Pergamon

Cement and Concrete Research 32 (2002) 1189–1197

CEMENT AND CONCRETE RESEARCH

Impact of specification changes on chloride-induced corrosion service life of bridge decks

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Received 15 August 2001; accepted 31 January 2002

Abstract

A model was developed to determine the time to first repair and to subsequently rehabilitate concrete bridge decks exposed to chloride deicer salts. Said model incorporates the statistical nature of factors affecting the corrosion process. The time to first repair and rehabilitate was predicted for 10 bridge decks built in Virginia between 1981 and 1994. The model was validated using historical service life data for 129 bridge decks built in Virginia between 1968 and 1972. The time for rehabilitation predicted for the newer set of bridge decks was approximately 13 years longer than the normalized time for rehabilitation projected for the older bridge decks. The increase in time for rehabilitation for the newer set of bridge decks was attributed to a reduction in the specified maximum water/cement ratio and increase in clear cover depth. The probabilistic model is shown to be an advancement over the deterministic model currently in use.

Keywords: Corrosion; Diffusion; Chloride; Reinforcement; Monte Carlo

1. Introduction

According to the Federal Highway Administration, approximately 30% of the nation's bridges are either structurally deficient or functionally obsolete. It is estimated that approximately US$90 billion will be required to rehabilitate or replace these bridges [1]. Chloride-induced corrosion of the reinforcing steel is known to be a major cause of premature rehabilitation of bridge structures. A better service life model is needed to allow planners to determine the remaining time to first repair and subsequently rehabilitate for a given bridge or set of bridges, and evaluate the effectiveness of the various protection methods.

The construction, environmental exposure conditions and process by which reinforcement corrodes are stochastic in nature. Service life models that incorporate the probabilistic nature of the process to varying degrees have been developed [2]. A service life model that fully recognizes the probabilistic nature of chloride-induced corrosion of bridge deck reinforcement may provide a better tool to planners. One way to incorporate the probabilistic nature of the process is to employ statistical computing techniques to the diffusion–cracking model [3], commonly thought to represent the deterioration process of bridge decks.

The diffusion–cracking model consists of two time periods. The first, known as the time for diffusion, is the time for chlorides to diffuse through the concrete clear cover to a concentration sufficient to initiate corrosion of the reinforcing steel. The second, known as the time for corrosion, is the time for corrosion products to build up around the reinforcing bar in sufficient quantities to cause cracking and spalling of the cover concrete to the end of functional service life. The end of functional service life is defined when 12% of the worst span lane of a bridge deck has deteriorated [4]. The time to first repair is defined when 2.5% of the worst span lane of a bridge deck has deteriorated [3].

The time for diffusion can be modeled by an apparent diffusion process that follows Fick's second law [5]. The

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0008-8846/02/$ – see front matter
PII: S0008-8846(02)00760-3

variables used for the apparent diffusion process include the clear cover depth (x), surface chloride concentration (C_o), apparent diffusion coefficient (D_c) and chloride initiation concentration ($C_{(x,t)}$).

The time for corrosion is generally thought to be 4–6 years for bare bar reinforcement [6,7]. Less is known about the time for corrosion for epoxy-coated reinforcement (ECR). Field studies have estimated 1–7 additional years for the time for corrosion damage of ECR [8–10].

The stochastic model uses the statistical resampling techniques known as the simple and parametric bootstrap to solve for the time to first repair and rehabilitate. The simple and parametric bootstrap are part of a general class of resampling techniques commonly known as Monte Carlo [11]. The parametric bootstrap uses field data to determine the parameters for known distributions that are assumed to represent the population of the variable. The time to first repair and rehabilitate are determined based on the diffusion–cracking model and values sampled from the probability distributions of the input variables for a number of iterations. The simple bootstrap assumes that the field data gives information not only about the center and spread of the entire population of the variable, but also about the shape of its distribution. The time to first repair and rehabilitate are determined based on the diffusion–cracking model and values sampled directly from the field data for a number of iterations.

A probabilistic model previously developed concluded that the parametric and simple bootstrap provide similar results [12]. To validate the model previously developed, it is necessary to compare the predicted service life to the service life observed in the field for similar bridge decks. A set of 129 bridge decks was investigated in the early 1970s as part of a project to determine the impact of a specification change in the late 1960s [13]. The service life of these bridges was investigated in 1994 as part of the Strategic Highway Research Program [6]. Updated service life data for these bridges provides the means to validate the probabilistic model and determine the impact of more recent changes in the specification.

The primary purpose of this study is to validate the probabilistic model previously developed using historical service life data from bridge decks built in Virginia. The secondary objective is to determine the effect of changes in the specification relative to chloride-induced corrosion of the reinforcing steel using one set of bridge decks built in Virginia between 1968 and 1972 and one set of bridge decks built in Virginia between 1981 and 1994.

