

Predicting Service Life of Chloride-Exposed Steel-Reinforced Concrete

by Dale P. Bentz, James R. Clifton, and Kenneth A. Snyder

In the last decade or so, numerous advances have occurred in the field of information technology. Through the use of computers, the amount of available information and the speed at which it can be retrieved have both increased dramatically. The proliferation of the Internet and the World Wide Web (WWW) now allows researchers to rapidly access a wealth of multimedia information on a seemingly infinite variety of topics. The World Wide Web also provides a convenient format for executing computer programs over the Internet, for example through the use of forms and common gateway interface (CGI) scripts or other Internet programming languages.

A computer-integrated knowledge system (CIKS) provides a means of

combining this wealth of information into a coherent system that produces useful results for both the academic and commercial communities.¹ A CIKS should provide the knowledge needed for solving problems with a range of complexities, based on an integrated set of knowledge which is interpreted by an underlying intelligent system.² For the concrete community, a subject of vital interest is the service life of concrete structures.³ One common mode of degradation for highway structures and those exposed to seawater is corrosion of the reinforcing steel. The diffusion rate at which chloride ions can reach the steel is one of the controlling factors in determining how long such a structure will last.

The present research concerns the development of a prototype CIKS with

the goal of predicting the service life of steel-reinforced concrete exposed to chloride ions. Starting from the mixture proportioning process, the system proceeds to predict chloride ion diffusivity coefficients and to finally predict the ingress profiles or time to corrosion initiation for a reinforced concrete exposed in a specific environment.

This prototype system demonstrates the potential for disseminating knowledge on specific topics in concrete technology to the construction industry through the World Wide Web. It is available for public access at the following uniform resource locator (URL): <http://ciks.cbt.nist.gov/~bentz/welcome.html>

New users must register by providing their name and specifying a password to be used in future sessions. In addition, from this main screen the user has the option to select either SI or inch-pound units to be used in all subsequent forms. A profile is maintained for each user so that future sessions can restore the parameters last input by that specific user (as long as the same units are selected from the welcome form). Online guidance, via separate help pages of text and graphics, is provided throughout the system as indicated by highlighted Guidance indicators.

Computer models

The current CIKS integrates a number of previously developed and new computer models into a single coherent system. The main menu provided upon accessing the system is shown in Fig. 1. A logical starting point for considering the service life of a concrete structure is the mixture proportioning process.

Main Menu

- 1) Ordinary strength concrete mixture proportioning (ACI 211.1-91)
- 2) High strength concrete mixture proportioning (with/without a water reducer)(ACI 211.4R-93 Guide)
- 3) Predict the chloride ion diffusivity of a concrete based on mixture parameters
- 4) Predict the service life of a reinforced concrete structure exposed to chlorides
- 5) Predict the chloride ion penetration profile of a concrete after a specific time
- 6) Advice on analyzing chloride ion penetration profile data
- 7) View the literature database on chloride ion diffusivity in concrete

Fig. 1 — Main menu for computer-integrated knowledge system for service life prediction of steel-reinforced concrete exposed to chloride ions.

With this in mind, the current ACI guidelines for proportioning ordinary strength (ACI 211.1-91⁴) and high-strength (ACI 211.4R-93⁵) concrete have been computerized using a combination of HyperText Markup Language (HTML) forms and CGI programs written in the C programming language. Upon selecting menu item 1, the system user is presented with forms (Fig. 2) for trial proportioning a normal concrete mixture, and specifies the needed parameters and data according to the appropriate ACI guidelines.^{4,5}

The choices for the boxes with a button shown in Fig. 2, based on ACI 211.1-91,⁴ are as follows:

- Specify slump:
Off or On (when "off," slump is selected by construction type as detailed further).
- Pozzolanic replacement method:
Volume basis or mass basis,

- Pozzolanic replacement material:
Silica fume, fly ash, or blast furnace slag,
- Aggregate surface property:
Angular or rounded,
- Construction type:
Reinforced foundation, footing, beam and wall, column, pavement, mass concrete, thin section, or predetermined slump,
- Air entrainment:
No or yes,
- ASTM cement type:
I, II, III, IV, or V, and
- Exposure condition:
Mild, moderate, severe, or salt or sulfate severe.

