Life-365™ Service Life Prediction Model™

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

Version 2.2.3

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Produced by the Life-365™ Consortium III

Life-365^{TM} v1.0 and v2.2.3 Credits

The 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™ v2.2.3 program and manual are adaptations of these documents, and were written by M. A. Ehlen, Ph.D. under contract to the Life-365 Consortium III, which consists of Master Builders, Cortec, Epoxy Interest Group (Concrete Reinforcing Steel Institute), Euclid Chemical, Grace Construction Products, National Ready-mixed Concrete Association, Sika Corporation, Silica Fume Association, Slag Cement Association

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Life-365™ Disclaimer

The Life-365™ Manual and accompanying Computer Program are intended for guidance in planning and designing concrete structures exposed to chlorides while in service. They are intended for use by 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 Manual and Computer Program 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 so as to fully understand the capabilities and limitations of the Life-365™ Service Life Prediction Model™ and 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 infrastructure repair and replacement. There are currently numerous strategies available for increasing the service life of reinforced structures exposed to chloride salts, including 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. Life-365 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 construction costs, it may still reduce life-cycle cost by lowering future repair costs.

A number of models for predicting the service life of concrete structures exposed to chloride environments or for estimating life-cycle cost of different corrosion protection strategies have been developed 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 caused some concern among the engineering community in the 1990s and in response, 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.

Another mechanism that results in corrosion of steel is carbonation of the concrete cover and the reduction of pH at the level of the reinforcing steel. Corrosion due to carbonation is a relatively

low probability and is generally associated with lower quality concrete and reduced cover. The Life-365 Service Life Prediction Model does not cover carbonation.

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 their own user-defined scenarios in tandem with minor adjustments to the values (e.g. D_{28}, m, C_t, 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 the values.

This manual is divided into five parts:

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

2. **User Manual.** This section is an operator's manual that gives instructions on how to use Life-365, the input parameters required, and the various options available to the user.

3. **ASTM C1556 Module.** This section describes how Life-365 provides and uses the ASTM C1556 process of estimating maximum surface chloride concentration based on calculations from field data.

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

5. **Appendix A. Test Protocols for Input Parameters.** This section provides recommended protocols for determining some of the input parameters used in Life-365.

2 Life-365™ Service Life Prediction Model™

Life-365 analyses can be divided into four sequential steps:

- Predicting the time to the onset of corrosion of reinforcing steel, 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 cost 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_t, 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.

2.1.1 Predicting Chloride Ingress due to Diffusion

The model predicts the initiation period assuming diffusion to be the dominant mechanism. Given the assumption that there are no cracks in the concrete, Fick's second law is the governing differential equation:

$$\frac{dC}{dt} = D \cdot \frac{d^2C}{dx^2},$$

<div align="right">Eq. 1</div>

where C = the chloride content,

D = the apparent diffusion coefficient,

x = the 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:

$$D(t) = D_{ref} \cdot \left(\frac{t_{ref}}{t}\right)^m,$$

<div align="right">Eq. 2</div>

where $D(t)$ = diffusion coefficient at time t,

D_{ref} = diffusion coefficient at time t_{ref} (= 28 days in Life-365), and

m = diffusion decay index, a constant.

Life-365 selects values of D_{ref} and m based on the details of the composition of the concrete mixture (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 from continually decreasing with time, the relationship shown in Eq. 2 is assumed to be only valid up to 25 years, beyond which $D(t)$ stays constant at the D(25 years) value.

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

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

where | $D(T)$ | = | diffusion coefficient at time t and temperature T,
D_{ref} = diffusion coefficient at time t_{ref} and temperature 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} = 293K (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 temperature data available for the location.

The chloride exposure conditions (e.g., rate of chloride buildup at the surface and maximum chloride content) are set by the model based on one of three alternate approaches:

1. Life-365 provides a database of values 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 (e.g., New York, NY).

2. The user can input their own data for these parameters.

3. The user can calculate a maximum surface concentration based on measured chloride levels using ASTM C1556 (and input their own data on time to buildup).