2. Methods and materials

This section describes the two sets of bridge decks included in this study and presents the method used to determine the time to first repair and rehabilitate for each set of bridge decks.

2.1. Bridges built between 1981 and 1994 (current study)

The bridge decks built between 1981 and 1994 ranged in age from 4 to 18 years at the time of data collection. Ten bridge decks were included in the study and were selected from geographically diverse areas of Virginia. Eight of the 10 bridge decks were constructed with ECR while two were constructed with bare reinforcement [14]. The decks were constructed under the same specification. The specified water/cement (w/c) ratio for the decks is a maximum of 0.45, reduced from the previous maximum specified w/c ratio of 0.47. The specified clear cover depth is 63.5–76.2 mm (2.5–3.0 in.). The specification requires a 28-day compressive strength of 27.6 MPa (4000 psi). The incorporation of ECR into the specification occurred at approximately the same time as the specified reduction in w/c ratio.

The time to first repair and rehabilitate the bridge decks built between 1981 and 1994 were determined using the diffusion–cracking model and probability distributions for the input variables. For comparison, the time to first repair and rehabilitate were also determined using average values for the input variables.

2.1.1. Probabilistic model

A computer routine was developed to run both a parametric and simple bootstrap, and the time to first repair and rehabilitate were determined for the 10 bridge decks in the study using the routine [12]. The parametric and simple bootstrap were found to produce similar results. The routine was created using the statistical based program called S-Plus, which combines built in statistical capabilities with user programmable mathematical functions and is very efficient for statistical computing techniques like Monte Carlo.

Where possible, field data was collected from the bridge decks. Where no field data was available, values were determined from the literature. Because the time for corrosion damage is not well defined, probabilistic considerations were not included for the time for corrosion deterioration. The model can be easily updated when the time for corrosion deterioration is better determined.

2.1.1.1. Data from the field. The field data used for the model includes the clear cover depth, surface chloride concentration and apparent diffusion coefficient. Approximately 40 clear cover depth measurements are available for the worst span lane of each bridge deck. Between 7 and 15 measurements are available for both the surface chloride concentration and the apparent diffusion coefficient. The surface chloride concentration is defined as the acid soluble concentration of chlorides 12.7 mm (1/2 in.) below the concrete surface. The apparent diffusion coefficients were determined using a minimum sum of square errors procedure on acid soluble chloride concentration measurements of powdered samples removed directly from the deck and from cores. All of the chloride concentration measurements were adjusted for the background chloride content. Table 1 sum-

Table 1
Summary of field data

	x (mm)			C_o (kg/m^3)			D_c (mm^2/year)		
Structure no.	No.	Average	S.D.	No.	Average	S.D.	No.	Average	S.D.
1015	40	55.5	6.3	12	5.24	1.0	12	51.6	22.8
1004_3	40	71.3	4.2	14	3.89	0.77	14	39.3	19.3
1136	40	61.7	4.8	15	4.60	1.5	15	16.8	6.86
1001	40	61.9	6.0	13	2.32	0.35	13	28.1	22.6
1019	40	53.3	5.8	13	2.02	0.55	13	28.8	12.6
2262	30	58.9	7.8	12	1.95	0.68	12	27.8	16.0
2021	40	59.2	7.1	11	0.73	0.28	11	5.2	2.7
1004_6	30	66.3	6.3	8	0.67	0.24	8	11.1	6.4
6037	50	43.6	5.3	7	0.41	0.29	7	11.2	9.2
6128	40	59.4	4.2	8	0.16	0.06	8	39.1	23.5

marizes the field data collected for this study. It should be noted that the actual data, not the summaries presented here, are used to determine the time to first repair and rehabilitate using the probabilistic model.

2.1.1.2. Data from the literature. Field data was not available for the chloride corrosion initiation concentration or time for corrosion deterioration. For $C_{(x,t)}$, a range of 0.6–1.2 kg/m^3 (1.0–2.0 lb/cy) is often suggested as a conservative estimate for use in the diffusion–cracking model [3]. The range typically reported in the literature is from 0.6 to 5.5 kg/m^3 (1.0–9.2 lb/cy) [15]. The range of 0.6–1.2 kg/m^3 (1.0–2.0 lb/cy) is investigated in this study. The effect of the increased range on the time to first repair and rehabilitate is discussed elsewhere [12]. A conservative estimate of 4 years is used for the time for corrosion deterioration for bare bars. Note that the historical performance results are for bridges built with bare bars.

2.1.2. Average value model

The time to first repair and rehabilitate are commonly determined using average values for the input variables in the diffusion–cracking model. For comparison, the time to first repair and rehabilitate were determined for the 10 bridge decks included in this study using the average value method. The average of the input variables is also presented in Table 1. An average value of 0.9 kg/m^3 (1.5 lb/cy) was used for the chloride initiation concentration. The lowest 2.5 and 12 percentile clear cover depths are used in the average value model and are presented in Table 2.

