Service Life Extension of Northern Bridge Decks containing Epoxy-Coated Reinforcing Bars

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INTRODUCTION

The use of epoxy-coated steel reinforcing bars has gained widespread acceptance as a means to extend the service life of reinforced concrete bridge decks and other reinforced concrete structures susceptible to corrosion. Deicing salts first began to be used on bridge decks in the late 1950s, and corrosion of the reinforcing steel emerged as a problem in the 1960s. In the early 1970s, epoxy-coated reinforcement was determined to be a viable solution to the corrosion problem.

Historically, the Federal Highway Administration and numerous state departments of transportation have performed extensive investigations on bridge decks using epoxy-coated reinforcing bars. However, recently the question being asked by leading corrosion researchers is, "How long will epoxy-coated reinforcing bars extend the service life of bridge decks?" In response to this question, CRSI has sponsored the work presented in this Research Series to provide a better understanding of the service life extension of epoxy-coated reinforcing bars in reinforced concrete bridge decks.

Bridge Decks Studied

Extensive condition assessments were conducted on 17 bridge decks in seven northern states: Iowa, Minnesota, New York, Ohio, Pennsylvania, Virginia, and Wisconsin. The bridge decks in Iowa had epoxy-coated reinforcing bar in the top and bottom mats. All other bridge decks had epoxy-coated reinforcing bar in the top mat only. The bridge decks varied in age from 9 to 27 years.

The first item in the overall condition assessment was a detailed visual examination and delamination survey performed on each bridge deck. *(photo below)* The damage level of each deck was calculated as the ratio of the total damaged surface area located in the inspected deck area (including spalls and delaminations) to the total surface area inspected. The crack density (ft/ft^2) was calculated by dividing the measured total length of the identified cracks by the total surface area.

S. K. Lee and Paul D. Krauss, "Long Term Performance of Epoxy-Coated Reinforcing Steel in Heavy Salt Contaminated Concrete," Final Report for Federal Highway Administration (Contract No. DTFH61-93-C-00027), October 2003.

For the full report see the Epoxy Coating section at **www.crsi.org**, *or contact CRSI directly.*

On the cover: Bridge deck in Franklin, Virginia

At right: Delamination survey using chain dragging methods.

Delamination survey.

Half-Cell Corrosion Potential

Half-cell corrosion potential is a standard measurement technique used to assess the likelihood of electrical current to flow through the reinforced concrete, which is related to the tendency of embedded steel to corrode. When measured half-cell potentials are plotted, they provide an indication of the location, area, and magnitude of the corrosion. Testing and sampling can then be concentrated in those areas.

Electrical continuity (low resistance) is a critical attribute for valid half-cell potential measurements and electrical continuity was measured in each bridge deck before performing half-cell potential measurements.

Equipotential contour maps were developed for each of the bridge decks based on the half-cell potential measurements gathered in the field. The bridge deck in Blacksburg, Virginia, for example, is shown in Figure 1. The darker zones indicate areas of active corrosion. Narrower spacings (i.e., steeper gradients) of equipotential contour lines may also indicate higher corrosion rates.

Equipotential contour maps can only be made on bridge decks where electrical continuity can be established. In practice, this means that the half-cell corrosion potential can only be measured on bridge decks with a top mat of epoxy-coated reinforcing bar and a bottom mat of uncoated reinforcing bar. Bridge decks with both the top and bottom mats of epoxy-coated reinforcing bar did not have any electrical continuity. Therefore, half-cell potentials could not be measured.

Corrosion Rate Measurement

Corrosion rate ($\mu A/cm^2$), measured in terms of corrosion current density, is a kinetic property indicating how fast corrosion is occurring at the time of measurement. Corrosion rate can change over time depending on a number of factors.

In this study, corrosion rate measurements were taken in the field mainly over the transverse reinforcing bars at seven or eight locations in each bridge deck in areas of high and low potential (as identified by the half-cell potential contour plots).

