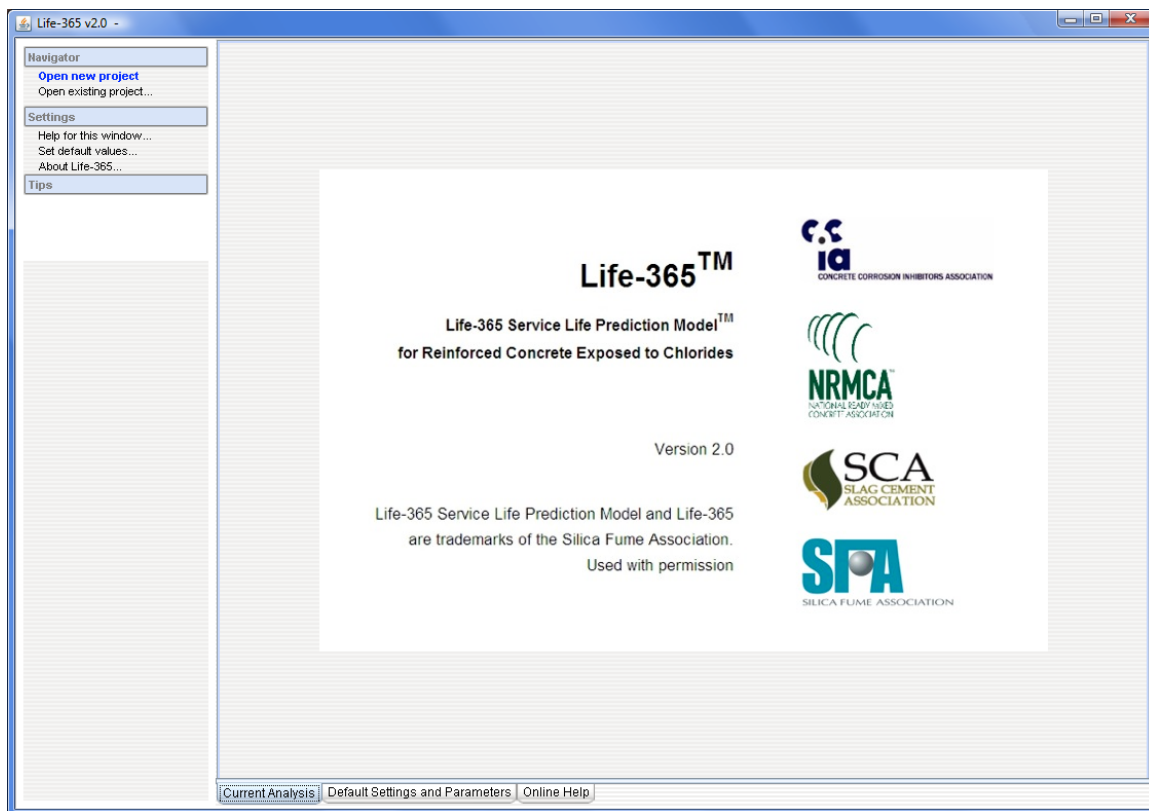


Life-365 Service Life Prediction Model™

**and Computer Program for Predicting the Service Life and
Life-Cycle Costs of Reinforced Concrete
Exposed to Chlorides**



January 8, 2008

Life-365™ Credits

The previous Life-365 v1.0 program and manual were written by E. C. Bentz and M. D. A. Thomas under contract to the Life-365 Consortium I, which consisted of W. R. Grace Construction Products, Master Builders, and the Silica Fume Association. The Life-365 v2.0 program and manual are adaptations of these, and were written by M. A. Ehlen under contract to the Life-365 Consortium II, which consists of the Concrete Corrosion Inhibitors Association, the National Ready Mix Concrete Association, the Slag Cement Association, and the Silica Fume Association.

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Life-365 Disclaimer

This Computer Program and accompanying Manual are intended for guidance in planning and designing concrete construction exposed to chlorides in service. These items are intended for the use of individuals who are competent to evaluate the significance and limitations of their content and recommendations and who will accept responsibility for the application of the material it contains. The members of the consortium responsible for the development of these materials shall not be liable for any loss or damage arising there from.

Performance data included in the Computer Program and the Manual are derived from publications in the concrete literature and from manufacturers' product literature. Specific products are referenced for informational purposes only.

Users are urged to thoroughly read this Manual to understand the capabilities and limitations of the Computer Program.

1 Introduction

The corrosion of embedded steel reinforcement in concrete due to the penetration of chlorides from deicing salts, groundwater or seawater is the most prevalent form of premature concrete deterioration worldwide and costs billions of dollars a year in terms of infrastructure repair and replacement. There are currently numerous strategies available for increasing the service life of reinforced structures exposed to chloride salts; these include the use of:

- low-permeability (high-performance) concrete,
- chemical corrosion inhibitors,
- protective coatings on steel reinforcement (e.g. epoxy-coated or galvanized steel),
- corrosion-resistant steel (e.g. stainless steel),
- non-ferrous reinforcement (e.g. fiber-reinforced plastics),
- waterproofing membranes or sealants applied to the exposed surface of the concrete,
- cathodic protection (applied at the time of construction), and
- combinations of the above.

Each of these strategies has different technical merits and costs associated with their use. Selecting the optimum strategy requires the means to weigh all associated costs against the potential extension to the life of the structure. Life-cycle cost analysis (LCCA) is being used more and more frequently for this purpose. LCCA uses estimated initial construction costs, protection costs, and future repair costs to compute the costs over the design life of the structure. Many concrete protection strategies may reduce future repair costs by reducing the extent of future repairs or by extending the time between repairs. Thus, even though the implementation of a protection strategy may increase initial costs, it may still reduce life-cycle costs.

A number of models for predicting the service life of concrete structures exposed to chloride environments or for estimating life-cycle costs of different corrosion protection strategies have been developed recently and some of these are available on a commercial basis. The approaches adopted by the different models vary considerably and consequently there can be significant variances between the solutions produced by individual models. This has caused some concern among the engineering community and in response to this, in May 1998 the Strategic Development Council (SDC) of the American Concrete Institute (ACI) identified the need to develop a “standard model” and recommended that a workshop be held to investigate potential solutions. In November 1998, such a workshop, entitled “Models for Predicting Service Life and Life-Cycle Cost of Steel-Reinforced Concrete”, was sponsored by the National Institute of Standards and Technology (NIST), ACI, and the American Society for Testing and Materials (ASTM). A detailed report of the workshop is available from NIST (Frohnsdorff, 1999). At this workshop a decision was made to attempt to develop a “standard model” under the

jurisdiction of the existing ACI Committee 365 “Service Life Prediction.” Such a model would be developed and maintained following the normal ACI protocol and consensus procedure for producing committee documents.

In order to expedite the process, a consortium was established under ACI’s SDC to fund the development of an initial life-cycle cost model based on the existing service life model developed at the University of Toronto (see Boddy et al., 1999). The funding members of this consortium, known as the Life-365 Consortium, were Master Builders Technologies, Grace Construction Products and the Silica Fume Association. Life-365 Version 1.0 was released in October 2000, and later revised as Version 1.1 in December 2001 to incorporate minor changes.

The current version has many limitations in that a number of assumptions or simplifications have been made to deal with some of the more complex phenomena or areas where there is insufficient knowledge to permit a more rigorous analysis. Users are encouraged to run various “user-defined scenarios” in tandem with the Life-365 prediction with minor adjustments to the values (e.g. D_{28} , m , C_b , C_s , t_p) selected by Life-365. This will aid in the development of an understanding of the roles of these parameters and the sensitivity of the solution to their values.

It is intended that Life-365 will eventually be handed over to ACI Committee 365 for review and possible adoption as an initial “standard” model, and that continued refinement and validation be carried out under the auspices of that committee.

This manual is divided into four parts:

Life-365 Model™ Description. This section provides a detailed explanation of how the model, Life-365, estimates the service life (time to cracking and first repair) and the life-cycle costs associated with different corrosion protection strategies. The mathematical equations and empirical relationships incorporated in the model are presented in this section.

Life-365 Users Manual. This section is an operator’s manual that gives instructions on how to use Life365 v2.0, the input parameters required, and the various options available to the user.

Background Information. This section presents published and other information to support the relationships and assumptions used in the model to calculate the service life and life-cycle costs. A discussion of the limitations of the current model is also presented.

Appendix A. This section provides recommended protocols for determining some of the input parameters used in Life-365.

2 Life-365 Model Description

The analyses carried out within Life-365 can be split into four separate steps:

- Predicting the time to the onset of corrosion, commonly called the initiation period, t_i ;
- Predicting the time for corrosion to reach an unacceptable level, commonly called the propagation period, t_p ; (Note that the time to first repair, t_r , is the sum of these two periods: i.e. $t_r = t_i + t_p$)
- Determining the repair schedule after first repair; and
- Estimating life-cycle costs based on the initial concrete (and other protection) costs and future repair costs.

2.1 Predicting the Initiation Period

The initiation period, t_i , defines the time it takes for sufficient chlorides to penetrate the concrete cover and accumulate in sufficient quantity at the depth of the embedded steel to initiate corrosion of the steel. Specifically, it represents the time taken for the critical threshold concentration of chlorides, C_c , to reach the depth of cover, x_d . Life-365 uses a simplified approach based on Fickian diffusion that requires only simple inputs from the user. It is intended that future versions of Life-365 will be capable of accounting for the combined effects of diffusion and convection, and also of chloride binding by the products of hydration. These capabilities have been implemented in more complex service life models (e.g., Boddy et al., 1999).

2.1.1 Predicting Chloride Ingress due to Diffusion

The model predicts the initiation period assuming diffusion to be the dominant mechanism. Fick's second law is the governing differential equation:

$$\frac{dC}{dt} = D \cdot \frac{d^2C}{dx^2}, \quad \text{Eqn. 1}$$

where C = chloride content,
 D = apparent diffusion coefficient,
 x = depth (from the exposed surface), and
 t = time.

The chloride diffusion coefficient is a function of both time and temperature, and Life-365 uses the following relationship to account for time-dependent changes in diffusion:

$$D(t) = D_{ref} \cdot \left(\frac{t_{ref}}{t} \right)^m, \quad \text{Eqn. 2}$$

where $D(t)$ = diffusion coefficient at time t ,
 D_{ref} = diffusion coefficient at time t_{ref} (= 28 days in Life-365), and
 m = constant (depending on mix proportions).

Life-365 selects values of D_{ref} and m based on the mix design details (i.e., water-cementitious material ratio, w/cm , and the type and proportion of cementitious materials) input by the user. In order to prevent the diffusion coefficient decreasing with time indefinitely, the relationship shown in Eqn. 2 is only valid up to 25 years. Beyond this time, the value at 25 years (D_{25}) calculated from Eqn. 2 is assumed to be constant throughout the rest of the analysis period.

Life-365 uses the following relationship to account for temperature-dependent changes in diffusion:

$$D(T) = D_{ref} \cdot \exp \left[\frac{U}{R} \cdot \left(\frac{1}{T_{ref}} - \frac{1}{T} \right) \right], \quad \text{Eqn. 3}$$

where $D(T)$ = diffusion coefficient at time t and temperature T ,
 D_{ref} = diffusion coefficient at time t_{ref} and temp. T_{ref} ,
 U = activation energy of the diffusion process (35000 J/mol),
 R = gas constant, and
 T = absolute temperature.

In the model, $t_{ref} = 28$ days and $T_{ref} = 293\text{K}$ (20°C). The temperature T of the concrete varies with time according to the geographic location selected by the user. If the required location cannot be found in model database, the user can input the necessary temperature data.

The chloride exposure conditions (e.g., rate of chloride build up at the surface and maximum chloride content) are selected by the model based on the type of structure (e.g., bridge deck, parking structure), the type of exposure (e.g., to marine or deicing salts) and the geographic location. Alternatively, the user can input data for these parameters.

The solution is carried out using a finite difference implementation of Fick's second law (Eqn. 1) where the value of D is modified at every time step using Eqns. 2 and 3.

2.1.2 Input Parameters for Predicting the Initiation Period

The following general user inputs are required for each project:

- Geographic location;
- Type of structure and nature of exposure;
- Depth of clear concrete cover to the reinforcing steel (x_d), and

- Details of each protection strategy scenario such as water-cement ratio, type and quantity of mineral admixtures or corrosion inhibitors, type of steel and coatings, presence of membranes or sealers.

From these input parameters the model selects the necessary coefficients for calculating the time to corrosion, as detailed above.

Surface Chloride Build Up

The model determines a maximum surface chloride concentration, C_s , and the time taken to reach that maximum, t_{max} , based on the type of structure, its geographic location, and exposure as selected by the user. For example, if the user selected a bridge deck in an urban area of Moline, Illinois, the model would use the surface concentration profile shown in Figure 1. Alternatively, the user can input the maximum.

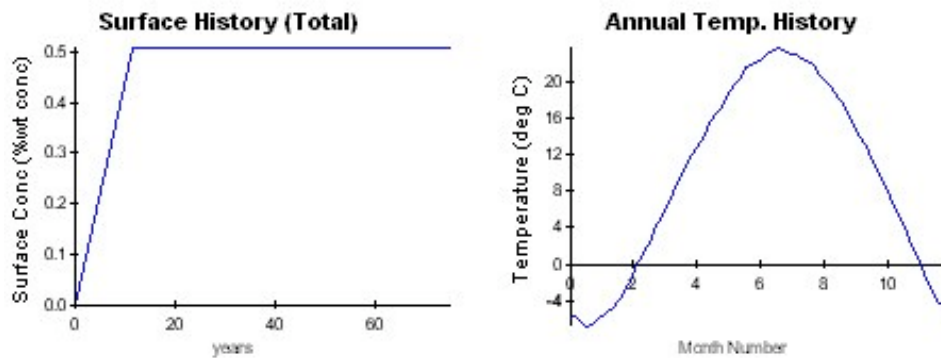


Figure 1. Examples of Concrete Surface History and Environmental Temperatures

Temperature Profile

The model determines yearly temperature profiles based on the user's input for geographical location using a database compiled from meteorological data. For example, if the user selected Moline, Illinois, the model would use the temperature profile and make the necessary adjustments to the diffusion coefficient using Eqn. 3. Alternatively the temperature profile can be defined by the user.

Base Case Concrete Mix

The base case concrete mix assumed by the model is plain Portland cement concrete with no special corrosion protection applied. For the base case, the following values are assumed:

$$\begin{aligned} D_{28} &= 1 \times 10^{(-12.06 + 2.40w/c)} \text{ m}^2/\text{s}, \\ m &= 0.20, \text{ and} \\ C_t &= 0.05\% \text{ (by mass of concrete).} \end{aligned}$$

The relationship between D_{28} and the water-cementitious materials ratio (w/c) is based on a large database of bulk diffusion tests. The nature of the relationship is shown opposite (corrected to 20°C). The value of m is based on data from the University of Toronto and other published data, and the value of C_t is commonly used for service-life prediction purposes (and is close to a value of 0.40% chloride based on the mass of cementitious materials for a typical structural concrete mix).

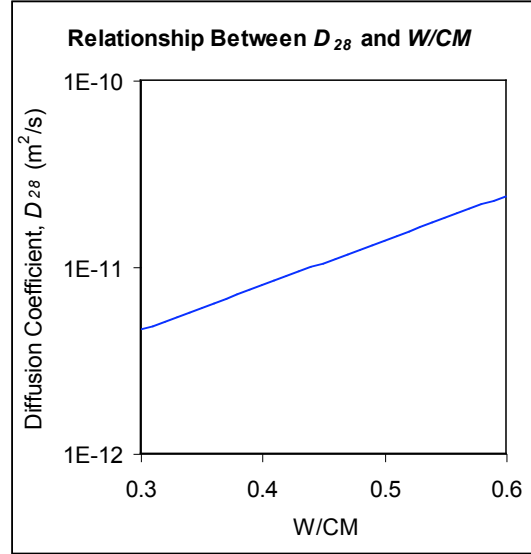


Figure 2. Relationship Between D_{28} and w/c

It should be noted that these relationships pertain to concrete produced with aggregates of normal density and may not be appropriate for lightweight concrete.

Effect of Silica Fume

The addition of silica fume is known to produce significant reductions in the permeability and diffusivity of concrete. Life-365 applies a reduction factor to the value calculated for Portland cement, D_{PC} , based on the level of silica fume ($\%SF$) in the concrete. The following relationship, which is again based on bulk diffusion data, is used:

$$D_{SF} = D_{PC} \cdot e^{-0.165 \cdot SF}$$

The relationship is only valid up to replacement levels of 15% silica fume. The model will not compute diffusion values (or make service life predictions) for higher levels of silica fume.

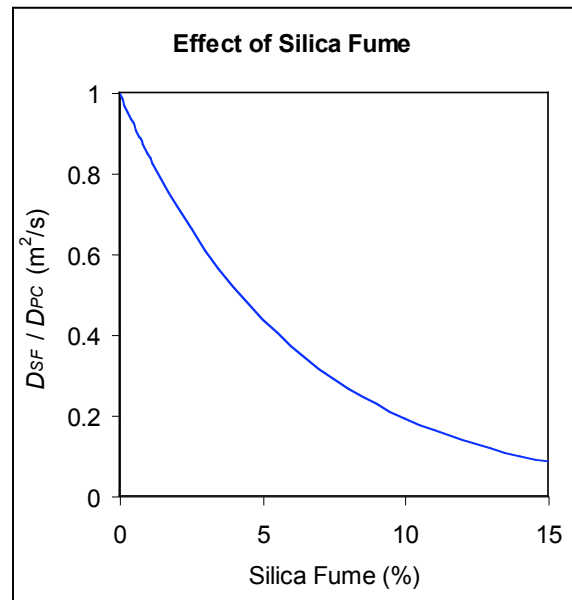


Figure 3. Effect of Silica Fume on D_{SF}

Life-365 assumes that silica fume has no effect on either C_t or m .

Effect of Fly Ash and Slag

Neither fly ash nor slag are assumed to effect the early-age diffusion coefficient, D_{28} , or the chloride threshold, C_t . However, both materials impact the rate of reduction in diffusivity and hence the value of m . The following equation is used to modify m based on the level of fly ash (%FA) or slag (%SG) in the mix:

$$m = 0.2 + 0.4(\%FA/50 + \%SG/70).$$

The relationship is only valid up to replacement levels of 50% fly ash or 70% slag, and thus $m \leq 0.60$. The model will not compute diffusion values (or make service life predictions) for higher levels of these materials.

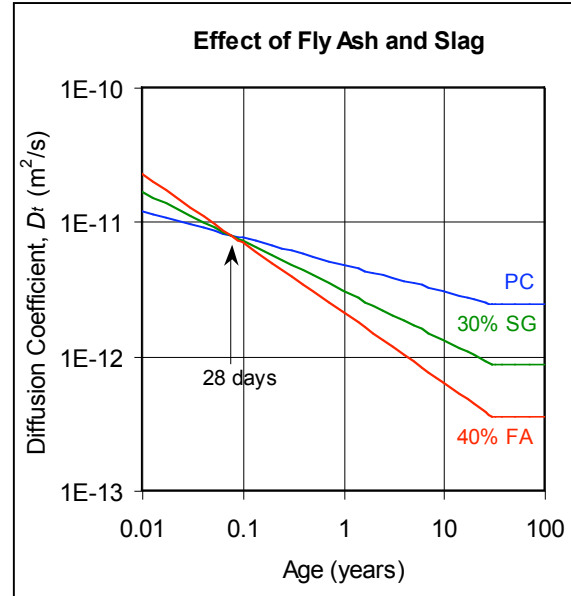


Figure 4 shows the effect of m for three mixes with $w/cm = 0.40$ and with (i) plain Portland cement (PC), (ii) 30% slag, and (iii) 40% fly ash. These mix proportions yield the coefficients listed in Table 1.