2.2. Bridges built between 1968 and 1972 (Newlon study)

A total of 129 bridge decks were included in the original study of the bridges built between 1968 and 1972 [13]. The bridge decks were built under a specification that included a maximum w/c ratio of 0.47 and a cover depth of approximately 50 mm (2 in.). All of the decks were built with bare bar reinforcement. Although the service life of the decks was investigated for these bridges previously, updated service life data through April 2001 was obtained from the Virginia Department of Transportation for this project.

Table 2
Clear cover depths for average value model

Structure no.	× 2.5% (mm)	× 12% (mm)
1015	43.2	48.1
1004_3	63.0	66.3
1136	52.3	56.1
1001	50.1	54.9
1019	41.9	46.5
2262	43.5	49.7
2021	45.4	51.0
1004_6	53.9	58.9
6037	33.3	37.5
6128	51.2	54.5

The 129 bridges were separated into Interstate highways, US routes and rural Virginia routes. In each route type, the number of bridges that received polymer overlays and the number of bridges that were replaced or received concrete overlays was recorded. Using the updated data, the mean service life was projected using Normal probability distributions for each route type or combination of route types. Previous studies demonstrated that bridge deck service lives are normally distributed [6].

2.3. Simulated supplementary cementitious materials (SCM)

As another comparison, the time to first repair and rehabilitate were determined using the probable reduced apparent diffusion coefficients if the bridge decks had been constructed with SCM. Previous laboratory work on the service life of concrete bridge structures showed that D_c was generally lower for bridge decks containing SCM than for bridge decks with ordinary Portland cement (OPC) concrete [16]. Multiplication factors of 1/1.7 and 1/4.6 were suggested to reduce D_c determined for OPC concrete to the probable D_c if the concrete contained SCM. The multiplication factors used field and laboratory data and accounted for 90% and 50% of the measured D_c values, respectively [16]. The apparent diffusion coefficients collected for the 10 bridges in this study were multiplied by the factors to simulate the presence of SCM, and the times to first repair and rehabilitate were determined using the probabilistic model. The D_c for bridge 1136 was not reduced because

Table 3
Average reduced D_c for simulated SCM

Structure no.	D_c90% (mm^2/year)	D_c50% (mm^2/year)
1015	30.4	11.2
1004_3	23.1	8.6
1136	16.8	16.8
1001	16.5	6.1
1019	16.9	6.3
2262	16.4	6.0
2021	3.1	1.1
1004_6	6.5	2.4
6037	6.6	2.4
6128	23.0	8.5

Table 4
Time to first repair and rehabilitation

	Probabilistic method			Average value method		Simulated SCM	
Structure no.	Percent corroded	Time to first repair (years)	Time to rehabilitation (years)	Time to first repair (years)	Time to rehabilitation (years)	Time to rehabilitation (years)	Time to rehabilitation (years)
1015	100	10	13	14	16	20	47
1004_3	100	23	31	39	43	50	126
1136	100	33	46	53	60	46	46
1001	100	28	48	64	76	80	207
1019	99	30	47	56	69	76	200
2262	96	31	56	67	86	92	238
2021	27	–	–	–	–	–	–
1004_6	19	–	–	–	–	–	–
6037	7	–	–	–	–	–	–
6128	0	–	–	–	–	–	–

the deck concrete contained fly ash, based on petrographic analysis. The average of the reduced diffusion coefficients is presented in Table 3.

3. Results

3.1. Bridges built between 1981 and 1994 (current study)

The time to first repair and rehabilitate determined by the probabilistic, average value and probabilistic models with simulated SCM are presented in Table 4. Because the parametric and simple bootstrap were determined to produce similar results, only the results of the parametric bootstrap were shown for the probabilistic model. Predicted times to first repair and rehabilitate longer than 100 years were deemed to be unrealistic and were not reported. Larger values of the time to first repair and rehabilitate were presented for the simulated SCM for all bridges where values were reported for the probabilistic model.

3.2. Bridges built between 1968 and 1972 (Newlon study)

The number of bridges in each category of route types and the number that received polymer or concrete overlays are presented in Table 5. Polymer overlays are often installed for preventative maintenance on bridge decks that are in relatively good condition. It is unlikely that the bridges that received polymer overlays reached their end of functional service life as we have defined it for the newer set of bridges. For this reason, the service life was projected separately for the bridge decks that received polymer overlays and the bridge decks that received concrete overlays. Table 6 summarizes the mean and standard deviation of the projected service life for each route type.

Table 5
Summary of bridges from Newlon study as of April 2001

Route type	No. of bridges	Percent	No. receiving polymer overlays	No. receiving concrete overlays
Interstate (IS)	35	27	16	3
US route	41	32	13	12
VA route	53	41	4	2
Total	129	100	33	17

4. Discussion

4.1. Probabilistic model vs. average value model

The average value method is simpler and easier to employ than the probabilistic method. However, with the exception of the cover depth, the average value approach does not reflect the variability of the input variables. In the average value approach, the surface chloride concentration, diffusion coefficient and chloride initiation concentration are assumed to be constant over the entire deck surface, and the chlorides are assumed to diffuse through the concrete uniformly to the 2.5 or 12 percentile depth of the reinforcing steel.

