no corrosion	0.6 (t)	Transverse cracks over width of travel lanes, no delaminations or spalls.	Cl^- below corrosion threshold and no corrosion or evidence of corroson induced concrete deterioration.
NY 9	9	Scotchkote 213	Top	1 segment with corrosion on bar surface and 1 segment with rib corrosion	8.9 (t)	Transverse cracks over width of travel lanes, no corrosion induced delaminations, no spalls.	Cl^- above corrosion threshold with some corrosion but no evidence of corroson induced concrete deterioration. For segment with bar corrosion Cl^- = 10.4 lb/yd^3. For segment with rib corrosion Cl^- = 7.3 lb/yd^3.
NY 10	9	Armstrong R349	Top	1 segment with rib corrosion and 1 segment with no corrosion	2.4 (t)	Transverse cracks over width of travel lanes, no delaminations or spalls.	Cl^- above corrosion threshold with rib corrosion on 1 of 2 segments but no evidence of corroson induced concrete deterioration. For segment with rib corrosion Cl^- = 3.3 lb/yd^3. For segment with no corrosion Cl^- = 1.6 lb/yd^3.
NY 11	11	Scotchkote 213	Top	1 segment with corrosion on bar surface, 2 segments with rib corrosion, and 4 segments with no corrosion	1.8 (t)	Transverse cracks over width of travel lanes, no delaminations or spalls.	Cl^- above corrosion threshold with some corrosion on 3 of 7 segments but no evidence of corroson induced concrete deterioration. For segment with bar corrosion Cl^- = 4.0 lb/yd^3. For segments with rib corrosion ave. Cl^- = 3.1 lb/yd^3. For segments with no corrosion ave. Cl^- = 0.6 lb/yd^3.

Table 25 - Summary of Findings for Structures with Epoxy Coated Rebar (continued)

No.	Age (years)	Epoxy Powder	Mat	Condition of Extracted Steel	Average Cl^- Content[1] (lb/yd^3)	Overall Condition of Structure	Comments
NY 12	10	Scotchkote 213	Top	4 segments with rib corrosion and 5 segments with no corrosion	5.0 (t)	Transverse cracks over width of travel lanes, no delaminations or spalls.	Cl^- above corrosion threshold with rib corrosion on 4 of 9 segments but no evidence of corroson induced concrete deterioration. For segments with rib corrosion ave. Cl^- = 7.4 lb/yd^3. For segments with no corrosion ave. Cl^- = 3.2 lb/yd^3.
NY 13	7	Scotchkote 214	Top	1 segment with rib corrosion and 2 segments with no corrosion	1.3 (t)	Transverse cracks over width of travel lanes, no delaminations or spalls.	Cl^- above corrosion threshold with rib corrosion on 1 of 3 segments but no evidence of corroson induced concrete deterioration. For segment with rib corrosion Cl^- = 3.9 lb/yd^3. For segments with no corrosion Cl^- = 0 lb/yd^3.
NY 14	9	Armstrong R349	Top	4 segments with no corrosion	3.3 (t)	Transverse cracks over width of travel lanes, no delaminations or spalls.	Cl^- above corrosion threshold but no corrosion or evidence of corroson induced concrete deterioration.
PA 1	10	Unknown	Top?	No cores taken	NT	No transverse cracking, spalls, or patches	Structure in good condition, no evidence of corrosion induced concrete deterioraton
PA 2	9	Unknown	Top?	No cores taken	0.4 (t)	No transverse cracking, spalls, patches, or delaminations	Cl^- below corrosion threshold, structure in good condition, no evidence of corrosion induced concrete deterioraton
PA 3	9	Unknown	Top?	No cores taken	0.6 (t)	No transverse cracking, spalls, patches, or delaminations	Cl^- below corrosion threshold, structure in good condition, no evidence of corrosion induced concrete deterioraton
PA 4	8	Unknown	Top?	No cores taken	NT	No transverse cracking, spalls, or patches	Structure in good condition, no evidence of corrosion induced concrete deterioraton
PA 5	8	Unknown	Top?	No cores taken	NT	No transverse cracking, spalls, or patches	Structure in good condition, no evidence of corrosion induced concrete deterioraton
PA 6	8	Unknown	Top?	No cores taken	NT	No transverse cracking, spalls, or patches	Structure in good condition, no evidence of corrosion induced concrete deterioraton
PA 7	8	Unknown	Top?	No cores taken	NT	No transverse cracking, spalls, or patches	Structure in good condition, no evidence of corrosion induced concrete deterioraton

