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Statistical Distributions for Chloride Thresholds of Reinforcing Bars

by John S. Lawler, Jonah C. Kurth, Stephen M. Garrett, and Paul D. Krauss

Reliability-based durability design of reinforced concrete structures requires a probabilistic service life modeling approach. Probabilistic service life modeling of chloride-induced corrosion should consider the statistical distributions of key parameters that influence corrosion initiation and subsequent damage. For typical reinforced concrete structures (such as bridge decks), these are chloride exposure, chloride penetration resistance of the concrete, chloride-induced corrosion threshold, depth of concrete cover, and corrosion propagation time. Assessing the impact of the use of corrosion-resistant reinforcement, such as epoxy-coated reinforcing bars (ECR), is typically performed through a selection of the chloride threshold and/or propagation time. This paper provides recommendations for statistical distributions for the chloride threshold to be used in service life modeling for structures containing carbon steel and ECR based on both experimental work reported in the literature and field investigations of existing structures conducted by the authors.

Keywords: carbon steel reinforcing bars; chloride threshold; corrosion; critical chloride content; durability; epoxy-coated reinforcing bars (ECR); probabilistic; service life; supplementary cementitious materials.

INTRODUCTION

Transportation agencies and others funding the construction of major infrastructure need assurance that their service life requirements will be met during the design and construction phases of such projects. This assurance may be provided through the framework outlined in *fib* Bulletin 34, "Model Code for Service Life Design,"[1] which describes processes for evaluating the limit states associated with durability and verifying that the design service life will be achieved. For reinforced concrete structures in the northern United States and Canada that will see de-icing salt and in other locales that will see marine exposure, a primary mechanism expected to limit service life is chloride-related corrosion of the reinforcing steel. Projections of the service life of concrete structures subject to such exposure may be achieved through modeling of chloride transport through the cover concrete and eventual corrosion initiation and propagation.

RESEARCH SIGNIFICANCE

Reliability-based durability design requires a probabilistic service life modeling approach, which necessitates that the parameters expected to govern the onset of corrosion-related damage be described stochastically (that is, in terms of statistical distributions). This paper provides recommendations for statistical distributions for the chloride threshold to be used in service life modeling for carbon steel and epoxy-coated reinforcing bars (ECR) based on experimental work reported in the literature and field investigations of existing structures. The thresholds may not be valid for all structure types and/or exposure conditions but serve as a rational approach for assessing risk of corrosion.

CORROSION-RELATED DISTRESS SEQUENCE

Corrosion-related deterioration of reinforced concrete damage generally has two stages: 1) time elapsed for corrosion to begin—that is, initiation time (t_i); and 2) time elapsed where corrosion continues and a buildup of corrosion product occurs—that is, propagation time (t_p). Corrosion propagation continues until the volume of corrosion product exceeds the amount needed to crack or spall the concrete and cause surface damage. This concept is the typical basis for service life models and is illustrated for a single set of conditions in Fig. 1.

Corrosion initiates when chloride concentrations exceed the corrosion threshold or carbonation fronts reach the bar depth. Initiation time is governed by a combination of parameters including chloride exposure, chloride transport (which may be influenced by cracking), concrete cover, chloride threshold, and carbonation rate. Propagation time is dependent on corrosion rate, which is influenced by moisture and oxygen availability and other factors, and the volume of corrosion product necessary to cause delamination or spalls.

Chloride threshold

For corrosion to initiate in reinforcing steel, chloride ions must accumulate to sufficient concentration, known as the chloride threshold, to disrupt the passivity of the steel surface. Although multiple factors (cement content and chemistry, moisture conditions, steel chemistry, corrosion conditions, localized corrosion potentials) affect the influence of chloride on corrosion, generally it is assumed that the chloride content at the bar level is the primary factor responsible for corrosion initiation and that the transition from noncorroding to corroding conditions can be represented as a single event that occurs at the chloride threshold.