Corrosion rate measurements are useful for determining local corrosion conditions and for comparing areas of the bridge deck. The following guidelines are generally used for uncoated ("black") reinforcing bars:

less than 0.1 $\mu A/cm^2$ — very low corrosion

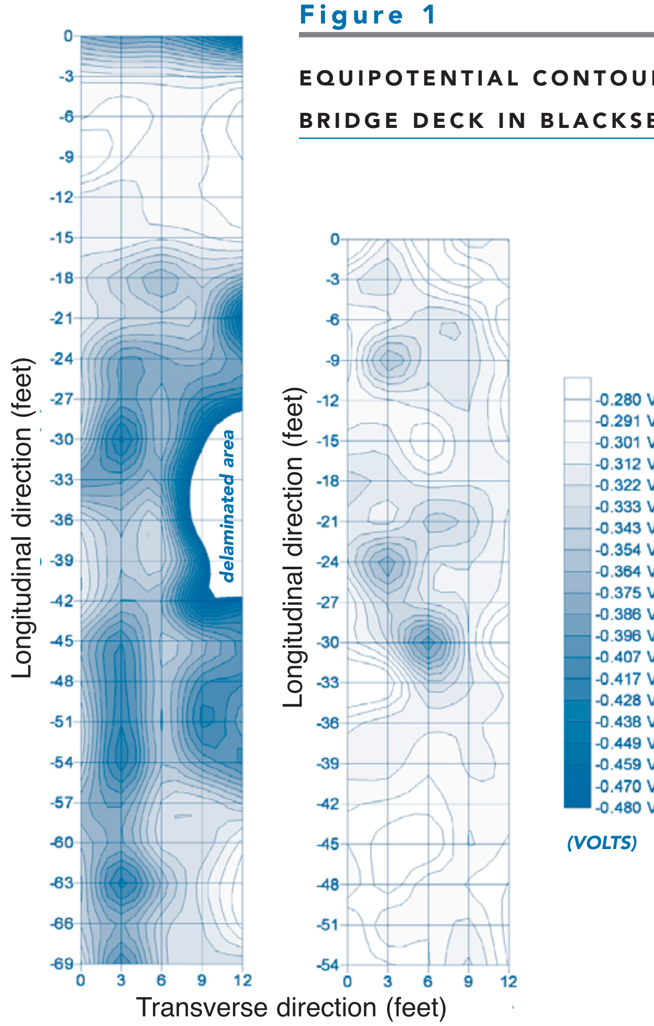
between 0.1 to 0.5 $\mu A/cm^2$ — low to moderate corrosion

between 0.5 to 1.0 $\mu A/cm^2$ — moderate to high corrosion

greater than 1.0 $\mu A/cm^2$ — very high corrosion.

Figure 1

EQUIPOTENTIAL CONTOUR MAP OF BRIDGE DECK IN BLACKSBURG, VIRGINIA



Coring and Depth of Cover

Based on the high and low corrosion rate locations, seven or eight 3-inch-diameter concrete core samples were obtained from each bridge deck – three to four from cracked areas and the remainder from uncracked areas. A total of 121 cores were obtained. Twelve core samples did not contain reinforcing bars but the remainder did.

A digital cover meter was used to locate the reinforcing bars and estimate the depth of cover over the reinforcing bars. Approximately 80 cover measurements were made in each bridge deck. The mean thickness of concrete cover over the reinforcing bars ranged from 2.0 to 3.6 inches.

Chloride Concentration Profiles

The cores were returned to the laboratory and samples taken by cutting 1/8-inch-thick slices from four different depths. These slices were pulverized for acid-soluble chloride analyses by the potentiometric titration method as described by ASTM C1152.

The chloride concentration profile results were then analyzed and the least-sum-of-squares curve was prepared. The curve was used to develop a theoretical chloride profile for the chloride data from the bridge deck. With an assumed residual chloride concentration and known exposure time, the estimated surface chloride concentration and chloride diffusion coefficient was determined based on Fick's Second Law. Fick's Second Law can be used to determine the length of time it takes chloride ions to migrate through the concrete in a bridge deck and reach the top mat of reinforcing steel.

Many cores contained cracks, which resulted in a large variation of chloride concentrations. The mean chloride concentration at bar depth of the cracked cores was almost twice as high as that of intact cores (1,763 versus 894 parts per million, ppm). For analytical purposes, chloride data taken from the cracked cores were assumed to be from homogeneous but poor-quality concrete.