Table 25 - Summary of Findings for Structures with Epoxy Coated Rebar (continued)

No.	Age (years)	Epoxy Powder	Mat	Condition of Extracted Steel	Average Cl^- Content[1] (lb/yd^3)	Overall Condition of Structure	Comments
PA 8	8	Unknown	Top?	No cores taken	NT	No transverse cracking, spalls, or patches	Structure in good condition, no evidence of corrosion induced concrete deterioraton
PA 9	6	Unknown	Top?	No cores taken	NT	No transverse cracking, spalls, or patches	Structure in good condition, no evidence of corrosion induced concrete deterioraton
PA 10	6	Unknown	Top?	No cores taken	NT	No transverse cracking, spalls, or patches	Structure in good condition, no evidence of corrosion induced concrete deterioraton
PA 11	6	Unknown	Top?	No cores taken	NT	No transverse cracking, spalls, or patches	Structure in good condition, no evidence of corrosion induced concrete deterioraton
PA 12	10			Excellent condition with no corrosion	0.2 (w)	Deck rating of 7 indicates light deterioration with no spalls or delaminations	Cl^- below corrosion threshold and no evidence of corrosion induced concrete deterioraton
PA 13	12	Flintflex 531-6080	Both	Excellent condition with no corrosion	1.6 (w)	Deck rating of 8 indicates light deterioration with no spalls, no corrosion induced delaminations	Cl^- above corrosion threshold but no evidence of corrosion induced concrete deterioraton
PA 14	11			Excellent condition with no corrosion	0.5 (w)	Deck rating of 7 indicates light deterioration with no spalls or delaminations	Cl^- below corrosion threshold and no evidence of corrosion induced concrete deterioraton
PA 15	10	Scotchkote 202	Top	Excellent condition with no corrosion	4.3 (w)	One delamination. Deck rating of 6 indicates moderate deterioraton.	Cl^- above corrosion threshold, no indication if delamination due to corrosion of ECR
VA 1 VA 2	13	Scotchkote 202	Both	4 segments with no indication of rust on coating	1.5 (t) 1.5 (t)	Widespread pattern and transverse cracking, no delaminations	Cl^- above corrosion threshold, no indication of significant corrosion even though coating was in poor condition (holidays and bare areas) at the time of construction.
WV 1	19	Unknown	?	No cores taken	NT	Light full and partial width transverse cracks, five delaminations (1, 1, 1, 6, 31 ft^2)	Cracks not believed to be corrosion induced, no indication if delaminations due to corrosion of ECR
WV 2	18	Unknown	?	No cores taken	NT	Only one full width transverse crack, no delaminations, spalls, or other cracks	Structure in good condition, no evidence of corrosion induced concrete deterioration after 18 years of service
WV 3	18	Unknown	?	No cores taken	NT	No cracking, spalling, patching, or delaminations.	Structure in good condition, no evidence of corrosion induced concrete deterioration after 18 years of service

Table 25 - Summary of Findings for Structures with Epoxy Coated Rebar (continued)

