# Predicting Service Life of Steel-Reinforced Concrete Exposed to Chlorides

## A discussion of real-world considerations for effective modeling

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With much of our current infrastructure in a state of decay, as assessed by the American Society of Civil Engineers most recently in 2013,[1] reinforced concrete is being designed with ever-increasing expectations for its service life. For example, transportation infrastructure elements, such as bridge decks, are now commonly being specified with an expectation of a minimum 75-year service life.[2] Without a proven 75-year track record of performance, engineers and designers often turn to service-life models to support their structural design decisions and mixture proportions/materials selections. While there are several concrete-specific service-life models that have been developed and improved within the past 15 years (Life-365™[3-5] and STADIUM,®[6] among others), during that same time period, advances have also been made in the user-friendliness and comprehensiveness of commercially available general-purpose modeling and simulation packages (such as ANSYS and COMSOL Multiphysics®). These general-purpose packages are employed by a large and diverse community of users, increasing the potential for cross-fertilization between application areas and providing access to a large library of modules, databases, and computational procedures that can be applied to concrete problems.

For users of the concrete-specific models or the general-purpose simulation packages, a key concern is whether the models provide adequate and accurate representations of real-world structures. Providing adequate and accurate simulations is far from a trivial exercise, as standardized procedures for properly characterizing the exposure environment (for example, chloride loading, temperature, relative humidity, time of wetness, and time of freezing); the reinforced concrete material properties (such as time-dependent and spatially dependent diffusion coefficient, temperature and moisture content, binding and reaction of ingressing chlorides, and free chloride levels required to initiate corrosion); and the impact of the often-present concrete cracking are generally lacking. The remainder of this article focuses on the case where service life is governed by the ingress of chloride ions and subsequent reinforcement corrosion in steel-reinforced concrete. The status of some commonly used existing models is briefly reviewed, along with some real-world concerns and considerations. Application of these modeling techniques to evaluating repair and maintenance strategies, as opposed to new construction, is highlighted and, in closing, a short-term prospectus on a future vision for modeling service life is provided. The purpose of this paper is not to recommend one service-life model over another, but rather to point out the expanding set of possible approaches now available to more accurately model real-world exposures.

## Basics of Chloride Ingress into Concrete

In its abstract form, the problem of predicting the service life of reinforced concrete exposed to chloride ions seems to be simple and straightforward. Fick's second law can be applied to describe the chloride ion concentration with time, $t$, and depth, $y$, as[7]

$$\frac{c(y,t)}{C_{ext}} = erfc\left(\frac{y}{2\sqrt{Dt}}\right) \qquad (1)$$

where *erfc* is the complementary error function ($erfc(y) = 1 - erf(y)$) (refer to **http://dlmf.nist.gov**); *D* is the effective chloride ion diffusion coefficient in the saturated concrete; and $C_{ext}$ is the external chloride ion concentration. If these two parameters, along with the chloride concentration needed to initiate corrosion of the particular reinforcement at the cover depth $C_{bar}$ are known, their values can be substituted into Eq. (1) and the equation solved for the time to initiate corrosion, which can be directly used as a conservative estimate of the service life of the structure (conservative, as it basically ignores the propagation stage of the corrosion process). However, this solution neglects many real-world details through the following implicit assumptions: 1) the concrete structure is a semi-infinite medium; 2) the external chloride concentration is constant; 3) the chloride ion diffusion coefficient does not depend on depth, time, or the other species present; and 4) the chloride ions are transported into a water-saturated concrete only via diffusion (no convection or capillary action) and do not otherwise interact/react with the concrete components. While perhaps useful for a back-of-the-envelope estimate of service life, Eq. (1) has significant limitations in its applicability to real-world scenarios, which is why few service-life models are based solely on Eq. (1).

Equation (1) can be solved analytically under the assumptions listed above, and even for some cases where a time-dependent function is inserted for *D*. An alternate solution approach is to solve the differential form of Fick's Law using a finite-element or finite-difference computer program to iteratively update the desired concentrations, based on elemental mass balances on a predetermined spatial grid representing the concrete structure in one, two, or three dimensions.[8,9] This approach is used in the more advanced service-life models, and it provides a high degree of flexibility, as material properties and boundary conditions can be updated at each successive time step as necessary. Time-dependent diffusion coefficients, seasonal chloride loadings, and repair strategies such as sealing the exposed surface[10] or applying a scarification and overlay treatment[11] can be conveniently implemented in such finite-element or finite-difference approaches.

## A Brief Look at Existing Models

Brief overviews of selected models are provided herein to set the context for the discussion of real-world considerations to follow. The reader is recommended to refer to the latest versions of the user's manuals and online files for definitive descriptions of the capabilities and limitations of each model.

### Life-365

Life-365 version 2.2.1 was released to the public in July 2013, according to the Life-365 website (**www.life-365.org**). It permits the modeling of both one-dimensional (1-D) and two-dimensional (2-D) chloride exposures and is largely concerned with life-cycle costing of various materials selection options, including steel/coating selection and concrete mixture proportions (for example, including silica fume or corrosion inhibitors). It permits a time-dependent apparent diffusion coefficient, with no explicit consideration of binding and reaction of the ingressing chloride ions. It allows for a time-dependent chloride exposure (surface concentration) and explicitly considers the influence of environmental temperature on diffusion. However, it is also based on the assumption that the concentration of chloride ions is continuously maintained at zero at the bottom surface of the concrete, which will result in a longer predicted service life than in the case where an adiabatic (no-transport) boundary condition is implemented at the bottom surface, such as might be the case when stay-in-place formwork is present.[10,11]

### STADIUM

The commercially available STADIUM 2.99 model places much emphasis on its capabilities to conduct multi-species transport with chemical (thermodynamic) equilibrium maintained, under saturated or partially saturated conditions, to predict the projected service life of new structures or the residual service life of existing ones. It contains extensive databases for both exposure conditions and corrosion thresholds for different types of reinforcing bar and can analyze the impact of protection solutions such as sealers, membranes, and thick overlays. The service-life predictions are supported by laboratory measurements of key concrete properties to serve as model inputs (STADIUM Lab 3.0).