In the probabilistic approach, the variability of each of the input variables is recognized. The surface chloride concentration, diffusion coefficient and chloride initiation concentration are not assumed to be constant over the entire deck surface. In the probabilistic approach, the deck is sectioned into many smaller points where the time for diffusion to corrosion initiation is calculated independent of the other locations, but in accordance with the probability distributions of the input variables. At individual simulated locations, the chlorides are assumed to diffuse through the concrete to the depth of the reinforcing steel at a rate defined

Table 6
Projected normalized service life (years) of bridges from Newlon study

	Bridges receiving concrete or polymer overlays		Bridges receiving concrete overlays (excluding polymer overlays)	
Route type	Average	S.D.	Average	S.D.
IS	28	4.8	28	4.9
US route	28	5.2	32	6.8
VA route	45	11.5	102	45.9
IS + US + VA	33	6.1	38	7.9
IS + US	28	4.5	34	7.1

by the probability distributions of the input variables. The time to first repair and rehabilitate are defined as the lowest 2.5 and 12 percentile values of all of the calculated times and, conceptually, corresponds to 2.5% and 12% of the area of the deck that has cracked and spalled.

The predicted time to first repair and rehabilitate was determined for each bridge using both the average value method and the probabilistic method (see Table 4). For the 10 bridge decks included in this study, the probabilistic method predicted times to repair and rehabilitation that were consistently shorter than the times to repair and rehabilitation predicted by the average value method.

It was observed that the probabilistic solution is heavily influenced by the variability of the input variables. Table 7 presents the results of the probabilistic solution for the time for diffusion to corrosion initiation for Bridge 1001 using decreasing values of the coefficient of variation for the input variables. The time for diffusion to corrosion initiation in the top row of the table uses the coefficients of variation for the data collected on the bridge deck. The coefficient of variation was then reduced for each input variable in steps to approximately zero. The percent difference between the resulting probabilistic estimate and the average value estimate is shown in the last column of the table. The percent difference between the estimates is reduced from 64% at the largest coefficients of variation to just 3% at the lowest coefficient of variation. For low coefficients of variation, the two methods produce similar results since there is little variability in these cases to be accounted for. If the variability is large, incorporating it into the model becomes increasingly important.

To investigate which of the input variables has the greatest influence on the predicted time for diffusion to corrosion initiation, the input values that contributed to the lowest 12% of the times for diffusion calculated in the simulation were separated out of the population of input values. The data from Bridge 1001 was used and the results are summarized in Table 8. The table includes the minimum, maximum and mean of the input variables that contributed to the lowest 12% of estimated times as well as the minimum, maximum and mean of all of the input variables sampled during the simulation. The minimum, maximum and mean of the actual data collected from the bridge deck is also included in the table.

The total population of data sampled during the simulation agrees well with the actual data collected from the bridge decks. As expected, the range of values sampled for the parametric bootstrap is longer than for the simple bootstrap. The input variables that contribute to the lowest 12% of all of the estimated times for diffusion to corrosion initiation tend to be from the side of the input distribution that predicts the shortest time for diffusion. For example, the average of all of the cover depth measurements used in the simulation is 62 mm (2.4 in.). The average of the cover depth measurements that contribute to the lowest 12% of the time for diffusion is only 59 mm (2.3 in.).

The trend is especially pronounced for the diffusion coefficient. The average of all of the diffusion coefficients used in the simulation (for Bridge 1001) is 28.1 mm^2/year (0.044 $in.^2$/year) while the average of the diffusion coefficients that contribute to the lowest 12% of the times for diffusion is approximately 68 mm^2/year (0.11 $in.^2$/year). The prediction of the time for diffusion to corrosion initiation is highly sensitive to the diffusion coefficient, and large values of the diffusion coefficient predict very small times for diffusion to corrosion initiation. In addition, the coefficient of variation for the diffusion coefficient is larger than the coefficients of variation for the other input variables, so more extreme values are expected to be in the population of the diffusion coefficient than the other input variables. Therefore, it is reasonable to say that shorter times for diffusion predicted by the probabilistic method, as compared to the average value method, can be attributed in a large part to the influence and variability of the diffusion coefficient. The variability of the other input variables contribute to a lesser degree.

To determine whether the influence of the variability is a reflection of the actual behavior of a bridge deck, or simply a consequence of the probabilistic method, the results were compared with the historical service life data for the bridge decks built between 1968 and 1972.

