Service Lives of Concrete Sealers

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Approximately 16 generic types and more than 450 concrete sealers are used as corrosion protection agents in the United States. However, no standard performance criteria that can be used to determine the cost-effectiveness of the various sealers exist. A study was performed to address the determination of the service lives (reapplication period) of sealers for concrete bridge components in the United States. The environmentally degrading forces of ultraviolet light and abrasion are considered, as is the leakage of the chloride ion through sealed concrete surfaces. A methodology is presented to determine sealer reapplication periods on the basis of the severity of the chloride exposure conditions, bridge site chloride diffusion rates, concrete cover depths, selected corrosion initiation protection period, and chloride leakage factors. The methodology is combined with a laboratory test method to determine sealer leakage factors, and sealer service lives are estimated for a water-based and solvent-based epoxy, a silane, and a siloxane for horizontally and vertically oriented concrete bridge components.

It has been said that steel reinforced concrete is the ideal composite construction material. Concrete is weak in tension but is strong in compression and durable in moist, oxygen-rich environments, whereas steel is strong in tension but is thermodynamically unstable in moist, oxygen-rich environments. The steel provides the tensile strength, and the high pH (pH 12 to 13) of the concrete pore water protects the steel from corroding.

However, certain environmental exposure conditions can disrupt the passive nature of steel in concrete. Carbon dioxide can penetrate porous concrete and through carbonation lower the pH of the concrete to the point at which the steel will spontaneously corrode. Chloride ions can diffuse through the porous concrete and initiate an autogenous corrosion process. Because of the relatively low water-to-cement ratios (less than 0.50) used in the United States carbonation-induced corrosion of the reinforcing steel occurs very infrequently. However, chloride ion-induced corrosion of reinforcing steel is a monumental problem in the United States, particularly for reinforced concrete bridges in the chloride-laden environments of coastal areas and in the northern snowbelt areas where chloride salts are used in winter maintenance activities.

Chloride ion-induced corrosion of reinforced concrete structures is well known. The chloride ion penetrates cracks or diffuses through the porous concrete, reaches a corrosion threshold value, and initiates the corrosion mechanism, and the expanding corrosion products crack and spall the cover concrete. One method that can be used to extend the service lives of steel reinforced concrete structures in chloride-laden environments is to significantly reduce the rate of diffusion of chlorides into the concrete. Concrete sealers, coatings, and membranes have been used extensively to block the ingress of chloride ions into reinforced concrete structures.

Because of their irrelatively low initial cost, concrete sealers offer an attractive solution to the problem of extending the service lives of concrete structures in chloride environments. However, to identify the true cost-effective solution(s) to the maintenance of concrete structures one must determine the minimum life-cycle cost, which is the true definition of cost-effectiveness. To determine the minimum life-cycle cost one must know the initial cost and the service life of the treatment. Thus, the maintenance engineer would know when and how many treatments would be applied over the service life of the structure.

This paper addresses the determination of the service life (reapplication period) of three generic types of concrete sealers applied to steel reinforced concrete bridges in the United States.

BRIDGE ENVIRONMENTS

The service life of a treatment is dependent on the severity of the environment. Decks are exposed to traffic abrasion and long periods of direct sunlight. Superstructure components, beams, and diaphragms are exposed to direct or indirect sunlight and wind abrasion. Substructure components, piers, pier caps, and abutments are exposed to ice, water, or wind abrasion and direct or indirect sunlight. Thus, the service life reduction factors for concrete bridge sealers include abrasion and ultraviolet light in addition to chloride ions. In the snowbelt areas of the United States decks are exposed to the severest conditions: direct exposure to abrasive traffic forces, ultraviolet light, and periodic applications of chloride deicing salts. In the southern coastal areas, however, piers are exposed to the severest conditions: direct exposure to water abrasion, ultraviolet light (part-time daylight exposure), and continuous exposure to chloride ions. Thus, sealer-degrading forces will vary relative to traffic condition: [average annual daily traffic (AADT) and percent trucks], geographical location (average annual snowfall or parts per million of chloride in the water), and latitude, component, and component orientation (period and intensity of ultraviolet light).

Of the range of environmental exposure conditions, traffic conditions result in the highest abrasive forces and a southern exposure may have the longest cumulative hours of ultraviolet light exposure.