Laboratory Examination

A total of 124 pieces of epoxy-coated reinforcing bar were extracted from the concrete cores and visually examined. The following rating system was used to characterize the condition of the reinforcing bars:

1 —no evidence of corrosion

2 —a number of small, countable corrosion areas

3 —corrosion area less than 20% of total surface

4 —corrosion area between 20% and 60 % of total surface

5 —corrosion area greater than 60% of total surface

A summary of condition rating of the 124 reinforcing bars is as follows:

Rating 1 (excellent) —74 percent

Rating 2 or 3 (fair) —10 percent

Rating 4 or 5 (poor) —16 percent

The extracted epoxy-coated reinforcing bars were also evaluated in terms of knife adhesion and coating thickness. In the knife adhesion test, an "X" is cut into the epoxy coating and the coating peeled back. Epoxy coating that is tightly adhered to the bar is generally more capable of consistently resisting corrosion.

Chloride Threshold

The chloride threshold is defined as the chloride content in concrete that will initiate corrosion on the reinforcing bars. A chloride threshold (C_{th}) of 300 ppm by weight of concrete sample is a widely recognized value for uncoated reinforcing bar.

There is not, however, a single well-established corrosion threshold value for epoxy-coated reinforcing bar. Corrosion initiation of epoxy-coated reinforcing bar is influenced by factors such as coating defect size and density, time of wetness, degree of disbondment, adhesion loss, temperature, single mat versus double mat, and concrete properties.

Table 1 presents several different chloride threshold values from available research literature. On this basis, researchers believe that the actual chloride threshold for epoxy-coated reinforcing bar varies on a project-by-project basis due to design, workmanship, concrete, and the quality of the epoxy coating.

Figure 2 shows a compilation of measured chloride concentration for the bridge decks analyzed in this study, along with data from a long-term laboratory study for FHWA that had an epoxy reinforcing bar rating of 1 (no corrosion) and having low corrosion current densities (< 0.2 μA/cm^2). Because the FHWA slabs were exposed to a 96-week Southern Exposure regime (cyclic wetting with 15 percent NaCl solution prior to 5 years of natural weathering), the chloride concentrations were much higher than the ones found for this study.

Based on the chloride data analysis, a chloride concentration of 1,185 ppm (the mean value of C_{th} from the data set) was considered a representative C_{th} of epoxy-coated reinforcing bars in bridge decks with coated bars in the top mat only. However, it was not possible, based on the data available, to derive a statistically significant value of C_{th} for epoxy-coated reinforcing bars in bridge decks with coated bars in both mats. Instead, the maximum observed value of C_{th} (3,750 ppm) observed without visible corrosion in the top-mat-only data was chosen as the value.