Table 7
Effect of coefficient of variation on probabilistic method

Time for diffusion to corrosion initiation, bridge 1001				
COV x	COV C_o	COV D_c	Time for diffusion probabilistic method (years)	Percent difference from average value solution
0.097	0.151	0.806	44	64
0.097	0.151	0.500	50	44
0.097	0.151	0.250	56	29
0.097	0.151	0.150	59	22
0.050	0.050	0.050	67	7
0.010	0.010	0.010	70	3
0.000	0.000	0.000	70	3

4.2. Validation of the model

4.2.1. Bridges built between 1981 and 1994 (current study)

Of the 10 bridge decks included in this study, four had measured surface chloride concentrations that were below 0.73 kg/m^3 (1.2 lb/cy) on average. Because of the low surface chloride concentrations on these bridges, times to first repair and rehabilitate calculated for these bridges were well above 100 years. The low surface chloride concentration of these bridge decks suggests that they are located on routes with low traffic volumes or remote locations. For this reason, they were treated as rural routes and were excluded from the validation analysis. For the remaining six bridge decks, the median time for diffusion to corrosion initiation, as determined by the probabilistic method, was 43 years.

Table 8
Input variables contributing to lowest 12% of calculated times

	Summary of input variables contributing to the time for diffusion to corrosion initiation (Bridge 1001)												
	x (mm)			C_o (kg/m^3)			$C_{(x,t)}$ (kg/m^3)			D_c (mm^2/year)			
Method	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Time
Pboot	45	59	76	1.6	2.5	3.7	0.6	0.85	1.17	22	67.9	202	Lowest 12%
Sboot	45	59	71	1.8	2.5	2.8	0.6	0.84	1.16	20.6	68.9	90	Lowest 12%
Pboot	41	62	87	1.3	2.3	3.8	0.6	0.9	1.2	0.1	25	202	Total
Sboot	46	62	71	1.8	2.3	2.8	0.6	0.9	1.2	10.2	28	90	Total
Actual	46	62	71	1.8	2.3	2.8	0.6	0.9	1.2	10.2	28.1	90.0	

The median time to diffusion as determined by the average value method was 61 years.

The bridges built between 1968 and 1972 were constructed using bare reinforcement. Most of the bridges constructed between 1981 and 1994 were constructed with ECR. To compare the predicted service of the bridges constructed between 1981 and 1994 to the historical service life data from the bridges constructed between 1968 and 1972, it was assumed that the time for corrosion deterioration to the end of functional service life for the bridges constructed between 1981 and 1994 was that of bare reinforcement, or approximately 4 years. The resulting median time for rehabilitation of the six bridge decks was 43 years for diffusion plus 4 years for corrosion deterioration (assuming bare reinforcement), or 47 years to the end of functional service life based on the probabilistic method. The resulting median time for rehabilitation was 65 years based on the average value solution.

4.2.2. Bridges built between 1968 and 1972 (Newlon study)

The average service life of bridge decks in Virginia has been reported to be 36 years with a standard deviation of 13 years, based on a normalized projection from a set of bridges built between 1968 and 1972 [6]. A review of updated service life data from the same set of bridges indicates that a bridge deck will be in service an average of 33 years before receiving either a polymer or concrete overlay (see Table 6). However, since polymer overlays are often installed for preventative maintenance on bridge decks that are in relatively good condition, it was not clear if bridges that received polymer overlays actually reached their end of functional service life as we have defined it. For this reason, bridge decks that received polymer overlays were not used to validate the model. The projected service life based on the updated data, excluding those that received polymer overlays, is 38 years with a standard deviation of 7.9 years.

In addition, it was observed that more bridges on Interstate and US routes received polymer or concrete overlays than those on Virginia routes.

Approximately 40% of the bridges included in the original Newlon study are located on rural routes. Note that 40% of the current study bridges built between 1981 and 1994 were also on rural routes. The average time until these bridge decks receive concrete overlays is 102 years, and the average time until these bridge decks receive either polymer overlays (likely for preventative maintenance) or concrete overlays is 45 years. The service lives projected for these rural bridge decks is substantially longer than for the bridge decks on Interstate and US routes, probably because the rural routes typically receive fewer applications of deicer salts because of their remote location and lower traffic volume. Because the projected service life of the rural structures was much longer than for the other structures, they were assumed to be of little concern and were not used to validate the model.

Of the 129 bridge decks included in the original Newlon study, 76 were found on Interstate or US routes. Of those 76 bridge decks, 29 received polymer overlays and were excluded. Of the remaining 47 bridge decks, 15, or 31.9%, received concrete overlays. The projected service life for these 47 bridge decks is 34 years, with a standard deviation of 7.1 years (see Table 6).