### Generalized simulation and modeling packages

There are a myriad of generalized simulation and modeling packages that can be applied to predicting concrete service life. As an example, the COMSOL Multiphysics package is employed in some of the specific examples that follow. While generalized transport/reaction can be simulated using specific modules within these packages, they also offer the possibility to link the transport module with mechanical/thermal response and/or corrosion modules, which should greatly enhance their future capabilities. One could envision a mechanical/thermal module predicting the cracking (pattern) in a three-dimensional (3-D) structure, which can then be input to a transport/reaction module to predict chloride ion ingress and binding, culminating with the application of a corrosion module to predict the active corrosion of the steel reinforcement. While this may seem to be a futuristic vision for such models, some of these capabilities have already been demonstrated in COMSOL,[12-14] and work on others is ongoing.

## Some Real-World Considerations

Several real-world issues should be considered in service-life modeling of concrete because they have a

## Table 1:
### Service-life comparison of 2-D model with and without reinforcing bar computed using COMSOL

| Corrosion criteria for $C_{ext}$ = 872.3 mol/m$^3$ | Concrete type and cover depth | Service life, (years) | | | | Change with reinforcing bar | Change with reinforcing bar damage zone |
|---|---|---|---|---|---|---|---|
| | | Fick's second law | Without reinforcing bar | With reinforcing bar | With reinforcing bar damage zone | | |
| $C_{bar}/C_{ext}$ = 0.1 | OPC, 2 in. (51 mm) cover | 14 | 34 | 27 | 28 | –21% | –18% |
| | OPC, 3 in. (76 mm) cover | 31 | 76 | 64 | 66 | –16% | –13% |
| | OPC, 4 in. (102 mm) cover | 56 | 137 | 120 | 122 | –12% | –11% |
| | 5% SF, 2 in. (51 mm) cover | 42 | 103 | 84 | 86 | –18% | –17% |
| | 7% SF, 2 in. (51 mm) cover | 70 | 172 | 140 | 143 | –19% | –17% |
| $C_{bar}/C_{ext}$ = 0.3 | Corrosion inhibitor, 2 in. (51 mm) cover | 35 | 86 | 65 | 68 | –24% | –21% |
| $C_{bar}/C_{ext}$ = 0.5 | Epoxy-coated reinforcing bar, 2 in. (51 mm) cover | 84 | 203 | 148 | 156 | –27% | –23% |

Note: Results are calculated with the reinforcing bar located at the specified cover depth.[16] OPC is ordinary portland cement; SF is silica fume.

significant impact on transport within structures. These issues include binding/reaction of ingressing chlorides, incorporating the physical existence of reinforcing bars into simulations, realistic boundary conditions at all surfaces, microclimate (temperature and humidity) characterization, chloride thresholds to initiate corrosion, cracking, crack repair materials and procedures, and rehabilitation strategies.

### Binding/reaction of ingressing chlorides

Ingressing chlorides can strongly interact with the cementitious matrix by either being absorbed by the calcium silicate hydrate gel and other cement hydration products or reacting with aluminate phases to form Friedel's salt and other compounds. In general, the total chloride ion content of an exposed concrete may be several times its free chloride ion content,[9,15] indicating the significance of these processes in increasing concrete service life by slowing ingress. Because the interaction with the matrix does slow down the ingress of chlorides, it is often implemented in computer models by using an apparent diffusion coefficient that lumps together diffusion and binding/reaction and is commonly determined from experimental chloride profiles measured on specimens of the concrete of interest.

A simple example is presented herein to reinforce the significance of including binding/reaction in service-life models. Table 1 provides a comparison of projected service life for a concrete with three different cover depths, the addition of silica fume at two different levels (5% or 7% by mass of cement), the addition of a corrosion inhibitor, or the use of epoxy-coated steel reinforcement. The influence of the latter two parameters on service life is simulated simplistically by increasing the ratio of $C_{bar}/C_{ext}$ required for the initiation of reinforcing bar corrosion.[16] For the base case with uncoated steel reinforcement and no corrosion inhibitor, the value of $C_{bar}/C_{ext}$ necessary to initiate corrosion was set at 0.1, based on typically accepted values for the chloride level required to initiate corrosion of uncoated steel,[17] contrasted to the specific external chloride exposure level selected in the present study (872.3 mol/m$^3$, corresponding to about a 5% NaCl solution). To account for the corrosion inhibitor, the requisite value of $C_{bar}/C_{ext}$ was increased to 0.3, based on the experimental results of O'Reilly et al.[18] Similarly, to account for epoxy-coated bars, $C_{bar}/C_{ext}$ was increased to 0.5, based on data provided in another report by O'Reilly et al.[19] The effect of silica fume was simulated by decreasing the bulk concrete diffusivity by a factor of 3 or 5 for the 5% and 7% addition levels, respectively, based on experimental data and computer modeling results summarized in Reference 20.

For the results in Table 1, the concrete chloride ion diffusivity of the base concrete with no silica fume was set at $1.5 \times 10^{-12}$ m$^2$/s, and a linear isotherm was used to