Table 1. Effects of Slag and Fly Ash on Diffusion Coefficients

	m	D_{28}	D_{10y}	D_{25y}
	(≤ 0.60)	($\times 10^{-13} \text{ m}^2/\text{s}$)	($\times 10^{-13} \text{ m}^2/\text{s}$)	($\times 10^{-13} \text{ m}^2/\text{s}$)
PC	0.20	79	30	25
30% SG	0.37	79	13	9.3
40% FA	0.52	79	6.3	3.9

Effect of Corrosion Inhibitors

The model accounts for two chemical corrosion inhibitors with documented performance: calcium nitrite inhibitor (CNI) and Rheocrete 222+ (a proprietary product from Master Builders; in the Life-365 software, it is referred to as “A&E,” for “amines and esters”). It is intended that more inhibitors be included when appropriate documentation of their performance becomes available.

Five dosage levels of 30% solution calcium nitrite are permitted in Life-365. The inclusion of CNI is assumed to have no effect on the diffusion coefficient, D_{28} , or the diffusion decay coefficient, m . The effect of CNI on the chloride threshold, C_t , varies with dose as shown in the following table.

Table 2. Effects of CNI on Threshold

CNI Dose		Threshold, C_t (% wt. conc.)
litres/m ³	gal/cy	
0	0	0.05
10	2	0.15
15	3	0.24
20	4	0.32
25	5	0.37
30	6	0.40

A single dose of Rheocrete 222+ (or amines and esters, as it is referred to in the software) is permitted in the model; the dose is 5 litres/m³ concrete. This dose of the admixture is assumed to modify the corrosion threshold to $C_t = 0.12\%$ (by mass of concrete). Furthermore, it is also assumed that the initial diffusion coefficient is reduced to 90% of the value predicted for the concrete without the admixture and that the rate of chloride build up at the surface is decreased by half (in other words it takes twice as long for C_s to reach its maximum value). These modifications are made to take account of the pore modifications induced by Rheocrete 222+ (or amines and esters), which tend to reduce capillary effects (i.e. sorptivity) and diffusivity.

Effect of Membranes and Sealers

Membranes and sealers are dealt with in a simplified manner: it is assumed that both membranes and sealers only impact the rate of chloride build-up. Membranes start with an efficiency of 100%, which deteriorates over the lifetime of the membrane; the default lifetime is 20 years. This means that the rate of build-up starts at zero and increases linearly to the same rate as that for an unprotected concrete at 20 years. In the example shown in Figure 5, the surface chloride for unprotected concrete increases at a rate of 0.04% per annum and reaches a maximum concentration of 0.60% at 15 years. Both the initial efficiency and the lifetime of the membrane can be changed by the user. Also the membrane can be reapplied at regular intervals in the same manner as sealers (described below).

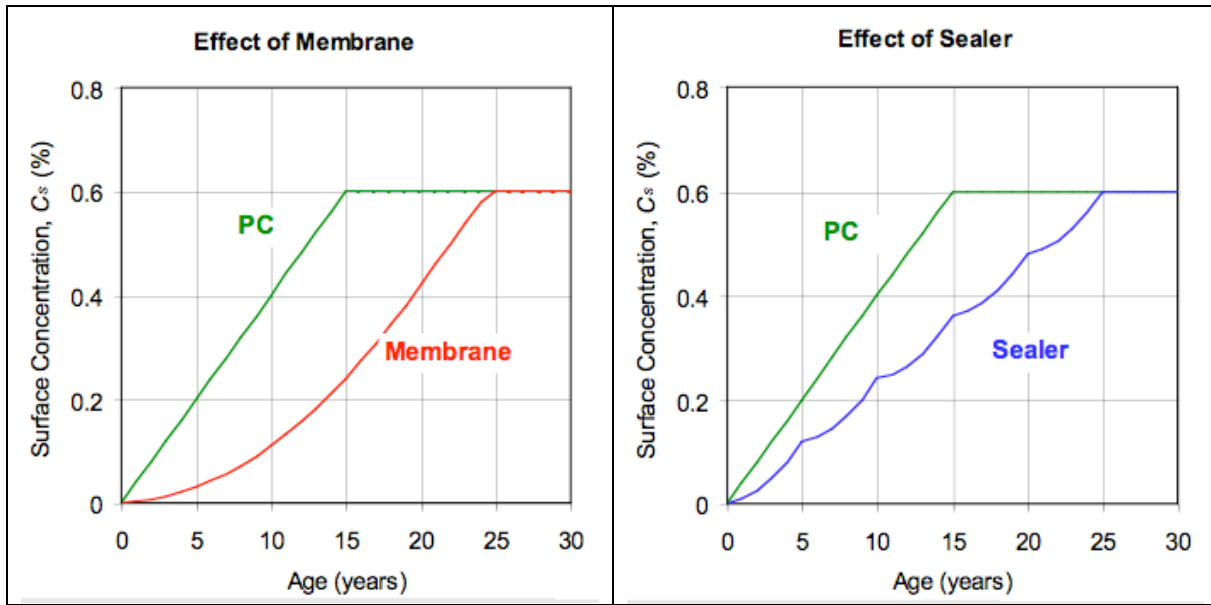


Figure 5. Effects of Membranes and Sealers

Sealers are dealt with in the same way, except that the default lifetime is only 5 years. The example in Figure 5 shows the effect of reapplying the sealer every 5 years. Each time the sealer is applied, the build-up rate is reset to zero and then allowed to build up back to the unprotected rate (0.04% per annum in the example) at the selected lifetime of the sealer (5 years in the example). Membranes and sealers can only be reapplied up to the time of the first repair.

Effect of Epoxy-Coated Steel

The presence of epoxy-coated steel does not affect the rate of chloride ingress in concrete, nor would it be expected to impact the chloride threshold of the steel at areas where the steel is unprotected. Consequently, the use of epoxy-coated steel does not influence the initiation period, t_i . However, it is assumed in the model that the rate of damage build up is lower when epoxy-coated steel is present and these effects are dealt with by modifying the propagation period, t_p (see below).

Effect of Stainless Steel

In the current version of Life-365 it is assumed that grade 316 stainless steel has a corrosion threshold of $C_t = 0.50\%$ (i.e., ten times black steel).

2.1.3 Solution Procedure

The Life-365 Computer Program uses a finite difference implementation of Fick's Second Law, the general advection-dispersion equation. Implicit in the model are the following assumptions:

- The material under consideration is homogeneous (e.g. no surface effects);

- The surface concentration is constant around the concrete member at any given time;
- The properties of the elements are constant during each time step, calculated at the start of each time step; and
- The diffusion constant is uniform over the depth of the element.

2.2 Predicting the Propagation Period

The propagation period, t_p , is fixed at 6 years. In other words, the time to repair, t_r , is simply given by $t_r = t_i + 6$ years. The only protection strategy that influences the duration of the propagation period is the use of epoxy-coated steel, which increases the period to $t_p = 20$ years. The propagation period can be changed by the user.

2.3 Repair Schedule

The time to the first repair, t_r , is predicted by Life-365 from a consideration of the properties of the concrete, the nature of any corrosion protection strategy and details of the environmental exposure. The cost and extent of this first repair (i.e., the percentage of area to be repaired) and the cost, extent, and schedule of future repairs are estimated by the user.

2.4 Probabilistic Predictions of Initiation Period

Life-365 includes probabilistic calculations using the method explained in a recent paper (Bentz 2003); see the paper for details. This method applies the following steps:

- Estimate time to first corrosion for average values of all input.
- For each of the five input variables of relevance (D_{ref} , C_s , m , C_i , x_d), perform five additional deterministic calculations with each of the variable sequentially adjusted by 10%.
- From the results of step b) compared to the result from step a), estimate the derivative of corrosion initiation time with respect to each of the five variables. This determines the sensitivity of the results to variations in each of the input variables.
- Use the results from step c) to estimate the single parameter of variability, similar to a standard deviation, for the log-normal assumed variation of time to corrosion initiation. Thus the distribution of time to first corrosion is assumed to follow a log-normal distribution, shown by Bentz to work well. The average value of this distribution is taken from the deterministic analysis in step a). The variability of this assumed distribution is determined from the results of steps b) and c).

2.5 Estimating Life-Cycle Costs

Price Information

The user is responsible for providing the following cost information to be used in the life cycle cost analysis:

- Cost of concrete mixes (including corrosion inhibitors) for the various strategies under consideration,
- Cost of repairs,
- Inflation rate, i , and
- Real discount rate, r .

Life-365 provides the following default costs for various rebar protection strategies:

- Black steel = \$1.00/kg (\$0.45/lb)
- Epoxy-coated rebar = \$1.33/kg (\$0.60/lb)
- Stainless steel = \$6.60/kg (\$2.99/lb)

The costs of these materials can be changed by the user.

2.6 Calculating Life-Cycle Costs

Present Worth Calculations

The total life-cycle costs are calculated as the sum of the initial construction costs and the discounted future repair costs over the life of the structure.

The initial construction costs are simply the cost of the concrete + the cost of the steel (or other reinforcement) plus the cost of any surface protection (membrane or sealer). These costs are expressed on the basis of a unit area of the structure (e.g. \$/m²).

Future repair costs are calculated on a “present worth” basis using the inflation rate, i , and the real discount rate, r , both provided by the user. The present worth, PW , of a future cost c (\$/m²) at time t (years) is given by the formula:

$$PW = c \left(\frac{1+i}{1+r} \right)^t \quad \text{Eqn. 4}$$

All the predicted future repair costs over the entire design life of the structure are calculated in this manner and added to the initial construction costs to give the total life-cycle costs.

3 Life-365 Users Manual

The concrete service life and life-cycle costing methodologies described in Chapter 2 are implemented in the Life-365 computer program in a way that allows for easy input of the environmental, concrete, and economic parameters, and for rapid sensitivity analysis of the parameters that most influence concrete service life and life-cycle cost. This chapter first describes the basic characteristics of approach and the software, and then describes optional additional features designed for experienced practitioners.

3.1 Installing Life-365 v2.0

Life-365 runs on personal computers, including those running Microsoft Windows, Apple OS X, and Linux. It requires Java 1.5 (or higher), which comes preinstalled with current versions of Windows and Mac OS X, or can be installed from the Java website.¹ To install Life-365 itself:

- **From the Life-365 CD:** In Windows, select “InstallWindows.bat”; on other operating systems, select “InstallNonWindows.jar.”
- **From the Life-365 installation zip file:** download and then unzip the file on your desktop, enter the folder of contents, and then make the Windows or non-Windows selection you would above.

3.2 Starting Life-365

Installing Life-365 puts a start menu item, “Life-365,” in your Windows Programs folder (accessible from the Start button in the lower left-hand corner of your screen); it will typically also put an icon on your desktop. (Other platforms such as Apple OS X may not, depending on your Java settings). To start Life-365, simply select this menu item or the desktop icon.

When Life-365 starts, your screen should look like Figure 6. This screen has two components. On the left-hand side there is a navigation menu that, under the **Navigator** section, lets you open new or existing Life-365 project files; under the **Settings** section, lets you change the default settings and get help with particular screens; and under the **Tips** section, displays text that gives you information and tips on using the software.

¹ Java 1.5 is produced by Sun Microsystems, Inc., and can be installed by downloading from <http://java.sun.com/javase/downloads/index.jsp> (accessed September 18, 2007).

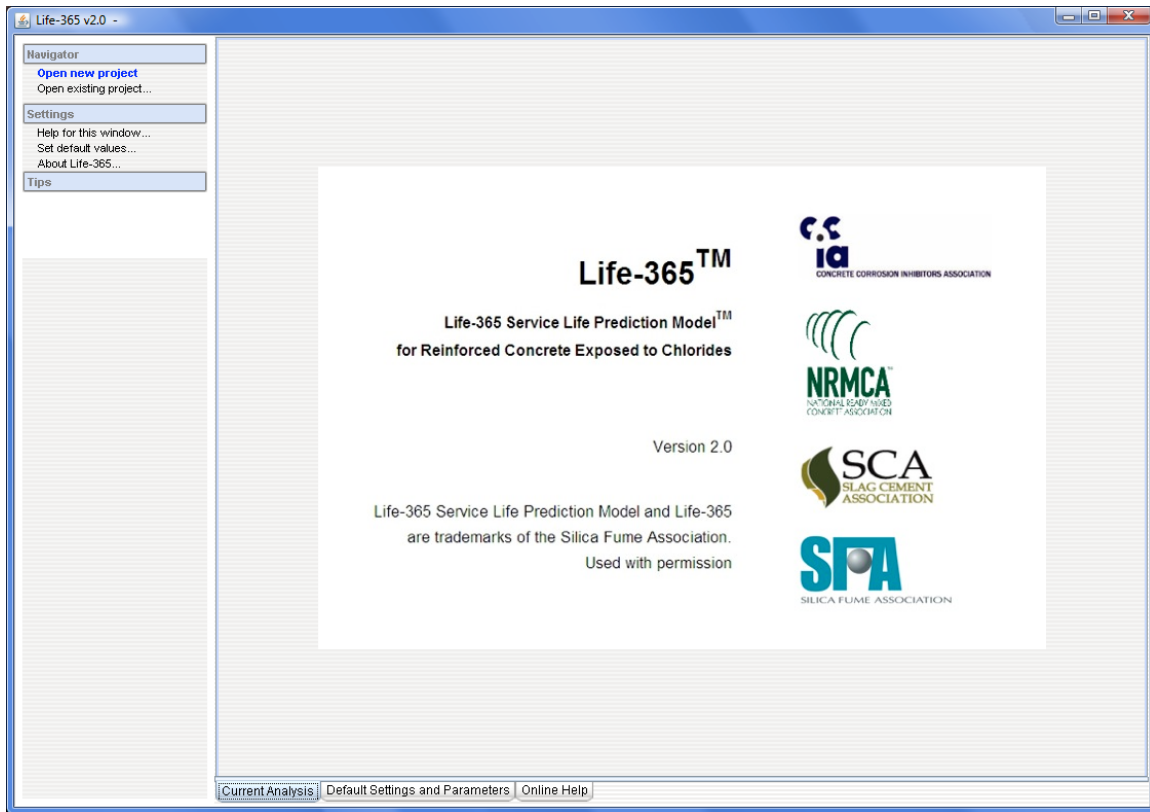


Figure 6. Startup Screen

There are also three tabs at the bottom of the screen:

1. The **Current Analysis** tab, which displays the current project on which you are working (on startup, this tab shows the opening banner in Figure 6);
2. The **Default Settings and Parameters** tab, which allows you to set the default values of parameters to be used in all projects (see Section 3.9.1, p. 34); and
3. The **Online Help** tab, which contains explanations for the key windows and features of Life-365.

To start a new project, select **Open new project** from the left-hand-side navigation menu; a complete project will be created for you, with two alternatives, each of which has a simple concrete mix. To open a previously created and saved project, select **Open existing project...**

When a new or existing project is opened, the main panel will show seven tabs at the top. To conduct an analysis, each tab can and should be accessed from left-most tab, **Project**, to right-most tab, **LCC Report**. (Additionally, the left-hand **Navigator** pane now

has a list of chronological **Steps**, e.g., **Define project...**, which helps direct you to specific tasks.). Each of the main tabs is discussed in turn.

3.3 Project Tab

The **Project** tab is the first of four tabs used to create the project, its alternatives, concrete mixes, and costs. This tab allows you to name the project and set the type and dimensions of the structure, the economic analysis parameters, and the number and names of the alternative projects (Figure 7).

The screenshot shows the 'Life-365 v2.0 - Example Project.life - New Project' window. The 'Project' tab is active, showing the 'Identify Project' section with fields for Title (New Project), Description (Default settings for a new project), Analyst (Analyst), and Date (12/15/2007). The 'Select Structure Type and Dimensions' section includes a dropdown for Type of structure (slabs and walls (1-D)), input fields for Thickness (200.00 mm), Reinf. depth (60.00 mm), Area (10000 square m), and Volume of concrete (2,000 cub. met.). A diagram of a slab and walls is shown with dimensions 200.00 mm and 60.00 mm. The 'Define Economic Parameters' section includes input fields for Base year (2008), Analysis period (75 yrs), Inflation rate (1.60%), and Real discount rate (3.00%). The 'Define Alternatives (up to 6)' section includes a table with columns for Name and Description.

Name (double-click to edit)	Description (double-click to edit)
Base case	A project that uses the normal mix of concrete
Alternative 1	A project that uses the a new mix of concrete

Figure 7. Project Tab

Identify Project

In this section you can set the **Title**, **Description**, **Analyst**, and **Date** of the project, most of which are used primarily to document the project file, but also are part of the summary report that is displayed and printed from the **LCC Report** tab.

Select Structure Type and Dimensions

In this section you set a number of fundamental parameters about the structure itself. Use the Type of structure drop-down box to select the structure, and most importantly, the primary means of chloride ingress, e.g., 1-D (one dimensional). (Use the Base unit drop-down box in the Default Settings and Parameters tab at the bottom of the Life-365

window to set whether all structural and concrete dimensions are measured in **SI metric**, **US units**, or **Centimeter metric**.)

Use the **Thickness** (for 1-D structures; or **Width** for 2-D structures) and **Area** fields to set the total volume of concrete, which is used to calculate total concrete installation costs, and to set the surface area of the concrete structure, which is used to calculate repair costs. Use the **Reinf. depth** field to set the distance over which chlorides travel from surface to the steel reinforcing, thereby determining concrete service life.

Finally, use the **Chloride concentration units** drop-down box to set the units of measure of the chloride exposure and concrete materials; if you select **SI metric** or **Centimeter metric** as your **Base unit**, then your **Concentration units** options are **% wt. conc.** and **kg/cub. m.**; if you select **US units**, then your options are **% wt. conc.** and **lb/cub yd.**

Define Economic Parameters

The four parameters in this section are used to set the period and interest rates over which life-cycle costs are computed. Set the **Base year** to be the current year or another year relevant to your analysis. Set the **Analysis period** to be the period of time over which life-cycle costs should be calculated; 75 years is a common period; some analysts select up to 150 years.

The **Inflation rate (%)** is the annual rate at which the prices of goods and services will increase over the future. The **Real discount rate (%)** is the annual rate at which future costs are discounted to base-year dollars, net of the rate of inflation (that is, it is the *real discount rate*, which does not include the effects of changes in the prices of goods and services). Federal infrastructure projects use a discount rate published in OMB Circular No. A-94. Life-365 v2.0 comes with the most recent figures of inflation and discount rate, as suggested by the OMB Circular and as published in *Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis* (2006).²

Define Alternatives

Use this section to set the number of alternatives will be analyzed and compared, and to set their names; use the **Add a new alt** and **Delete currently selected alt** buttons to set the number of alternatives, double-click the mouse on the alternative in the **Name** field to set the name, and double-click the mouse in the **Description** field to set a description.

3.4 Exposure Tab

The **Exposure** tab (Figure 8) is used to set the exposure of the concrete to external chlorides, and to set the monthly temperatures to which the concrete is exposed.