The form for a high-strength mixture,⁵ menu item 2, is similar to that shown in Fig. 2, with the following exceptions: aggregate surface property, construction type, air entrainment, and

exposure condition are not included; slump must be specified; the use/absence of a high-range water-reducing agent is specified; and the target strength is specified either after 28 or 56 days of curing. Once all parameters have been specified, the user simply clicks on the **Submit form to determine mixture proportions** button and the resultant trial mixture proportions are returned (Fig. 3), following execution of the mixture proportioning program, written in the C programming language. Based on the trial mixture proportions, the program also returns a predicted value for the chloride ion diffusivity (*D*) of the in-place concrete⁶ and its maximum expected temperature increase under adiabatic (no heat loss) conditions.⁷

The prediction of chloride ion diffusivity from mixture proportions is based on a statistically designed com-

Ordinary Strength Concrete Mixture Proportioning
Based on ACI 211.1-91 Standard Practice

Compressive strength psi (Permitted range of 2000-6000 psi)

Max. Agg. Size in. [Guidance](#)

Dry Rodded Unit Weight of Agg. lbs per cubic ft.

You may specify slump by changing value below and turning "Specify Slump" to On or you may have slump selected based on construction type selected further down (by leaving "Specify Slump" at its Off value).

Slump in.

Specify Slump

Fineness modulus of fine aggregate

Other Parameters

Construction type (for slump selection) [Guidance](#)

Air Entrainment

Cement Type (ASTM)

Exposure Conditions [Guidance](#)

Batch size cubic yards

[Return to main menu](#)

Fig. 2 — HTML input form for the mixture proportioning of a conventional concrete (above and bottom left).

Pozzolanic Material Information

Pozzolanic Replacement %

Replacement Method

Replacement Material

Pozzolan Specific Gravity

Aggregate Data

Aggregate Surface Property [Guidance](#)

Coarse Fine

Specific Gravity (SSD)

Moisture Content % [Guidance](#)

Aggregate absorption % [Guidance](#)

Trial Mixture Proportioning Recommendations

- w/c ratio = 0.62
- Slump = 2.00 in
- Air content = 1.00%
- Requested Batch Size = 1.00 cubic yards

Trial Mixture Proportions in lb/yd³ (lb per batch)

water	=	282	(282.00)
cement	=	459	(459.00)
pozzolan	=	0	(0.00)
coarse agg.	=	1975	(1975.00)
fine agg.	=	1473	(1473.00)

Estimated chloride ion diffusion coefficient at 90% of achievable hydration is $3.4e-01$ in²/yr
Estimated 90% confidence limits are [4.0e-02, 2.9e+00] in²/yr
[Click here for service life prediction module for rebar corrosion](#)
Estimated specific heat for concrete is 1.03 J/g°C
Estimated heat release at maximum hydration is 51.3 J/g
Maximum expected temperature rise in adiabatic conditions is 49.7°C
Estimated heat release after 28 days hydration is 48.9 J/g
Expected temperature rise in adiabatic conditions after 28 days is 47.3°C
— Temperature rise prediction based on techniques outlined in:
Waller, V., Delarrard, F., and Roussel, P., Modelling the Temperature Rise in Massive HPC Structures, 4th Int'l. Symp. on Utilization of High Strength-High Performance Concrete, Paper 170, Paris, 1996.

Fig. 3 — (Above) Example results of submitting the form in Fig. 2, showing trial mixture proportions and predicted chloride ion diffusivity and thermal properties.