EXPERIMENTAL DESIGN

Approximately 16 generic concrete sealer types and more than 450 products are on the market in the United States. However, only two sealing mechanisms are being used: surface agents or pore blockers and penetrating agents or hydrophobic materials. Two sealers each were selected from the two sealing groups: a water-based and a solvent-based epoxy as pore blockers and a silane and siloxane as penetrating sealers.

Since surface finish and exposure orientation influence the performance of a sealer, two specimen types were cast: rough trowel-finished horizontal slabs and a wall surface cast against oiled plywood. A total of 15 horizontal slabs of 91 × 91 × 10 cm were cast. The wall was 30 cm thick, 1.83 m high, and 4.88 m long. Temperature and shrinkage cracking was controlled with a 1.3-cm-diameter steel reinforcing bar with a 5.1-cm cover depth. The wall and slabs

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were cast from the same batch of redi-mix concrete (380 kg of cement, 759 kg of sand, and 1038 kg of stone per cubic meter of concrete), which had a water-to-cement ratio of 0.47. The fresh concrete had a 13-cm slump, 5.4 percent air content, and a unit weight of 2370 kg/m^3. The 28-day compressive strength was 38 MPa.

The 15 slabs were moist cured outdoors for 7 days with wet burlap; this was followed by 24 days of air curing outdoors. The slabs were demolded and placed on concrete blocks to simulate bridge deck exposure conditions. The four sides of the slabs were coated with epoxy, the top surface was lightly grit blasted, and the sealers were applied in the middle to upper middle application range. Three slabs were sealed with each of the four sealer types, and three control slabs were not sealed, but the surfaces were lightly grit blasted.

The wall was cured outdoors in the forms for 7 days; this was followed by 24 days of air curing outdoors. The shaded surface of the wall was lightly grit blasted and was sectioned off into 70-cm-wide vertical strips that were separated by 10-cm-wide stripes spray-painted red. The vertical test sections were sealed with the same sealer types and the same application rates as the horizontal slabs except for the siloxane sealer, whose manufacturer suggested a different coverage range for vertical surfaces. Of five test sections one was sealed with each of the four sealer types and one control section was not sealed but was lightly grit blasted.

In addition, the four sealer types were applied to two existing bridge decks. The sealer test sections were 90 cm wide and were separated by 10-cm-wide unsealed stripes. The sealer test sections were perpendicular to the direction of the traffic and extended from the edge of the 3-m-wide breakdown lane, across the breakdown lane, and across one 3.65-m-wide traffic lane. Before the sealer treatment the test sections were lightly grit blasted. The bridge decks are located near Blacksburg, Virginia. The Pepper's Ferry Bridge, a low-traffic-volume bridge, carries Virginia Route 114, a secondary route, over the New River and had an AADT in 1990 of 12,430. The other bridge, a high-traffic-volume bridge, carries Interstate 81 over Virginia Route 611. It had an AADT of 24,270 in 1990. Table 1 presents the sealer application rates along with the method of application for the horizontal laboratory test slabs, the vertical laboratory wall test sections, and the bridge deck test sections. All sealers were applied in accordance with the manufacturers' recommendations.

The environmental exposure conditions for the slabs, wall, and bridge decks were full direct sunlight and cyclic ponding with sodium chloride solution, partial direct sunlight and cyclic running sodium chloride solution, and full direct sunlight, deicer salt applications, and traffic wear, respectively. The slabs were ponded with 3 percent (by weight) sodium chloride solution continuously for 3 days; this was followed by 4 days of air drying. The average depth of the ponding solution was 8 mm, and the ponding dikes were covered with a white plexiglass sheet during ponding to prevent a greenhouse effect. For the wall test sections a 3 percent sodium chloride solution was pumped from a reservoir up to a distribution pipe that evenly distributed the solution to the test sections. The chloride solution flowed down over the wall, collected in the reservoir, and recirculated.

The wall wetting period was 8 hr for 3 consecutive days; this was followed by 4 days of drying. The flow rate across each test section was about 0.015 L/sec. The outdoor period of exposure to chloride for the slabs, wall, and bridge decks was 30 weeks, extending over a winter, spring, and summer.