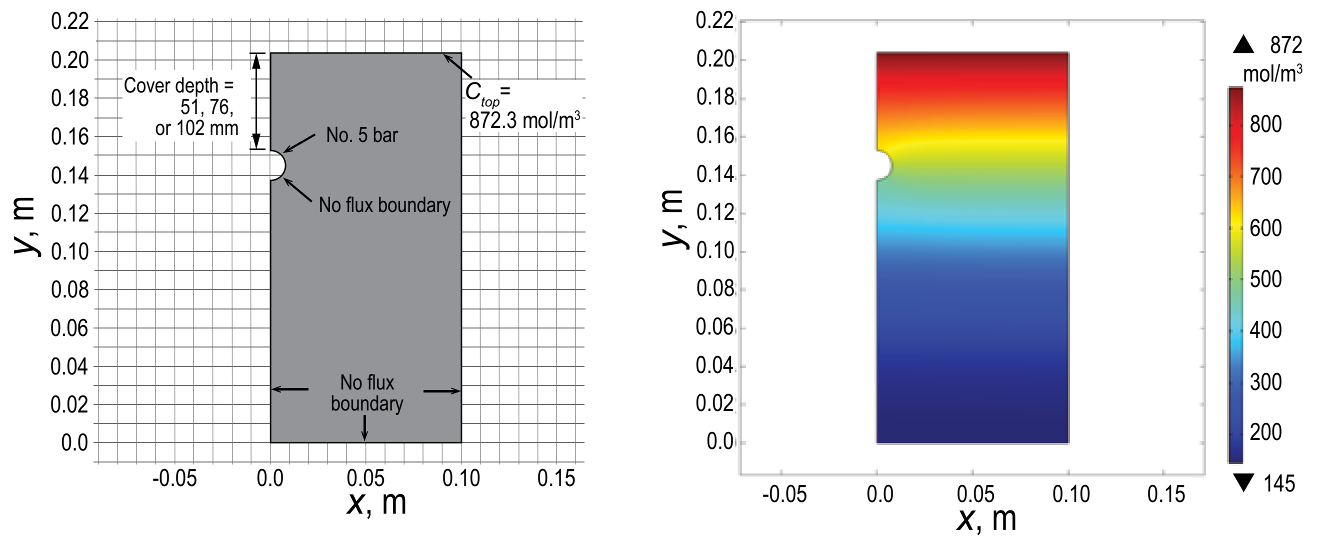


**Fig. 1: Geometry of base case model for an 8 in. (200 mm) thick bridge deck with a 2 in. (51 mm) cover depth with a single No. 5 reinforcing bar (left). Free chloride ion concentration with reinforcing bar in model at time = 500 years (right). Color-coded plot (red is high and blue is low concentration) shows an accumulation of chloride ions at the top surface of the reinforcing bar[16]**

describe the relationship between free and bound chloride.[9,16] In comparison to a simple Fick's second law solution (Eq. (1)), when binding and reaction are included in the 2-D model (Fig. 1), the service life is increased by a factor of nearly 2.5, as indicated by the values in the column labeled "Without reinforcing bar" in Table 1. This increase is nearly constant for all of the different scenarios presented in Table 1. However, each concrete mixture proportion presents its own binding/reaction characteristics, so this lifetime extension factor of 2.5 is not likely universal. The main conclusion from the results in Table 1 is that binding/reaction does have a significant influence on the ingress of chloride ions into concrete.

## Incorporating physical reinforcing bar into a simulation

Equation (1) provides no consideration for the physical presence of steel reinforcement in concrete. Due to the small diameter of steel reinforcing bar relative to the typical dimensions of a concrete structure, most developers of finite-element/finite-difference-based models also ignore the physical presence of steel reinforcing bars and calculate the chloride ion concentration at the user-supplied cover depth for a "homogeneous" concrete. However, the physical presence of a bar does influence the chloride concentration profile, as ingressing ions can effectively pile up at the top surface of the bar, which increases the concentration locally and therefore possibly reduces the service life (time to initiation of corrosion). [21] To investigate this further, the simulations from the previous section were repeated with the addition of a single No. 5 reinforcing bar located at the cover depth, with all other parameters maintained at their original values. As shown in Fig. 1 and Table 1, accounting for the physical presence of the reinforcing bar did lead to a localized increase in the chloride concentration at the top bar surface and a corresponding reduction in the expected service life by 12 to 27%. Because the true nature of the interfacial transition zone around the reinforcement is not well-quantified, a second set of simulations was conducted in which a damaged (interfacial) zone was placed around the bar with a thickness of 100 μm and a diffusivity 10 times that of the bulk concrete. Although the damaged zone somewhat reduced the localized concentrations of chlorides at the top bar surface, the service lives were still decreased by 11 to 23% relative to the case where the reinforcing bar was physically omitted from the simulation. This simple example illustrates that service-life models that do not explicitly account for the physical presence of steel reinforcement could be overpredicting service life by up to 25% or more (a predicted 75-year service life might be closer to 55 years), consistent with the projections of Kranc et al.[21]

## Boundary conditions at bottom surface

A somewhat related situation concerns the boundary conditions that are applied at the bottom (downstream) surface of the concrete. If this boundary is assumed to maintain a zero concentration of chloride ions due to frequent washing by rain or other chloride-free water, the equilibrium solution will be a linear profile of chloride ions varying from the external (top-surface) concentration to zero through the concrete thickness. However, if an adiabatic (no-transport) bottom-surface boundary condition is assumed instead (such as might be the case with stay-in-place formwork,[9,10] the equilibrium solution will be a constant chloride concentration (equal to the external value) throughout the thickness of the concrete member. The latter scenario will result in a reduced service-life prediction. This case is becoming of practical concern to some state departments of transportation that have constructed bridge decks with epoxy-coated reinforcement only in the top mat and uncoated bars in the bottom mat. As these bridge decks continue to age, the chlorides will advance beyond the epoxy-coated reinforcement and encounter the uncoated bars, potentially initiating corrosion in the bottom bars before corrosion of the epoxy-coated (top) bars is initiated. The level of chlorides achieved at the depth of the uncoated bars will depend strongly on the bottom boundary condition, which determines whether ingressing chlorides can exit the concrete at the bottom surface.