Prediction of the Chloride Ion Diffusivity of a Concrete Based on Mixture Parameters

Please supply the following parameters (defaults provided)

w/c ratio

Volume fraction of Aggregate %

Degree of Hydration

A paper on the modelling techniques used to estimate D is available online by clicking on the title in the following reference:

Bentz, D.P., Detwiler, R.J., Garboczi, E.L., Halanckova, P., and Schwartz, L.M., *Multi-Scale Modeling of the Diffusivity of Mortar and Concrete*, RILEM International Conference on Chloride Intrusion into Concrete, 1995.

Click [here](#) to view the database of experimental diffusivities.

[Return to main menu](#)

Fig. 4 — HTML input form for predicting chloride ion diffusivity based on mixture proportioning and anticipated hydration.

puter experiment which identified water-cement ratio (w/c), volume fraction of aggregates, and degree of hydration as the three major variables influencing the diffusivity of a conventional concrete mixture without mineral admixtures.⁶ From the results of this computer experiment, an equation was developed for estimating chloride ion diffusivity coefficients using these three variables. In addition, the CIKS also returns an estimate of the 90 percent confidence limits for the estimated D value, based on regression of the developed equation to the computer experiment data.

Values for w/c and volume fraction of aggregates are directly available from the trial mixture proportioning process. The long-term degree of hy-

dration is estimated as 90 percent of the theoretical maximum achievable hydration, based on the w/c . For w/c greater than or equal to 0.42, there is sufficient capillary porosity for all of the cement to react so that this theoretical maximum is 1, while for lower w/c , this theoretical maximum degree of hydration is given by $(w/c)/0.42$.⁸ Alternatively, within the CIKS system, a separate form (menu item 3) exists to estimate the chloride ion diffusion coefficient along with its 90 percent confidence limits, given user inputs for the w/c , volume fraction of aggregates, and expected degree of hydration, as shown in Fig. 4.

Once a D value has been estimated, it can be employed in a model to predict the service life of a reinforced concrete structure exposed to an external source of chlorides. The simplest approach to this problem, implemented as menu item 4, is to use Fick's second law and solve for t in the following equation:⁹

$$\frac{C_{corr}}{C_{ext}} = \operatorname{erfc} \frac{x}{2\sqrt{Dt}}$$

where C_{corr} is the concentration of chloride ions needed at the reinforcement to initiate corrosion, C_{ext} is their external concentration, x is the depth of the rein-

forcement, D is the chloride ion diffusivity, t is the predicted service life, and $\operatorname{erfc}(x) = 1 - \operatorname{erf}(x)$.⁸ Weyers et al.¹¹ have modified this approach slightly to consider the statistical variation in the depth of the reinforcement bar (assuming a normal distribution characterized by a mean and standard deviation), employing chloride ion concentrations reported in mass of chloride per unit volume of concrete, and taking C_{ext} to be the chloride ion concentration measured at a depth of 12.7 mm (0.5 in.). The approach outlined in their report was implemented in the current CIKS.

An alternative to the simple erf solution of Fick's second law is to employ a one-dimensional finite difference solution,¹² which directly incorporates the time-dependent variability of the exposure environment and the performance differences between the bulk and surface layer concrete. The model, menu item 5, developed in the present research allows for the following parameters to be specified by the user:

1) A two-state cyclic "square wave" exposure consisting of an external chloride ion concentration of $C_{0,1}$ of duration t_1 , followed by an external chloride ion concentration of $C_{0,2}$ of duration t_2 , along with the total duration of the exposure (Fig. 5);

2) A two-layer composite concrete structure consisting of bulk concrete with a user-specified diffusion coefficient and a surface layer of a user-specified thickness with a different (higher

⁹The Gauss error function, $\operatorname{erf}(x)$, is defined based on an analytical integral equation. Values can be found in tables in many mass and heat transfer texts¹⁰ and library routines for the calculation of $\operatorname{erf}(x)$ and $\operatorname{erfc}(x)$ are readily available in most computer programming languages.