The solution for time to initiation of corrosion is carried out using a finite difference implementation of Eq. 1 where the value of D is modified at every time step using Eq. 2 and Eq. 3.

2.1.2   Input Parameters for Predicting the Initiation Period

The following inputs are required to predict the initiation period:

*   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 supplementary cementitious materials and corrosion inhibitors, type of steel and coatings, and type and properties 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_{maxp}, based on the type of structure, its geographic location, and exposure, as input by the user. For example, if the user selects a bridge deck in an urban area of Moline, Illinois, the model will use the surface concentration profile shown in the left panel of Figure 2.1. Alternatively, the user can input his own profile, in terms of maximum surface concentration and the time (in years) to reach that maximum. Life-365 v2.2.3 includes the additional ability to input a maximum surface concentration based on ASTM C1556 data calculations.
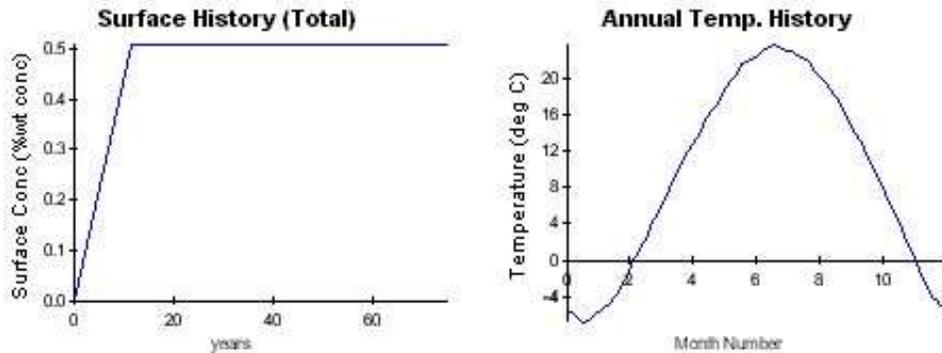
Figure 2.1. Examples of Concrete Surface History and Environmental Temperatures

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 selects Moline, Illinois, the model will use the temperature profile in the right panel in Figure 2.1. Alternatively, the user can input temperature profile relevant to the location, in terms of monthly average temperatures in either degrees Celsius (if the project is using SI units) or degrees Fahrenheit (if the project is using US units).

Base Case Concrete Mixture

The base case concrete mixture assumed by the model is plain portland cement concrete with no special corrosion protection strategy. For the base case, the following values are assumed:

$$D_{28} = 1 \times 10^{(-12.06 + 2.40w/cm)} \text{ meters-squared per second (m}^2\text{/s)} , \qquad \text{Eq. 4}$$

$$m = 0.20, \text{ and} \qquad \text{Eq. 5}$$

$$C_t = 0.05 \text{ percent (\% wt. of concrete).} \qquad \text{Eq. 6}$$

The relationship between D_{28} and the water-cementitious materials ratio (w/cm) is based on a large database of bulk diffusion tests. The nature of the relationship is shown in Figure 2.2 (corrected to 20°C). The value of m is based on data from the University of Toronto and other published data and decreases the diffusion coefficient over the course of 25 years, after which point Life-365 holds it constant at the 25-year value, to reflect the assumption that hydration is complete. The