PERFORMANCE MEASUREMENTS

To assess the service life performances of the sealers, chloride content, ultraviolet light exposure times, and traffic abrasion rates were measured. The chloride contents of the slabs were measured at three locations and depths (1.3, 2.5, and 3.8 cm) at the end of the 10, 20, and 30 weeks. Since there were three slabs for each treatment, a total of nine chloride contents were measured at each depth for each sealer. The chloride contents of each wall test section were measured at five locations at the same three depths used for the slab sections. The background chloride contents of the slab and wall concrete were determined and subtracted from the measured values to

TABLE 1 Sealer Treatments of Slabs, Wall, and Bridge Deck Test Sections

Slabs and Bridge Deck Test Sections	Treatment	Application Rate m^2/l	Application Method
Water-based epoxy	single	53	slabs - brush deck - roller
Solvent-based epoxy	first second	88 132	slabs & deck - brush
Silane	single	47	slabs & deck - low pressure sprayer
Siloxane	single	39	slabs & deck - flood & brush
Wall Test Sections			
Water-based epoxy	single	53	brush
Solvent-based epoxy	first second	88 132	brush
Silane	single	47	low pressure sprayer
Siloxane	single	53	low pressure sprayer

determine the ingress chloride contents. The chloride contents of the bridge deck test sections were not measured because they had been in service for some time before they were treated, and thus it was not possible to measure the chloride exclusion effectiveness of these sealed sections. The chloride contents were determined in accordance with the ASTM Standard Method [C-114, Section 19, Chloride (Reference Method)].

The number of hours of exposure to sunlight or ultraviolet light were recorded for the slabs and the wall sections. The sunlight exposure hours for the bridge deck would be about the same as those for the slabs because the slabs had the same horizontal orientation as the decks and the decks were within 10 km of the slab locations on the campus of Virginia Polytechnic Institute and State University.

The rate of traffic wear was measured by using a 3-m straightedge extending across the traffic lane, and the wear profile was determined by measuring the depth of wear at 15-cm intervals. The low-traffic deck had been in service for only 2 years, and thus the total wear was too small to be measured at the time that the measurements were taken with a ruler measuring to the nearest 0.01 mm, whereas the high-volume deck had been in service for 27 years and the wear rate was easily determined.

Table 2 presents the chloride contents, sunlight exposure hours, and deck traffic wear rate.

ANALYSIS AND DISCUSSION

As shown in Table 2 the wear rate of a bridge with an AADT of 24,270 is about 0.17 mm/year in the United States. Penetrating sealers have typical penetration depths of 1.5 to 3.0 mm. Thus, the maximum service life of a penetrating sealer on a high-traffic-volume bridge deck (AADT of 20,000 to 30,000) is about 9 to 10 years. On less traveled roadways the maximum service life due to the wear effect may be longer, because more heavily traveled routes may be shorter. Note that the penetration depth is the greatest depth of penetration. Thus, when the wear depth reaches the penetration depth much of the sealer, and therefore its effectiveness, will have been worn away. On the basis of wear a conservative maximum service life of penetrating sealers on bridge decks with AADTs of 20,000 to 30,000 is about 8 years. For components that are subjected to less abrasive forces such as columns, piers, pier caps, beams, and abutments, a maximum service life of 10 years is a reasonably conservative estimate.

For pore-blocking epoxy sealers the maximum service life on abrasion surfaces is 1 year. Visual observations revealed that these sealers wore off both the low- and high-traffic-volume decks in less than 1 year.

TABLE 2 Chloride Contents, Sunlight Exposure Hours, and Traffic Wear Rate for Sealer Performance Tests