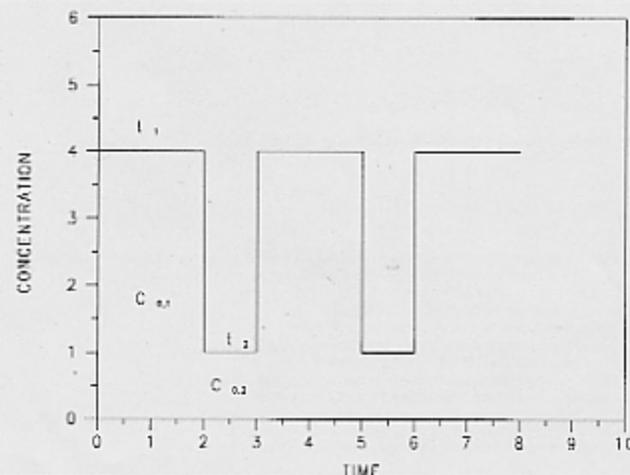


Fig. 5 — Illustration of the two-state cyclic "square-wave" function used in characterizing an exposure environment.

Database of Values for Concrete Chloride Ion Diffusivity

Reference	w/c ratio	moist curing age	Mix cement (kg/m ³)	Design water (kg/m ³)	agg. (kg/m ³)	Estimated D (m ² /s*1e12)
1	0.43	1.5y	139	166	NG	2.5
2	0.4	1.0w	420	168	NG	3
3	0.4	4.0w	420	168	NG	2
4	0.4	14.0w	420	168	NG	1
5	0.54	1.0w	300	162	NG	4
6	0.54	4.0w	300	162	NG	3
7	0.54	14.0w	300	162	NG	2.5
8	0.5	2.0m	330	165	2066	2.86-3.65
9	0.5	2.0m	330	165	1094	1.19-1.94
10	0.48	3.0w	355	170.4	1945	20
11	0.47	24.9d	400	188	NG	1.9
12	0.35		450	157.5	1655	2.8-3.1
13	0.4		420	168	1692	4.4-5.4
14	0.5		390	195	1636	5.6-13.6
15	0.75		250	187.5	1784	9.0-39.7
16	0.5	3.0m	519	257	1524	2-3

Fig. 6 — Portion of the database providing experimentally measured values of chloride ion diffusion coefficients for concrete available in the literature.

Prediction of Service Life of Reinforced Concrete Structure Exposed to Chlorides

Please supply the following parameters (defaults provided) (Click here for guidance)

External chloride concentration lb/yd³

Chloride concentration needed at reinforcement to initiate corrosion lb/yd³

Reinforcement depth inches

Standard deviation in reinforcement depth inches

Chloride Diffusion Coefficient in²/in/yr

Click [here](#) to estimate D from mix design data.

Estimation of service life is based on solution of Fick's second law for diffusion into a semi-infinite media as described elsewhere.

[Return to main menu](#)

Fig. 7 — HTML input form for predicting service life of concrete exposed to chloride ions based on analysis using Fick's second law.

or lower) diffusion coefficient than that of the bulk concrete;

3) An adsorption isotherm (Langmuir type) relating bound to free chloride¹⁵; and

4) The aluminate (tricalcium aluminate and tetracalcium aluminoferrite) contents of the cement to account for the formation of Freidel's salt¹⁴ from reactions between the aluminates and the diffusing chloride ions.

For the case where the concrete diffusivity can be described by a two-layer model and all the previously stated effects can be ignored, an analytical solution for the concentration profile as a function of time has been obtained by Andrade et al.,¹⁵ based on the solution originally derived by Carslaw and Jaeger in terms of heat transfer variables.¹⁶ This solution can also be viewed within the CIKS by selecting main menu item 6, **Advice on analyzing chloride ion penetration profile data**. The current model in the CIKS considers only diffusion under saturated conditions; it should be noted that comprehensive models

for diffusion into partially saturated concrete have been previously developed by Saetta et al.¹⁷ Although much more computationally intensive, models such as that of Saetta et al. may also someday be executable over the WWW.