² See: Rushing, Amy S., and Fuller, Sieglinde K., *Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis*, NISTIR 85-3273-18. Gaithersburg, MD: National Institute of Standards and Technology, April 2006. At the time of this publication, long-run general inflation was estimated at 1.6 percent and the long-run real discount rate at 3.0 percent. Private sector projects, however, can use their own rates of inflation and discount.

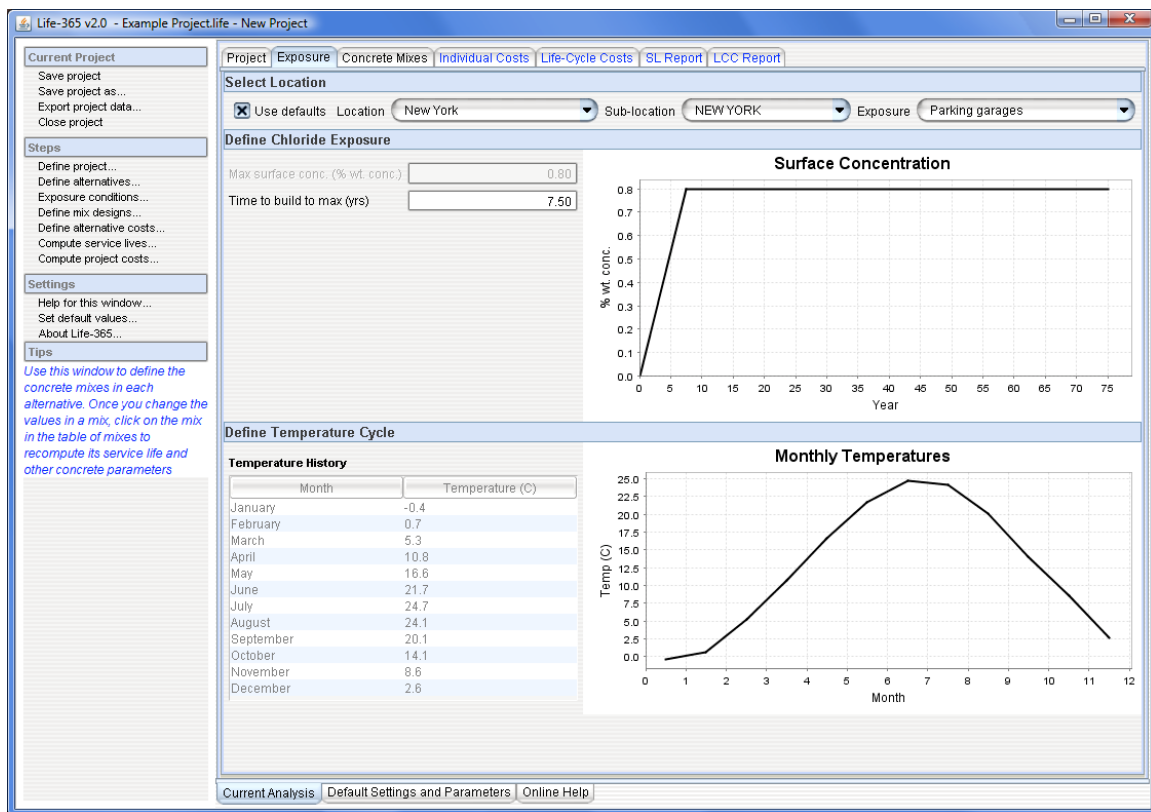


Figure 8. Exposure Tab

Select Location

When the **Use defaults** box is checked, you can select a **Location**, **Sub-location**, and **Exposure** that closely matches the conditions of your project, and Life-365 will use its database of locations to estimate the **Max surface conc.** of chlorides in the upper panel and the **Temperature History** in the lower panel. Life-365 also suggests values for **Time to build to max (yrs)**. When the **Use defaults** button is not checked, then the user must manually input the concentration and temperature values.

Define Chloride Exposure

The initial onset, rate of buildup, and maximum level of external chloride concentrations affect the rate of chloride ingress and ultimately concrete service life. Use the following variables to set these rates, and confirm them with the **Surface Concentration** graph on the right.

Max surface conc. – the maximum level of chloride buildup that the concrete structure will experience over its lifetime, measured either in % wt. conc. or base unit-specific units, i.e., either kg/cub. m. (SI metric) or lb/cub yd (US units).

Time to build to max (yrs) – the number of years for the buildup to reach its maximum level. It is assumed that the buildup is zero at the beginning of the structure’s life and that it increases linearly.

Define Temperature Cycle

When the **Use defaults** box is not checked, the user needs to input the annual temperature cycle to which your project is exposed. These temperatures are part of the service life calculations that determine the effects of temperature on concrete diffusivity. If the user selected either **SI metric** or **Centimeter metric** as the **Base unit** in the **Project** tab, then the temperatures must be input in degrees Celsius; if the user selected **US units** as the base unit, then temperatures must be input in degrees Fahrenheit.

3.5 Concrete Mixes

The **Concrete Mixes** tab (Figure 9) is used to define the concrete mixes for each project alternative defined in the **Project** tab.

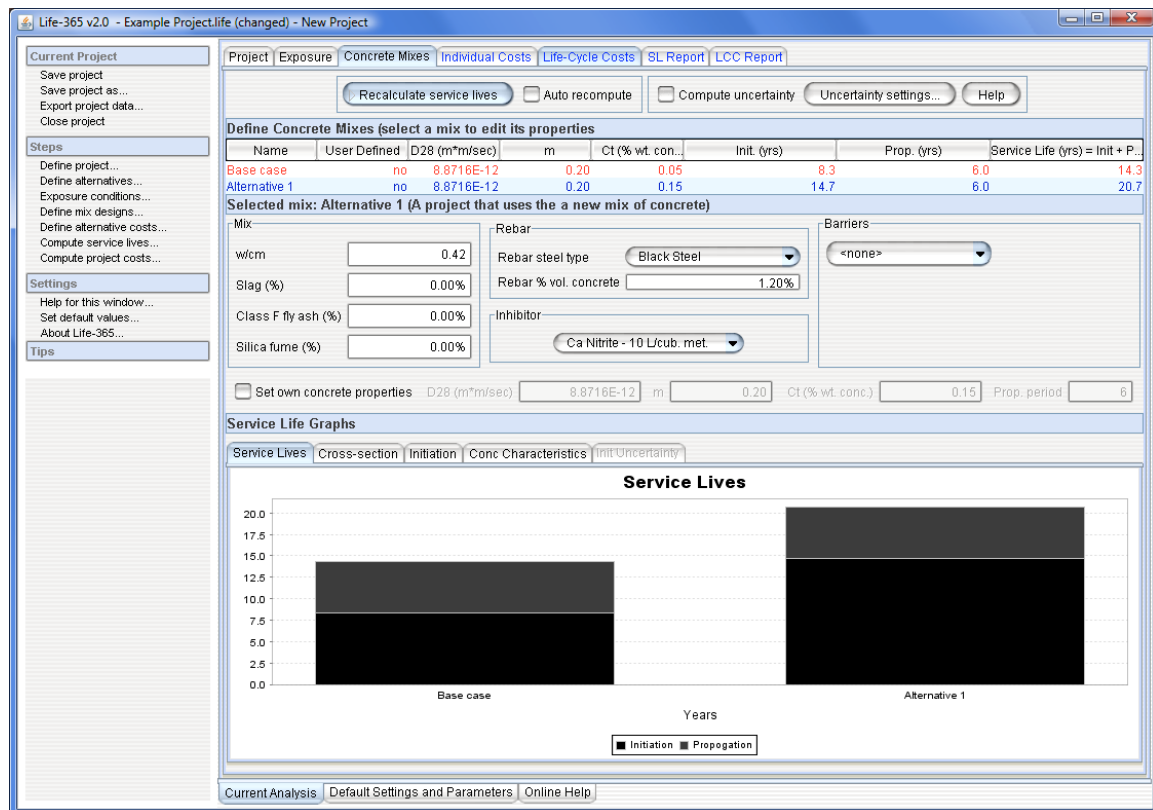


Figure 9. Concrete Mixes Tab

Define Concrete Mixes

This section allows the user set several computation settings and to view the number and details each mix design. Because the calculation of concrete service life is computationally expensive, you need to press the **Recalculate service lives** button to make these calculations after any changes to the concrete mixes (or you can check the **Auto recompute** button and have Life-365 automatically recalculate service lives each time you make a change to a mix.)

Check-mark the **Compute uncertainty** box if you want Life-365 to compute the uncertainty of service life for each concrete mix. In general, this is a computationally expensive calculation and reserved for advanced users of Life-365; see Section 3.10 for details on how to use service life uncertainty in your analysis. For now, leave this box unchecked.

Selected mix

This section lists the mix properties of the concrete mix selected in the upper, **Define Concrete Mixes**, panel, and allows you to edit these properties. To see the mix properties of any one of your concrete mixes, simply click the row of the mix in this upper panel.

Mix group – use this section to set the water-cementitious ratio (**w/cm**) of your concrete mix, and whether and to what level you are using **Slag**, **Class F fly ash**, or **Silica fume** in your mix. If the **Chloride concentration units** in the **Project** tab are set to **% wt. conc.**, then these materials will be entered in **%** terms, otherwise they will be measured in **kg/cub. m.** or **lb/cub. yd**, depending on your **Base unit** selection in the **Project** tab.

Rebar & Inhibitors group – use this section to select the type of reinforcing steel used in your structure (**Black steel**, **Epoxy coated**, or **316 Stainless**, which affects the initiation period and propagation period of the concrete service life). The **Rebar % vol. concrete** field is used to input the percent of the concrete that is steel; this is used to calculate the cost of steel in your concrete structure (the costs of the steels are set in the **Individual Costs** tab, under the **Default Concrete and Repair Costs** tab). Use the **Inhibitor** drop-down to include in your mix any corrosion inhibitors you have specified. The units of measure of these inhibitors are either **l/cub. m.** (liters per cubic meter) or **gal/cub. yd** (gallons per cubic yard), depending on the **Base unit** selected in the **Project** tab.

Barriers group – use this section to specify a membrane or sealant for your concrete. If the **Use defaults** box is checked, then you simply select the default membrane or sealant you want; if not checked, then you must specify the values of **Initial efficiency (%)**, **Age at failure (yrs)**, and **# times reapplied**.

Service Life Graphs

The **Service Life Graphs** section contains a series of graphs that illustrate the performance of the concrete, by time and by the dimensions of the concrete.

Service Lives. The Service Lives tab (Figure 10) shows the service life of each alternative mix design as well as the component initiation period and propagation period.



Figure 10. Service Lives Tab

Cross-section. The cross-section tab (Figure 11) shows a cross-section of the chloride concentration of the concrete mix at the point of initiation. The mix shown is selected from the left-hand-side **Select:** drop-down box.

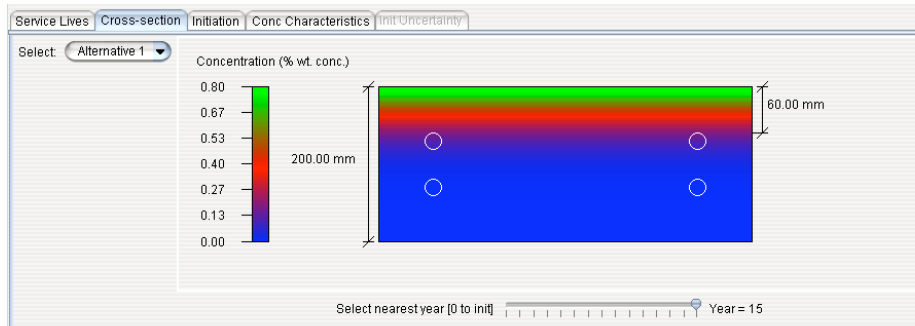


Figure 11. Cross-section Tab

The chloride concentration scale on the left hand side indicates the meaning of the colors in the right hand graph. The top of the white rebar “holes” should indicate the level of chloride concentration at initiation, which in this graph is approximately 0.05% wt of concrete.

Initiation. This tab (Figure 12) shows two graphs, by alternative: the concentration of chlorides at the time of initiation, by depth of the structure (the left graph, **Conc Versus Depth**); and the concentration of chlorides at the rebar depth, by point in time, up to initiation (the right graph, **Conc Versus Time at Depth**). The left graph

includes a vertical dashed line indicating the depth of reinforcing, and the right graph a dashed line indicating the year of initiation.

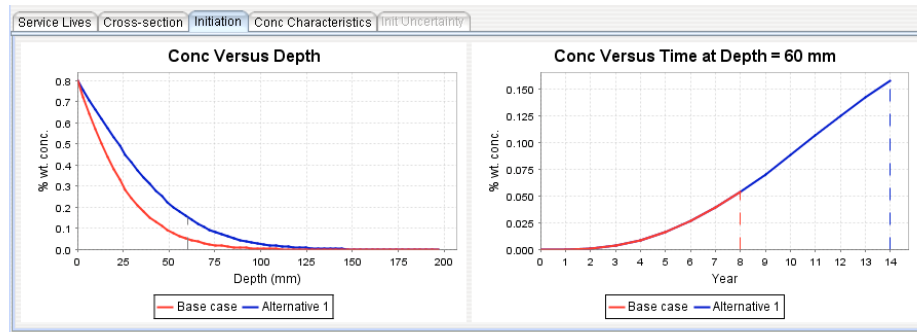


Figure 12. Concrete Initiation Graphs

For this particular figure, the left graph shows that the “Alternative 1” mix (indicated by the blue line) has a lower concentration of chlorides at the rebar depth (and everywhere else) than the “Base case” mix; this is due to that fact that the Alternative 1 mix includes inhibitors which increase the critical level of chloride concentration necessary to cause initiation of corrosion.

The right graph shows that the Base case mix hits initiation in about 8 years at a rebar chloride concentration of about 0.05% weight of concrete, while the Alternative 1 mix hits initiation in about 14 years with a rebar concentration of 0.15% weight of concrete. Together, these graphs show that the Alternative 1 mix has a higher service life due to a higher tolerance of chlorides at the rebar.

Concrete Characteristics. Finally, the **Conc Characteristics** tab (Figure 13) displays two additional graphs that help interpret the performance of the concrete mixes. The left-hand-side graph, **Diffusivity Versus Time**, shows how the calculated concrete chloride diffusivity changes over the initiation periods, by mix. The right-hand-side graph, **Surface Concentration Versus Time**, shows how the concrete surface conditions change over the same period.

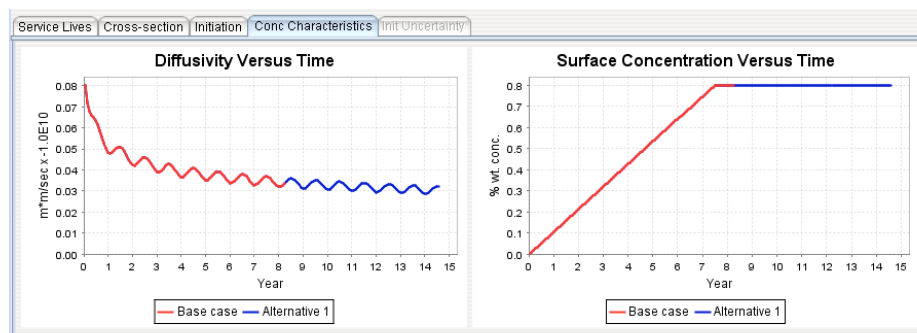


Figure 13. Concrete Characteristics Tab

For this particular graph, the left-hand graph indicates that both mixes have the same chloride diffusivity characteristics (the two mixes could potentially have very different characteristics and thus lines in this graph); the oscillations are caused by the effect of annual temperature variation. The right-hand graph shows that both mixes have the same surface concentrations; this would not be true if the mixes had membrane or sealant applications.

3.6 Individual Costs

The **Individual Costs** tab (Figure 14) allows you to edit the different constituent concrete costs, and view the effects they have on the constituent costs that make up life-cycle cost.

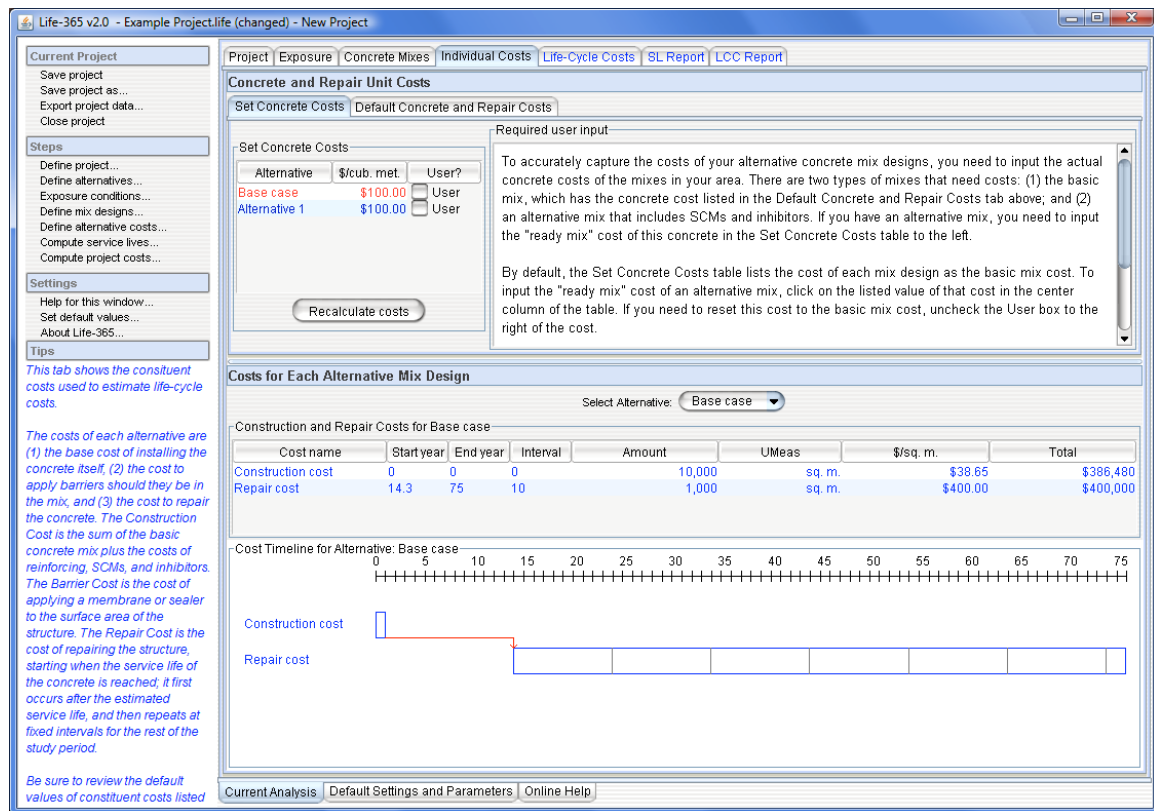


Figure 14. Individual Costs Tab

The screenshot shows the 'Default Concrete and Repair Costs' tab. It is organized into three main sections:

- Concrete & Steel:**
 - Concrete (\$/cub. met.): \$100.00
 - Black stl (\$/kg): \$1.00
 - Epoxy-coated stl (\$/kg): \$1.33
 - Stainless stl (\$/kg): \$6.60
- Barriers & Inhib.:**
 - Memb. (\$/sq. m.): \$33.00
 - Sealer (\$/sq. m.): \$7.00
 - Inhibitor (\$/L): \$1.50
- Repairs:**
 - Repair (\$/sq. m.): \$400.00
 - Area to repair (%): 10.0%
 - Fixed repair interval (yrs): 10

A 'Set as defaults' button is located at the bottom center.