Chloride Contents at Depths of 1.3 and 2.5 cm, kg/m^3							
Week	**10**		**20**		**30**		**Sunlight Exposure Hours**
Depth	**1.3**	**2.5**	**1.3**	**2.5**	**1.3**	**2.5**	
Slabs							
Control	1.1	0.1	2.2	0.1	4.1	0.6	950
Water-Epoxy	0.7	0.0	1.6	0.0	3.8	0.5	950
Solvent-Epoxy	1.0	0.1	2.1	0.1	4.1	0.6	950
Silane	0.0	0.0	0.0	0.0	0.1	0.0	950
Siloxane	0.0	0.0	0.0	0.0	0.0	0.0	950
Wall							
Control	1.9	0.2	3.4	0.1	4.5	0.7	190
Water-Epoxy	0.2	0.1	0.4	0.0	1.1	0.0	190
Solvent-Epoxy	0.2	0.0	0.6	0.1	1.6	0.2	190
Silane	0.1	0.0	0.1	0.0	0.2	0.0	190
Siloxane	0.0	0.0	0.1	0.0	0.4	0.0	190
Decks		**Sunlight Exposure Hours**			**Wear Rate mm/Year**		
Low-volume		950			---		
High-volume		950			0.17		

It is well known that ultraviolet light degrades epoxies. Because of the penetrating nature of the silane and siloxane, it is expected that sunlight degradation would be much less. As shown in Table 2 there is little to no difference in the amount of chloride contamination over 30 weeks between the silane- and siloxane-sealed slabs and wall sections that cannot be explained by the higher surface absorption of the wall. Note that if ultraviolet light did degrade these sealers, then the wall should contain less chloride than the slab, because the wall was exposed to only 20 percent of the sunlight to which the slabs were exposed and only one-third the total cumulative hours of exposure to chloride solution.

Relative to the amount of chloride ingress into the two surface types, the ingress of chlorides was much faster for the wall than the slabs (see control chloride contents Table 2). At 30 weeks both control test specimens contained the same amount of chloride when the wall chloride exposure time was one-third that of the slabs (Table 2). However, the rate (chlorides/exposure time) of chloride ingress into the wall and slabs are about the same for the epoxy sealers. Because of the poor sealing characteristics of epoxies, the maximum service life will be less than those for the silane and siloxane tested. The service lives of these epoxies on nonabrasion surfaces would then be based on a chloride leakage factor, as would those for the silane and siloxane tested.

Leakage factor is the amount of chloride that passes through a sealed concrete surface over a period of time. The period of time chosen for the laboratory testing period was 30 weeks. Thirty weeks was chosen because a long time period is needed for the rate of chloride ingress to reach a near steady-state diffusion rate. Also, the magnitude of the chloride content at the 2.5-cm depth must be sufficiently large as to not induce a significant error in the service life estimate through errors in measuring small chloride contents. The logic used to estimate the service lives of sealers is to multiply the laboratory service life determined from field site conditions by the allowable leakage factor to laboratory leakage factor ratio ($LR_{\text{allowable}}/LR$). The allowable leakage factor is determined from field site conditions (amount of chloride present, chloride diffusion rate, and cover depth of the reinforcing steel) and the selected corrosion protection period. The corrosion protection period (time to initiate corrosion) generally used in the United States is 50 years. Note that the service lives presented here include the effects of ultraviolet light and other weathering damage on chloride leakage through the sealed surfaces.

The diffusion of chloride ions through porous materials such as chloride is described by Fick's Second Law:

$$C_{(x,t)} = C_0(1-erf(X/2)\sqrt{D_ct}) \tag{1}$$

where

$C_{(x,t)}$ = chloride concentration at depth X after time t;
C_0 = equilibrium chloride concentration; for the case of bridge components the equilibrium chloride concentration is 1.3 cm below the surface;
erf = error function;
D_c = chloride diffusion constant;
t = time; here it was taken as the desired 50 years of protection from corrosion initiation; and
X = depth at which the chloride content is calculated; depth X for estimating sealer service life is the depth of 2.5 percent of the reinforcing steel, which is dependent on the design cover depth and quality of construction; here, X is 4.1 cm, from an average depth of 5.1 cm with a standard deviation of 0.5 cm.

Note that the solution presented here is an approximate solution because the chloride concentration (C_0) is taken as an average chloride level. With a constant rate of chloride leakage the total allowable chloride concentration ($C_{0-\text{total}}$) is twice the value of C_0.