value of C_t is commonly used for service-life prediction purposes (and is close to a value of 0.40 percent chloride based on the mass of cementitious materials for a typical concrete mixture used in reinforced concrete structures).
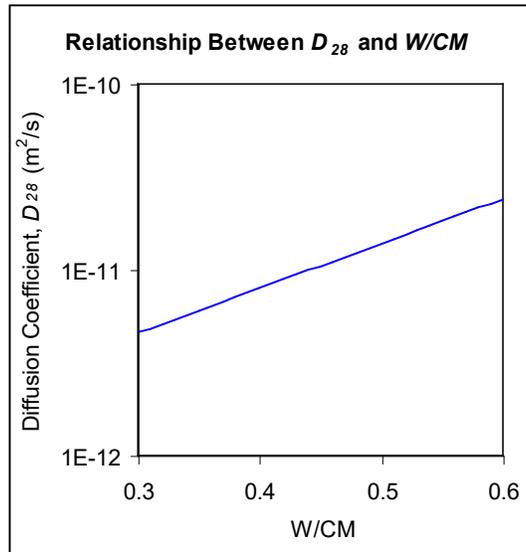
Figure 2.2. Relationship Between D_{28} and w/cm

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:

$$D_{SF} = D_{PC} \cdot e^{-0.165 \cdot SF}. \qquad \text{Eq. 7}$$

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

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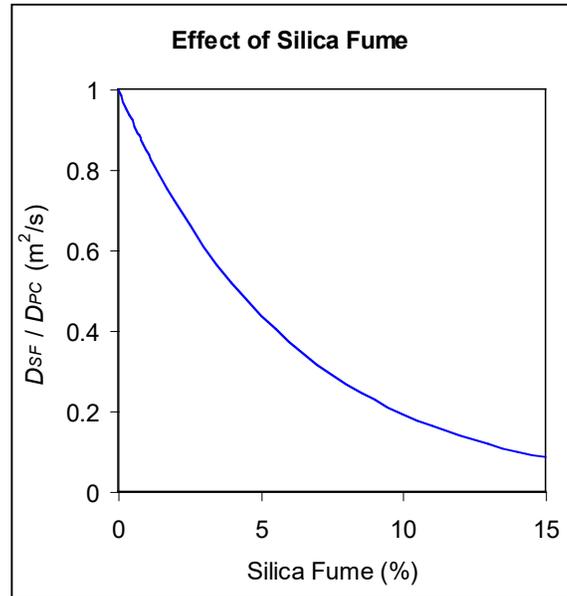
Figure 2.3. Effect of Silica Fume on D_{SF}

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 affect 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 mixture:

$$m \quad = \quad 0.2 + 0.4(\%FA/50 + \%SG/70). \qquad \text{Eq. 8}$$

The relationship is only valid up to replacement levels of 50 percent fly ash or 70 percent slag and m itself cannot exceed 0.60 (which would occur if fly ash and slag were used at these maximum levels), that is, m must satisfy $m \le 0.60$. Life-365 will not compute diffusion values (or make service life predictions) for higher levels of these materials, and after 25 years holds the diffusion constant at the 25-year value to reflect that hydration is complete.

Figure 2.4 shows the effect of m for three mixtures with *w/cm* = 0.40 and with plain portland cement (PC), 30 percent slag, and 40 percent fly ash. Table 1 lists these mixture proportions and their computed the diffusion coefficients, for 28 days, 10 years, and 25 years. For years greater than 25, Life-365 uses the computed 25-year diffusion coefficient.
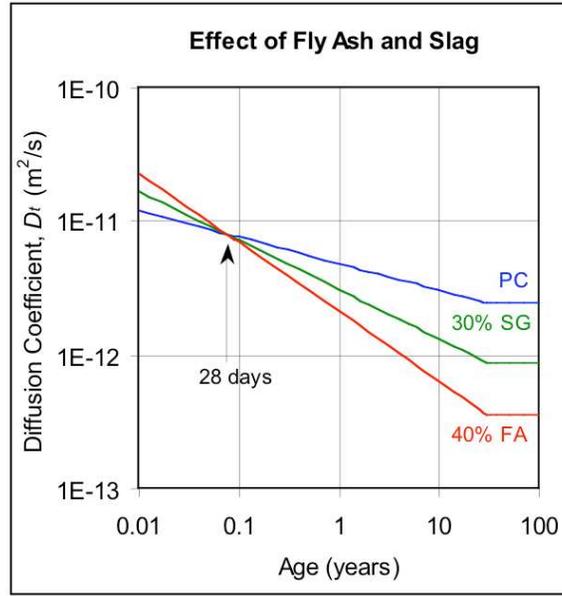
Figure 2.4. Effects of Fly Ash and Slag on D_t