Figure 15. Default Concrete and Repair Costs

Set Concrete Costs

In the upper-left corner of the screen, the **Set Concrete Costs** tab allows the user to set specific values for the concrete mix costs. Because there are many factors that affect this cost, including the inclusion of SCMs (e.g., slag), the user must set the appropriate values.

Default Concrete and Repair Costs

This section (Figure 15) lists the costs of the three main categories of concrete mix costs: **Concrete & Steel**, **Barriers & Inhib.**, and **Repairs**. When you first start your project, Life-365 uses the default values of these costs listed in the **Default Settings and Parameters** tab at the bottom of the Life-365 screen. (These are converted, when necessary, from the units of measure listed in this tab to the units used in your project. If you save your project and access it later, it will list again your project values of cost.) If you would like to make the values currently shown in this project to be the default values for all future projects, press the **Set as defaults** button.

Costs for Each Alternative Mix Design

Based on these costs, the **Costs for Each Alternative Mix Design** section lists up to three costs: (1) the “Construction cost,” or the cost of mixing/placing the concrete; (2) the “Barrier cost,” or the cost of applying a membrane or sealer; and (3) the “Repair cost,” or the cost of repairing the concrete over the study period. Use the **Select Alternative:** drop-down box to select which alternative you want to view in this panel, as well as in the **Cost Time-line for Alternative:** graph below.

Cost Timeline

This section shows a time-line of the two costs. The graph in Figure 14 shows in particular the base concrete cost occurring between year 0 and year 1, and then the concrete repair costs starting 14 years after construction (and because of it, as indicated by the red arrow) and continuing every 10 years (as indicated by the vertical gray lines within the white box) until year 75. Use the **Select Alternative** drop-down box above to switch back and forth between mixes and thus see the effects of the mixes on concrete repair schedules.

3.7 Life-Cycle Costs

Once the general, environmental, concrete mix, and individual costs have been entered, the resulting life-cycle costs of the alternative mixes can be compared in the **Life-Cycle Costs** tab (Figure 16).

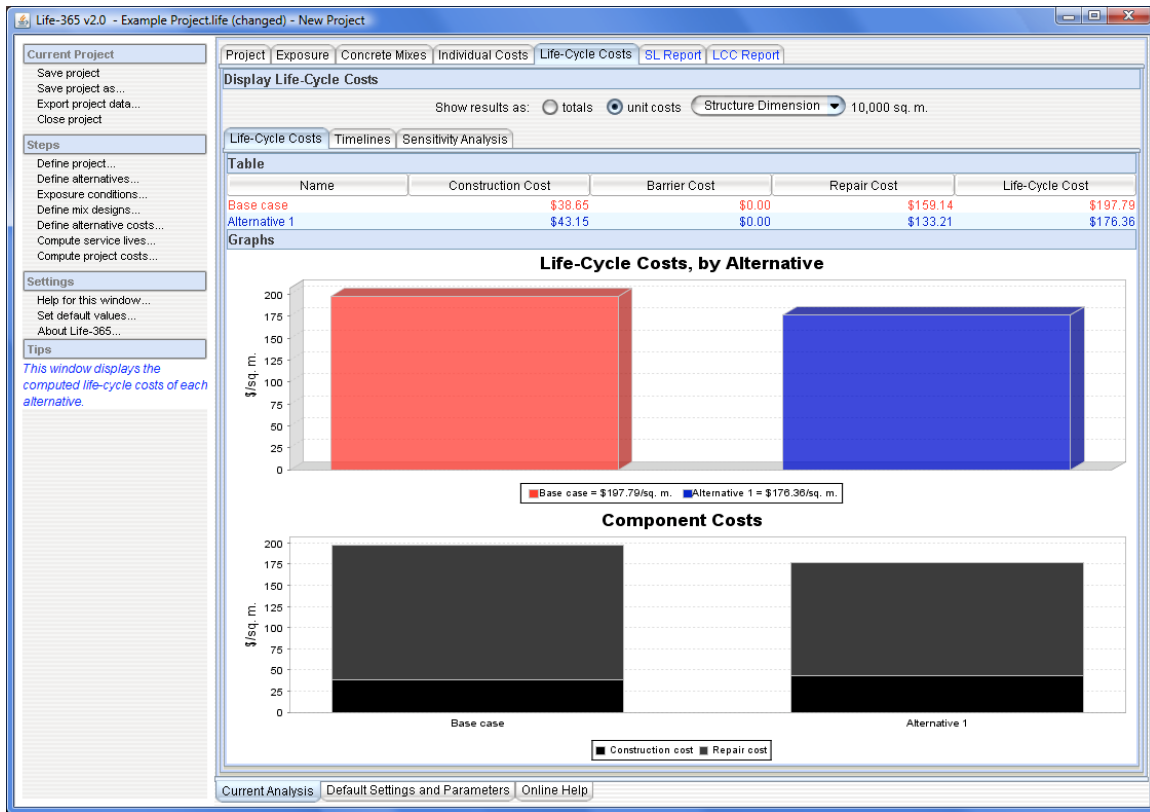


Figure 16. Life-Cycle Costs Tab

Life-Cycle Costs

This first tab displays the life-cycle costs of each alternative, both as a total (in the upper panel) and by component cost (in the lower panel). For the particular mixes shown in the figure, the Base case mix has a life-cycle cost of \$197.79 per sq. meter, while the Alternative 1 mix has a life-cycle cost of \$176.36 per sq. meter.

Timelines

The **Timelines** tab (Figure 17) shows the constituent costs over time. (This tab will typically show just one of the four timeline figures, but will show all four when the user checks the **Show all four timeseries graphs together** box.) The upper two panels show the individual-year and cumulative *constant-dollar costs*, that is, costs that have been adjusted to account for the effects of increases in the prices of material and labor (the inflation rate) and time-value of money (the real discount rate), and that are summed to compute life-cycle costs.

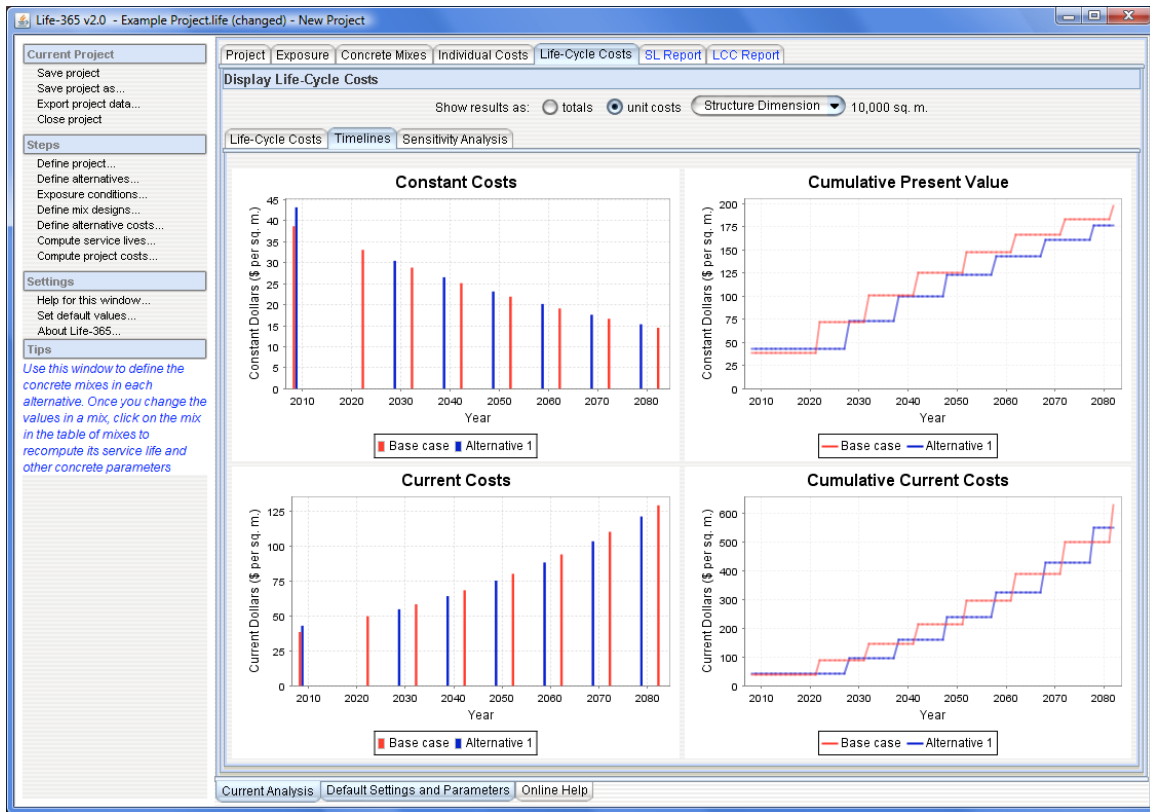


Figure 17. Life-Cycle Costs: Timelines Tab

The lower two panels show the individual-year and cumulative *current-dollar costs*, which are the costs adjusted for inflation only. This current-dollar measure is not a measure of life-cycle costs, but is a useful estimate of the actual, physical dollars that will be spent on each project over the study period.

For these particular alternatives, the upper-right **Cumulative Constant Costs** gives a good explanation of why Alternative 1 (the blue line in the graph) has lower life-cycle costs: while it does have a slightly higher construction cost and identical repair costs, it has fewer repairs due to the longer service life (specifically, its first repair occurs later), resulting in a level in the last year of the study period that is lower than the red line.

Sensitivity analysis

An important component of life-cycle analysis is sensitivity analysis, or determining how sensitive your results are to changes in any of the underlying economic, concrete, or constituent costs. After making your first, best-guess estimates of these parameters in the previous tabs, Life-365 gives you at least two ways of conducting sensitivity analysis: the first way is to simply change any of the parameters in the previous tabs and see what effects it has on each alternative's life-cycle costs; for example, you can easily change the environmental conditions of the mixes, or some of the mix properties of your mixes.

A second, efficient way to conduct sensitivity analysis on a subset of all parameters is to use the **Sensitivity analysis** tab (Figure 18). In this tab, you select one of the predefined parameters listed in the left-hand tree, select a range of values for this parameter, by selecting from the **Variations** drop-down box in the lower-left-hand portion of the tab (where, for example, a 100% variation of an discount rate of 3% will create inflation rates of between 0% and 6%). Life-365 will then compute the life-cycle costs of each alternative across this range of parameters and compare them in the right-hand graph. The vertical dashed line is positioned at the value of the parameter you selected previously as your “best guess” estimate.

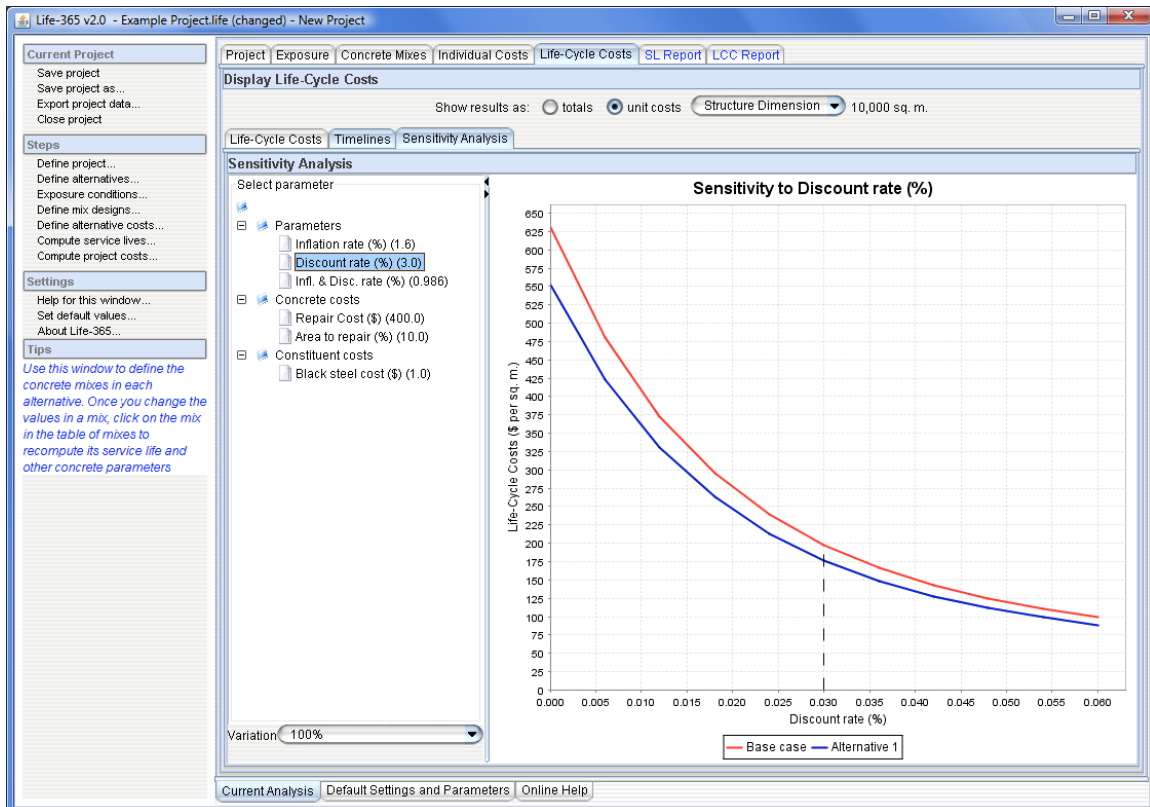


Figure 18. Life-Cycle Costs: Sensitivity Analysis Tab

The particular graph in Figure 18 shows the effects of varying the discount rate between 0% and 6% (as indicated by the graph’s horizontal axis). The graph shows that the Base case mix has higher life-cycle costs across our range of discount rates; said another way, the Alternative 1 mix has lower life-cycle costs than the Base case mix, regardless of the (reasonable) real discount rate selected.

3.8 Service Life and Life-Cycle Cost Reports

Finally, Life-365 provides two pre-defined reports of your project: a **SL Report** (for "Service Life Report"; Figure 19) and an **LCC Report** (or "Life-Cycle Cost Report"; Figure 20). These two reports list many but not all of the parameters used in your analysis. Each report can be printed by pressing the **Print** button at the bottom of the window. (If you do not have a printer installed, then Life-365 will ask you to install one first.)

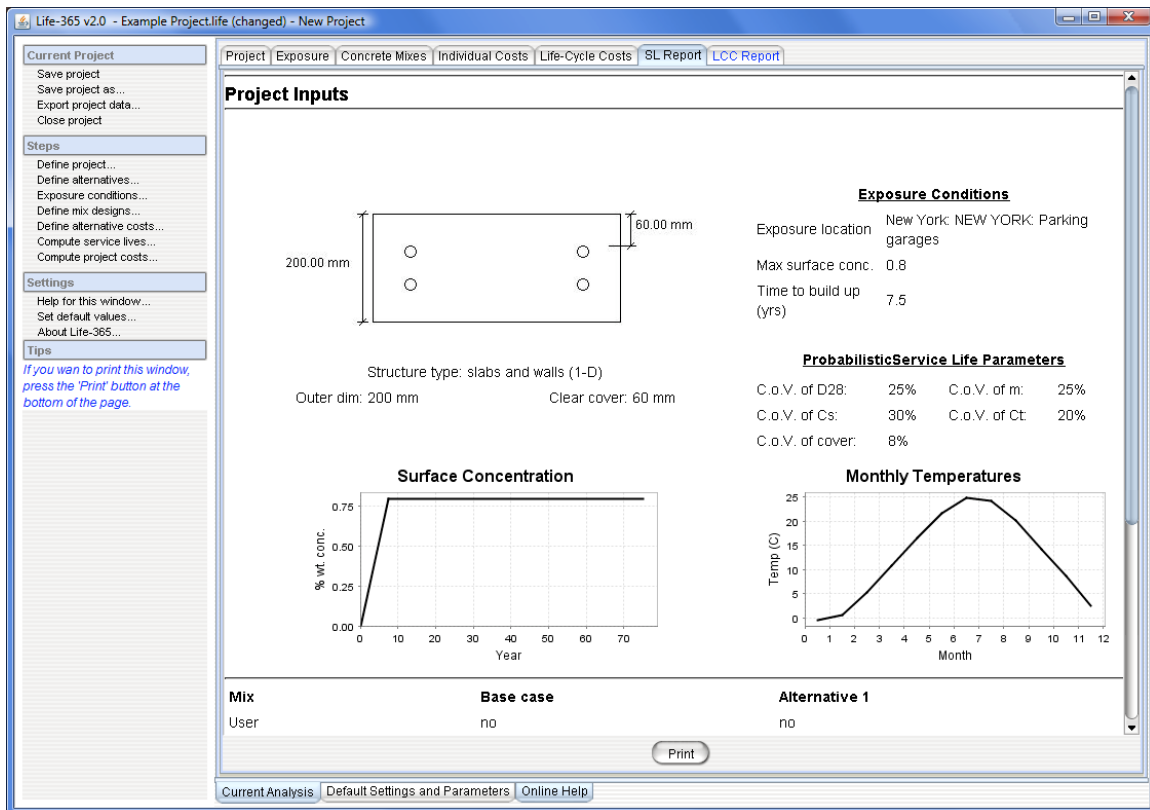


Figure 19. Service Life (SL) Report

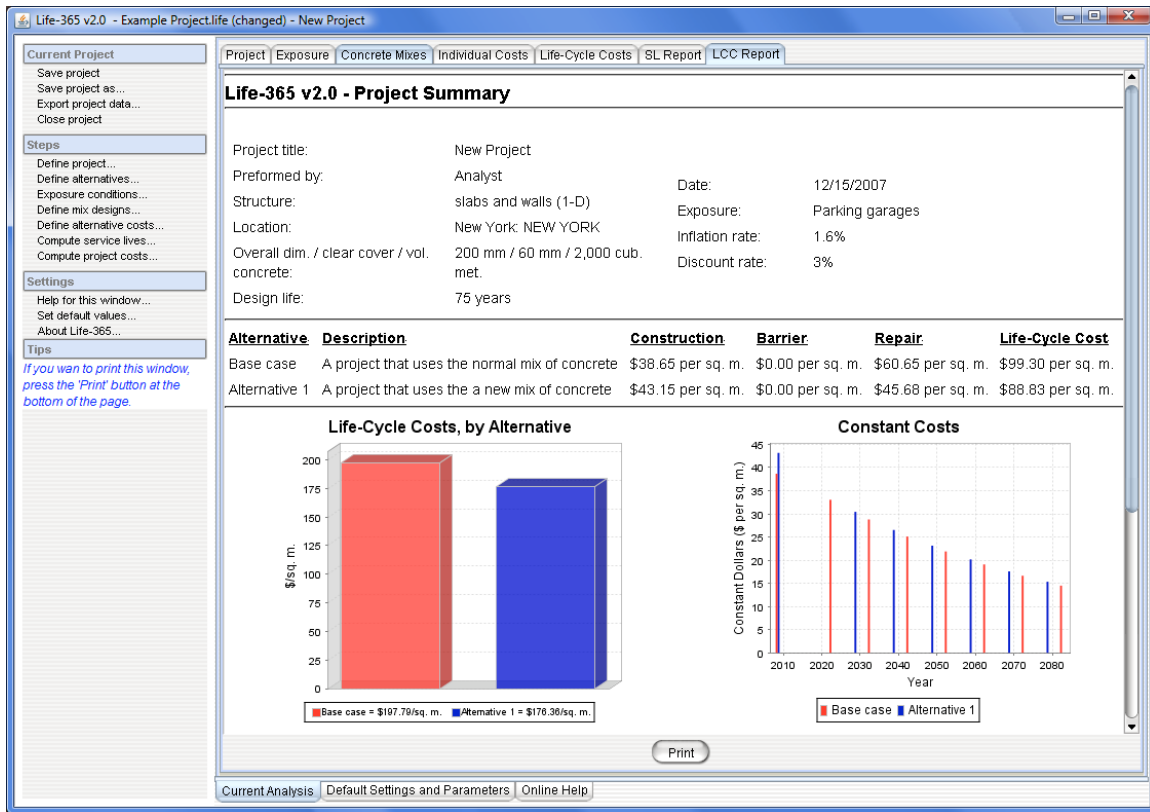


Figure 20. LCC Report

A more comprehensive report of your analysis can be done, quite simply, by taking “screenshots” of each tab and pasting them into a word-processing document like Word. (In Microsoft Windows, a screenshot is taken by pressing the “Shift” and then “PrtSc” keys and then pasting it into another document by pressing the “Ctrl” + “v” keys. In Mac OS X, press “Shift” + “Apple” and then “3” to grab the screenshot, and then “Command” + “v” to paste.)