The five specific steps used in the procedure are as follows:

1. Estimate the average chloride concentration level ($C_{0-\text{ave}}$) that is allowed to build up over 50 years that will keep the chloride concentration at the select rebar depth (in this case 4.1 cm) below the corrosion threshold level of 0.71 kg/m^3 for the various field environmental effective chloride diffusion constants (D_c). The total allowable chloride ($C_{0-\text{total}}$) is (2.0) ($C_{0-\text{ave}}$).
2. Estimate the equivalent field time that corresponds to 30 weeks of ponding of untreated specimens by using the field environmental effective diffusion constants (D_c) and the 30-week C_{0-30} values. The resulting time equivalency is expressed at t_{eq}.
3. By using the time equivalent (t_{eq}) and the total allowable chloride content ($C_{0-\text{total}}$) determine the average 50-year allowable equivalent chloride content ($C_{0-\text{eq}}$).
4. Determine the laboratory leakage factor (in percent) and compare it with the allowable leakage factor (in percent). The laboratory percent leakage (LR) is the 1.3-cm-depth chloride content of the sealed surface divided by the 1.3-cm-depth chloride content of the unsealed (control) surface. The allowable percent leakage ($\text{LR}_{\text{allowed}}$) is $C_{0-\text{eq}}$ divided by the field site chloride exposure concentration (C_0).
5. By using the ratio of the leakage factors ($\text{LR}_{\text{allowed}}/\text{LR}$) and the equivalent time (t_{eq}) determine the estimated service life (reapplication time) for the specific site conditions (t_{sl}).

The following example is presented to assist the reader in following the logic used to estimate the service lives of sealers in various bridge site environments. The bridge site chloride environmental exposure conditions in the United States have been categorized as low (C_0, 0 to 2.4 kg/m^3), moderate (C_0, 2.4 to 4.8 kg/m^3), high (C_0, 4.8 to 5.9 kg/m^3), and severe (C_0, 5.9 to 8.9 kg/m^3) with diffusion constants (D_c) of 0.32, 0.58, and 0.84 cm^2/year present in each of the four categories.

For an effective field D_c of 0.32 cm^2/year, a depth X of 4.1 cm below the surface, and the corrosion chloride initiation concentration of 0.71 kg/m^3, the $C_{0-\text{ave}}$ at 50 years is 1.51 kg/m^3. $C_{0-\text{total}}$ is then 3.02 kg/m^3.

$$C_{(x,t)} = C_{0-\text{ave}}[1 - erf(X/2\sqrt{D_ct})] \tag{2}$$

$$0.71 = C_{0-\text{ave}}[1 - erf(4.1/2\sqrt{(0.32)(50)})]$$

The equivalent field time t_{eq} calculated from the results of the 30-week laboratory test, which has chloride equilibrium concentration (C_{0-30}) at a 1.3-cm depth of 4.1 kg/m^3 and a chloride content ($C_{x,t}$) of 0.6 kg/m^3 at depth X of 2.5 cm with the effective field diffusion constant (D_c) of 0.32 cm^2/year, is 4.8 years.

$$C_{(x,t)} - C_{0-30}[1 - erf(X/2\sqrt{D_ct})] \tag{3}$$

$$0.6 = 4.1[1 - erf(2.54/2\sqrt{0.32t_{\text{aq}}})]$$

TABLE 3 Bridge Component Exposure Matrix for Sealer Life Determination on Horizontal Specimens (in Years)

Environment	Co used (kg/m^3)	Diffusion Constant, D_c (cm^2/yr)		
		$D_c = 0.32$ $t_{eq} = 4.8$	$D_c = 0.58$ $t_{eq} = 2.6$	$D_c = 0.84$ $t_{eq} = 1.8$
Severe (range: 5.9-8.9)	8.9	SIL 6.3 SLX 10	SIL 1.5 SLX 10	SIL 0.7 SLX 10
High (range: 4.8-5.9)	5.9	SIL 9.6 SLX 10	SIL 2.3 SLX 10	SIL 1.0 SLX 10
Moderate (range: 2.4-4.8)	4.8	SIL 10 SLX 10	SIL 2.8 SLX 10	SIL 1.2 SLX 10
Low (range: 0-2.4)	2.4	SIL 10 SLX 10	SIL 5.7 SLX 10	SIL 2.4 SLX 10

NOTE: If the service life t_{sl} exceeded 10 years, then 10 years was recorded as the maximum service life. It is reasoned that the maximum service of all sealer is limited by weathering forces to 10 years. For bridge decks, service life is limited by traffic abrasion to 8 years.