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

	m (<=0.60)	D_{28} (x 10^{-13} m²/s)	D_{10y} (x 10^{-13} m²/s)	D_{25y} (x 10^{-13} m²/s)
PC	0.20	79	30	25
30 percent SG	0.37	79	13	9.3
40 percent 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 other types of inhibitors can be included in the model when appropriate documentation of their performance becomes available.

Ten dosage levels of 30 percent 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.

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Table 2. Effects of CNI on Threshold

CNI Dose		Threshold, C_t (% wt. conc.)
liters/m³	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

In addition, 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 liters/m³ concrete. This dose of the admixture is assumed to modify the corrosion threshold to $C_t = 0.12$ percent (by mass of concrete). Furthermore, it is also assumed that the initial diffusion coefficient is reduced to 90 percent 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: Life-365 assumes that both membranes and sealers only impact the rate of chloride buildup and can only be reapplied up to the time of the first repair. Membranes start with an efficiency of 100 percent, which deteriorates over the lifetime of the membrane; a lifetime of 20 years; and no re-applications. 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. As shown in the left panel of Figure 2.5, surface chlorides for unprotected concrete (labeled "PC") increases at a rate of 0.04 percent per annum and reaches a maximum concentration of 0.60 percent at 15 years. In the right panel, surface chlorides for concrete protected by a default membrane increase at a lower rate, but then reach the same rate after 20 years. The user can also set his own values for initial efficiency, lifetime of the membrane, and re-applications.
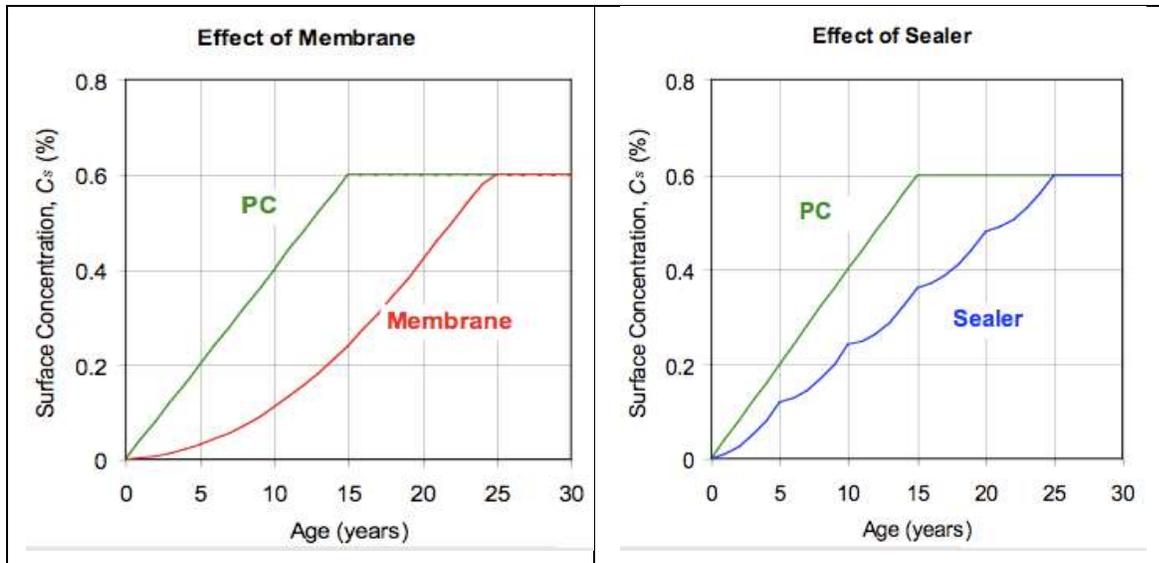
Figure 2.5. Effects of Membranes and Sealers

Sealers are dealt with in the same way, except that the default lifetime is only 5 years. The example in Figure 2.5 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 percent per annum in the example) at the selected lifetime of the sealer (5 years in the example).