3.9 Supporting Features

In addition to the main, project-level windows, Life-365 includes a window for setting default settings and parameters to be used in all of your analysis, and a series of context-help windows.

3.9.1 Default Settings and Parameters

This tab, shown in Figure 21, allows the user to edit the common parameters that are relatively constant across the different analyses to be conducted, such as the units of measure, location of project, economic conditions, and concrete costs.

Life-365 v2.0

Navigator

- Open new project
- Open existing project...

Settings

- Help for this window...
- Set default values...
- About Life-365...

Tips

This tab lists online help pages for many of the analysis tabs.

Default Units of Measure

Units of Measure

Base Units: **SI metric** Concentration Units: **% wt. conc.**

Default Region and Exposure Conditions

Region: **NEW YORK** Sub-location: **NEW YORK** Exposure: **Parking garages**

☒ Use defaults

Economic Parameters

Default Economic Parameters and Costs

Base year (e.g., 2008): **2008** Analysis period (yrs): **75** Inflation rate (%): **1.60%** Discount rate (%): **3.00%**

Concrete & Steel		Barriers & Inhib.		Repairs	
Concrete (\$/cu. met.)	\$100.00	Memb. (\$/sq. m.)	\$33.00	Repair (\$/sq. m.)	\$400.00
Black stl (\$/kg)	\$1.00	Sealer (\$/sq. m.)	\$7.00	Area to repair (%)	10.00%
Epoxy-coated stl (\$/kg)	\$1.33	Inhibitor (\$/L)	\$1.50	Fixed repair interval (yrs)	10
Stainless stl (\$/kg)	\$6.60				

Color Palette (Concrete and Cost Graphs)

Base case **Alternative 1** **Alternative 2** **Alternative 3** **Alternative 4** **Alternative 5**

Set Changes

Save **Reset to last saved values** **Reset to Life-365 default values** **<- Back to Analysis**

Current Analysis | **Default Settings and Parameters** | Online Help

Figure 21. Default Settings and Parameters Tab

Before conducting even your first analysis, it is recommended that you access this tab and make the default settings appropriate to you, including your location and concrete costs, and then press the **Save** button. Your first project, then, will use your best estimates of these parameters for your projects.

3.9.2 Online Help

The **Online Help** tab (Figure 22) lists a series of pages describing the functionality of and tips on using each window.

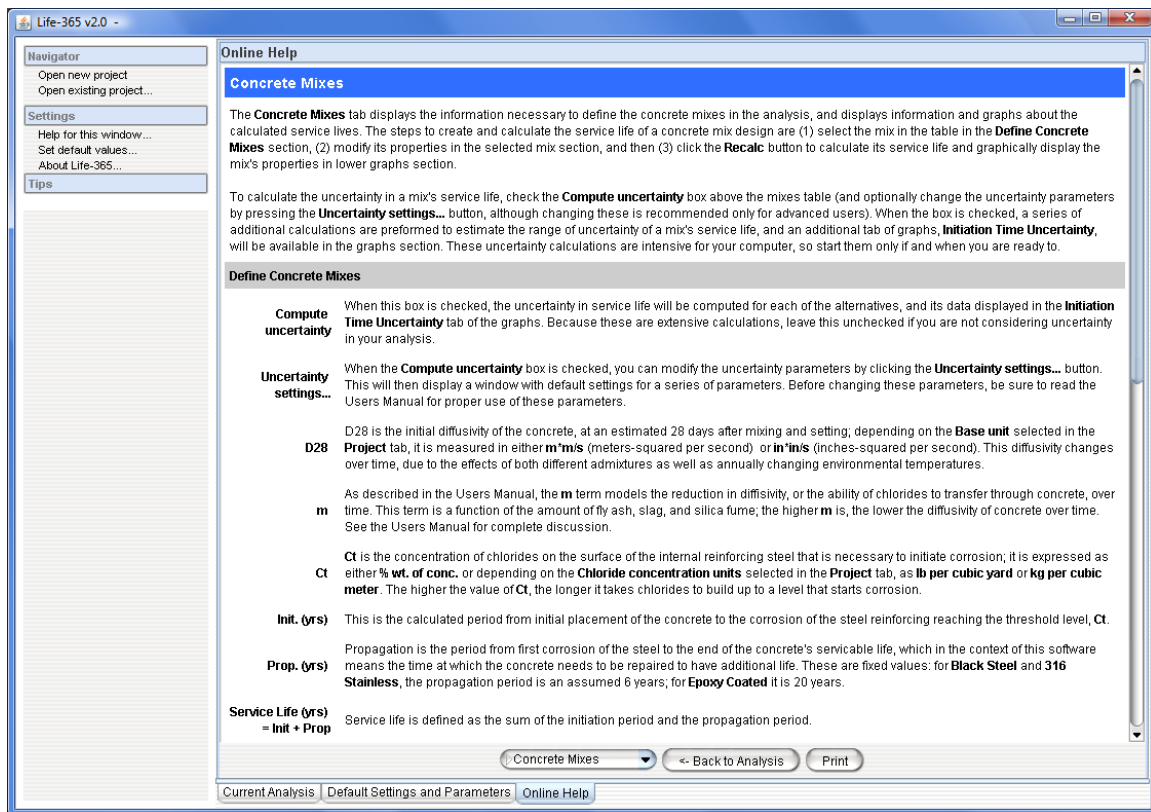


Figure 22. Online Help

Individual pages can be accessed by selecting from the drop-down box at the bottom of the panel (in Figure 22, this box displays “Concrete Mixes”). If, instead, you are working on a particular window, say, the **Project** tab, and you want to access the help page for that window, simply go to the left-hand navigation panel and select **Help for this window...** from the **Settings** section. Finally, the currently displayed help page can be printed by pressing the **Print** button.

3.10 Advanced Analysis: Service Life Uncertainty

The analysis described in Section 3.2 through Section 3.8 is, in and of itself, generally a sufficient analysis procedure: it calculates the “best-guess” estimates of service life and life-cycle costs, given the economic conditions, environmental conditions, concrete mix values, and economic costs inputted by the user.

There may be, however, uncertainty about some of these conditions, for example, what the interest rates will be over the study period, what temperature fluctuations will be, what the effects of concrete admixtures are on the structure’s service life, and what repair costs will be over the study period. Many of these uncertainties can be addressed through sensitivity analysis, of which the **Sensitivity Analysis** tab (Figure 18) is an example. Formal uncertainty analysis would include many of the above parameters and procedures.

To help understand the impact of uncertainty about a number of the input parameters on the initiation period and thus concrete service life, Life-365 comes included with a formal method for estimating the uncertainty of a concrete mix's service life. Based on Bentz (2003) and the formulas in Chapter 2, it varies the following parameters in these formulas to estimate the probability density function of initiation period of the concrete mix design:

- the diffusion rate at 28 days, D_{28} ,
- the diffusion decay index, m ,
- the maximum surface chloride level, C_s
- the chloride threshold to initiate corrosion of steel, C_t , and
- the clear cover to reinforcement.

The resulting probability and cumulative-probability density functions are used in Life-365 to calculate the effects of concrete service life uncertainty (only) on life-cycle costs.

As illustrated by Figure 23, the user activates Life-365 to compute concrete mix uncertainty by checking the **Compute uncertainty** box in the upper part of the **Concrete Mixes** tab.

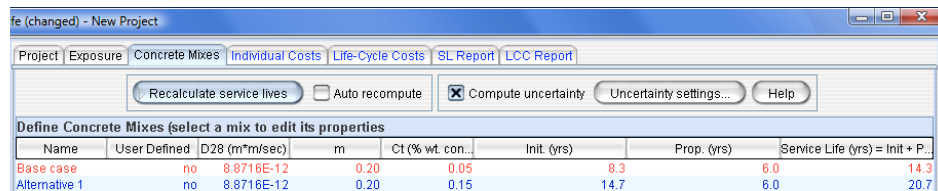


Figure 23. Concrete Mixes Tab: Initiation Time Uncertainty Tab

When either is selected, Life-365 will display a small window (Figure 24) describing this process and how it may slow down the overall performance of Life-365. Selecting **Yes** in this window then and pressing the **Recalculate service lives** button will invoke the uncertainty calculations, thereby adding some panels to some windows. If you do select **Yes**, you can later turn the uncertainty calculations off by unchecking the same **Compute uncertainty** checkbox.

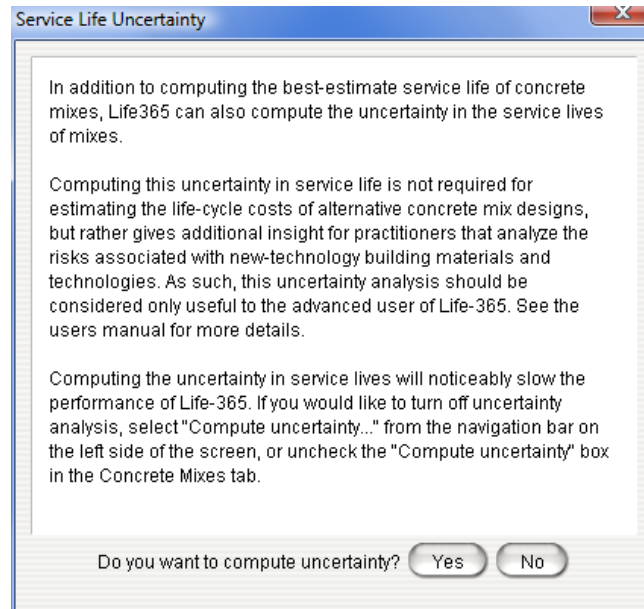


Figure 24. Uncertainty Prompt

When the **Yes** button is pressed (and then the **Recalculate service lives** button), the uncertainty in service life is computed for each concrete mix listed in the **Concrete Mixes** tab, and the **Initiation Time Uncertainty** panel in this tab is activated. These graphs are both important but relatively difficult to interpret; to give the users the necessary tools to interpret these graphs, let's examine in detail the two figures more closely.

Consider the probability curves in Figure 25. The Base case (the red line) is based on a simple mix, with no additives such as silica fume, fly ash, inhibitors, membranes or sealants; Alternative 1 (the blue line) has added inhibitors. Based on the "best-guess" values in the project windows, the Base case has a calculated initiation period of 8 years and Alternative 1 an initiation period of 14 years.

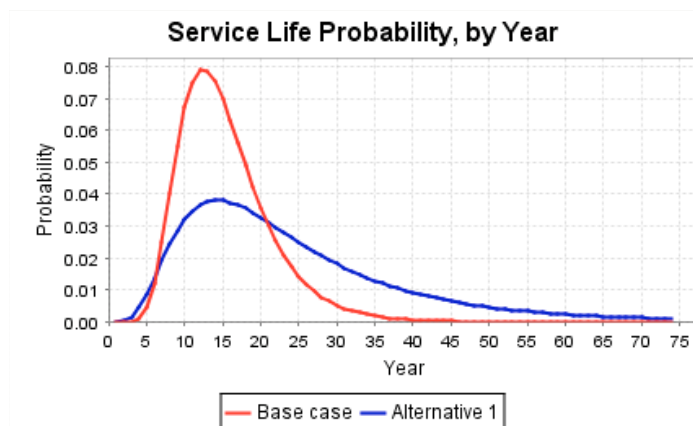


Figure 25. Probability of Service Life Years, by Year

Several important points can be made with this graph: first, it is hard if not impossible to interpret anything about the “best-guess”-based service lives (8 and 14 years, respectively) from this graph: the highest point on each line is the most probable initiation period (or most likely to occur) but typically not also the expected, or average initiation period (the expected value of service given a large number of statistical trials). Note that this average value is equal to the deterministic value of initiation period calculated when uncertainty analysis is turned off. Second, the Base case (red line) is higher than the Alternative 1 (blue line) and peaks earlier in years. Neither of these, however, tell us anything about how these uncertainties determine if one of the concrete mixes is life-cycle cost effective in a probabilistic sense, that is, across the range of initiation periods each mix can experience.

To do this, we need the cumulative probability density functions, shown Figure 26, which simply add each year’s individual probability to create cumulative probabilities.

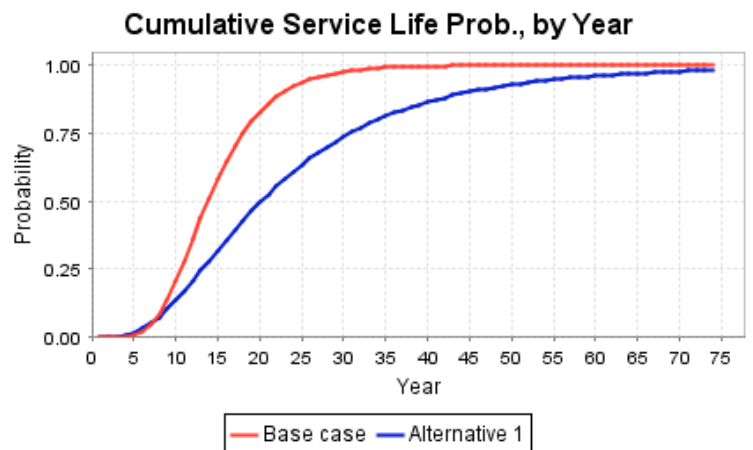


Figure 26. Cumulative Probability of Service Life, by Year

Using this graph, it can be difficult to determine which, if either, concrete mix has the longest service life in a probabilistic sense. We will, therefore, attempt here to give a basic example of how to do this. Consider, for example, the values of the red and blue line at Year 14 on the horizontal axis. Given that the blue line is below the red line at this year, the probability graph specifically says:

The blue line (Alternative 1) has a lower probability of being 14 years (or less) than the red line (Base case).

Said differently, this statement says that Alternative 1 is less likely to have a service life of 14 years or less than the Base case. If, instead, we say the converse of the above italicized statement, we get a more useful statement:

The Alternative 1 mix has a higher probability of being more than 14 years than the Base case mix.

That is, the Alternative 1 mix, by being below the Base case mix, has a lower probability of having an initiation period of that many years. Since it is below the Base case line for all values above 8 years, it is a reasonable conclusion that Alternative 1 has a longer service life in a probabilistic sense.³

The usefulness of this dominance can be summarized as follows:

If one of the cumulative probability lines is below the others for all years in the study period, or almost all of the years, then the corresponding concrete mix has the statistically highest number of years for its initiation period.

In cases where there is not clear statistical dominance of one service life over the other(s), we can still calculate the effects of different outcomes of initiation periods (and thus service lives) on life-cycle cost, using the following technique: choosing to compute uncertainty creates a new panel in the lower portion of the **Life-cycle costs: Life-cycle costs** tab (Figure 27 and Figure 28).

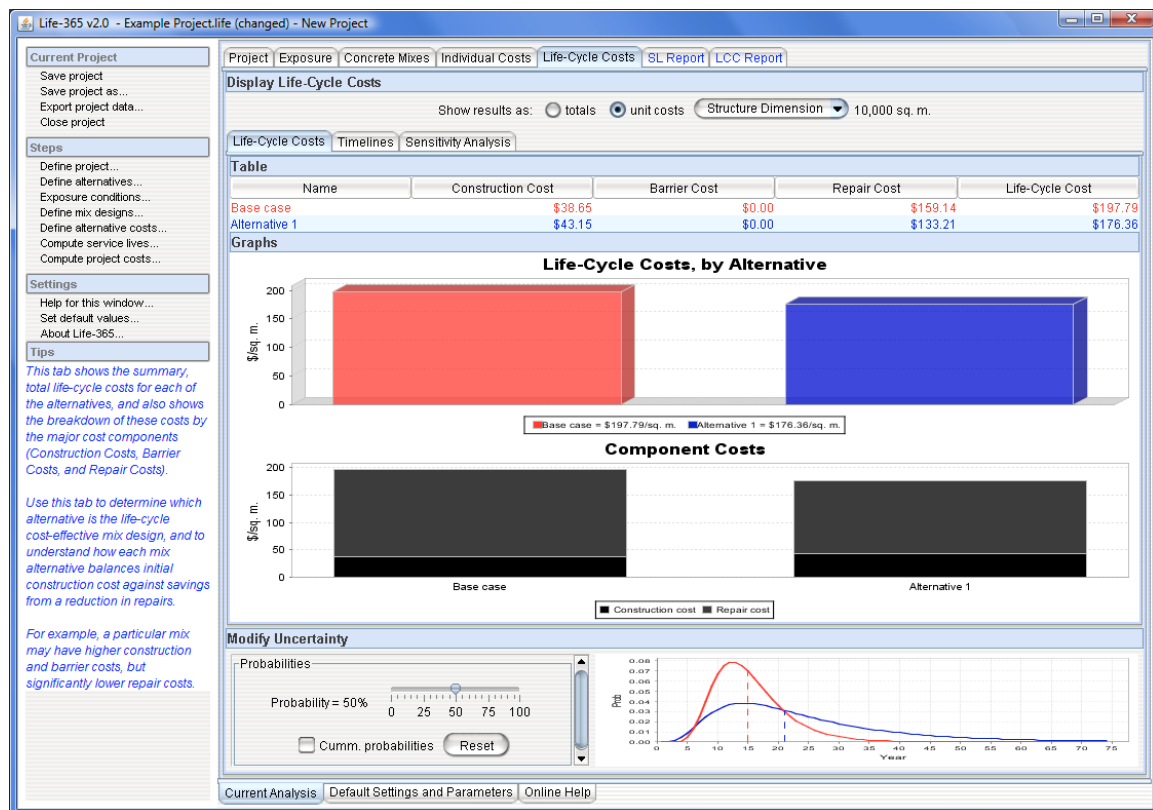


Figure 27. Life-cycle Costs Tab with Modify Uncertainty Panel

³ While the red line is below the blue line over the 5 to 8 year range, the probabilities of these values occurring are small. Technically, we need to use the calculation of *second-order statistical dominance* to determine if in fact Alternative 1 has the longest initiation period in a probabilistic sense, but in this example case we can draw this conclusion from examination of the graph.

When first created, this panel sets the probability slider to “50,” which means that there is a 50 percent probability that each concrete mix’s service life will be less than the indicated value (again, 8 years for the Base case mix and 14 years for the Alternative 1 mix) and a 50 percent probability that it will be more than the indicated value. In Figure 27, the service lives are displayed as 14 and 21 years (that is, each mix’s initiation period plus a propagation period of 6 years).