## Micro-climate characterization

Real-world concrete structures are characterized by two exposure environments: a local climate (effects such as ambient temperature, relative humidity, and wind speed) and a microclimate that is determined by the interaction of the concrete with its local environment. The microclimate of the concrete in a splash zone can be quite different from the microclimate of the concrete just a short distance away. Local climates can be characterized using readily available meteorological databases[22] and can be used to predict concrete surface conditions[23] for use as inputs in service-life models.[24] Most commonly employed concrete-specific service-life models use one or more weather databases to account for geographical differences in exposure environments. Little quantitative data exist for direct characterization of microclimates. Instead, chloride loadings of actual concrete structures are typically assessed, and these data are used to infer information concerning the prevailing microclimates.[25]

## Chloride thresholds to initiate corrosion

Whether Eq. (1) is solved analytically or numerically (using a finite difference or finite-element model), a key parameter for predicting service life is the chloride ion concentration required to initiate corrosion of the reinforcing steel. This parameter varies as a function of concrete mixture proportions,[26] admixtures (corrosion inhibitors[27]) employed, steel type,[28] and coating properties (when present).[19] As just one example, the chloride concentration needed to initiate corrosion of epoxy-coated reinforcement is reported to be 4.6 times greater than that needed to initiate corrosion of uncoated reinforcing steel.[19] The data in Table 1 demonstrate that increasing the requisite value of $C_{bar}/C_{ext}$ to initiate corrosion by a factor of 5, from 0.1 to 0.5, increases the service life from 34 years to 203 years for a 2 in. (51 mm) cover depth when the reinforcing bar is not physically included in the model, or from 27 years to 148 years when the reinforcing bar is physically included.

## Cracking

One of the key real-world concerns rarely addressed by service-life models is the issue of cracking.[9,16,25,29] Most service-life predictions are provided under the assumption that either the concrete will not crack or any cracks will be immediately and successfully repaired. The subsequent issue of whether the crack repair material will provide the requisite 75-year service life originally specified for the base concrete is often ignored. However, cracks can be incorporated in 2-D and 3-D simulation models if their geometry is appropriately specified. Thus, it should be straightforward to extend existing concrete-specific models to incorporate transverse and/or longitudinal cracks (and other common crack patterns). Transverse cracks have already been incorporated into some of the generalized modeling and simulation packages,[9,16] and other models have considered more complex 3-D cracking patterns.[29] As shown in Fig. 2, the presence of a crack produces a substantial increase in ingressing chloride in its vicinity. In the real world, the common location of such transverse

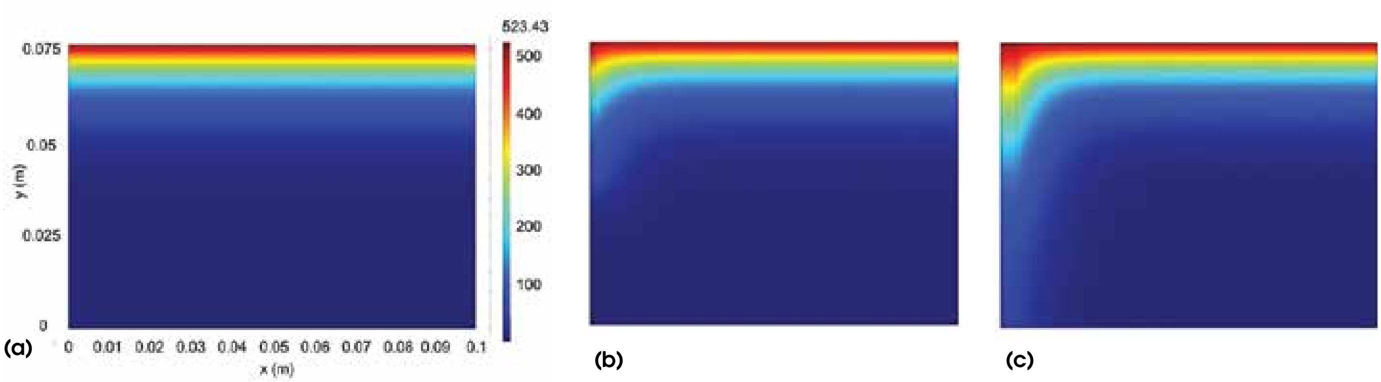


Fig. 2: Color-coded concentration maps in units of mol/m³ (red is high and blue is low as indicated in color bar in (a)) for three 2-D simulations of a 3.94 in. (100 mm) wide by 2.95 in. (75 mm) deep portion of a concrete slab at 30 days: (a) no crack; (b) 4 mils (102.9 μm) wide by 1.44 in. (36.6 mm) deep crack with a 0.039 in. (1 mm) wide damaged zone; and (c) 15.4 mils (392 μm) wide by 2.89 in. (73.4 mm) deep crack with a 0.16 in. (4 mm) wide damaged zone.[8] When present, the crack is located at the upper left-hand corner

## Table 2:
### Service life with methacrylate or epoxy crack filler in a large crack (500 µm wide by 40 mm deep with a 4 mm wide surrounding damage zone (DZ)) with different DZ diffusivities[16]

| Variable | | | Service life, (years) | Change |
|---|---|---|---|---|
| | No DZ repair $D_{DZ} = 20{*}D_{concrete}$[9] | 51 mm cover | 6 | **(82%)** |
| | | 76 mm cover | 42 | **(45%)** |
| | | 102 mm cover | 101 | **(26%)** |
| Methacrylate | Crack filler repair $D_{DZ} = D_{methacrylate}$ | 51 mm cover | 32 | **(6%)** |
| | | 76 mm cover | 75 | **(1%)** |
| | | 102 mm cover | 137 | 0% |
| | Crack filler repair $D_{DZ} = D_{concrete}$ | 51 mm cover | 33 | **(3%)** |
| | | 76 mm cover | 76 | 0% |
| | | 102 mm cover | 137 | 0% |
| Epoxy | Crack filler repair $D_{DZ} = D_{epoxy}$ | 51 mm cover | 42 | 24% |
| | | 76 mm cover | 83 | 9% |
| | | 102 mm cover | 144 | 5% |
| | Crack filler repair $D_{DZ} = D_{concrete}$ | 51 mm cover | 34 | 0% |
| | | 76 mm cover | 76 | 0 % |
| | | 102 mm cover | 138 | 1 % |