Once a user specifies all of the above parameters and submits the form for this module, the underlying C program returns a plot showing the predicted total and free chloride ion concentrations

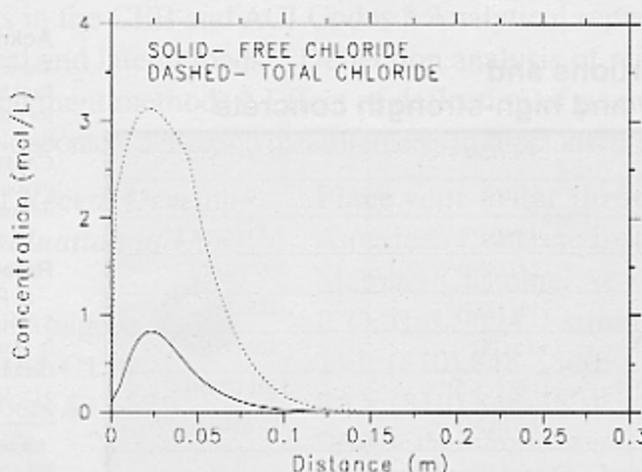


Fig. 8 — Example results for predicted chloride ion (free and total) profiles for a conventional 24 MPa (3500 psi) concrete.

as a function of depth. Knowing the depth of the reinforcement and the chloride concentration necessary to induce corrosion, the user can then determine if the chloride ion concentration at the reinforcement is such that corrosion will be probable after the specified exposure time. In addition to returning this plot, the program also optionally sends a file, containing a numerical listing of the inputs and results, by e-mail to a user-specified address.

Databases

Several prototype databases have been developed and included in the current version of the CIKS. The first is a simple bibliographical listing of recent articles dealing with the penetration of chloride ions into cement-based materials and can be accessed via item 7 of the CIKS main menu. It should be noted that this database actually resides on a different computer than the CIKS itself, illustrating the access of a distributed system of knowledge using the World Wide Web.

The second database, a portion of which is shown in Fig. 6, is a compilation of concrete chloride ion diffusivity coefficients available in the literature, along with mixture proportions and curing times, when provided in the original references. This database is accessible from both the form for predicting chloride ion diffusivity from mixture proportions and the form for estimating the chloride ion ingress profile, as described previously. Within this database, clicking on a highlighted reference number will show the complete bibliographic reference for the chosen data set. If the name of one of

the authors is highlighted in a reference listing, clicking on the name will access a final database, which provides an alphabetical listing of researchers active in the field of chloride ion diffusion in concrete, including their mailing addresses.

Example session

As an example of the use of the CIKS, let us compare the performance, with respect to chloride resistance, of a conventional (24.1 MPa [3500 psi] 28-day compressive strength) and a high-performance (48.3 MPa [7000 psi])

concrete. We will specify a nonair-entrained concrete with a low slump of 50 mm (2 in.). For the high-strength concrete, the maximum aggregate size will be 25 mm (1 in.) and no high-range water-reducing admixture will be employed. The other parameters will be specified as shown in the input forms in Fig. 2.

The results in Table 1 contrast the trial mixture proportions, the predicted chloride ion diffusion coefficients, and the predicted service lives for the two mixtures. The confidence limits for D for the conventional concrete are seen to be much wider than those for the high-performance concrete, due to the fact that the confidence limits naturally tend to widen away from the mean parameter values used in the computer experiment ($w/c = 0.45$, volume of aggregate = 67.5 percent, and degree of hydration = 0.6).

For the prediction of service life, in addition to the estimated diffusivity coefficients, the other values, as shown in Fig. 7, were taken from Example 1 (representative of a bridge deck in Kansas) in the report by Weyers et al.¹¹ The high-strength concrete, mainly due to its lower porosity, is seen to offer a service life that is over seven times as long as the conventional concrete. In this case, by doubling the compressive strength, we have achieved even a greater proportional increase in estimated service life.

For the ordinary strength mixture, the estimated chloride ion diffusivity, along with the mixture proportions, were input into the form for predicting the chloride ingress profile. An exposure consisting of 120 days at a concentration of 4 mol/L followed by 240 days at a concentration of 0.1 mol/L was se-

lected, with a total exposure time of 7200 days.