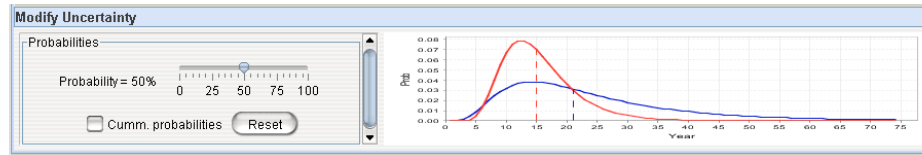


Figure 28. Modify Uncertainty Panel

At the 50-percent values, all of the Life-365 life-cycle cost graphs should display results identical to (or, due to rounding errors, very similar to) the best-guess-based values computed when uncertainty is not activated.

The purpose of the slider panel in Figure 28 is to allow the user to modify the uncertainty values for each alternative and see what effect the new values have on life-cycle costs. Since the 50-percent values represent the “best guess” of each mix’s alternative based on laboratory experiments, most other values would be subjective judgments. As a minimal constraining factor, Life-365 requires these changes to be the same for all of the alternatives, i.e., if the user changes the probability slider to 75 percent, then the probability of all concrete mixes has been changed to 75 percent. Given that the concrete mixes have different probability functions, a change to 75 percent, for example, will create different service lives.

To summarize, the probability slider shown in Figure 28 is, ultimately, most useful if the analyst can show that one alternative is the life-cycle cost-effective alternative regardless of the service life uncertainty selected. This task should be part of a broader analysis of the sensitivity of the life-cycle costs to uncertainty in the economic, environmental, concrete, and cost parameters.

3.11 Special Applications

3.11.1 Epoxy-Coated Rebars for the Top Reinforcing Only

One common practice in concrete slab design is to use epoxy-coated rebar for the top layer of steel, which is directly exposed to chlorides, and a less-expensive black steel for the bottom layer; using this mixed set of steels gives the structure the benefit of longer service life while keeping steel costs down.

Life-365 does not have a way to calculate the steel costs of this mix set; it accepts either epoxy-coated or black steel as the reinforcing, but not both. You can, however, modify

the costs of the reinforcing in the **Individual Costs** tab so that these costs are more accurate.

Here is a simple example, using the two figures below. Let's say that the cost of epoxy-coated steel is \$2.93 and the cost of black steel is \$2.20; these costs are shown in the left panel of Figure 29. If approximately 1/2 of the steel in the hybrid epoxy-black steel slab is epoxy, then the average cost of steel is

$$(\$2.93 + \$2.20) \div 2 = \$2.57 / \text{lb.}$$

We can input, then, this average price in the **Epoxy-coated stl** box (as shown in the right panel of the figure) and Life-365 will use this average price for all slabs that use Epoxy-coated steel.

Concrete & Steel	
Concrete (\$/cub. yd)	\$76.46
Black stl (\$/lb)	\$2.20
Epoxy-coated stl (\$/lb)	\$2.93
Stainless stl (\$/lb)	\$14.55
Default Costs	
Concrete & Steel	
Concrete (\$/cub. yd)	\$76.46
Black stl (\$/lb)	\$2.20
Epoxy-coated stl (\$/lb)	\$2.57
Stainless stl (\$/lb)	\$14.55
Hybrid Costs	

Figure 29. Default and Modified Steel Costs for Hybrid Epoxy/Black Steel Slab

Note: for this averaging to work, you must use this hybrid epoxy-black set of steels for all alternative mixes you specify that have epoxy-coated steel as the top layer. At this time, Life 365 has no information on the extension of service life obtained with the hybrid epoxy-black set of steel reinforcing. It is obviously less than the 20 years built into the program for fully coated steel.

Furthermore, according to one report (Concrete Reinforcing Steel Institute 1998), this hybrid steel set has an effective propagation period of 15 years. To input this period in the concrete mixes, check the **Set own concrete properties** box in the **Concrete Mixes** tab and enter "15" for the propagation period.

4 Life-365 Background Information

Life-365 has been produced as a “first step” in the development of a more comprehensive model for predicting the life-cycle costs associated with reinforced concrete structures exposed to chlorides. The processes of chloride transport, loss of passivity on embedded steel, corrosion of the steel and subsequent damage of the surrounding concrete are highly complex phenomena and not completely understood. Consequently it is necessary to simplify many of the complexities and make assumptions where insufficient knowledge is available. All models do this to a certain extent. This does not necessarily invalidate the model, but it does place a responsibility on the authors to ensure potential users of the model are made aware of any assumptions and limitations.

The purpose of this section of this document is to provide an explanation of the assumptions used in the development of Life-365, the sources of supporting information and the limitations of the model. Suggestions are also made to indicate how improvements might be made in the modeling approach as more data become available.

4.1 Service-Life Estimate

The service life is defined as the period between construction and the time to the first repair, t_r . The time, t_r , may be determined using a quantitative service life model to predict the time to cracking (or unacceptable damage) for a particular element in a given environment; a number of such models exist. Many of these models adopt the two-stage service life model first proposed by Tuutti (1982) in which the deterioration is split into two distinct phases as shown in Figure 30.

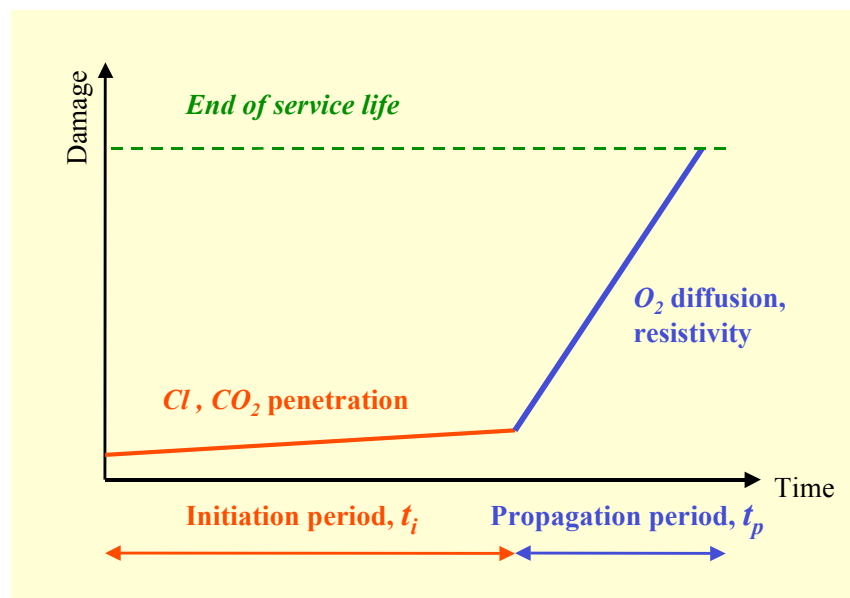


Figure 30. Components of Concrete Service Life

4.1.1 Initiation Period

The initiation period, t_i , defines the time it takes for chlorides to penetrate from the external environment through the concrete cover and accumulate at the embedded steel in sufficient quantity to break down the protective passive layer on the steel and thereby initiate an active state of corrosion. The length of this period is a function of the concrete quality, depth of cover, the exposure conditions (including the level of chloride at the surface and the temperature of the environment) and the threshold chloride concentration, C_t , required to initiate corrosion. No damage (due to chlorides or corrosion) is assumed to occur during this period.

A simple approach to predicting the initiation period is to assume that ionic diffusion is the sole mechanism of chloride transport and to solve Fick's second law of diffusion using an apparent chloride diffusion coefficient to characterize the concrete under consideration. A further assumption made is that the concrete is completely saturated. Although there are relatively simple numerical solutions to Fickian diffusion (for saturated concrete), many workers have chosen to implement Fick's law in a finite difference model to better facilitate changes in concrete properties and exposure conditions in space and time. The chloride transport model used for analysis in Life-365 is an example of such a model and has been described in detail elsewhere (Boddy et al., 1999). This diffusion coefficient is corrected for time and temperature effects in Life-365 as explained in Section 2.1.

Clearly assuming that the concrete remains saturated and chloride ingress only occurs by ionic diffusion is an oversimplification. Other models have been developed that account for unsaturated conditions and the effects of convective transport (Saetta et al., 1993, Martin-Pérez et al., 1998). Indeed, the chloride transport model within Life-365, known as Conflux, is capable of dealing with combined diffusion and convection, the latter resulting from either pressure or moisture gradients within the concrete (Boddy et al., 1999). These capabilities were not implemented within the current version of Life-365. The decision to adopt a more simplified approach for Life-365 was based on making the model accessible to engineers as a design tool for a wide range of general applications. Accounting for multi-mechanistic transport in partially saturated concrete requires detailed knowledge of site-specific conditions and a wide range of material properties that are not usually available to the engineer at the design stage. It is envisaged that future versions of Life-365 will be more rigorous in the treatment of unsaturated flow without compromising the general applicability of the model.

4.2.2 Propagation Period

The propagation period, t_p , defines the time necessary for sufficient corrosion to occur to cause an unacceptable level of damage to the structure or element under consideration. The length of this period depends not only on the rate of the corrosion process, but also on the definition of "unacceptable damage". This level of damage will vary depending on the requirements of the owner and the nature of the structure. The corrosion rate will be influenced by a large number of factors including the nature of the embedded metal, properties of the surrounding concrete and the composition of the pore solution within the

concrete, and the environmental conditions (particularly temperature and moisture availability). Models have been developed to predict the corrosion rate and even the build of damage (for example Martin-Perez et al., 1998), but few of these have been validated or calibrated with field data.

In view of the complexity of the corrosion process, a common approach has been to assign fixed values to the propagation period based on empirical observations. This approach has been adopted by Life-365.

4.2 Input Parameters for Calculating the Service Life (Time to First Repair)

The following is a list of the indices required by Life-365 to calculate the time to first repair, t_r :

- C_s** Surface concentration (kg/m^3 , pcy, %)
 This is the chloride concentration at the surface ($x = 0$) of the concrete. This can be input as a fixed value or allowed to increase linearly with time up to a maximum value (and thereafter remain constant). The rate of build up and maximum value can be selected by Life-365 based on the geographic location and nature of the structure or can be provided by the user.
- D** Diffusion coefficient (m^2/s)
 This is a material property that is either selected by Life-365 on the basis of mix proportions provided by the user or selected directly by the user.
- m** Diffusion decay index (dimensionless)
 This property describes the time-dependent changes in the diffusion coefficient due to the continued hydration of the concrete (see Eqn. 2 in Section 2.1.1). It is either selected by Life-365 on the basis of mix proportions provided by the user or selected directly by the user.
- C_t** Chloride threshold (kg/m^3 , pcy, % - same units as C_s)
 This is the concentration of chloride required to initiate corrosion of the embedded steel reinforcement. The value is either selected by Life-365 on the basis of the type and quantity of corrosion inhibitor, and the nature of the reinforcement, or it is a user-defined input.
- t_p** Propagation period (years).
 This is the time taken for the corrosion process to cause sufficient damage to warrant repair. The value is either selected by Life-365 on the basis of the type of reinforcement or it is a user-defined input.
- T** Temperature ($^{\circ}\text{C}$)
 The annual temperature profile is selected by Life-365 on the basis of the geographical location chosen by the user or a profile (with month, temperature coordinates) may be input by the user.

4.2.1 Surface Concentration

The surface chloride concentration is the main driving force for chloride penetration in Life-365. The model selects the rate of chloride buildup and the maximum surface concentration based on the type of exposure (and structure) and the geographic location; the following exposure conditions are included:

- Marine splash zone (defined as being in the tidal range or within 1 m of the high-tide level)
- Marine spray zone (defined as being more than 1 m above the high-tide level but occasionally exposed to salt water spray)
- Within 800 m of the ocean
- Within 1.5 km of the ocean
- Parking garages
- Rural highway bridges
- Urban highway bridges

The first four categories can only be selected if a coastal geographical region is chosen. For example, if the user chooses Tampa, Florida as a location, all seven of the above options are offered. However, if Wichita, Kansas is selected only the last three exposure conditions are offered.

For structures in a marine environment, the model assumes the following values:

Table 3. Build-up Rates and Maximum %, Various Chloride Zones

	Build-up Rate (%/year)	Maximum (%)
Marine splash zone	instantaneous	0.8
Marine spray zone	0.10	1.0
Within 800 m of the ocean	0.04	0.6
Within 1.5 km of the ocean	0.02	0.6

The values for airborne deposition of chloride vary widely depending on the environment. The default values listed can be considered maximum values. Actual values obtained from structures range from 0.004%/year to greater than 0.1% /year. The data indicate the rate of airborne chloride deposition is a function of the frequency of rain, and proximity to ocean breezes. Very little information is published on this topic, so ***it is advised that users verify the rate of airborne chloride build-up and the maximum surface concentration using local data where available.***

The surface concentrations for bridge decks and parking structures exposed to deicing salts are selected from a database developed for Life 365. This database was developed solely as a guide for users and should be verified with local project data. The database combines deicing salt application data from surveys performed by the Salt Institute between 1960 and 1984, and data related to chloride build-up rates for U.S. highways from Weyers et al (1993). The database values were also compared against chloride content data collected from miscellaneous parking structures in the United States, and chloride data for bridges presented by Babei and Hawkins (1987). The information in the database was used to construct the map in Figure 31, which shows how the chloride build-up rates vary across North America.

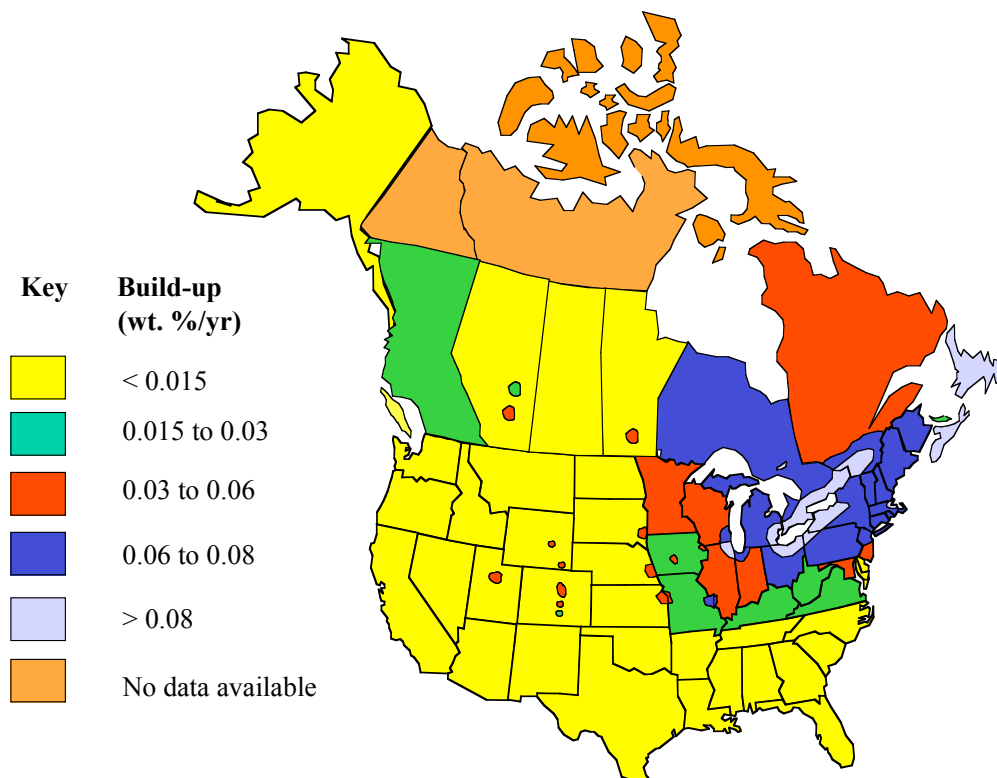


Figure 31. Chloride Levels, by Region of North America

The maximum surface concentration for parking structures located in the regions where deicing salt use is the greatest (light blue in Figure 31) is assumed to reach 1.0 % wt. of concrete. Elsewhere, the maximum surface concentration for parking structures is assumed to reach 0.8%. The following factors are applied to the surface concentration and build-up rates to account for differences in deicing salt use in heavy traffic areas and the wash-off that occurs on bridges exposed to rain.

Table 4. Build-up Rates and Maximum %, by Structure Type

	Build-up Rate (%/year)	Maximum (%)
Parking Structures	See Fig. 31	1.0/0.8
Urban Bridges	85% of value in Fig. 31	0.85/0.68
Rural Bridges	70% of value in Fig. 31	0.70/0.56

The database used to estimate the chloride build-up rate and maximum surface concentration in the model is still under development. The database needs to be further refined and calibrated using data from structures in the field. The database is included in this version of Life-365 only to provide a “first-cut” approximation for users, so ***users are advised to use chloride data from local sources where available.***

Given the preliminary nature of the surface concentration data, users are encouraged to compare the output using the values selected by Life-365 against output generated from user-defined chloride build-up rates and maximum surface concentrations. The Life-365 values are easily overridden in the **Exposure** tab.

4.2.2 Diffusion Coefficient

PC Concrete

Life-365 assumes a time-dependent diffusion coefficient as defined by Eqn. 2 of this document. The value of D_{28} is dependent on the water-cementitious material ratio (w/cm) of the concrete and a relationship between D_{28} and w/cm was developed for the model using unpublished data from tests at the University of Toronto and published data from the same type of test. Only data from “bulk diffusion tests” (similar to the procedure outlined in the Scandinavian standard test NT Build 443) were used in the analysis (Sandberg and Tang, 1994; Frederiksen et al., 1997; Tang and Sorensen, 1998; Stanish, 2000; Steen, 1995; Sandberg et al., 1996).

This test basically involves exposing a fully saturated concrete specimen to a chloride solution in such a way that unidirectional diffusion is the only mechanism of chloride transport. After a specified period of immersion samples are ground from the exposed surface in precise depth increments (e.g. 1-mm increments) and these samples are analyzed for chloride content. The diffusion coefficient is then found by fitting a standard numerical solution (often called the “error function” solution) of Fick’s 2nd Law of Diffusion to the experimental data.

Figure 32 shows the relationship between D_{28} and w/cm for concrete at 20°C using data from this test. The data shown represent Portland cement concretes (without mineral admixtures) that were exposed to chlorides at early ages (generally 28 days or less) and profiled after relatively short periods of immersion (generally 28 to 56 days). This relationship was developed by Stanish (2000).