No.	Age (years)	Epoxy Powder	Mat	Condition of Extracted Steel	Average Cl^- Content[1] (lb/yd^3)	Overall Condition of Structure	Comments
WV 4	17	Unknown	?	No cores taken	5.3 (t)	Light transverse cracks in about half the deck, no delaminations	Cracks not believed to be corrosion induced, Cl^- above corrosion threshold with no evidence of corrosion induced concrete deterioration after 17 years of service
WV 5	17	Unknown	?	No cores taken	2.4(t)	Widespread transverse cracks, no spalling or patching, no corrosion induced delaminations.	Cracks not believed to be corrosion induced, Cl^- above corrosion threshold with no evidence of corrosion induced concrete deterioration after 17 years of service
WV 6	18	Unknown	?	No cores taken	NT	Very few cracks, no corrosion induced delaminations	Cracks not believed to be corrosion induced, no evidence of corrosion induced concrete deterioration after 18 years of service
WV 7	17	Unknown	?	No cores taken	NT	No cracking, spalling, patching, or delaminations	Structure in good condition, no evidence of corrosion induced concrete deterioration after 17 years of service
WV 8	17	Unknown	?	No cores taken	NT	No apparent deficiencies, one delamination of 1 ft^2	Structure in good condition, no indication if delamination due to corrosion of ECR
WV 9	17	Unknown	?	No cores taken	NT	Full width transverse cracks, three small shallow circular spalls, no delaminations	Cracks not believed to be corrosion induced, no evidence of corrosion induced concrete deterioration after 17 years of service
WV 10	17	Unknown	?	No cores taken	NT	No cracking, spalling, patching, or delaminations	Structure in good condition, no evidence of corrosion induced concrete deterioration after 17 years of service
WV 11 WV 12	17	Unknown	?	No cores taken	NT	Transverse cracks, no delaminations	Cracks not believed to be corrosion induced, no evidence of corrosion induced concrete deterioration after 17 years of service
WV 13 WV 14	17	Unknown	?	No cores taken	3.3 (t) 2.1 (t)	Transverse cracks in both bridges, no delaminations in southbound bridge, one delamination of 1 ft^2 in northbound bridge has a spall associated with it	Cracks not believed to be corrosion induced, Cl^- above corrosion threshold with no indication if delamination due to corrosion of ECR

Table 25 - Summary of Findings for Structures with Epoxy Coated Rebar (continued)

No.	Age (years)	Epoxy Powder	Mat	Condition of Extracted Steel	Average Cl^- Content[1] (lb/yd^3)	Overall Condition of Structure	Comments
ON 1	9	Unknown	All	3 segments with no corrosion	~1.2 (t)	A few major vertical cracks and scattered pattern cracking	Only minor evidence of premature concrete deterioration
ON 2	9	Armstrong R361	All	1 segment had corrosion at a bare area, 4 segments with no corrosion	4.0 to 6.4 (t)	Some vertical cracks and pattern cracking	No evidence of active corrosion
C 1	7	Scotchkote 213	Top	2 segments with no corrosion	0.2 (w)	Wide longitudinal construction cracks, no delaminations	Relatively new deck (but cracked), Cl^- below corrosion threshold and no evidence of corrosion induced concrete deterioration
C 2	8	Scotchkote 213	Top	1 segment with no corrosion	0.3 (w)	A few longitudinal cracks, no corrosion induced delaminations	Relatively new deck (but with a few cracks), Cl^- below corrosion threshold and no evidence of corrosion induced concrete deterioration
C 3	3	Scotchkote 213	Top	1 segment with no corrosion	0.4 (w)	No delaminations	Relatively new deck, Cl^- below corrosion threshold and no evidence of corrosion induced concrete deterioration
C 4	3	Scotchkote 213	Top	1 segment with no corrosion	0.2 (w)	No delaminations	Relatively new deck, Cl^- below corrosion threshold and no evidence of corrosion induced concrete deterioration, located in cold marine environment, not yet exposed to roadway deicers
C 5	10	Scotchkote 213	All	1 segment with significant corrosion, 1 segment with no corrosion	11.0 (w) 15.8 (w)	Precast panels closest to roadway surface have cracking, rust staining, spalling	Highly permeable concrete, low concrete cover resulted in high Cl^- content and corrosion induced concrete deterioration
C 6	12	Armstrong R361	All	1 segment with no corrosion	0.3 (w)	Scattered pattern cracking and some vertical cracks	Cl^- below corrosion threshold and no premature concrete deterioration (also ON 2)
C 7 C 8	12	Brown color	Top	2 segments with no corrosion	0.8 (w) 0.5 (w)	Severe transverse and random cracking, no delaminations	Cl^- below corrosion threshold, cracking not corrosion induced
C 9	12	Green color	Top	1 segment with no corrosion	0.6 (w)	Minor cracking, no corrosion induced delaminations	Cl^- below corrosion threshold and no evidence of corrosion induced concrete deterioration