Chloride threshold can be expressed in a variety of ways: 1) chloride mass relative to weight of cement (% by wt. cem.); 2) chloride mass relative to weight of concrete (% by wt. conc., ppm, or lb/yd^3); or 3) chloride ion to hydroxyl

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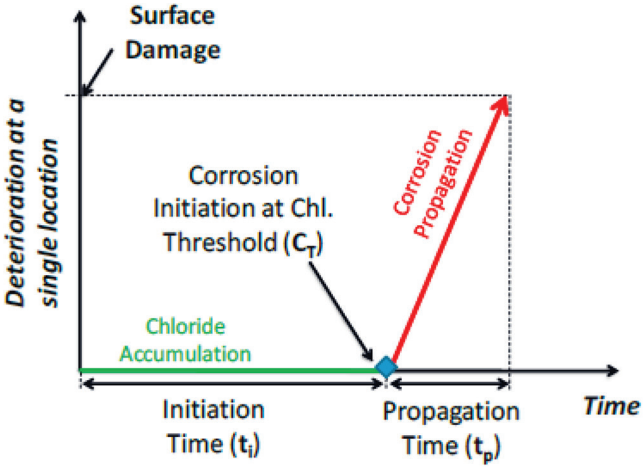


Fig. 1—Corrosion sequence (adapted from Tuutti[2]).

ion ratio [Cl⁻]:[OH⁻]. For this paper, the basis for chloride threshold is presented as percent by weight of cement, and results from other references have been converted to this as noted.

Chloride threshold is one of the two key parameters used in service life models to interpret the impact of the use of corrosion-resistant reinforcement, such as ECR, on structure performance and is the focus of this discussion. The other key parameter is propagation time. A full discussion of propagation time is beyond the scope of this paper, but it should be noted that the propagation time for ECR has been observed to be greater than the propagation time for carbon steel. This increase is estimated at 14 years by one group of researchers.[3]

Probabilistic service life modeling

The probabilistic approaches laid out in *fib* Bulletin 34[1] are based on a reliability philosophy, which is widely considered to be the most appropriate means of verifying service life during design. This philosophy recognizes that, during design, the final as-built configurations and factors that affect service life (such as cover and concrete performance) are undefined and uncertain but can be estimated based on probability distributions. Therefore, to estimate the likelihood of achieving the desired service life, estimates of critical parameters must be made and considered relative to the anticipated deterioration mechanisms. This method inherently acknowledges that service life cannot be exactly predicted and is analogous to the structural load and resistance factor-based design used in modern design codes, such as AASHTO LRFD[4] or ACI 318.[5]

Service life estimates developed in this way are interpreted relative to a target confidence level for achieving the desired service life. A common target confidence level for achieving a specified service life is 90%. This confidence level represents the probability of failure to meet the intended service life at 10%, and is consistent with the recommendations given in Annex A2.2 of *fib* Bulletin 34.[1] This is a substantially higher standard than the "expected" life, which is often considered for deterministic service life modeling of concrete durability based on average inputs and which generally reflects only a 50% confidence of achieving the target life.

Probabilistic service life modeling of chloride-induced corrosion should consider the statistical distributions of the key parameters that influence corrosion initiation and subsequent damage. For typical reinforced concrete structures, these are chloride exposure, chloride penetration resistance of the concrete, chloride-induced corrosion threshold, depth of concrete cover, and corrosion propagation time.

CHLORIDE THRESHOLDS FOR CARBON STEEL REINFORCING BARS

Review of literature

Chloride corrosion thresholds for carbon steel reinforcing bars were considered based on a review of published literature, including projects with laboratory and field-testing components. In general, laboratory studies have evaluated chloride thresholds by testing concrete samples with either cast-in chlorides or with externally applied chloride. Testing chloride thresholds by introduction of cast-in chlorides is problematic, because the steel may not have time to passivate prior to initiation of corrosion. For this review, it was determined that studies referencing field measurements or externally applied chloride sources better represented chloride initiation in actual structures.