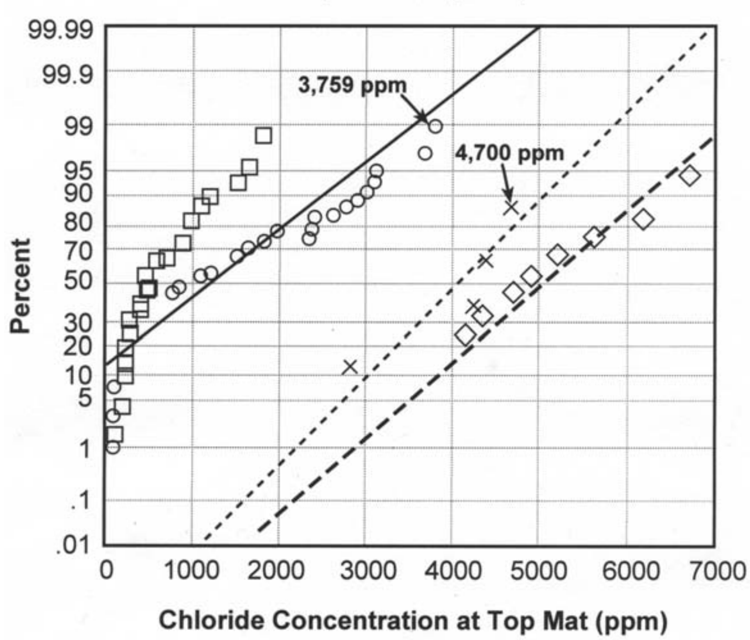
Table 1

CHLORIDE THRESHOLD VALUES

Source	Chloride Threshold		Maximum Chloride Concentration Without Corrosion Observed
	Lower Limit	Upper Limit	
Sohanghpurwala et al.		300 ppm (1.2 pcy)	
Weyers et al.		300 ppm (1.2 pcy)	
Fanous et al.	900 ppm (3.6 pcy)	1,875 ppm (7.5 pcy)	
Sagues et al.	300 ppm (1.2 pcy)	900 ppm (3.6 pcy)	
Hartt et al.			1,643 ppm (6.6 pcy)
Hartt and Lee et al.			3,859 ppm (15.4 pcy)
FHWA study et al.			4,700 ppm (18.3 pcy)
CRSI Phase I study			3,759 ppm (14.7 pcy)
CRSI Phase II study			1,787 ppm (7.1 pcy)

Figure 2

CHLORIDE CONCENTRATIONS OF BRIDGE DECKS IN STUDY



circle = CRSI Phase I
square = CRSI Phase II
diamond = FHWA Slab (ECR in Both Mats)
x = FHWA Slab (ECR in Top Mat)

Service Life Prediction Model

A statistical model was developed based on the field and laboratory data to predict the service life of bridge decks. The prediction model is based on Tutti's conceptual model, as shown in Figure 3, and can be expressed as:

$$T_d = T_{init} + T_{prop} \quad (1)$$

where

T_d = time to reach a particular damage level

T_{init} = time to corrosion initiation

T_{prop} = time of corrosion propagation

Time to corrosion initiation (T_{init}) for reinforcing bars embedded in concrete was modeled based on Fick's Second Law and is based on the depth of concrete cover, the surface chloride concentration, the residual chloride concentration within the concrete, age of the structure, and the chloride diffusion constant.

Time of corrosion propagation (T_{prop}) – or the length of time the corrosion will manifest itself in concrete cracking, spalling, and delamination – is typically assumed to be 3 to 6 years for uncoated reinforcing bars. For this analysis, T_{prop} was estimated to be 5 years for reinforced concrete bridge decks containing uncoated bars and for decks containing epoxy-coated reinforcing bars in the top mat only.

This is likely a very conservative assumption for decks built with epoxy-coated reinforcing bars in the top mat because the coated bars typically exhibit a much longer time between corrosion initiation and visible concrete distress.

Furthermore, the corrosion rate of bridge decks built with two mats of epoxy-coated reinforcing bars should be considerably less than those built with uncoated bars, because the electrical conductivity is less.

Therefore, T_{prop} will be longer, although there are not enough field data on which to base an empirical value of T_{prop}.

For purposes of this analysis, a T_{prop} of 15 years was conservatively assumed based on the age of the oldest Iowa bridge deck exhibiting no corrosion damage and reduction of macro-cell current density.

Model Validation

The service life prediction model developed for this project was validated against two sets of field results obtained by others: the West Virginia Department of Transportation (WVDOT) and Iowa State University (ISU).

In 1993, the WVDOT performed a series of condition surveys for eight 17-year old concrete bridge decks, four of which were constructed with epoxy-coated reinforcing bars and the other four, uncoated bars. The results were compared to evaluate the benefits of using epoxy-coated reinforcing bars.