4.2.3. Comparison

Although the bridges included in the Newlon study were built under a different specification than the bridges included in the current study, the as-built cover depths were very similar, as presented in Table 9. Because both sets of bridges were randomly sampled throughout Virginia, it is assumed that the average surface chloride concentration is the same for both sets of bridges. Likewise, the average chloride initiation concentration is assumed to be the same for both sets of bridges. Because the two sets of bridges were built under different specified maximum w/c ratios, the diffusion coefficients were not assumed to be equal for the two sets of bridges. Because there is very little difference between the two sets of bridge decks in terms of the average as-built clear cover depths, the assumed surface chloride concentrations, the assumed chloride initiation concentrations, and the assumed times for corrosion deterioration, the

Table 9
Clear cover depth for bridges

		As-built cover depth	
Years built	Specified cover depth (mm)	Average (mm)	S.D. (mm)
1968–1972	50.8–63.5	61.0	12.4
1981–1995	63.5–76.2	65.0	8.9

effect of the differing *w*/*c* ratio can be evaluated in terms of the difference in the probable diffusion coefficients.

The projected normalized mean service life of the bridges, on Interstate and US routes, built between 1968 and 1972 is 34 years (excluding those that received polymer overlays). The median time for rehabilitation for the bridge decks built between 1981 and 1994, excluding those with very low C_o values, is 47 years, based on the probabilistic method and 65 years based on the average value method. The difference in service life between the two sets of bridge decks is 13 years and 31 years for the probabilistic and average value methods, respectively.

Because the other input variables are shown, or assumed, to be nearly equal, the differences in the predicted service life of the two sets of bridges may be explained by the differences in their average diffusion coefficients. The average D_c for the six bridge decks included in this analysis that were built between 1981 and 1994 is approximately 32 mm^2/year (0.050 in.^{2}/year). According to the results of the sensitivity analysis discussed elsewhere [12], the average D_c for the bridge decks built between 1968 and 1974 would have to be approximately 1.3 times the average D_c for the bridges built between 1981 and 1994 to account for the 13 year difference in the service life estimates using the probabilistic method. The average D_c for the bridge decks built between 1968 and 1974 would have to be approximately 2.0 times the average D_c for the bridges built between 1981 and 1994 to account for the 31 year difference in the service life estimates using the average value method.

A review of the available literature was performed to determine the effect of the *w*/*c* ratio on the diffusion coefficient. Three literature sources were identified that present the influence of the *w*/*c* ratio on the diffusion coefficient of laboratory prepared specimens determined by various methods [17–19]. In all cases, the concrete specimens were laboratory prepared and underwent diffusion in the saturated condition. The temperature of the tested specimens varied for each study. The diffusion coefficient is a function of the degree of saturation, where higher saturation levels typically produce higher diffusion coefficients. Therefore, the diffusion coefficient for saturated lab specimens is typically larger than the diffusion coefficient for specimens collected from bridge decks, since bridge decks rarely exist in the saturated condition.

Data from all three sources provided some indication of the expected difference in D_c between concrete mixes with *w*/*c* ratios of 0.45 and 0.47, although some interpolation or extrapolation was necessary for two of the sources. Also, because the diffusion coefficients were determined using slightly different methods and under slightly different conditions, direct comparison was not attempted. Instead, the ratio of D_c at *w*/*c* equal to 0.47 over D_c at *w*/*c* equal to 0.45 was determined in an attempt to negate the influence of differences in the temperature, level of saturation, and testing method. The results are presented in Table 10. It is clear that although the absolute magnitude of D_c estimated using data from the three sources differs, the ratio of $D_{c(0.47)}/D_{c(0.45)}$ is nearly equal for all three sources. The average ratio of D_c for *w*/*c* equal to 0.47 over *w*/*c* equal to 0.45 is 1.12.

Table 10
Diffusion coefficients based on *w*/*c*

	Diffusion coefficient (mm^2/year)	
Ref. [17]		
w/*c*	28 days @ 20 °C	20 years @ 20 °C
0.45	330	109
0.47	369	121
$D_{c(0.47)}/D_{c(0.45)}$	1.12	1.11
Ref. [18]		
w/*c*	15° C	25° C
0.45	57	112
0.47	64	123
$D_{c(0.47)}/D_{c(0.45)}$	1.12	1.10
Ref. [19]		
w/*c*	27° C	
0.45	341	
0.47	391	
$D_{c(0.47)}/D_{c(0.45)}$	1.15	

Earlier it was noted that the average D_c for the bridges built between 1968 and 1972 would have to be approximately 1.3 times larger than the D_c for the bridges built between 1981 and 1994 to account for the 13 year difference in the predicted time for rehabilitation using the probabilistic method at the most conservative level of chloride initiation, 0.6–1.2 kg/m^3 (1.0–2.0 lb/cy). The average D_c for the bridges built between 1968 and 1972 would have to be approximately 2.0 times larger than the D_c for the bridges built between 1981 and 1994 to account for the 31 year difference in the predicted time for rehabilitation using the average value method at the most conservative level of chloride initiation, 0.6–1.2 kg/m^3 (1.0–2.0 lb/cy). Based on the *w*/*c* data in the literature, the sensitivity of D_c, and assuming a time to cracking of 4 years, the change in *w*/*c* ratio between the two sets of bridges would account for approximately 40% of the additional service life determined by the probabilistic method and approximately 15% of the additional service life determined by the average value method.