Over the past few decades, a number of studies and literature reviews have been undertaken to define critical threshold for carbon steel reinforcement. This has included major research efforts by European consortiums for the BRITE-EURAM Project in the mid-1990s; DuraCrete and DARTS projects in the early 2000s; the development of *fib* Bulletin 34 in the mid-2000s; and RILEM Committee 235-CTC most recently. In addition, multiple researchers have published literature reviews comparing results reported in the literature over the previous few decades.[6,7] These publications showed a range in total critical chloride contents of 0.1 to 2.2% by weight of cement, with typical reported values between 0.2 and 0.6%. *fib* Bulletin 34 models and data are based substantially on work published by the DuraCrete project,[8] an effort funded by the European Union on service life modeling of reinforced concrete conducted in the 1990s and early 2000s. A similar approach is described in *fib* Bulletin 76,[9] which was published in 2015.

Multiple papers and reports have attempted to quantify carbon steel chloride thresholds in terms of statistical distributions. Some key sources are shown in Table 1. The references in Table 1 show three primary publications as the basis for selection of critical chloride concentration: work by 1) Hansson and Sørensen[14]; 2) Breit[12]; or 3) Gehlen.[15] These publications found critical chloride thresholds ranging between 0.2 and 0.8% by weight of cement, with average values in the range of 0.5 to 0.6% by weight of cement. Other studies have reported single threshold values between 0.1 and 3.1% by weight of cement.[13]

Both the DuraCrete project[8] and Böhni[10] report a mean value of 0.48% by weight of cement for critical chloride concentration and advocate the use of a beta distribution. A key property of the beta distribution is that it can be used to describe stochastic variables over intervals of finite length;

Table 1—Critical chloride concentration statistical distributions for uncoated reinforcement

Source	Distribution type	Values, % by wt. cem.
Böhni[10]	Beta distribution	Lower bound: 0.2 Upper bound: 2.0 Mean: 0.48 Standard deviation: 0.15
fib Bulletin 34[1]	Beta distribution	Lower bound: 0.2 Upper bound: 2.0 Mean: 0.6 Standard deviation: 0.15
DuraCrete[8] Schiessl[11] Breit[12]	Normal distribution	Mean: 0.48 Standard deviation: 0.15
Other studies[13]	Single threshold value	Approximately 0.1 to 3.1
Authors' recommendation	Beta distribution	Lower bound: 0.2 Upper bound: 2.0 Mean: 0.48 Standard deviation: 0.15

that is, the distribution can be limited to a given range. In the authors' experience, the lesser of the two average values reported (0.48% versus 0.60% by weight of cement) fits better with the findings of previously evaluated structures and is recommended for use in service life modeling, especially for new structures where conservatism is warranted.

Supplementary cementitious materials

Supplementary cementitious materials such as fly ash, silica fume, or slag cement affect the cement paste in a number of ways that may influence corrosion. In general, they consume hydroxyl radicals in their secondary reactions; increase resistance to chloride penetration; and increase the electrical resistivity of the paste. They may also play a role in chemical binding of chloride ions.[10] All things being equal, consuming available hydroxyl radicals would increase the chloride ion to hydroxyl ion ratio $[Cl^-]:[OH^-]$, which would have a detrimental effect on the critical chloride concentration. The other changes would be beneficial to reducing the probability of corrosion initiation by an increase in other service life model parameters, such as chloride penetration resistance (for example, diffusion).

Concrete Society Technical Report No. 61[16] published recommendations for considering the effect of concrete containing fly ash, slag, or silica fume on critical chloride concentrations. Overall, these materials effectively reduce the chloride threshold concentration, as shown in Eq. (1). This relationship is similar to data referenced by others.[17] For fly ash contents of less than 10% or slag cement contents of less than 20%, the threshold value is the same as concrete with only ordinary portland cement

$$Cement_{eqv} = CM \cdot \begin{bmatrix} 1-\max\left[0.010\left(\%FA-10\right),0\right] \\ -\max\left[0.005\left(\%SG-20\right),0\right]-0.025\cdot\%SF \end{bmatrix} \quad (1)$$

where CM is the total weight of cementitious material; $\%FA$ is the proportion of fly ash (applicable for up to 50%); $\%SG$ is the proportion of slag cement (applicable for up to 80%); and $\%SF$ is the proportion of silica fume (applicable for up to 20%).