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 increasing the propagation period, t_p, from 6 years to 20 years.

Effect of Stainless Steel

In the current version of Life-365 it is assumed that grade 316 stainless steel has a corrosion threshold of $C_t = 0.50$ percent (i.e., ten times the black steel C_t of 0.05 percent).

2.1.3   Initiation-Period Fickian Solution Procedures

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 of chlorides around the concrete member is constant, for any given point in 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.

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- For concrete slabs (one-dimension calculations), the diffusion process is only active in the top portion of the slab and therefore only modeled in Life-365 in the top 10 inches of a slab that is deeper than that (Figure 2.6).

Depth modeled = 10.00
2.00 in
30.00 in
Life-365™ will model service life for depths up to 10.0; see Users Manual for discussion.
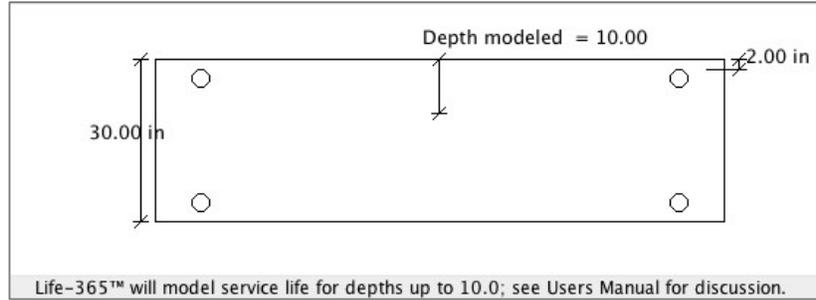
Figure 2.6. Limited Modeling of Diffusion in Slabs Deeper than 10 Inches

One-Dimension Calculations (Walls and Slabs)

For the one-dimensional slabs and walls, the time-to-initiation is estimated deterministically using a one-dimensional Crank-Nicolson finite difference approach, where the future levels of chlorides in the concrete are a function of current chloride levels. Specifically, the level of chloride at a given slice of the concrete i and next time period $t+1$ is determined by

$$-ru_{i+1}^{t+1} + (1+2r)u_i^{t+1} - ru_{i-1}^{t+1} = ru_{i+1}^{t} + (1-2r)ru_i^{t} + ru_{i-1}^{t},$$

where

$r \quad = \quad d^t \dfrac{(dt)}{2(dx)^2}$ is dimensionless Courant–Friedrichs–Lewy (CFL) number,

d^t = the diffusion coefficient at time t, in meters-squared per second,

dt = the time step, in seconds,

dx = the distance increment (total depth divided by number of slices),

u_i^t = chloride level (%wt of concrete) at time t and slice i,

$i \quad = 1,..., I$ is the particular slice of concrete (and $i = 0$ is the top slice that holds the external concentration of chlorides), and

$t \quad$ = the time step in the initiation-to-corrosion period.

Rearranging terms and putting them in matrix form, the chloride levels at each time period $t+1$ are solved from the equation

$$AU^{t+1} = BU^t,$$

where

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$$A = \{a_i^{t+1}\} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ -r & 1+2r & -r & 0 & 0 \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ 0 & 0 & -r & 1+2r & -r \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix},$$

$$U^{t+1} = \{u_i^{t+1}\} = \begin{vmatrix} u_1^{t+1} \\ \ldots \\ u_i^{t+1} \\ \ldots \\ u_I^{t+1} \end{vmatrix},$$

$$B = \{b_i^{t+1}\} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ r & 1-2r & r & 0 & 0 \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ 0 & 0 & r & 1-2r & r \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}, \text{ and}$$

$$U^t = \{u_i^t\} = \begin{vmatrix} u_1^t \\ \ldots \\ u_i^t \\ \ldots \\ u_I^t \end{vmatrix}.$$

The individual $u_{i,j}^{t+1}$ are then be solved by rearranging terms:

$$U^{t+1} = A^{-1}BU^t.$$

The number r is required to be small for numerical accuracy.