Table 25 - Summary of Findings for Structures with Epoxy Coated Rebar (continued)

No.	Age (years)	Epoxy Powder	Mat	Condition of Extracted Steel	Average Cl^- Content[1] (lb/yd^3)	Overall Condition of Structure	Comments
C 10	14	Scotchkote	Top	1 segment with no corrosion	1.6 (w)	No delaminations	Cl^- above corrosion threshold but no corrosion induced concrete deterioration
C 11	13	Scotchkote	Top	1 segment with no corrosion	0.8 (w)	Transverse cracking, no delaminations	Cl^- below corrosion threshold and no evidence of corrosion induced concrete deterioration
C 12	16	Flintflex 531-6080	Both	1 segment with no corrosion	1.0 (w)	No corrosion induced delaminations	Cl^- at corrosion threshold and no evidence of corrosion induced concrete deterioration (also PA 13)
C 13	14	Scotchkote 202	Top	1 segment with no corrosion	8.0 (w)	No delaminations detected this evaluation	Cl^- above corrosion threshold but no evidence of corrosion induced concrete deterioration (also PA 15)
C 14	9	Armstrong R349	Top	1 segment with slight corrosion	2.1 (w)	Wide transverse cracks, no delaminations	Cl^- above corrosion threshold, minor corrosion on only one segment, no evidence of corrosion induced concrete deterioration (also NY 14)
C 15	9	Scotchkote 213	Top	1 segment with significant corrosion	11.1 (w)	Several wide and numerous hairline transverse cracks, one delamination of 2 ft^2	High Cl^- above corrosion threshold, wide range in Cl^- contents, no correlation established between core locatons and Cl^- contents (also NY 9)
C 16	9	Armstrong R349	Top	1 segment with slight corrosion	6.9 (w)	Several hairline transverse cracks, no delaminations	High Cl^- above corrosion threshold but no evidence of corrosion induced concrete deterioration (also NY 10)
C 17	13	Scotchkote	Top	1 segment with some corrosion	1.9 (w)	Overall condition not reported, cores in excellent condition	Cl^- above corrosion threshold but no evidence of corrosion induced concrete deterioration
C 18	16	Scotchkote 202	?	1 segment with some corrosion	2.9 (w)	Minor cracks <5% of deck area, delaminations <1% of deck area	Cl^- above corrosion threshold but no indication if concrete deterioration is due to corrosion of ECR
C 19	11	Brown color	Top	2 segments with no corrosion	0.6 (w)	No cracking or delaminations	Cl^- below corrosion threshold and no evidence of corrosion induced concrete deterioration

CONCLUSIONS

The following conclusions are based on the results and findings from the evaluations of the performance of ECR in bridge decks, bridge barrier walls (parapets), and a noise barrier wall.

- The overall condition of the bridge decks was considered to be good. Even though deck cracking was prevalent, it did not appear to be corrosion related. Very few of the decks had any delaminations and/or spalls. Most of the delaminations were not associated with the ECR. The maximum extent of delamination reported was less than 1 percent of the deck area. However, the actual extent of delamination was not reported.
- A bridge in West Virginia had a total of approximately 3.7 m^2 (40 ft^2) of delaminated area out of a total deck area of 1653.6 m^2 (17,800 ft^2), approximately 0.25 percent of the deck area, after 19 years of service life. The largest of these delaminations was centered on a construction joint and most likely not corrosion related. Chloride contents are not available for this deck and the report does not indicate if the delaminations are corrosion induced. The State of West Virginia indicated in its report that based on its previous experience, a typical deck of the same design but with black steel would have more delaminations (5 to 20 percent of the deck area being common). A detailed chloride analysis is also required to determine long-term performance of ECR in aggressive environments.
- The chloride concentrations at the rebar level for most bridges was at or above the corrosion threshold for black steel. However, the chloride levels in some others were still below the threshold. Most of these decks had not been in service long enough for the chloride levels to reach the threshold level. For these bridges it may be too soon to determine the effectiveness of ECR.
- Corrosion on the extracted ECR segments was determined to be minor in most of the extracted cores. No evidence of corrosion was found on 81 percent of the extracted ECR segments even though chloride concentrations, up to 3.8 kg/m^3 (6.4 lb/yd^3) were well above the chloride threshold level for initiating corrosion in black steel.
- ECR did not appear to perform as well when the concrete was cracked as when the concrete was not cracked. There was more corrosion activity on ECR segments extracted