For example, assuming a theoretical mixture design with total cementitious content of 650 lb/yd^3 and 20% fly ash replacement, the equivalent cement content used for estimating chloride threshold would be: $650 \times [1 - \max[0.010(20 - 10), 0] - 0 - 0] = 585$ lb/yd^3. This reduction in equivalent cement content results in a reduction in chloride threshold from 0.077% to 0.069% by weight concrete (assuming a unit weight of 150 lb/ft^3). This approach is conservative given the other assumed benefits associated with supplementary cementitious materials, as stated previously.

CHLORIDE THRESHOLD FOR EPOXY-COATED REINFORCING BARS

Background on ECRs

ECRs have been used since the early 1970s and are the most common corrosion-resistant reinforcing bars present in concrete structures subject to severe exposures. This is due in part to their cost-effectiveness—that is, the benefits provided relative to the cost premium—compared to other types of corrosion-resistant reinforcing. Application of an epoxy coating to the surface of reinforcing bars provides protection by introducing a physical barrier to chloride ions as well as to oxygen and water. This barrier can help to prevent corrosion by limiting access of chloride to the anode and by limiting reactions that can occur at the cathode. It also introduces an insulating layer between adjacent reinforcing bars that can increase the electrical resistance of the system.

Numerous laboratory and field studies have been conducted to evaluate the extent of corrosion protection provided by epoxy bars.[17-22] These have generated somewhat contradictory findings: there are examples of poor performance of ECR (such as the much-studied Florida Keys bridges), but many investigations have identified better performance than would be expected from carbon steel reinforcing bars. There is general agreement that corrosion on ECR initiates at holidays or defects in the coating. While holidays may occur during the coating process, the most common source of defects on ECR as installed in concrete is handling damage on the jobsite and during installation. Others have suggested that exposure to moisture over time can lead to debonding of the coating[21,23] and this can promote corrosion. Another factor that must be considered in evaluating the historical performance of ECR is the evolution of specifications and coating practices. Starting in the late 1980s and early 1990s, some significant modifications to the governing ASTM specification (ASTM A775) were enacted, including: 1) increasing the minimum coating thickness from 5 mils to the current 7 mils in 1992 (with the objective of reducing the number of holidays occurring on deformations); 2) significantly limiting the amount of allowable repair damage to 1% in each linear foot in 1989; and 3) enacting more severe quality control testing requirements, including conducting bend tests to 180 degrees in 1994. Modifications to coating practices have included a

Table 2—Studies investigating field performance of epoxy-coated reinforcing bars (ECR)

Year of investigation and reference	Construction date	States where bridge located	Number of structures examined	Bar samples	Comments/features
2001 to 2002[24]	1973 to 1981	MN, WI, NY, PA, OH, VA, IA	17	119	Included decks with ECR top and bottom mats and with ECR top mats only
2007[25]	1984 to 1985	GA, NC	4	43	Substructures with all ECR bars
2009[26]	1974 to 1976	WV	6	42	Included decks with ECR top and bottom mats and with ECR top mat only
2011[27]	1979 to 1993	IA	8	112	Included decks with ECR top and bottom mats and with ECR top mat only
2011[28]	1958	IL	10	37	Included decks with ECR top and bottom mats; water-soluble chloride testing due to chloride-containing aggregate
2016[29]	2000	IN	1*	12	Deck with ECR top and bottom mat
2017[30]	2003	IN	1*	10	Deck with ECR top and bottom mat
2017[31]	1960	IN	1	6	Deck with ECR top and bottom mat
2016 to 2017[32]	1989 to 2005	IL	5†	16	Included decks with ECR top and bottom mats and with ECR top mats only
2017[33]	1980	MN	1	4	Deck with ECR top mat only
2017[34]	1978	MO	1	12	Included deck with ECR top and bottom mats

*Structure built after 1993.