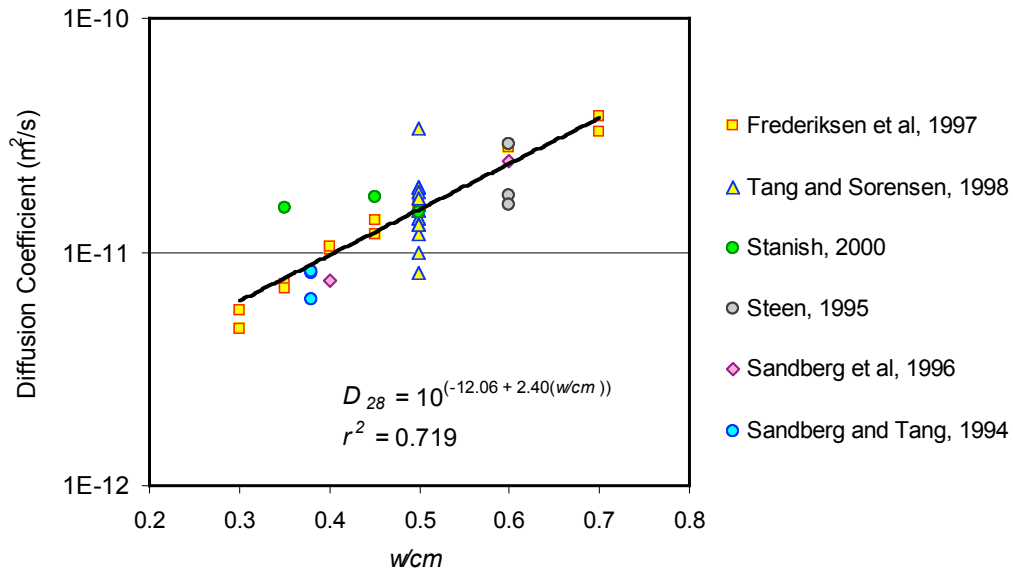


Figure 32. Effects of w/cm on Diffusion Coefficient

Based on this relationship, the predicted early-age diffusion coefficient for a Portland cement concrete with $w/cm = 0.40$ is $D_{28} = 7.9 \times 10^{-12} \text{ m}^2/\text{s}$ at 20°C . This value might seem high compared to diffusion coefficients calculated from chloride concentration profiles for structures in service. For instance, Weyers (1998) presented D values calculated from chloride profiles for bridges in different states and these values were found to range from $1.0 \times 10^{-12} \text{ m}^2/\text{s}$ in northern states to $6.7 \times 10^{-12} \text{ m}^2/\text{s}$ in warmer southern states. However, these values represent “lifetime average” diffusion coefficients (i.e., the time dependent effects have been averaged out over the period of time from the first salt exposure to the time of sampling) and relate to structures exposed to lower average temperatures. Life-365 accounts for time and temperature effects using the relationships in Eqn. 2 and Eqn. 3. For example, the calculated diffusion coefficient at 10 years for a Portland cement concrete with $w/cm = 0.40$ is $D_{10y} = 2.5 \times 10^{-12} \text{ m}^2/\text{s}$ at 10°C . This is not inconsistent with the range of values presented by Weyers (1998).

Effect of Silica Fume

The effect of silica fume on the early-age diffusion coefficient of concrete was also determined using bulk diffusion data from the University of Toronto and various published sources. Figure 33 shows the relationship between silica fume content and the diffusion coefficient. The graph shows the ratio of the diffusion coefficient with silica fume (D_{SF}) to the control mix without silica fume (D_{PC}).

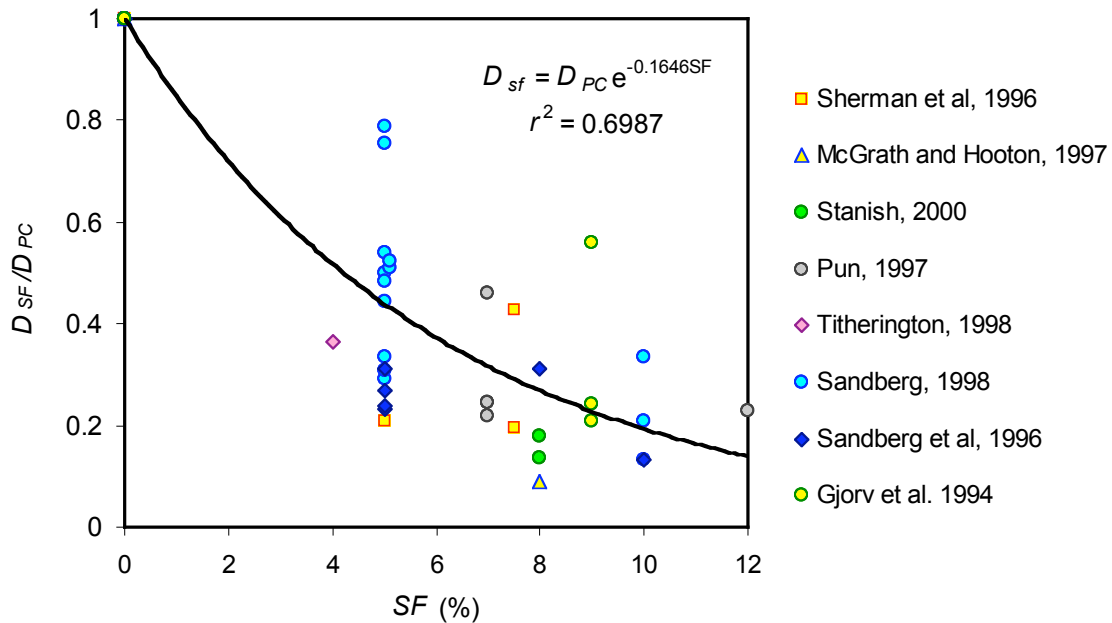


Figure 33. Effects of Silica Fume on Diffusion Coefficient

Effect of Other Mineral Admixtures

Results showing the effect of slag and fly ash on the early-age diffusion coefficient of concrete are inconclusive; various data show that these materials can either increase or decrease the value. Life-365 assumes that fly ash and slag do not affect the value of D_{28} but that they do significantly influence the time-dependent nature of the diffusion coefficient (see below).

Other materials, such as metakaolin, may be expected to have a beneficial effect on either the initial value of the diffusion coefficient or the degree to which the diffusivity reduces with time. However, there are insufficient data to develop a general relationship within the model and the user is referred to the published literature and encouraged to input these materials as user-defined scenarios.

4.2.3 Diffusion Decay Index (m)

A number of workers have shown that the relationship between diffusivity and time is best described by a power law (Bamforth, 1998; Thomas and Bamforth, 1999; Tang and Nilsson, 1992; Mangat and Molloy, 1994; Maage et al., 1995), where the exponent is potentially a function of both the materials (e.g. mix proportions) and the environment (e.g. temperature and humidity). The following equation has frequently been suggested in the literature:

$$D(t) = D_{ref} \cdot \left(\frac{t_{ref}}{t} \right)^m \quad \text{Eqn. 5}$$

where: $D(t)$ = diffusion coefficient at time t
 D_{ref} = diffusion coefficient at some reference time t_{ref}
 m = constant (depending on mix proportions)

Bamforth (1999) recently proposed the following values for m based on a review of published diffusion coefficients from more than 30 sources:

Table 5. Values of m , Various Concrete Mixes

Concrete Mix	m
PC Concrete	0.264
Fly Ash Concrete	0.700
Slag Concrete	0.620

These values are based on published information mainly from marine studies. It is felt that the rate of decay in marine conditions, where there is a constant supply of moisture (in most cases), may be somewhat higher than in bridges and parking structures, where the continued hydration reactions may be decreased by the reduced moisture availability. Furthermore, Bamforth gives no indication as to how the value of m will change with the level of fly ash and slag. Many of the studies referred to by Bamforth were based on relatively high levels of fly ash (e.g. 30 to 50%) and slag (e.g. 50 to 70%). Thus it was decided to adopt a more conservative approach in Life-365 and allow the value of m to vary in the range 0.20 to 0.60, based on the level of fly ash (%FA) or slag (%SG) in the mix. The relationship used is as follows:

$$m = 0.2 + 0.4(\%FA/50 + \%SG/70) \quad \text{Eqn. 6}$$

Other workers have proposed relationships between m and other parameters such as the w/cm ratio and silica fume content of the mix (Mangat and Molloy, 1994; Maage et al., 1995). These are not considered in the current version of Life-365, but may be

incorporated in later versions. The user is encouraged to examine the influence of m by comparing different values in user-defined scenarios.

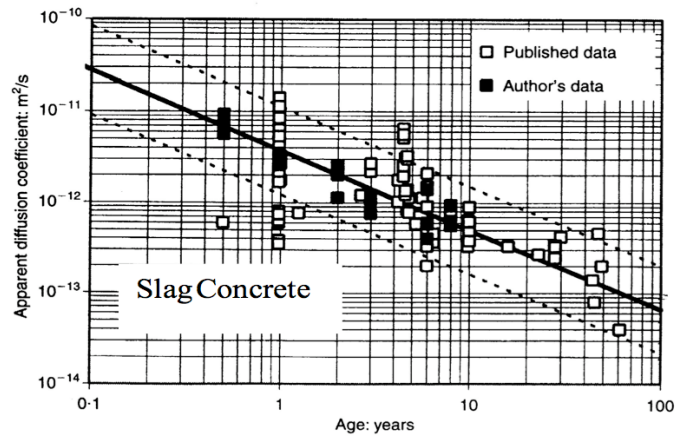
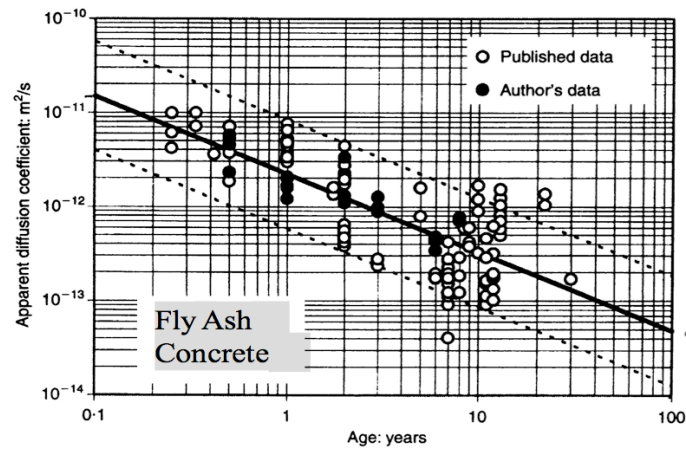
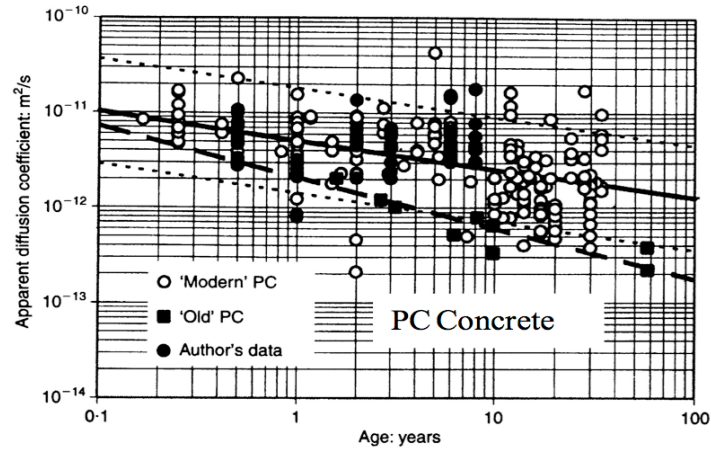


Figure 34. Effects of Age on Diffusivity

It is considered that allowing D to decrease with time indefinitely is unrealistic. It is reasonable to assume that there is some limiting value of diffusion representing the condition of complete hydration in the concrete mix. In Life-365 the diffusion coefficient decays with time according to Eqn. 6 until the concrete reaches the age of 25 years. Thereafter the diffusion coefficient remains constant for the rest of the analysis period (i.e., $D_t = D_{25y}$ for $t \geq 25$ years).

4.2.4 Chloride Threshold

There is a vast quantity of published data related to the chloride threshold in concrete. The concept of having a single value below which no corrosion occurs and above which corrosion is initiated is almost certainly not valid. However, the risk and rate of corrosion undoubtedly increase as the chloride concentration in the pore solution in contact with the steel surface increases. The actual relationship between corrosion and chloride content is likely to be influenced by a whole range of parameters including the type, composition and quantity of Portland cement and other supplementary cementing materials, the moisture content and temperature inside the concrete, the porosity and pore structure of the concrete, the nature (composition) of the steel surface, and the presence of other species in the pore solution (e.g. alkalis). At this time there are no clearly defined relationships that can easily be incorporated into a simple service life model. Consequently, Life-365 does assume a single chloride threshold value (C_t) despite the obvious limitations of such an approach.

In selecting an appropriate value for C_t reference was made to the work of Glass and Buenfeld (1995) who presented a comprehensive review of the literature on this topic. They found that threshold values published in the literature ranged anywhere from 0.17 to 2.5% chloride (expressed as total chloride by mass of cementitious material). Based on their analysis of the available information they concluded that:

Without further work no improvement can be made to the suggested chloride threshold levels of 0.4% for buildings exposed to a temperate European climate and 0.2% for structures exposed to a more aggressive environment.

These values refer to total chloride as a percentage of the mass of cementitious materials. The range 0.2 to 0.4% by mass of cement is equivalent to a range of 0.03 to 0.07% by mass of concrete (for typical concretes with cement contents in the range 350 to 400 kg/m³). Consequently a value of $C_t = 0.05\%$ by mass of concrete was adopted for Life-365.

Effect of Corrosion Inhibitors

As discussed in Section 2.1.2, Life-365 accounts for two corrosion inhibitors at this time; these are calcium nitrite and an organic inhibitor (Rheocrete 222+; also referred to as amines and esters, or “A&E” in the software). These inhibitors are accounted for by allowing the following increase in the chloride threshold level:

Table 6. Doses and Thresholds, Various Inhibitors

Dose		Threshold, C_t
litres/m ³	gal/cy	% wt. conc.
<u>Rheocrete 222+⁴</u>		
5	1	0.12
<u>Calcium Nitrite Inhibitor</u>		
10	2	0.15
15	3	0.24
20	4	0.32
25	5	0.37
30	6	0.40

These increased values are based on the results of corrosion studies published in the literature (Nmai and McDonald, 1999; Berke and Rosenberg, 1989). Other inhibitors will be included as published information on their efficiency becomes available.

Rheocrete 222+ also reduces the initial diffusion coefficient to 90% of the value predicted for the concrete without the admixture and decreases the rate of chloride build up at the surface by half (in other words it takes twice as long for C_s to reach its maximum value). These modifications are made to take account of the pore modifications induced by Rheocrete 222+, which tend to reduce capillary effects (i.e. sorptivity) and diffusivity (Miltenberger et al., 1999; Miller and Miltenberger, 2001).

Effect of Stainless Steel

In the current version of Life-365 it is assumed that grade 316 stainless steel has a corrosion threshold of $C_t = 0.50\%$ (i.e., ten times black steel). This value was taken from the FHWA study conducted by MacDonald et al (1998).

4.2.5 Propagation Period

The propagation period used in Life-365 is $t_p = 6$ years. This value was selected on the basis of the studies of Weyers and others (Weyers, 1998; Weyers et al. 1993) who determined that the length of the period between corrosion initiation and cracking varied in the range from 3 to 7 years for bridge decks in the U.S.A.

It is recognized that the rate of corrosion and, hence, the propagation period is a function of many parameters such as temperature, moisture content and the quality of the concrete

⁴ In the software, Rheocrete 222+ is referred to as "A&E," for amines and esters.

(e.g. oxygen diffusivity and electrical resistivity). It is envisaged that future versions of Life-365 will be able to account for changes in the value of t_p on the basis of environmental and material properties.

Effect of Epoxy-Coated Steel

The use of epoxy-coated steel is a commonly used corrosion protection strategy in North America. The performance of epoxy coatings in protecting steel from corrosion is varied (Manning, 1996; Weyers et al., 1998; Pyc et al., 2000) and depends on a wide range of parameters (MacDonald et al., 1998). Based on extrapolations from accelerated laboratory data, MacDonald et al. (1998) predicted that epoxy-coated top bars might be expected to extend the estimated time to corrosion from between 12 to 19 years. A full treatment of the published data on the efficacy of epoxy-coated bars is beyond the scope of this manual.

In Life-365 the propagation period is extended to $t_p = 20$ years when epoxy-coated reinforcement is selected. However, this is just a (somewhat arbitrarily selected) default value and the user is strongly encouraged to change this value based on local experience. Also, the user may consider modifying the repair frequency when epoxy-coated bars are used.

4.2.6 Temperature

The temperature profiles for different geographic regions were compiled using data collected from the World Meteorological Organization 1961-1990 Global Climatic Normals Database.

4.3 Input Parameters for Calculating Life-cycle costs

All the input parameters related to calculating the initial construction and repair costs are provided by the user. Life-365 has default values that are supposed to represent typical costs. However, the user is strongly urged to check all these default values and modify them based on the costs in the local marketplace.

4.4 Summary

The solutions provided by Life-365 are only intended as approximations to be used as a guideline in designing a reinforced concrete structure exposed to chlorides. The calculated service life and life cycle cost information produced by the model should not be taken as absolute values. Many assumptions have been made to simplify the model and make it accessible to engineers who may not have specific expertise in the area of chloride transport and reinforcement corrosion. This has resulted in a number of limitations in the model.

The user is encouraged to run various “user-defined scenarios” in tandem with the Life-365 prediction with minor adjustments to the values (e.g. D_{28} , m , C_b , C_s , t_p) selected by Life-365. This will aid in the development of an understanding of the roles of these parameters and the sensitivity of the solution to their values. Finally, Life-365 is very

much a “work in progress.” It will continue to evolve as further information becomes available.

References

- Bamforth, P.B. 1998. "Spreadsheet model for reinforcement corrosion in structures exposed to chlorides." In *Concrete Under Severe Conditions 2* (Ed. O.E. Gjorv, K. Sakai and N. Banthia), E&FN Spon, London, pp. 64-75.
- Bamforth, P.B. 1999. "The derivation of input data for modelling chloride ingress from eight-year U.K. coastal exposure trials." Magazine of Concrete Research, Vol. 51, No. 2, pp.
- Bentz, E.C. 2003. "Probabilistic modeling of service life for structures subjected to chlorides," Materials Journal, Vol. 100 (5), pp. 391-397.
- Berke, N.S. and Rosenberg, A. 1989. "Technical Review of Calcium Nitrite Corrosion Inhibitor in Concrete", Transportation Research Record 1211, Concrete Bridge Design and Maintenance, Steel Corrosion in Concrete, Transportation Research Board, National Research Council, Washington D.C.
- Boddy, A., Bentz, E., Thomas, M.D.A. and Hooton, R.D. 1999. "An overview and sensitivity study of a multi-mechanistic chloride transport model." Cement and Concrete Research, Vol. 29, pp. 827-837.
- Concrete Reinforcing Steel Institute. 1998. "Life-cycle costs reinforce epoxy-coated bar use," Concrete Products, Penton Media, Inc., p. 82.
- Frederiksen, J.M., Sorensen, H.E., Andersen, A., and Klinghoffer, O. 1997. HETEK, The Effect of the w/c ration on Chloride Transport into Concrete -Immersion, Migration and Resistivity Tests, Report No. 54.
- Frohnsdorff, G., 1999, Modeling Service Life and Life-Cycle Cost of Steel Reinforced Concrete, Report from the NIST/ACI/ASTM Workshop, November 9-10, 1998, National Institute of Standards and Technology Report NISTIR 6327, 43 p.
- Gjorv, O.E., Tan, K., and Zhang, M-H. 1994. "Diffusivity of Chlorides from Seawater into High-Strength Lightweight Concrete" ACI Materials Journal, Vol. 91 (5), pp. 447-452.
- Glass, G.K. and Buenfeld, N.R. 1995. "Chloride threshold levels for corrosion induced deterioration of steel in concrete." Chloride Penetration into Concrete, (Ed. L.-O. Nilsson and J. Ollivier), pp. 429-440.
- Maage, M., Helland, S. and Carlsen, J.E. 1995. "Practical non-steady state chloride transport as a part of a model for predicting the initiation period." Chloride Penetration into Concrete, (Ed. L.-O. Nilsson and J. Ollivier), pp. 398-406.
- MacDonald, D., Pfeiffer, D. and Sherman, M. 1998. "Corrosion evaluation of epoxy-coated, metallic-clad, and solid metallic reinforcing bars in concrete." FHWA-RD-98-153, Federal Highways Administration, Washington, D.C.