Based on the sensitivity of the cover depth [12], the slight increase in as-built clear cover depth of the newer set of bridges would cause an increase in the time for rehabilitation of approximately 5 years, which is approximately 40% of the time for rehabilitation determined by the probabilistic method and approximately 15% of the time for rehabilitation determined by the average value method, assuming a time to cracking of 4 years.

Therefore, the combined effect of the decreased D_c caused by the lower *w*/*c* ratio and the slightly increased clear cover depth accounts for nearly all of the 13-year difference in time for rehabilitation between the historical data and the probabilistic method. The remainder can be attributed to inaccuracies associated with the projected normalized service life of the older bridges and lack of precision associated with the probabilistic model. The combined effect of the decreased D_c

and slightly larger cover depth accounts for only about 30% of the difference in the time for rehabilitation between the historical data and the average value method.

Based on these observations, it is reasonable to conclude that the probabilistic method provides results that most accurately reflect the behavior of the bridge decks included in this study, and that the additional service life expected for the set of bridges built between 1981 and 1994, when they are assumed to have times for corrosion deterioration similar to bare reinforcement, can be explained by the reduction in the *w*/*c* ratio and slight increase in the cover depth. In addition, the observed field and laboratory data showed variability across the bridge decks, and it is intuitively desirable to incorporate this variability into the model.

It should be noted that if the time to cracking were larger than 4 years, the difference between the service lives of the two sets of bridges would be larger. For instance, if the time to cracking were 10 years, instead of 4 years, the median time for rehabilitation for the set of bridged built between 1981 and 1994 would be 53 years based on the probabilistic method. The difference between the service lives of the two sets of bridges would be 19 years for the probabilistic method. When the time to cracking is assumed to be 10 years, the combined effect of the reduced D_c and increased cover depth would account for approximately 60% of the additional service life determined by the probabilistic method.

4.3. Simulated SCM

The median time for rehabilitation (assuming 4 years for the time for corrosion deterioration) for the six bridge decks included in the validation study was 62 years for the reduced D_c that accounted for 90% of the SCM data and 163 years for the reduced D_c that accounted for 50% of the SCM data. Assuming the same coefficient of variation as the historical service life data, the normalized times for rehabilitation predicted for the simulated SCM decks were plotted along with the normalized times for rehabilitation of the decks build between 1968 and 1972 and those built between 1981 and 1994. The results are presented in Fig. 1.

It is clear from Table 4 and Fig. 1 that the reduced apparent diffusion coefficient that SCM provide can significantly increase the service life of bridge structures, especially if the added SCM reduces the D_c below approximately 10 mm^2/year (0.016 in.^{2}/year).

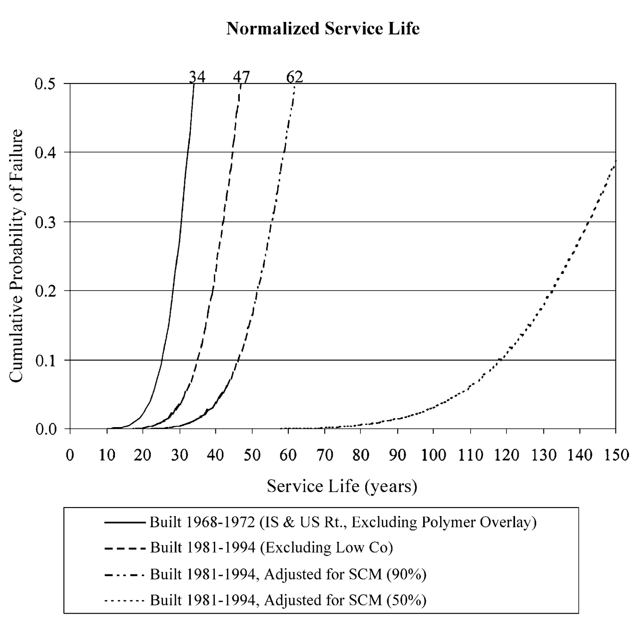

Fig. 1. Normalized service life estimates.

5. Conclusions and recommendations

The following conclusions and recommendations are made based on the results of the study.

• For the 10 Virginia bridge decks included in this study, the time to first repair and rehabilitate predicted by the probabilistic method was shorter than the time to first repair and rehabilitate predicted by the average value method. The difference was primarily attributed to the variability of the apparent diffusion coefficient and the sensitivity of the time to first repair and rehabilitate to the apparent diffusion coefficient. For input variables with low coefficients of variation, the average value method and the probabilistic methods provide results that are similar.