Note: Bulk concrete diffusivity is $1.5 \times 10^{-12}$ m²/s and end of service life is defined as when $C_{bar}/C_{ext} = 0.1$. Percent change calculated from base case results for uncracked concrete (Table 1 without reinforcing bar included in the simulation); red and bold text indicates a reduced service life. Chloride ion diffusivities in epoxy and methacrylate crack fillers are assumed to be $1.0 \times 10^{-13}$ m²/s and $2.0 \times 10^{-12}$ m²/s, respectively.[32-35] (Note: 1 mm = 0.04 in.)

cracks directly above individual lengths of reinforcing bar in the top mat of reinforcement[30] only compounds the situation and further intensifies the negative influence of cracking on service life. While the cracks in Fig. 2 have a rectangular shape, a triangular (tapered) geometry may be more appropriate for future studies, along with consideration of the potential for the crack to become filled with salt deposits and/or porous corrosion products, thus further modifying its transport properties.

### Crack repair materials and procedures

Because cracks are rarely included in service-life modeling, even less is known about the influence of crack repair materials and procedures on service life. Ideally, a properly filled crack will provide a barrier to chloride ingress at least equivalent to that of the bulk (uncracked) concrete. Of course, this requires that the chloride ion diffusion coefficient in the repair polymers be similar to or lower than that of the concrete being repaired, which can be the case when epoxy or methacrylate crack fillers are used.[16] However, a further consideration is how well the crack filler penetrates the damaged zone surrounding the crack. In the simulation, this zone is modeled as a separate region of the concrete that has a chloride ion diffusivity that is larger than that of the bulk (intact) concrete, based on the observations of Win et al.[31] As shown in Table 2 and Fig. 3, simulation results indicate that the assumption made concerning chloride ion diffusion in the damaged zone has a significant impact on projected service life.[16] In the case where the crack filler only fills the crack and does not penetrate into the surrounding damaged zone, that zone effectively becomes the new weak link in the barrier. In this case, service life can be reduced by as much as 82% in comparison to that of the bulk (uncracked) concrete.

## Rehabilitation Strategies

In addition to the use of crack fillers, more extensive repair and maintenance strategies are often employed to prolong the service life of concrete structures. Two commonly employed approaches are to apply a sealant over the entire exposed surface[10] or to mill away a layer of the existing concrete (scarification) followed by application of an overlay.[11] Both of these common repair strategies can be investigated via a 1-D chloride ion penetration profile simulation available at **http://concrete.nist.gov/clpenmillandfill.html**. As an example, Fig. 4 shows the free chloride ion concentration profiles for an 8 in. (203 mm) thick bridge deck with stay-in-place formwork and a top cover depth of 3 in. (76 mm).[11] In this case, the original concrete ($D = 2.72 \times 10^{-11}$ m²/s) deck is exposed to chlorides for 6 years, at which point a 1 in. (25 mm) layer of concrete is removed from the upper deck surface and replaced with a 2 in. (50 mm) thick high-performance concrete (HPC) overlay ($D = 1 \times 10^{-12}$ m²/s). As the overlay concrete initially contains no chlorides, the chlorides in the original layer beneath the overlay begin to diffuse in both directions away from the location of their peak concentration at the surface of the exposed (milled) layer. During this diffusion process, the concentration at the original cover depth of 3 in. (76 mm) increases until the 8th year and then gradually dissipates. If the scarification and overlay procedure is delayed for too long, the chloride ion concentration