Two-Dimension Calculations (Square and Round Columns)

For two-dimensional columns, the time-to-initiation ideally can be estimated using a two-dimensional Crank-Nicolson equation:

$$(1+2r)u_{i,j}^{t+1} - \frac{r}{2}\left(u_{i-1,j}^{t+1} + u_{i+1,j}^{t+1} + u_{i,j-1}^{t+1} + u_{i,j+1}^{t+1}\right) = (1-2r)u_{i,j}^t$$

Eq. 9

$$+ \frac{r}{2}\left(u_{i-1,j}^t + u_{i+1,j}^t + u_{i,j-1}^t + u_{i,j+1}^t\right)$$

where each term is defined as in the one-dimensional case above, but where each $\{i, j\}$ term is a square from the ith row and jth column of a square matrix of terms. Since the chloride surface concentrations and interior steel locations are symmetric to the vertical and horizontal centerlines of the column cross-section, we can solve using just one quadrant of the cross-section. As shown

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in Figure 2.7, we use the upper left quadrant, where the "surface" cells are the external levels of chloride, and therefore exogenous parameters in the calculations, and the "interior" cells are those to be calculated.

$$\begin{bmatrix} \text{surface} & \text{surface} & \text{surface} & \text{surface} \\ \text{surface} & \text{interior (a)} & \text{interior (a)} & \text{interior (b)} \\ \text{surface} & \text{interior (a)} & \text{interior (a)} & \text{interior (b)} \\ \text{surface} & \text{interior (c)} & \text{interior (c)} & \text{interior (d)} \end{bmatrix}$$

Figure 2.7. Single Quadrant in 2D Column

Also due to symmetry, we can represent the interior cells (those that need to be calculated) by using reflections of certain values; specifically, particular $u_{i,j}^{t+1}$ values in Eq. 9 above are represented by their mirror value.

1. Interior (a) points are solved for using Eq. 9 above.
2. Interior (b) points are solved for using the following modified version:

$$(1+2r)u_{i,j}^{t+1} - \frac{r}{2}\left(u_{i-1,j}^{t+1} + u_{i+1,j}^{t+1} + u_{i,j-1}^{t+1} + u_{i,j-1}^{t+1}\right) = (1-2r)u_{i,j}^{t}$$

$$+ \frac{r}{2}\left(u_{i-1,j}^{t} + u_{i+1,j}^{t} + u_{i,j-1}^{t} + u_{i,j-1}^{t}\right)$$

Eq. 10

3. Interior (c) points are solved for using the following modified version:

$$(1+2r)u_{i,j}^{t+1} - \frac{r}{2}\left(u_{i-1,j}^{t+1} + u_{i-1,j}^{t+1} + u_{i,j-1}^{t+1} + u_{i,j+1}^{t+1}\right) = (1-2r)u_{i,j}^{t}$$

$$+ \frac{r}{2}\left(u_{i-1,j}^{t} + u_{i-1,j}^{t} + u_{i,j-1}^{t} + u_{i,j+1}^{t}\right)$$

Eq. 11

4. Interior (d) points are solved for using the following modified version:

$$(1+2r)u_{i,j}^{t+1} - \frac{r}{2}\left(u_{i-1,j}^{t+1} + u_{i-1,j}^{t+1} + u_{i,j-1}^{t+1} + u_{i,j-1}^{t+1}\right) = (1-2r)u_{i,j}^{t}$$

$$+ \frac{r}{2}\left(u_{i-1,j}^{t} + u_{i-1,j}^{t} + u_{i,j-1}^{t} + u_{i,j-1}^{t}\right)$$