The average delamination of four bridge decks containing epoxy-coated reinforcing bars was virtually zero whereas the other four decks containing uncoated bars exhibited about

Figure 3

SERVICE LIFE PREDICTION MODEL

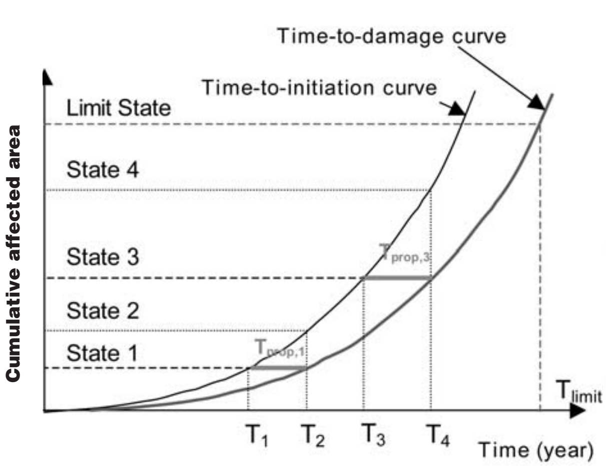
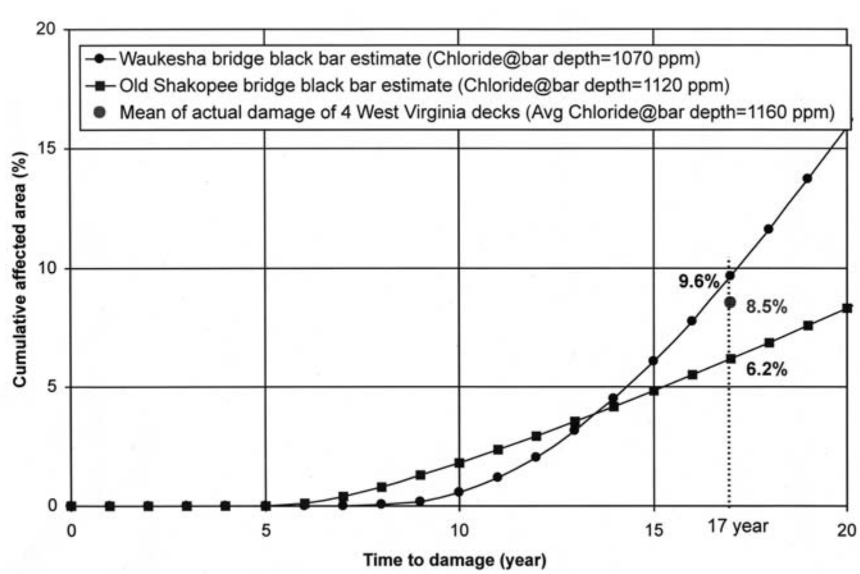


Figure 4

COMPARISON OF MODELED AND FIELD DATA



8.5 percent average delamination. CRSI's Research Series No. 1 (available at www.crsi.org) provides a summary of this research.

For purposes of model validation, the model results for uncoated bar cases from two bridge decks (Waukesha, Wisconsin and Old Shakopee, Bloomington, Minnesota) were compared against the West Virginia data. Good agreement between the modeled and field data was found (as shown in Figure 4).

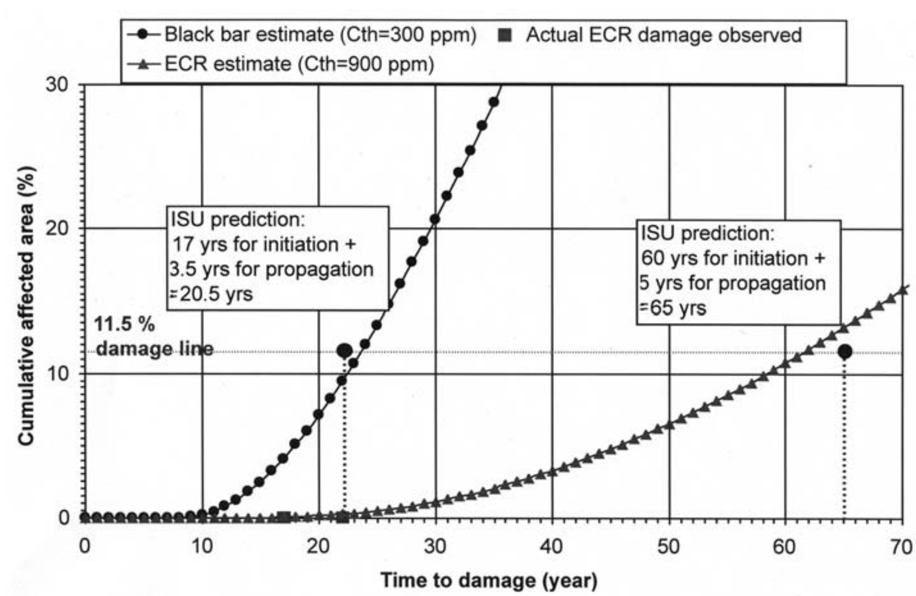
In 2002, researchers at ISU made service life predictions for Iowa bridge decks containing epoxy-coated and uncoated reinforcing bars. This work is summarized in CRSI's Research Series No. 10 (also available at www.crsi.org).