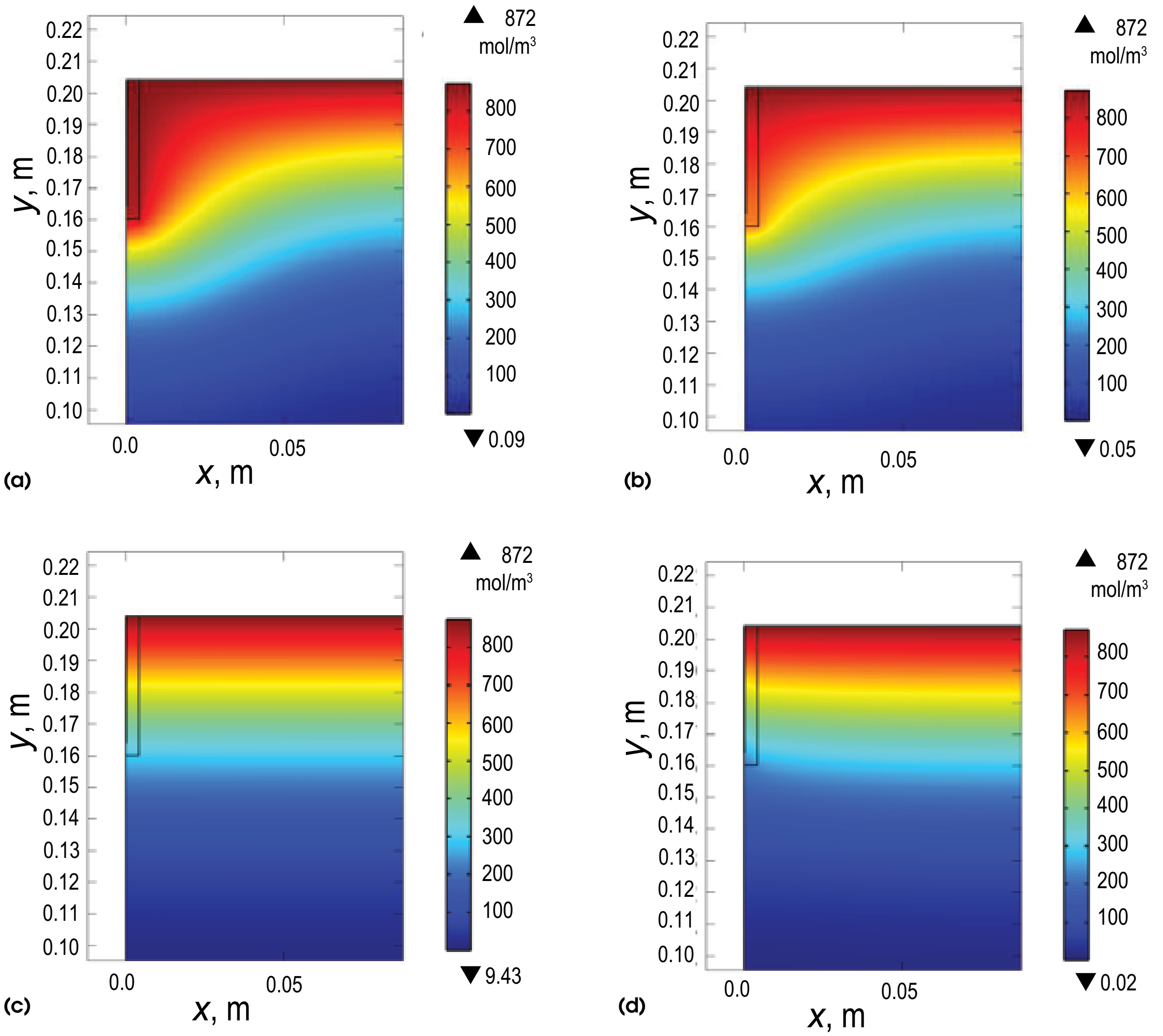


**Fig. 3: Free chloride concentration in units of $mol/m^3$ around a large 500 μm wide crack with a 4 mm (0.16 in.) wide DZ at 75 years in OPC concrete showing the effect that the DZ diffusivity has on the resulting chloride distribution.[16] Labels on x- and y-axes indicate distances in units of m: (a) the crack is saturated with chloride solution; (b) the crack is filled with epoxy and the DZ remains at $20D_{concrete}$. In (c) the DZ is assumed to be restored to the bulk concrete diffusivity; and (d) the DZ diffusivity is assumed to be equal to the epoxy diffusivity**

level at the original cover depth may become sufficient to initiate corrosion soon after the overlay is applied.

Using this approach, as shown in Table 3, a scarification and overlay strategy can be developed as a function of original cover depth, the presence of stay-in-place formwork, and scarification and overlay depths. In this case, because subsequent chloride levels at the cover depth(s) are controlled by the initial buildup prior to scarification, the depth of the HPC overlay has no influence on the latest acceptable timing of the scarification and overlay procedure, but the depth of the scarification itself does have a limited impact.

## Future Needs and Prospectus

While many advances have been made in the development and deployment of service-life models, there is still much to be done to improve corrosion-based service-life models for steel-reinforced concrete exposed to chlorides, including their continuing verification and validation.[36,37] More detailed and comprehensive models will require equally detailed and comprehensive values for input parameters describing the intended service environment and concrete/steel material properties. However, through the use of simulation models, parametric studies can be employed to determine which parameters have the greatest influence on the predicted service life and which parameters can be estimated with a lower degree of accuracy.[3,5] Chloride-ingress models that consider multiple species and multiple transport mechanisms and that couple cracking models and corrosion

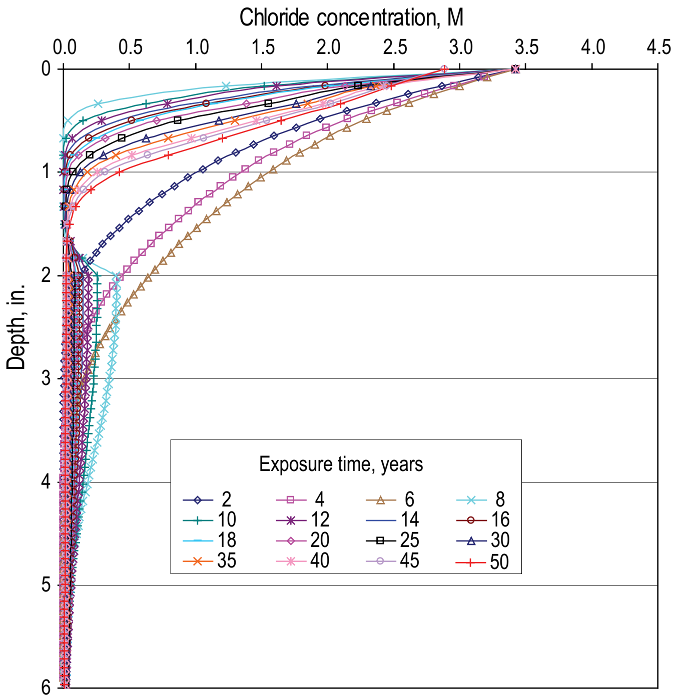


**Fig. 4: Chloride concentrations within a concrete bridge deck having stay-in-place metal forms, a 3 in. (76 mm) original cover depth, a 1 in. (25 mm) scarification, and a 2 in. (51 mm) HPC overlay treatment applied at 6 years[11]**

modules are likely the wave of the future, as they should provide a more accurate representation of real-world degradation.

Equally important as model development, there is a need to educate the design and engineering community and to provide guidelines for conducting meaningful analysis of concrete service life. This is part of a broader need to develop a comfort level among the practicing community in regularly using simulation and modeling tools for durability design and analysis as well as for structural design and analysis.

## References

1. American Society for Civil Engineers, 2013 Report Card for America's Infrastructure, www.infrastructurereportcard.org/a/#p/home. (last accessed Jan. 8, 2014).

2. AASHTO LRFD Bridge Design Specifications, sixth edition, American Association of State Highway and Transportation Officials, Washington, DC, 2013, 1938 pp.

3. User's Manual, Life-365™ Service Life Prediction Model and Computer Program for Predicting the Service Life and Life-Cycle Cost of Reinforced Concrete Exposed to Chlorides, version 2.2, Dec. 11, 2013.

4. Ehlen, M.A., and Kojundic, A.N., "Life-365™ v2.2—Adding User Estimates of Chloride Exposure," *Concrete International*, V. 36, No. 5, May 2014, pp. 41-44.