• The time to first repair and rehabilitate predicted by the probabilistic method more closely matches that of historical data than the time to first repair and rehabilitate predicted by the average value solution. The additional service life expected for the set of bridge decks built between 1981 and 1994 can be attributed to the decrease in *w*/*c* ratio and slight increase in as-built cover depth.

• The normalized mean time for diffusion to corrosion initiation of 12% of the steel for the bridges included in this study, excluding those with very low surface chloride concentrations, is 43 years. The mean time for rehabilitation depends on the time for corrosion deterioration for ECR.

• The addition of SCM added to bridge decks similar to the ones included in this study should increase the time for diffusion to corrosion initiation by at least 15 years.

• Lowering the apparent diffusion coefficient of bridge decks significantly lengthens the time for diffusion to corrosion initiation. Methods to reduce the apparent diffusion coefficient, including SCM, should be investigated for use in bridge decks.

Acknowledgments

The study funding was provided by the Virginia Department of Transportation. Their support is gratefully acknowledged.

References

[1] Federal Highway Administration, Our Nation's Highways — Selected Figures and Facts, U.S. Department of Transportation, Washington, DC, 2000.

[2] E.J., Gannon, A life cycle cost model for use in the optimization of concrete bridge deck repair and rehabilitation, Dissertation in Civil Engineering, The Pennsylvania State University, University Park, PA, 1998.

[3] R.E. Weyers, B. Prowell, M.M. Sprinkel, M. Vorster, Concrete bridge protection, repair, and rehabilitation relative to reinforcement corrosion: a methods application manual, SHRP-S-360, Strategic Highway Research Program, Washington, DC, 1993.

[4] M.G. Fitch, R.E. Weyers, S.D. Johnson, Determination of end of functional service life for concrete bridge decks, Transportation Research Record (1490) (1995) 60–66.

[5] Z.P. Bazant, Physical model for steel corrosion in concrete sea structures — theory, ASCE Journal-Structural Division 105 (6) (1979) 1137–1153.

[6] R.E. Weyers, M.G. Fitch, E.P. Larsen, I.L. Al Qadi, W.P. Chamberlin, P.C. Hoffman, Concrete bridge protection and rehabilitation: chemical physical techniques, service life estimates, SHRP-S-668, Strategic Highway Research Program, Washington, DC, 1994.

[7] P.D. Cady, R.E. Weyers, Deterioration rates of concrete bridge decks, Journal of Transportation Engineering 110 (1) (1984) 35–44.

[8] B.S. Covino Jr., S.D. Cramer, G.R. Holcomb, J.H. Russell, S.J. Bullard, C. Dahlin, J.S. Tinnea, Performance of Epoxy-Coated Steel Reinforcement in the Deck of the Perley Bridge, Ministry of Transportation, Ontario, Canada, 2000.

[9] K.C. Clear, Effectiveness of epoxy-coated reinforcing steel, Final Report, Canadian Strategic Highway Research Program, Ottawa, Canada, 1998.

[10] R.E. Weyers, M.M. Sprinkel, W. Pyc, J. Zemajtis, Y. Liu, D. Mokarem, Field investigation of the corrosion protection performance of bridge decks and piles constructed with epoxy-coated reinforcing steel in Virginia, VTRC 98-R4, Virginia Transportation Research Council, Charlottesville, VA, 1997.

[11] B. Efron, R.J. Tibshirani, An Introduction to the Bootsrap, Chapman & Hall, New York, NY, 1993.

[12] T.J. Kirkpatrick, R.E. Weyers, C.M. Anderson-Cook, M.M. Sprinkel, Stochastic model for the chloride induced corrosion service life of bridge decks, Cement and Concrete Research, 2001 (Submitted for publication).

[13] H.H. Newlon, A survey to determine the impact of changes in specifications and construction practices on the performance of concrete in bridge decks, VHRC 73-R59, Virginia Highway Research Council, Charlottesville, VA, 1974.

[14] T.J. Kirkpatrick, Impact of specification changes on chloride induced corrosion service life of Virginia bridge decks, Thesis in Civil and Environmental Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA, 2001.

[15] G.K. Glass, N.R. Buenfeld, Presentation of the chloride threshold level for corrosion of steel in concrete, Corrosion Science 39 (5) (1997) 1001–1013.

[16] J. Zemajtis, Modeling the time to corrosion initiation for concretes with mineral admixtures and/or corrosion inhibitors in chloride-laden environments, Dissertation in Civil and Environmental Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA, 1998.

[17] K. Stanish, Predicting the diffusion coefficient of concrete from mix parameters, University of Toronto Report, Toronto, Canada, 2000.

[18] C.L. Page, N.R. Short, A. El Tarras, Diffusion of chloride ions in hardened cement pastes, Cement and Concrete Research 11 (3) (1981) 395–406.

[19] S. Goto, D.M. Roy, Diffusion of ions through hardened cement pastes, Cement and Concrete Research 11 (5/6) (1981) 751–757.