This is intended to model a 4-month winter period during which deicing salts are applied, followed by an 8-month period of relatively low external chloride ion concentrations. The parameters for chloride binding were based on those given in the paper by Sergi et al.,¹³ with C_3A and C_4AF mass fractions of 4 percent and 8 percent, respectively. The diffusivity coefficient for the top 5 mm (0.2 in.) of the concrete was selected to be double that of the value for the bulk concrete given in Table 1, based on the lower volume fraction of aggregates generally present in the surface layer. The resultant predicted profile after the 7200 days of exposure is given in Fig. 8. Due to the reactions with the aluminates and the binding of chlorides, the total chloride concentration is much higher than the free chloride levels. In this case, if the reinforcement was located at a depth of 50 mm (2 in.), substantial levels of free chloride (on the order of 0.5 mol/L) would be present at the reinforcement depth after 7200 days of exposure, consistent with the projected short service life given in Table 1 for a constant exposure condition.

Discussion

The previous example illustrates the potential of employing the prototype CIKS in the design process. A variety of different trial mixture proportions can be quickly evaluated with respect to their expected service life for chloride-ion induced corrosion, and also with respect to their susceptibility to thermal cracking via the projected adiabatic temperature rise. The diffusion

coefficients predicted by the computer models can be compared to those in the existing experimental results database.

The potential of utilizing the Internet and WWW for the dissemination of knowledge in the field of concrete technology appears very promising. As the technology advances, more individuals will have direct access to the Internet. Updating a CIKS, such as the prototype described here, becomes a much simpler task, as one no longer needs to worry about the distribution of a set of update diskettes or CD-ROMs, but need only change the information on the server machine. Thus, responses to user feedback can be greatly expedited.

User feedback for the present system would be most welcome; comments can be e-mailed to one of the authors by using (clicking on) the e-mail address provided at the bottom of the form welcoming new users to the CIKS. The multimedia nature of the WWW allows for the seamless integration of text, images, movies, and even sound into a single coherent system. This should allow for the development of online guides and tutorials.⁸

Planned research will focus on two major extensions to this prototype system. The first will deal with the development of an online system for assisting in the mixture proportioning optimization process and the second will focus on extending service life predictions to other degradation mechanisms, such as sulfate attack and leaching. In the latter case, the code previously developed for a computer program addressing a variety of mechanisms for modelling the degradation of underground low-level waste concrete vaults¹⁸ should be readily adaptable to the present CIKS system.

Acknowledgments

The authors would like to thank Clarissa Ferraris, Paul Stutzman, and Nick Carino of BFR/NIST for useful comments and suggestions concerning this prototype CIKS and Lisa Gill of CAML/NIST for assistance with the computation of confidence limits for the predicted chloride ion diffusion coefficients.

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⁸For an extensive compilation of images for engineering and science instruction, including a variety of laboratory procedures of importance in concrete technology, see the NSF SUCCEED Engineering Visual Database at URL <http://www.cc.vt.edu/evd>.

Table 1: Mixture proportions and properties for ordinary and high-strength concrete

28-day compressive strength MPa (psi)	24.1 (3500)	48.3 (7000)
w/c	0.62	0.31
Air content	1 percent	1.5 percent
Cement [kg/m ³ (lb/yd ³)]	272 (459)	597 (1006)
Water [kg/m ³ (lb/yd ³)]	167 (282)	185 (312)
Fine aggregate [kg/m ³ (lb/yd ³)]	874 (1473)	470 (792)
Coarse aggregate [kg/m ³ (lb/yd ³)]	1172 (1975)	1201 (2024)
D [10^{-12} m ² /s (in. ² /yr)]	7.0 (0.34)	0.9 (0.044)
90 percent confidence limits for D [10^{-12} m ² /s (in. ² /yr)]	[0.8, 60.0] (0.04, 2.9)	[0.6, 1.4] (0.03, 0.07)
Estimated service life	4 years	30 years

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Selected for reader interest by the editors.



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