†Three of five structures built after 1993.

focus on quality control demonstrated by the CRSI certification program for the manufacturing plants of ECR that began in 1991. In general, these modifications may be expected to result in improved performance of ECR in modern structures compared to historic ones.

Field studies of ECRs

To address the uncertainty regarding the performance of the ECR, on behalf of various agencies, the authors conducted field studies in 13 states of bridge decks and bridge substructures exposed to chlorides and constructed with ECR; the majority of these structures were built before 1993. In these studies,[24-34] summarized in Table 2, similar field and laboratory investigations were conducted as discussed later. In total, 55 structures were evaluated and more than 400 ECR samples were extracted and analyzed. Some of the decks that were evaluated were built with ECR in both the top and bottom mat of reinforcing, while others included ECR only in the top mat and contained carbon steel bars in the bottom mat. It is noted that this latter configuration has been shown to result in reduced durability.[24]

The scope of work in each investigation included visual and delamination surveys, reinforcing cover surveys, and sampling of cores containing bars. In some cases, corrosion potential or other corrosion-related testing was performed. The locations of the core sampling were generally selected so as to obtain sample bars on which corrosion had developed recently (by sampling bars close to but not necessarily in small delaminations). Further, some bars were taken at locations away from damaged concrete to allow evaluation of chloride ingress in undamaged concrete.

The condition of the bars sampled during these investigations and the chloride concentration in the concrete surrounding the bars were characterized. On a number of bar samples, the coating thickness was measured with an electromagnetic coating thickness gauge. For some bar segments, where corrosion product had developed under the coating, the coating thickness was measured directly using a micrometer on portions of coating cut from the bar segment. The corrosion activity of each bar was assessed using the rating scale illustrated in Fig. 2, which shows representative corrosion conditions of extracted bars. Bars with a rating of 3 or greater were deemed to be actively corroding, while those with a rating of less than 2 were judged to be not active.

The chloride concentration in the concrete at the depth of each bar was determined by interpolating from chloride profiles (chloride concentration with depth concentrated around the bar depth) measured for each core using acid-soluble chloride testing techniques (ASTM C1152 or C114). An exception to this was the investigations of the Illinois bridges,[28] which contained dolomitic limestone aggregate known to contain bound chloride; on these bridges, water-soluble chloride testing was conducted generally according to ASTM C1218.

Typically, little or no corrosion was noted at chloride concentrations below approximately 1000 ppm (0.64% by weight of cement), levels that would be expected to be associated with corrosion in carbon steel bars. The studies confirmed that corrosion in ECR tends to occur initially at defects, and that the presence of these defects can permit corrosion even at relatively low chloride levels. Figure 3 shows a bar sample from a bridge deck in Iowa where corrosion was judged to be active at chloride levels of approximately 650 ppm (0.42% by weight of cement). Defects in the coating of bars in an in-place condition are not uniformly distributed, and likely vary depending on the epoxy film

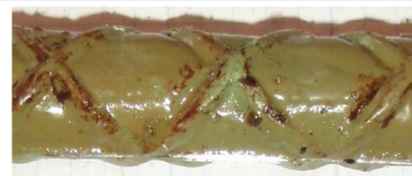
Value	Description	Representative photographs Epoxy-coated	
1	No evidence of corrosion		Not Active
2	A number of small, countable corrosion spots		Not Active
3	Corrosion area less than 20% of total surface area		Active
4	Corrosion area between 20% to 60% of total surface area		Active
5	Corrosion area greater than 60% of total surface area		Active

Fig. 2—Figure of typical reference photos for categorizing active and nonactive epoxy-coated bar corrosion.

Fig. 3—Bar sample (core 2) from U.S. Route 30 Bridge[27] showing corrosion at preexisting damage site (arrow).

thickness, overall quality control of coating fabrication, and damage that occurs during bar handling and placement. Clear differences in corrosion resistance were noted for bars coated with older generation epoxy and with thinner coatings. Note: Conversions from chloride by weight of concrete to chloride by weight of cement were made assuming 611 lb/yd^3 (363 kg/m^3) of cement, a typical cement content for bridge deck concrete.