Mangat, P.S. and Molloy, B.T. 1994. "Prediction of long term chloride concentrations in concrete." Materials and Structures, Vol. 27, 1994, pp. 338-346.

Manning, D.G. 1996. "Corrosion performance of epoxy-coated reinforcing steel: North American experience." Construction and Building Materials, Vol. 10 (5), pp. 349-365.

Martin-Peréz, B., Pantazopoulou, S.J. and Thomas, M.D.A. 1998. "Finite element modelling of corrosion in highway structures." Second International Conference on Concrete Under Severe Conditions - CONSEC '98, Tromso, Norway, June.

McGrath, P., and Hooton, R.D. 1997. "Effect of Binder Composition on Chloride Penetration Resistance of Concrete", Proceedings of the Fourth International Conference on Durability of Concrete, (Ed. V.M. Malhotra), ACI SP-171, American Concrete Institute, Detroit.

Miller, B.D. and Miltenberger, M.A. 2001. "The effects of corrosion-inhibiting admixtures on chloride transport in concrete." In Ion and Mass Transport in Cement-Based Materials, (Ed. Hooton et al.), American Ceramic Society, Westerville OH, pp. 367-376.

Miltenberger, M., Luciano, J., and Miller, B., 1999. "Comparison of Chloride Diffusion Coefficient Tests for Concrete", Proceedings of the 8th International Conference on Durability of Building Materials and Components, National Research Council Canada, Ottawa.

Nmai, C.K., and McDonald, D. 1999. "Long-term Effectiveness of Corrosion-Inhibiting Admixtures and Implications on the design of Durable Reinforced Concrete Structures: A Laboratory Investigation", RILEM International Symposium on The Role of Admixtures in High Performance Concrete, Monterrey, Mexico.

NTBuild, 1995. NordTest Method for Accelerated Chloride Penetration Into Hardened Concrete, NTBuild 443.

Pun, P. 1997. Influence of Silica Fume on Chloride Resistance of Concrete, M.A.Sc. Thesis, University of Toronto.

Pyc, W.A., Weyers, R.E., Sprinkel, M.M., Weyers, R.M., Mokarem, D.W. and Dillard, J.G., 2000. "Performance of Epoxy Coated Reinforcing Steel ", Concrete International, Vol. 22 (2), pp.57-64.

Rushing, Amy S., and Fuller, Sieglinde K., *Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis*, NISTIR 85-3273-18. Gaithersburg, MD: National Institute of Standards and Technology, April 2006

Saetta, A., Scotta, R., and Vitaliani, R. 1993. "Analysis of chloride diffusion into partially saturated concrete." ACI Materials Journal, Vol. 90 (5), pp. 441-451.

Sandberg, P. Recent Studies of Chloride Ingress in Uncracked Marine Concrete at various Exposure times and Elevations, Report TVBM-3080 Lund University Lund Institute of Technology, Division of Building Materials

Sandberg, P. and Tang, L. 1994. "A Field Study of the Penetration of Chlorides and Other Ions into a High Quality Concrete Marine Bridge Column", Concrete Durability (Ed. V. M. Malhotra), ACI SP-145, American Concrete Institute, Detroit, pp. 557-571.

Sandberg, P., Pettersson, K. and Jorgensen, O. 1996. "Field Studies of Chloride Transport into High Performance Concrete" Performance of Concrete in a Marine Environment, ACI SP-163, American Concrete Institute, Detroit, pp. 233-254.

Sherman, M.R., McDonald, D.B., and Pfeifer, D.W. 1996. "Durability Aspects of Precast, Prestressed Concrete Part 2: Chloride Permeability Study" PCI Journal, Vol. 41 (4).

Stanish, K. 2000. Predicting the Diffusion Coefficient of Concrete from Mix Parameters, University of Toronto Report.

Steen, P.E. 1995. "Chloride Penetration in Marine Environment Part 2: Results from Field Test on Coastal Bridges in Norway", Proceedings of the Nordic Seminar in Lund: Corrosion of Reinforcement: Field and Laboratory Studies for Modelling and Service Life, Feb 1-2, 1995.

Tang, L. and Nilsson, L-O. 1992. "Chloride diffusivity in high strength concrete at different ages." Nordic Concrete Research, pp. 162-171.

Tang, L. and Sorensen, H.E. 1998. Evaluation of the Rapid Test Methods for Measuring the Chloride Diffusion Coefficients of Concrete, Nordtest Project No. 1388-98, SP Report 1998:42.

Thomas, M.D.A. and Bamforth, P.B. 1999. "Modelling chloride diffusion in concrete; effect of fly ash and slag." Cement and Concrete Research, Vol. 29, pp. 487-495.

Titherington, M.P. 1998. The Influence of Steam Curing on the Chloride Resistance of High Performance Concrete, M.A.Sc. Thesis, University of Toronto.

Tuutti, K. 1982. "Corrosion of steel in concrete." Swedish Cement and Concrete Research Institute, Report No. 4-82.

Weyers, R.E., Fitch, M.G., Larsen, E.P., Al-Quadi, I.L., Chamberlin, W.P., and Hoffman, P.C., 1993. Concrete Bridge Protection and Rehabilitation: Chemical Physical Techniques, Service Life Estimates, SHRP-S-668, Strategic Highway Research Program, National Research Council, Washington, D.C., 357 p.

Weyers, R.E. 1998. "Service life model for concrete structures in chloride laden environments." ACI Materials Journal, Vol. 95 (4), pp. 445-453.

Weyers, R.E., Pyc, W., and Sprinkel, M.M. 1998. "Estimating the Service Life of Epoxy Coated Reinforcing Steel", ACI Materials Journal, Vol. 95 (5), pp. 546-557.

Appendix A. Test Protocols for Life-365 Input Parameters

Background

Life-365 is a corrosion service-life calculation tool that contains algorithms to estimate “best guess” values for many input parameters. These default values are provided to users simply as a place to start. The default value algorithms were developed from experimental data and peer reviewed journal articles. However, developing default values for all potential products and combinations of materials was not practical. Default values were included for protection strategies with sufficient published performance data to model reliably. It is envisioned that additional strategies will be included in future versions of the software.

The limitations of this approach were recognized by the model developers, so the “User Defined Scenario” option was created to allow users to evaluate alternative strategies by entering project or product-specific data. This appendix is intended to guide the individual selecting values for the “User Defined Scenario” option. It is recommended to obtain the input parameters for Life-365 through the test protocols outlined herein.

The input parameters used to calculate the time to corrosion damage in Life-365 are:

1. Maximum surface chloride content, C_{max}
2. The rate of surface chloride build-up, k
3. The sealer efficiency factor, e
4. The concrete temperature history
5. The concrete cover, x_d
6. The apparent chloride diffusion coefficient, D_{28}
7. The diffusion coefficient decay constant, m
8. The critical chloride threshold for corrosion initiation, C_t
9. The corrosion propagation time, t_p

Commentary and Recommended Test Protocols

Maximum surface chloride concentration, C_{max}

The maximum surface concentration, C_{max} , is a function of the environment and concrete porosity. Theoretically, C_{max} is the amount of chloride at the concrete surface. In practice, the surface concentration is determined from the chloride content of the outer 5 to 10 mm of concrete. The default values used in Life-365 were developed through experience, but can be adjusted by entering appropriate values in the “Structure/Exposure Conditions” dialog box. Adjustments to C_{max} are justified when concrete is placed in non-typical environments such as highly concentrated or dilute brine solutions, chloride contaminated soils, or when local data indicates that the default values are unreasonable or unjustified.

Theoretical maximum surface concentrations can be calculated from the solution concentration, the solution density, the concrete porosity, and the concrete density. For example, seawater has a chloride concentration of approximately 2% chloride by mass and has a density of approximately 1.01 kg/L. If the concrete porosity is 15% by volume, and has a density of 2.30 kg/L, the theoretical maximum is:

$$C_{max} = 0.02 \times 1.01 \times 0.15 \div 2.30 \times 100 = 0.13 \%$$

This theoretical example calculation would apply to a marine structure below the water line, but the critical location is the tidal zone where the concrete is exposed to cyclic wetting and drying. During the drying cycle, salt crystallization occurs in the concrete pores so the chloride concentration is much higher, typically around 0.8 %. Therefore, appropriate adjustments to the design values should be based on surface-chloride content determinations from structures in similar environments. Typically, C_{max} values are less than 1.0% by mass of concrete in uncracked structures.

Surface chloride build-up rate, k

The rate of chloride build-up applies to structures in environments such as bridges and parking structures exposed to periodic deicing salt application, or to structures exposed to air-borne chloride such as beachfront high-rise balconies. This parameter is influenced by wash-off from rainfall or maintenance, and by treatments containing hydrophobic compounds such as sealers. The default values in Life-365 are based on deicing salt application. The geographic variation in North America is indicated in Figure 4.2 in the Manual.

Changes to k affect the time to reach C_{max} . Users can change k using the “Structure/Exposure Conditions” dialog box, or the sealer efficiency factor.

The appropriate test protocol for determining the base build-up rate for ordinary hydraulic cement concrete in a particular environment is:

1. Obtain concrete powder samples from a representative specimen using a rotary drill and a bit with a diameter 1.5 times the maximum aggregate size.
2. Obtain a minimum powder sample of 5 grams. This mass can be obtained by carefully collecting the powder from a 5 to 10-mm deep hole.
3. A minimum of 5 powder samples should be taken from the surface of a structure at each age.
4. The total chloride content of the powder samples should be obtained in accordance with AASHTO T260.
5. The initial chloride content should be subtracted from the total chloride measurement to obtain the adjusted surface chloride content.
6. Record the mean and standard deviation of the adjusted surface chloride content for the structure.
7. Repeat steps 1 through 6 at least 3 times during the first 5 years of exposure. Preferably, sampling should continue on a regular basis thereafter.

8. The “best-fit” slope of the time vs. adjusted surface chloride content plot is the build-up rate for the structure. This base build-up rate is entered in the “Structure/Exposure Conditions” dialog box.

Important considerations:

- Rain or maintenance wash downs will reduce the surface concentration.
- Salt crystallization in cracks will increase the surface concentration.
- Areas which puddle will have higher surface concentrations
- The mean build-up rate for several structures in a region should be used.
- The build-up rate for any particular structure will vary over time. It is common for chloride to build-up rapidly during the first couple years, and then stabilize.

The sealer efficiency factor, e

The appropriate test protocols for determining the impact of a surface treatment product on the build-up rate should include tests on capillary absorption and the relative chloride build-up from a cyclic-ponding exposure history.

Capillary absorption is the primary mechanism by which chloride is drawn into the concrete surface, and it is therefore indicative of the relative build-up rate. Products that impart hydrophobic properties to the concrete surface such as sealers should be tested in accordance with the procedures outlined in NCHRP 244 Series II. The initial efficiency factor is calculated as the percent reduction in chloride content in the treated concrete relative to the untreated concrete after 21 days of soaking in 15% NaCl solution.

For example, the data from NCHRP 244 Table B-30 indicates the reference concrete gained 0.235% and silane treated concrete had gained 0.050%. The initial efficiency factor, e , is therefore 0.787 or 79 percent.

$$e = (0.235 - 0.050) \div 0.235 = 0.787$$

If the efficiency is expected to degrade over time, confirmation of the product’s effectiveness should be obtained in a similar manner. In such cases, the sealer efficiency should be tested as a function of time, or depth of abrasion.

The relative chloride build-up from a cyclic-ponding exposure history is also an appropriate means to verify the efficiency factor. Chloride content data obtained from a controlled comparative study such as the ASTM G109 procedure, or from side-by-side field exposure studies is acceptable. The relative rate of chloride build-up should be calculated from samples representative of the top 10-mm of concrete that have been corrected for the initial chloride content, as described above. Side-by-side exposure panels are particularly suitable in situations where environmental conditions may have effects on sealer installation.

Concrete temperature history

The default values used for the concrete temperature history are 30-year normal mean monthly air temperatures for North America. The user can change these values using the “Structure/Detailed Temperature” dialog box.

Concrete cover, x

The depth of concrete cover varies within a structure. This is a user-defined input. The user should select an appropriate value. Users should verify the concrete cover distribution obtained in a structure using appropriate non-destructive survey techniques.

Apparent chloride diffusion coefficient, D_{28}

There are numerous test methods being used to determine the chloride diffusion coefficient for concrete, but each method produces a slightly different numerical result. In the absence of an ASTM standard, the model developers adopted the Norwegian standard method, NT BUILD 443, for Life-365. This laboratory procedure calculates D_{28} directly from a chloride content profile.

The method to obtain the D_{28} reference value is summarized as:

1. After 28 days standard laboratory curing, a specimen is surface dried and coated with epoxy paint on all surfaces except the finished surface.
2. The specimen is then immersed in a sealed container of chloride solution for 35 days.
3. Concrete powder is obtained by dry grinding six 2-mm thick layers from the specimen.
4. The total chloride content of the powder samples and initial (background) chloride content is obtained.
5. The initial (background) chloride content is subtracted from the measured total chloride content.
6. The chloride diffusion coefficient is back calculated from the adjusted chloride content-depth data.

If the user desires to obtain D_{28} from other methods, correlation between the alternate method and NT BUILD 443 must be established.

It is important to note that the NT BUILD 443 test method is a laboratory test performed under saturated conditions. In this controlled environment, chloride diffusion is the primary chloride transport mechanism. Concrete structures that are partially saturated may experience chloride ingress from multiple transport mechanisms. Therefore, the diffusion coefficient back calculated from sampling structures is generally not an appropriate input for Life-365.

A copy of NT BUILD 443 test can be requested from Nordtest via:

E-mail: nordtest@vtt.fi

Diffusion coefficient decay constant, m

The chloride diffusion coefficient for concrete reduces over time when sufficient moisture is available for continued hydration. Life-365 captures the effect of continued hydration as described in Eqn. 8 using the decay constant, m . The diffusion coefficient must be obtained using NT BUILD 443 at several points in time to calculate m . The value of m is the negative of the slope of the diffusion coefficient-time data when plotted as log time vs. log D .

Since the rate of hydration is more rapid at early ages than at later ages, it is imperative that calculation of m includes data for concrete at least 5 years old. The minimum testing requirement is NT BUILD 443 tests at 28 days, 1 year, and 5 years age. Preferably, the concrete should be stored prior to testing in an environment that is similar to that of the intended structure, without exposure to chloride.

Critical chloride threshold for corrosion initiation, C_i

The corrosion threshold concentration of chloride is influenced by numerous variables, and is therefore not a singular value. The C_i values selected for defaults in Life-365 are conservative estimates and are consistent with the results presented in numerous publications.

There currently is no standard test procedure to determine the chloride threshold in concrete. However, reasonable assessment of the chloride threshold values can be obtained from a properly conducted ASTM G 109 test, with the following modifications:

1. Cast a minimum of three additional specimens containing reinforcement and three unreinforced specimens for destructive chloride content measurements. Pair each unreinforced specimen with a reinforced specimen because corrosion activity will likely initiate at different times in each specimen.
2. Monitor the total corrosion current using linear polarization along with the standard macrocell current and half-cell potential measurements.
3. At the first sign of corrosion activity, obtain the chloride content at the reinforcing steel level in the companion unreinforced specimen. Corrosion activity is indicated by (1) a sharp reduction in half-cell potential, (2) the presence of a macrocell current, and/or (3) a sharp reduction in the polarization resistance.
4. Verify corrosion visually and determine the chloride content at the reinforcement level in the reinforced specimen when an integrated macrocell current of 75 coulombs is obtained. Stable corrosion activity is typically present at this point.
5. If corrosion exists only under the end treatment, the chloride content measurements from the pair of specimens is discarded.

6. If more than 95% of the visual corrosion exists in the exposed section, the chloride threshold value can be calculated as the average of the adjusted chloride contents determined from the pair of specimens. In the absence of crevice corrosion under the end treatment, the chloride threshold value is determined by the average of the six chloride content measurements.

The important factors to consider when evaluating chloride threshold test results:

1. Electrically accelerated tests change the environment adjacent to the reinforcing steel and can provide erroneous results.
2. Galvanic corrosion can contribute to premature failures.
3. Bar preparation prior to casting specimens can influence the test results.
 - Bar preparation techniques that minimize crevice corrosion under end treatments are critical.
 - Crevice corrosion at the end treatment can cause premature failures.
 - The presence of mill scale on the reinforcing will produce lower chloride threshold values.
4. Corrosion is a random phenomenon, so multiple specimens are necessary.
5. Reinforcing steel composition is variable, so tests on different heats of steel will produce different absolute values.
6. Corrosion requires the presence of oxygen and moisture. Concrete that is dry, totally saturated, sealed, or has low water and oxygen permeability will have a higher chloride threshold.
7. The chloride threshold is influenced by the pH of the surrounding concrete. When the pH drops below 11, corrosion of steel will initiate without chloride.
8. Visual observation of corrosion must accompany any test method to properly interpret half-cell potential and macrocell corrosion measurements.
9. Admixed chloride interferes with some corrosion inhibition mechanisms.

Corrosion propagation time, t_p

Presently, there are only a few published studies documenting the impact of corrosion rate on the time from corrosion initiation to cracking. In addition, there is no industry accepted test procedure for the measurement of t_p . Until an acceptable industry standard is developed, the corrosion propagation time may be measured by subjecting the specimens to continued cyclic ponding according to ASTM G 109 type specimens until cracking or delamination is detected.

Continued research on this topic is necessary to advance modeling efforts.

In the absence of an industry accepted mechanistic model that incorporates the volume of reinforcing, the concrete strength, the depth of cover, and corrosion rate, Life-365 has

allocated a fixed time period value for corrosion propagation. Users opting to modify this value should do so based on experience with similar structures in similar environments.

Table 7. Model Inputs and Test Conditions

Model Input	Test Requirement	No. Tests	Frequency	Comments
Concrete Cover, x	Cover depth survey (Mean and std.deviation)	1/project (Data needed to establish variability baseline)	Initial	Calibrate rebar locator for resistivity of concrete mixture!
Surface Chloride Build-up Rate, k Max. Conc., Cs	AASHTO T260 Acid-Soluble	1/500 ft ² or 5 minimum per element	Initial, at 2 years, then every 5 years	Drill & collect 5 grams of powder from 5 to 10-mm deep hole with drill diameter ≥ 1.5 max aggregate size.
Sealer efficiency, e	NCHRP 244 Series II	1/application area	Initial	verify reduced absorption prior to reapplication
Diffusion Coefficient Also need: Chloride profile Mixture proportions	Bulk Diffusion, Da (Develop correlation for alternate methods)	Set of 2 at regular interval initially, then 2 cores min. per later sampling (Initial data needed to establish variability, subsequent tests for D changes over time)	Initial, at 1 year, then every 5 years (minimum of 3 tests at above times required to calculate m)	Result depends on the method D changes with age Environment effects cyclic wetting and drying chloride profiles Absorption causes build-up
Chloride Threshold Ct	Modified ASTM G 109 Visual evidence & chloride profiles (see text)	Minimum of 6 specimens per test (see text)	Replicate test program to confirm values desirable	Too late if staining, cracking and delamination are visible.
Corrosion rate/ propagation time tp	Linear polarization and Continuation of ASTM G 109 until cracking	Research needed	Research needed	Research needed