Eq. 12

As an example, to solve the interior points at time $t+1$ for the 9 interior cells in Figure 2.7, we have 9 equations and 9 unknowns, where the variables are declared according to Figure 2.8.

$$\begin{bmatrix} \bar{u}_{0,0} & \bar{u}_{0,1} & \bar{u}_{0,2} & \bar{u}_{0,3} \\ \bar{u}_{1,0} & \bar{u}_{1,1} & \bar{u}_{1,2} & \bar{u}_{1,3} \\ \bar{u}_{2,0} & \bar{u}_{2,1} & \bar{u}_{2,2} & \bar{u}_{2,3} \\ \bar{u}_{3,0} & \bar{u}_{3,1} & \bar{u}_{3,2} & \bar{u}_{3,3} \end{bmatrix}$$

Figure 2.8. Single Quadrant Variables in 2D Column

To help simplify the equations, given that at time $t+1$ all t values are known, the right-hand side of each equation can be represented by a function

$$\bar{u}_{i,j}(t) = (1-2r)u_{i,j}^t + \frac{r}{2}\left(u_{i-1,j}^t + u_{i+1,j}^t + u_{i,j-1}^t + u_{i,j+1}^t\right),$$

the nine equations are then:

$$(1+2r)u_{1,1}^{t+1} - \frac{r}{2}\left(u_{0,1}^{t+1} + u_{2,1}^{t+1} + u_{1,0}^{t+1} + u_{1,2}^{t+1}\right) = \bar{u}_{1,1}(t)$$

$$(1+2r)u_{1,2}^{t+1} - \frac{r}{2}\left(u_{0,2}^{t+1} + u_{2,2}^{t+1} + u_{1,1}^{t+1} + u_{1,3}^{t+1}\right) = \bar{u}_{1,2}(t)$$

$$(1+2r)u_{1,3}^{t+1} - \frac{r}{2}\left(u_{0,3}^{t+1} + u_{2,3}^{t+1} + u_{1,2}^{t+1} + u_{1,2}^{t+1}\right) = \bar{u}_{1,3}(t)$$

$$(1+2r)u_{2,1}^{t+1} - \frac{r}{2}\left(u_{1,1}^{t+1} + u_{3,1}^{t+1} + u_{2,0}^{t+1} + u_{2,2}^{t+1}\right) = \bar{u}_{2,1}(t)$$

$$(1+2r)u_{2,2}^{t+1} - \frac{r}{2}\left(u_{1,1}^{t+1} + u_{3,1}^{t+1} + u_{2,1}^{t+1} + u_{2,3}^{t+1}\right) = \bar{u}_{2,2}(t) \qquad \text{Eq. 13}$$

$$(1+2r)u_{2,3}^{t+1} - \frac{r}{2}\left(u_{1,1}^{t+1} + u_{3,1}^{t+1} + u_{2,2}^{t+1} + u_{2,2}^{t+1}\right) = \bar{u}_{2,3}(t)$$

$$(1+2r)u_{3,1}^{t+1} - \frac{r}{2}\left(u_{2,1}^{t+1} + u_{2,1}^{t+1} + u_{3,0}^{t+1} + u_{3,2}^{t+1}\right) = \bar{u}_{3,1}(t)$$

$$(1+2r)u_{3,2}^{t+1} - \frac{r}{2}\left(u_{2,2}^{t+1} + u_{2,2}^{t+1} + u_{3,1}^{t+1} + u_{3,3}^{t+1}\right) = \bar{u}_{3,2}(t)$$

$$(1+2r)u_{3,3}^{t+1} - \frac{r}{2}\left(u_{2,3}^{t+1} + u_{2,3}^{t+1} + u_{3,2}^{t+1} + u_{3,2}^{t+1}\right) = \bar{u}_{3,3}(t)$$