For comparison purposes, the bridge deck from Botetourt County, Virginia, was selected for modeling because it had similar mean depth of cover and was projected to have comparable damage to uncoated bars. Using chloride threshold values assumed by ISU (900 ppm for epoxy-coated reinforcing bars and 300 ppm for uncoated bars), the Botetourt County bridge deck was modeled; results are shown in Figure 5.

Both comparisons demonstrate that the service life prediction model can produce reasonably accurate service life predictions compared to actual deck performance.

Figure 5

BOTETOURT BRIDGE PERFORMANCE COMPARED TO PREDICTIONS



Modeling Results

Using the service life prediction model, a time-to-damage curve was developed for each bridge deck and the results compared to observed field data. Three examples are contained herein. For comparative purposes, time-to-damage curves were also developed assuming that the bridge decks were reinforced with uncoated reinforcing bars, epoxy-coated reinforcing bars in the top mat only, or epoxy-coated reinforcing bars in both mats.

The value of C_{th} was varied for each bridge deck to allow the modeled results to correspond to observed field data. Among the 11 bridge decks with epoxy-coated reinforcing bars in the top mat only, using a C_{th} of 1,185 corresponded well to the field data from four decks. However, the modeled C_{th} for the other seven bridge decks with epoxy-coated reinforcing bars in both mats ranged from 1,850 to 3,850 ppm.

BLACKSBURG BRIDGE DECK

The bridge deck in Blacksburg, Virginia, exhibited the worst physical damage (8.2 percent of the surface area of the deck contained spalls and delaminations) among the decks investigated in this study.

As shown in Figure 6, the prediction model indicates that if uncoated bars had been used to construct this bridge deck, the deck would have exhibited corrosion damage on about 20 percent of the deck after 22 years in service – well beyond serviceability – compared to the actual damage of 8.2 percent.

MAHONING BRIDGE DECK

The bridge deck in Mahoning, Ohio had a high level of chloride contamination and a shallow media depth of concrete cover over the top mat of reinforcing bar.

The prediction model (shown in Figure 7) indicated that if uncoated reinforcing bar was used, the bridge deck would have exhibited corrosion damage on about 57 percent of the deck after 27 years of service. For prediction of the service life of the bridge deck using epoxy-coated reinforcing bars, a value of 2,750 ppm was assigned to the chloride threshold Cth to make the modeled values correspond with the observed damage level of 0.7 percent at 27 years.