## Table 3:
### Recommended latest timing of initial scarification and overlay procedures[11]

| Decks with stay-in-place formwork | | | | |
|---|---|---|---|---|
| | | Scarification depth | | |
| | | 0.5 in. (12.7 mm) | 1.0 in. (25.4 mm) | 1.5 in. (38.1 mm) |
| Original cover depth | Overlay depth | Recommended deck age for treatment, (years) | | |
| 2.0 in. (50.8 mm) | 1.5 in. (38.1 mm) | 2 | 2 | 2 |
| 2.0 in. (50.8 mm) | 2.0 in. (50.8 mm) | 2 | 2 | 2 |
| 2.5 in. (63.5 mm) | 1.5 in. (38.1 mm) | 2 | 4 | 4 |
| 2.5 in. (63.5 mm) | 2.0 in. (50.8 mm) | 2 | 4 | 4 |
| 3.0 in. (76.2 mm) | 1.5 in. (38.1 mm) | 4 | 6 | 6 |
| 3.0 in. (76.2 mm) | 2.0 in. (50.8 mm) | 4 | 6 | 6 |
| Decks without stay-in-place formwork | | | | |
| | | Scarification depth | | |
| | | 0.5 in. (12.7 mm) | 1.0 in. (25.4 mm) | 1.5 in. (38.1 mm) |
| Original cover depth | Overlay depth | Recommended deck age for treatment, (years) | | |
| 2.0 in. (50.8 mm) | 1.5 in. (38.1 mm) | 6 | 6 | 6 |
| 2.0 in. (50.8 mm) | 2.0 in. (50.8 mm) | 6 | 6 | 6 |
| 2.5 in. (63.5 mm) | 1.5 in. (38.1 mm) | 10 | 10 | 10 |
| 2.5 in. (63.5 mm) | 2.0 in. (50.8 mm) | 10 | 10 | 10 |
| 3.0 in. (76.2 mm) | 1.5 in. (38.1 mm) | 16 | 18 | 18 |
| 3.0 in. (76.2 mm) | 2.0 in. (50.8 mm) | 16 | 18 | 18 |

5. Ehlen, M.A.; Thomas, M.D.A.; and Bentz, E.C., "Life-365 Service Life Prediction Model™ Version 2.0," *Concrete International*, V. 31, No. 5, May 2009, pp. 41-46.

6. Henchi, K.; Samson, E.; Chapdelaine, F.; and Marchand, J., "Advanced Finite-Element Predictive Model for the Service Life Prediction of Concrete Infrastructures in Support of Asset Management and Decision-Making," *Computing in Civil Engineering,* L. Soibelman and B. Akinci, eds., American Society of Civil Engineers, Reston, VA, 2007, pp. 870-880.

7. Crank, J., *The Mathematics of Diffusion*, second edition, Oxford University Press, London, UK, 1975, 414 pp.

8. Bentz, D.P.; Clifton, J.R.; and Snyder, K.A., "Predicting Service Life of Chloride-Exposed Steel-Reinforced Concrete," *Concrete International*, V. 18, No. 12, Dec. 1996, pp. 42-47.

9. Bentz, D.P.; Garboczi, E.J.; Lu, Y.; Martys, N.; Sakulich, A.R.; and Weiss, W.J., "Modeling of the Influence of Transverse Cracking on Chloride Penetration into Concrete," *Cement and Concrete Composites*, V. 38, Apr. 2013, pp. 65-74.

10. Birdsall, A.W.; Guthrie, W.S.; and Bentz, D.P., "Effects of Initial Surface Treatment Timing on Chloride Concentrations in Concrete Bridge Decks," *Transportation Research Record, Journal of the Transportation Research Board*, No. 2028, 2007, pp. 103-110.

11. Guthrie, W.S.; Nolan, C.D.; and Bentz, D.P., "Effect of Initial Timing of Scarification and Overlay Treatment on Chloride Concentrations in Concrete Bridge Decks," *Transportation Research Record, Journal of the Transportation Research Board*, No. 2220, 2011, pp. 66-74.

12. Ghods, P.; Karadakis, K.; Isgor, O.B.; and McRae, G., "Modeling the Chloride-Induced Corrosion Initiation of Steel Rebar in Concrete," *Proceedings of the 2009 COMSOL Conference*, Boston, MA, 2009. (available for downloading at the COMSOL website)

13. Lu, Y.; Garboczi, E.J.; Bentz, D.P.; and Davis, J.M., "Modeling Chloride Transport in Cracked Concrete: A 3-D Image-Based Microstructure Simulation," *Proceedings of the 2012 COMSOL Conference*, Boston, MA, 2012. (available for downloading at the COMSOL website)

14. Al-Kutti, W.A.; Rahman, M.K.; Shazali, M.A.; and Baluch, M.H., "Enhancement in Chloride Diffusivity due to Flexural Damage in Reinforced Concrete Beams," *Journal of Materials in Civil Engineering*, ASCE, V. 26, No. 4, Apr. 2014, pp. 658-667.

15. Luping, T., and Nilsson, L.O., "Chloride Binding Capacity and Binding Isotherms of OPC Pastes and Mortars," *Cement and Concrete Research*, V. 23, No. 2, Mar. 1993, pp. 247-253.

16. Jones, S.; Martys, N.; Lu, Y.; and Bentz, D.P., "Simulation Studies of Methods to Delay Corrosion and Increase Service Life for Cracked Concrete Exposed to Chlorides," submitted to *Cement and Concrete Composites*, 2014.

17. Cady, P.D., and Weyers, R.E., "Chloride Penetration and Deterioration of Concrete Bridge Decks," *Cement, Concrete, and Aggregates*, V. 5. No. 2, Jan. 1983, pp. 81-87.