TABLE 4 Bridge Component Exposure Matrix for Sealer Life Determination on Vertical Specimens (in Years)

Environment	Co used (kg/m^3)	Diffusion Constant, D_c (cm^2/yr)		
		$D_c = 0.32$ $t_{eq} = 5.0$	$D_c = 0.58$ $t_{eq} = 2.8$	$D_c = 0.84$ $t_{eq} = 1.9$
Severe (range: 5.9-8.9)	8.9	SIL 3.8 SLX 1.9	SIL 0.9 SLX 0.5	SIL 0.4 SLX 0.2
High (range: 4.8-5.9)	5.9	SIL 5.7 SLX 2.9	SIL 1.4 SLX 0.7	SIL 0.6 SLX 0.3
Moderate (range: 2.4-4.8)	4.8	WBE 1.3 SIL 7.1 SLX 3.5	SIL 1.7 SLX 0.9	SIL 0.7 SLX 0.4
Low (range: 0-2.4)	2.4	SBE 1.8 WBE 2.6 SIL 10 SLX 7.1	SBE 0.4 WBE 0.6 SIL 3.4 SLX 1.7	SIL 1.5 SLX 0.7

NOTE: If the service life t_{sl} exceeded 10 years, then 10 years was recorded as the maximum service life. It is reasoned that the maximum service of all sealer is limited by weathering forces to 10 years.

Continuing the example, $C_{o-total}$ for 50 years is 3.02 kg/m^3 and t_{eq} equals 4.8 years, then by straight-line interpolation the allowable equivalent equilibrium constant (C_{oeq}) is 0.29 kg/m^3.

$$C_{oeq} = C_{o-total}\,(t_{eq}/50) \qquad (4)$$

$$C_{oeq} = (3.02)(4.8/50)$$

The allowable leakage factor ($LR_{allowable}$) is equal to allowable equivalent equilibrium constant (C_{oeq}) divided by the bridge field site environmental chloride equilibrium (C_o). For a moderate environment the worst-case condition ($C_o = 4.8$ kg/m^3) will be used. Thus , $LR_{allowable}$ is 6.0 percent.

$$LR_{allowable} = (C_{oeq}/C_o)\,100 \qquad (5)$$

$$LR_{allowable} = (0.29/4.8)100$$

The laboratory LR from the 30-week test with sealed and untreated (control) chloride contents at a depth of 1.3 cm of 0.2 and 4.1 kg/m^3, respectively, is 4.9 percent.

$$LR = (C_{o-1s}/C_{o-1c})100 \qquad (6)$$

$$LR = (0.2/4.1)100$$

The estimated service life (t_{sl}) for this sealer applied to the defined specific bridge conditions in a moderate environment with the specified effective diffusion constant is 5.9 years.

$$t_{sl} = (LR_{allowable}/LR)(t_{eq}) \qquad (7)$$

$$t_{sl} = (6.0/4.9)(4.8)$$

Tables 3 and 4 present the estimated service lives for horizontal and vertical bridge structure surfaces, respectively, for various field bridge site exposure conditions with an average cover depth of 5.1 cm and a standard deviation of 0.5 cm. To limit the percentage of reinforcing steel that would be above the corrosion threshold of 0.71 kg/m^3 to 2.5 percent, the depth X would be equal to 4.1 cm [5.1 − (1.96) (0.5)]. Thus, if the sealers presented in Tables 3 and 4 were applied to new horizontal and vertical surfaces and reapplied after each time period shown, in 50 years the chloride concentration at the depth of the shallowest 2.5 percent of the reinforcing steel will reach the corrosion threshold level.

In conclusion, the results of the study presented here provide a means of estimating the corrosion protection service lives of sealers based on the environmental exposure conditions of ultraviolet light damage, abrasion, and leakage of chloride through the sealed surface. Although the methodology was presented for bridge component exposures in the United States for new structures, the methodology is applicable to all reinforced concrete structure types in chloride-laden environments and existing chloride-contaminated structures. For chloride-contaminated structures the corrosion initiation concentration would have to be adjusted to account for the present chloride contamination level. Service life protection periods can also be determined for existing structures. The corrosion protection periods for existing structures will most likely be less than 50 years.

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