from cores taken at locations where the deck was cracked. Even with high chloride concentrations, up to 7.6 kg/m^3 (12.8 lb/yd^3), no visible or negligible corrosion was found on ECR segments extracted from cores taken in uncracked locations. The cracks give both chlorides and moisture easy and direct access to the ECR which appears to accelerate the corrosion process. The lack of cracks appears to hinder the corrosion process.

- In California, corrosion on the extracted ECR segments was more severe at locations of heavy cracking, shallow concrete cover, 15 to 25 mm (0.6 to 1.0 in), and high chloride concentrations, 9.7 to 15.0 kg/m^3 (16.4 to 25.3 lb/yd^3). Moisture/water and a high chloride content present at the rebar level for a considerable length of time are responsible for the observed corrosion.
- The Ontario Ministry of Transportation reported that corrosion on the extracted ECR segments was more severe at a location of heavy cracking, shallow concrete cover, 15 mm (0.58 in), and a high chloride concentration, 9.4 kg/m^3 (15.8 lb/yd^3). This ECR segment was extracted from a noise barrier wall panel which had significant corrosion induced concrete distress. Moisture/water and a high chloride concentration at the rebar level are once again responsible for the corrosion observed. The concrete in this barrier wall was also very permeable (21 293 and 22 722 coulombs). A typical bridge deck does not have such a low concrete cover and/or highly permeable concrete.
- Coating disbondment and softening occurred as a result of prolonged exposure to a moist environment. In California, coating disbondment occurred at both corroded and non-corroded areas and was generally detected at visible holidays. In Indiana, the ECR segments showed no signs of coating disbondment. In Michigan, coatings on ECR segments extracted from moist concrete could easily be removed. In New York, coating deterioration was not found on any of the ECR segments. Tests performed in Ontario showed adhesion of the epoxy coating to the steel substrate decreases with time. Approximately 54 percent of the ECR segments evaluated under the Canadian SHRP program still had good adhesion of the epoxy coating.
- The number of defects in the epoxy coating and the amount of disbondment influence the performance of ECR. Many of the extracted ECR segments contained defects: holidays, bare areas, mashed areas, or a combination of one or more of these. In California, high

chloride concentrations, up to 4.6 kg/m^3 (7.7 lb/yd^3) did not initiate corrosion when there were no defects (holidays) in the coating, indicating that non-damaged epoxy coatings provide an adequate barrier to chlorides. In Virginia, there were no indications of significant corrosion even though the initial condition of the coating was poor and numerous holidays and bare areas were present.

- A comparison of the performance of ECR in decks with only the top mat of reinforcing steel epoxy coated with decks with both the top and bottom mat of reinforcing steel epoxy coated suggests superior performance when both mats are epoxy coated.
- The bridges evaluated in California were originally constructed with black steel. Based on the dates of original construction and first redecking, it appears that the use of black steel only provided 10 to 12 years of service life. However, it is possible that there were other contributing factors besides the use of black steel: shallow cover and a lower quality of concrete.
- The use of an adequate good quality concrete cover, adequate inspection, finishing, and curing of the concrete, and the proper manufacturing and handling of ECR complement the use of ECR in providing effective corrosion protection for concrete bridge decks.
- ECR has provided effective corrosion protection for up to 20 years of service, corrosion was not a significant problem in any of the decks evaluated. No signs of distress were found in the first bridge decks built with ECR. There was no evidence of any significant premature concrete deterioration that could be attributed to corrosion of the ECR. Some of the cores were intentionally taken at locations representing a "worst case." Therefore, these cores may not be representative or indicative of the overall performance that can be obtained from ECR. Little or no maintenance or repair work done has been done on most of the decks.

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