18. O'Reilly, M.; Darwin, D.; Browning, J.; Xing, K.; Locke Jr., C.E.; and Virmani, Y.P., "Effect of Corrosion Inhibitors on Concrete Pore Solution Composition and Corrosion Resistance," *ACI Materials Journal*, V. 110, No. 5, Sept.-Oct. 2013, pp. 577-585.

19. O'Reilly, M.; Darwin, D.; Browning, J.; and Locke Jr., C.E., "Evaluation of Multiple Corrosion Protection Systems for Reinforced Concrete Bridge Decks," The University of Kansas Research, Inc., Lawrence, KS, 2011 (revised 2012).

20. Bentz, D.P., "Influence of Silica Fume on Diffusivity in Cement-Based Materials. II. Multi-Scale Modeling of Concrete Diffusivity," *Cement and Concrete Research*, V. 30, No. 7, July 2000, pp. 1121-1129.

21. Kranc, S.C.; Sagüés, A.A.; and Presuel-Moreno, F.J., "Decreased Corrosion Initiation Time of Steel in Concrete due to Reinforcing Bar Obstruction of Diffusional Flow," ACI Materials Journal, V. 99, No. 1, Jan.-Feb. 2002, pp. 51-53.

22. Wilcox, S., and Marion, W., "Users' Manual for TMY3 Data Sets," Technical Report NREL/TP-581-43156, National Renewable Energy Laboratory, Golden, CO, May 2008, 50 pp.

23. Bentz, D.P., "A Computer Model to Predict the Surface Temperature and Time-of-Wetness of Concrete Pavements and Bridge Decks," NISTIR 6551, U.S. Department of Commerce, Washington, DC, 2000, 19 pp.

24. Bentz, D.P.; Ehlen, J.A.; Ferraris, C.F.; and Winpigler, J., "Service Life Prediction Based on Sorptivity for Highway Concrete Exposed to Sulfate Attack and Freeze-Thaw Conditions," Federal Highway Administration Report No. FHWA-RD-01-162, 2002, 62 pp.

25. Lundquist, W.D.; Darwin, D.; Browning, J.; and Miller, G.G., "Effect of Cracking on Chloride Content in Concrete Bridge Decks," *ACI Materials Journal*, V. 103, No. 6, Nov.-Dec. 2006, pp. 467-473.

26. Oh, B.H.; Jang, S.Y.; and Shin, Y.S., "Experimental Investigation of the Threshold Chloride Concentration for Corrosion Initiation in Reinforced Concrete Structures," *Magazine of Concrete Research*, V. 55, No. 2, Apr. 2003, pp. 117-124.

27. Ann, K.Y., and Song, H.-W., "Chloride Threshold Level for Corrosion of Steel in Concrete," *Corrosion Science*, V. 49, No. 11, Nov. 2007, pp. 4113-4133.

28. Darwin, D.; Browning, J.; O'Reilly, M.; Xing, L.; and Ji, J., "Critical Chloride Corrosion Threshold of Galvanized Reinforcing Bars," *ACI Materials Journal*, V. 106, No. 2, Mar.-Apr. 2009, pp. 176-183.

29. Savija, B.; Pacheco, J.; and Schlangen, E., "Lattice Modeling of Chloride Diffusion in Sound and Cracked Concrete," *Cement and Concrete Composites*, V. 42, Sept. 2013, pp. 30-40.

30. Kyle, N.L., "Subsidence Cracking of Concrete over Steel Reinforcement Bar in Bridge Decks," MS thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA, 2001.

31. Win, P.P.; Watanabe, M.; and Machida, A., "Penetration Profile of Chloride Ion in Cracked Reinforced Concrete," *Cement and Concrete Research*, V. 34, No. 7, July 2004, pp. 1073-1079.

32. Parthasarathy, R.; Misa, A.; Park, J.; Ye, Q.; and Spencer, P., "Diffusion Coefficients of Water and Leachables in Methacrylate-Based Crosslinked Polymers Using Absorption Experiments," *Journal of Materials Science: Materials in Medicine*, V. 23, No. 5, 2012, pp. 1157-1172.

33. Coniglio, N.; Nguyen, K.; Kurji, R.; and Gamboa, E., "Characterizing Water Sorption in 100% Solids Epoxy Coatings," *Progress in Organic Coatings*, V. 76, No. 9, Sept. 2013,

pp. 1168-1177.

34. Holz, M.; Heil, S.; and Sacco, A., "Temperature-Dependent Self-Diffusion Coefficients of Water and Six Selected Molecular Liquids for Calibration in Accurate 1H NMR PFG Measurements," *Physical Chemistry Chemical Physics*, V. 2, No. 20, 2000, pp. 4740-4742.

35. Woolf, L.A., "Isothermal Diffusion Measurements on the Systems Water-Sodium Chloride, Water-Pentaerythritol and Water Pentaerythritol-Sodium Chloride at 25°," *Journal of Physical Chemistry*, V. 67, No. 2, Feb. 1963, pp. 273-277.

36. Bentz, D.P., "Verification, Validation, and Variability of Virtual Standards," *Proceedings*, 12th International Congress on the Chemistry of Cement, Montreal, QC, Canada, 2007.

37. Luping, T., and Lindvall, A., "Validation of Models for Prediction of Chloride Ingress in Concrete Exposed in De-icing Salt Road Environment," *International Journal of Structural Engineering*, V. 4, No. 1/2, 2013, pp. 86-99.

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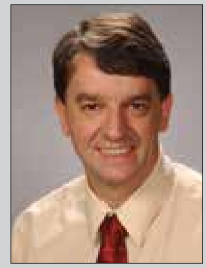
Received and reviewed under Institute publication policies.



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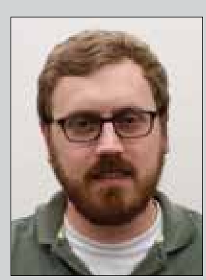

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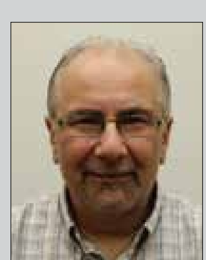

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