A histogram of the number of sampled epoxy coated bars judged to be active or inactive versus chloride concentration is given in Fig. 4. The chloride concentration associated with actively corroding bars was observed to be distributed over a range of values. Corrosion initiated on a limited number of bars with chloride concentrations similar to thresholds typically associated with carbon steel; however, the barrier

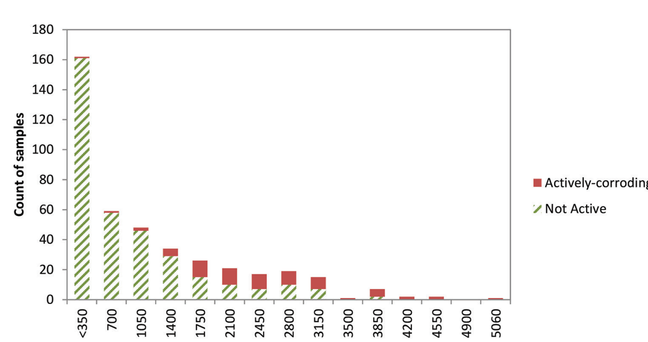


Fig. 4—Histogram of actively corroding versus nonactive extracted ECR samples from evaluated bridge decks and substructures.

provided by the epoxy coating provided effective protection to most of the bars. In addition, greater amounts of chloride in the surrounding concrete were associated with more aggressive corrosion. The presence of corrosion on these bars indicated that at some time prior to sampling, the chloride concentration had exceeded the specific chloride threshold at that location.

As chloride concentration increased, the fraction of sampled bars that were actively corroding at that given chloride level increased. Figure 5 shows a plot of this fraction versus chloride concentration. For large sample sets, this fraction represents the probability that corrosion has initiated on the ECR at or below that chloride level. In this way, this fraction can be considered an estimate of the cumulative distribution of the chloride threshold for these bars. Large sample sets are available from the reported investigations at lower chloride levels (less than 2000 ppm [1.3% by weight of cement based on a typical cement content of 6.5 sacks]). Relatively few bars were obtained in concrete with chloride concentrations above 2000 ppm, and as a result, the estimate of the cumulative distribution above this level is erratic. However, the data up to 2000 ppm approximates a normal distribution, and a normal distribution fitted to this data is also given in Fig. 5. While this fitted distribution does not match the full observed sample, it does match the distribution well through approximately the first 50% of the observed conditions. The initial portions of the distribution will control service life predictions, since during probabilistic service life modeling in which a small probability of failure (such as 10%) is allowed, the portion of the distribution representing conditions most conducive to corrosion will govern. This approach assumes that the likelihood of corrosion of the bars at chloride concentrations above 2000

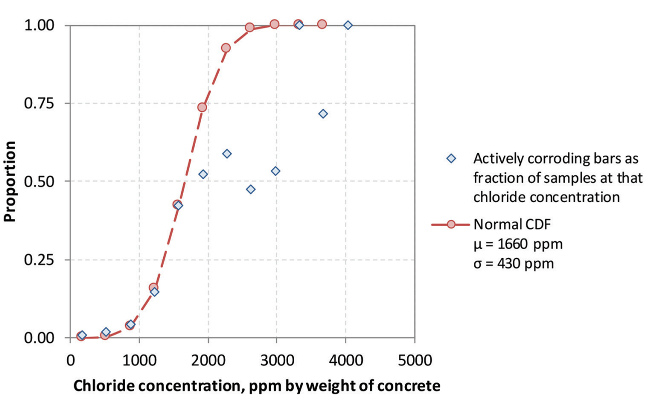


Fig. 5—Plot of actively corroding ECR as fraction of samples at that chloride concentration—an estimate of cumulative distribution of chloride threshold for ECR—versus chloride concentration at bar depth. Assumed normal cumulative distribution function (CDF) fit to data is also shown.

ppm is higher than was actually observed (albeit based on a limited number of sampled bars representing these conditions) and that the use of this distribution may result in an overprediction of corrosion. As a result, the fitted distribution is conservative, which is appropriate for modeling purposes, especially for modeling of new structures where the goal is to ensure that a design service life is met, and underrepresenting risk would be unacceptable.