Figure 6

BLACKSBURG DECK PERFORMANCE COMPARED TO PREDICTIONS

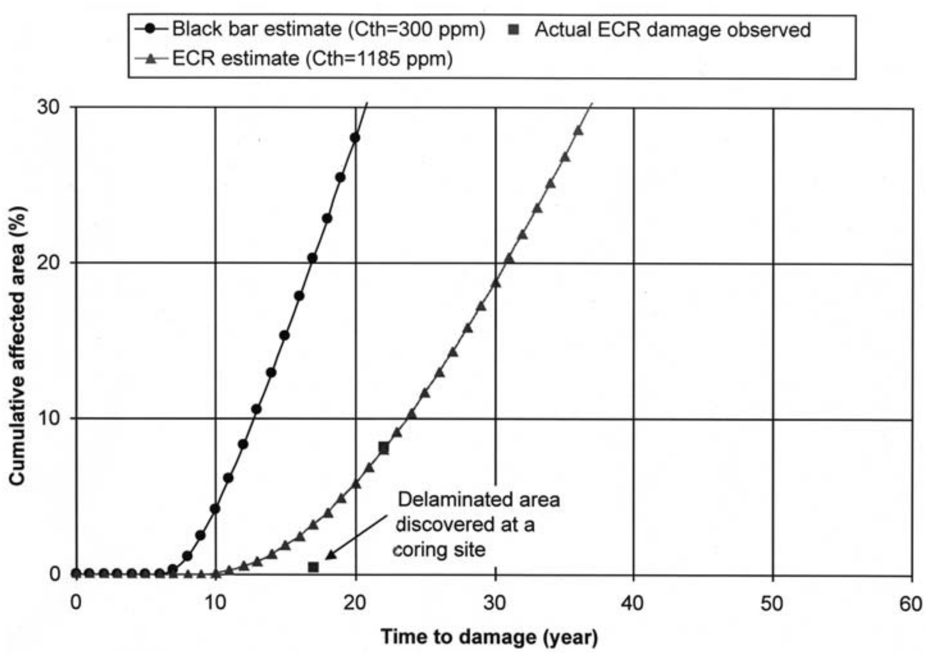
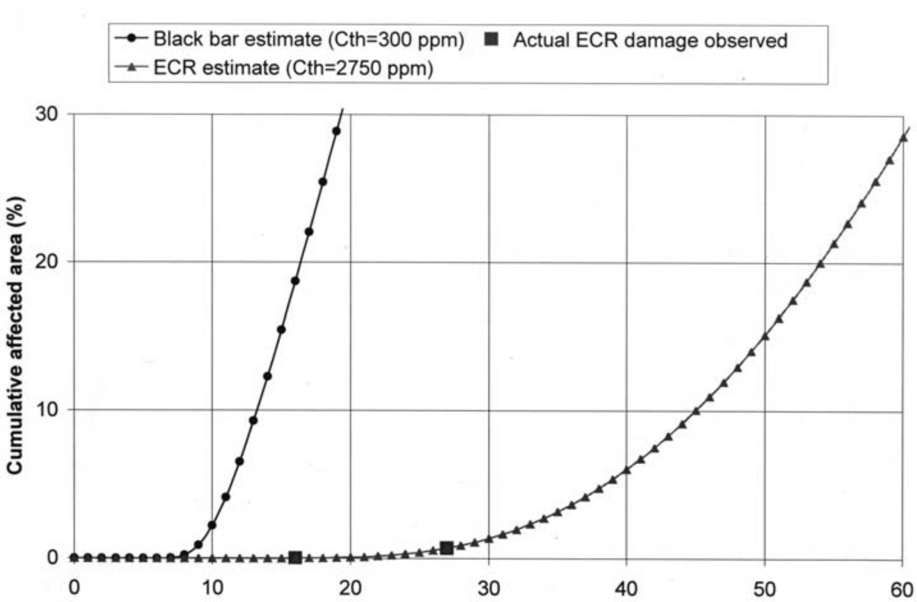


Figure 7

MAHONING DECK PERFORMANCE COMPARED TO PREDICTIONS



POLK BRIDGE DECK

The Polk bridge deck in Des Moines, Iowa, had epoxy-coated reinforcing bars in the top and bottom mats. Because there was no damage observed in the bridge decks from Iowa, the modeled results could not be curve-fit to field data.

The model results show that if the bridge deck was built with uncoated reinforcing bar, it would take approximately 17.5 years to reach a damage level of 10 percent. The same deck built with epoxy-coated reinforcing bar would take approximately 92 years to reach the same damage level. A combination of C_{th} of 3,750 ppm and T_{prop} of 15 years was used for modeling.

Conclusions from Service Life Modeling

In this study, it was assumed that a bridge deck would end its functional service life when cumulative damage of the deck reached 10 percent of the total deck surface area. The service life extension of a bridge deck was calculated by subtracting the service life of bridge deck as if it were built with uncoated reinforcing bar from the service life as built with epoxy-coated reinforcing bar.

The modeling results indicate that, for bridge decks built with epoxy-coated reinforcing bar in the top mat only, an average service life extension of more than 40 years is possible. For bridge decks built with epoxy-coated reinforcing bar in both top and bottom mat, an average service life extension of 82 years or more is possible.