Further, this distribution for the chloride threshold may overestimate the risk of corrosion to epoxy coated bars in new bridge decks for the following additional reasons:

1. A majority of the samples were taken with the express purpose of finding corroding bars. Therefore, the fraction of sampled bars at a given chloride level that are corroding is likely to be higher than would have been achieved through random sampling.

2. As mentioned earlier, changes to specifications governing the production of epoxy bars were made in the late 1980s and early 1990s to improve the quality of epoxy coated bars, and most of the bridges examined in the investigations described here were constructed prior to 1993. Further, this analysis included all sampled bars, including those with damaged or thin coatings. Therefore, the sampled bars represent conditions more conducive to corrosion than would be expected for new construction using ECR.

Based on these findings, the proposed chloride threshold for ECR may be practically and conservatively considered as a normally distributed variable for the purposes of probabilistic modeling. The referenced studies reported chloride concentrations as a portion of the total weight of concrete. For use in generalized modeling, these results were converted to a chloride concentration by weight of cement by assuming that the sampled concrete was a 6.5-sack mixture, as might have been used in AASHTO bridge construction between approximately 1970 and 1990.

For modeling new bridge elements with varied mixture proportions, this distribution may be adjusted relative to the weight of cement in the specific mix design used. Table 3 provides an example of this conversion. These values may also be adjusted for use of SCMs in a manner similar to that outlined for Eq. (1). Care must be taken when applying the data set presented in this report to concrete mixtures which vary significantly from the proportions and constituents used in common transportation applications.

COMPARISON OF THRESHOLDS

The recommended probability distributions for chloride threshold in terms of percent by weight cement for carbon steel reinforcing bars and ECR are compared in Fig. 6. These distributions indicate that the ECR corrosion resistance is more variable (as evidenced by a "flatter" distribution) and

Table 3—Proposed chloride-induced corrosion parameters for ECR service life modeling

Case	Cement content, lb/yd^3 (kg/m^3)	Chloride concentration, % by weight of concrete (ppm)		Chloride concentration, % by weight of cement	
		Mean	Standard deviation	Mean	Standard deviation
Referenced studies (6.5 sacks)	611 (363)	0.165 (1650)	0.045 (50)	1.06	0.28
Example proposed mixture design (7 sacks)	658 (390)	0.178 (1780)	0.049 (490)	1.06	0.28

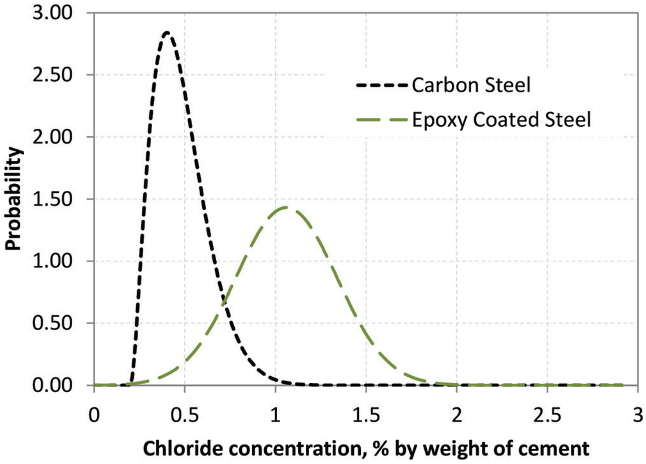


Fig. 6—Recommended probability distributions for chloride threshold for carbon steel-reinforcing bars and ECR.

that the minimum chloride concentration at which some risk for corrosion is present are similar for both types of reinforcing bars. This is not unexpected, because corrosion in ECR was observed to develop where damage to the coating exposed the underlying carbon steel surface. However, comparing the distributions for the two types of reinforcing steel, the observed overall ability of the ECR to resist chloride exposure before corrosion initiates is greater than that of carbon steel reinforcing bars.

The beneficial effects of the use of ECR on structure durability resulting from this improved performance is only adequately considered through probabilistic modeling. It is noted that not all software available for performing service life analysis allows the user to adjust inputs to consider statistical distributions during probabilistic analysis. The ability to tailor the model inputs in recognition of site conditions and anticipated material performance and construction details is an important component of an accurate modeling approach.

CONCLUSIONS

A probabilistic approach is necessary to perform reliability-based service life analysis, and this requires that the statistical distribution of key input parameters be estimated. One of these key parameters is the chloride threshold.

Despite the extensive research performed on the initiation of corrosion in carbon steel reinforcing bars in the presence of chlorides, limited information is available regarding the statistical distributions of the chloride threshold on such bars. The work reported by Breit[12] is a suitable basis for such a distribution, which is described by a beta distribution with a mean and standard deviation of 0.48% and 0.15% by weight of cement, respectively.

A good understanding of the chloride threshold is important for considering the potential benefits of the use of corrosion-resistant reinforcing bars, such as epoxy-coated reinforcing bars. Given that the use of corrosion-resistant reinforcing bars is a popular and cost-effective method for extending the service life of concrete structures subject to chloride exposure, the ability to logically assess the impact of its use is vital. Based on field investigations conducted by the authors to evaluate the performance of epoxy coated bars in in-service structures, an estimate of an equivalent critical chloride threshold distribution for epoxy bars has been developed and is described by a normal distribution with mean and standard deviation of 1.05% and 0.29% by weight of cement, respectively. These values should be used with an "equivalent cement content" if supplementary cementitious materials are being considered; refer to Eq. (1).

The chloride threshold distribution developed during the course of this work is limited to conventionally reinforced concrete structures exposed to moisture and chlorides, as well as seasonal wetting and drying cycles. This data set is based on the examination of similar vintage, reinforced concrete bridge decks (with one study conducted on marine substructures) with generally similar portland cement-only concrete mixtures. While correction methods to account for the presence of supplementary cementitious materials in modern, high performance mix designs and higher total cementitious content have been proposed, the chloride threshold distribution for epoxy-coated reinforcement could be further refined for modern concrete mixes and for concrete structures in different environments (for example, structures in marine environments). Further research efforts are necessary to develop appropriate threshold distributions for all exposure conditions and validate performance for modern mix designs. Engineering judgment must be used to estimate the true risks of corrosion for any particular application.

AUTHOR BIOS

ACI member **John S. Lawler** *is a Principal with Wiss, Janney, Elstner Associates, Inc. (WJE), Northbrook, IL. He is a member of ACI Committees 222, Corrosion of Metals in Concrete; 239, Ultra-High-Performance Concrete; and 365, Service Life Prediction. He received his BS in engineering physics from Hope College, Holland, MI, and his MS and PhD in civil engineering from Northwestern University, Evanston, IL. His research interests include structural evaluation, corrosion, repair and rehabilitation design, and materials evaluation and research.*

ACI member **Jonah C. Kurth** *is Director of Engineering at Structural Technologies, Columbia, MD. He received his BS in civil engineering from the University of Michigan, Ann Arbor, MI, and his MS in civil engineering from the Georgia Institute of Technology, Atlanta, GA. He is an active member of ACI Committees 357, Offshore and Marine Concrete Structures; 562, Code Requirements for Assessment, Repair and Rehabilitation of Existing Concrete Structures; and 563, Specifications for Repair of Concrete in Buildings. His research interests include condition assessment and repair design of industrial, power generation, and manufacturing facilities.*

ACI member **Stephen M. Garrett** *is a Senior Associate at WJE. He received his BS and MS in civil engineering from the University of Illinois, Urbana, IL. His research interests include structural analysis, field investigation, material testing, nondestructive evaluation, corrosion testing, and repair and rehabilitation design of steel and reinforced concrete structures.*

Paul D. Krauss *is a Principal at WJE. His research interests include concrete and polymer concrete materials, reinforced concrete corrosion, structure rehabilitation, and durability assessments.*

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