To be able to solve for each $u_{i,j}^{t+1}$ through matrix mathematics, the square matrices of $u_{i,j}^{t+1}$ and $u_{i,j}^t$ terms are converted to $(i*j) \times 1$ matrices, e.g.,

$$U^{t+1} = \left\{ u_{i,j}^{t+1} \right\} = \begin{bmatrix} u_{0,0}^{t+1} & u_{0,1}^{t+1} & \cdots & & & & \\ u_{1,0}^{t+1} & u_{1,1}^{t+1} & \cdots & & & & \\ \cdots & \cdots & \cdots & & & & \\ & & & u_{i,j}^{t+1} & & & \\ & & & & \cdots & \cdots & \cdots \\ & & & & \cdots & u_{I-1,J-1}^{t+1} & u_{I-1,J}^{t+1} \\ & & & & \cdots & u_{I,J-1}^{t+1} & u_{I,J}^{t+1} \end{bmatrix} \Rightarrow \dot{U}^{t+1} = \left\{ u_k^{t+1} \right\} = \begin{bmatrix} u_{0,0}^{t+1} \\ u_{0,1}^{t+1} \\ \cdots \\ u_{1,0}^{t+1} \\ u_{1,1}^{t+1} \\ \cdots \\ u_{i,j}^{t+1} \\ \cdots \\ u_{I-1,J-1}^{t+1} \\ u_{I-1,J}^{t+1} \\ \cdots \\ u_{I,J-1}^{t+1} \\ u_{I,J}^{t+1} \end{bmatrix}.$$

For the 9x9 example, then, the $\dot{U}^{t+1}$ vector is

$$\dot{U}^{t+1} = \left\{ u_k^{t+1} \right\} = \begin{bmatrix} \bar{u}_{0,0} \\ \bar{u}_{0,1} \\ \bar{u}_{0,2} \\ \bar{u}_{0,3} \\ \bar{u}_{1,0} \\ u_{1,1} \\ u_{1,2} \\ u_{1,3} \\ \bar{u}_{2,0} \\ u_{2,1} \\ u_{2,2} \\ u_{2,3} \\ \bar{u}_{3,0} \\ u_{3,1} \\ u_{3,2} \\ u_{3,3} \end{bmatrix}$$

and the equations in Eq. 13 can be represented by $A\dot{U}^{t+1}$. The chloride levels at each time period $t+1$ are solved from the equation

$$A\dot{U}^{t+1} = B\dot{U}^t,$$

or

$$\dot{U}^{t+1} = A^{-1}B\dot{U}^t. \qquad \text{Eq. 14}$$

Inverting matrix A, however, is computationally expensive; computing initiation periods could take from 1 to 15 minutes (or longer) per alternative. To overcome this time expense, Life-365 uses a successive relaxation technique (SOC).

Validation of Initiation Period Estimates

Significant work has been conducted to compare the estimates of initiation period calculated by Life-365 v2.2.3 against those of other models. Regarding 1-D (slab and wall) estimates, the Life-365 v2.2.3 estimates have been compared to both Fick's second law Error Function Solutions as well as Life-365 v1.1 estimates. With regard to 2-D square and round columns, the Life-365 v2.2.3 estimates have been compared to Life-365 v1.1 estimates.

For the 1-D case in particular, work has been conducted to compare the Life-365 v2.2.3 estimates (and indirectly the Life-365 v1.1 estimates) of initiation period to Fick's second law error function solution,

$$c(x,t) = c_s\left[1 - erf\left(\frac{x}{\sqrt{4Dt}}\right)\right], \qquad \text{Eq. 15}$$

(where $c(x,t)$ is the concentration at depth x and time t, c_s is the surface concentration, erf is the error function, and D is the diffusion coefficient), which for particular settings are theoretically equivalent.[1] Tests of estimates by the two methods show a good 'fit' of the two concentration values shown in Figure 2.9.[2]

Table 3. Life-365 v2.2.3 and ERF Comparison

#	Slab Depth (mm)	Rebar Depth (mm)	Surface Conc. (%wt)	Init Conc (%wt)	D28 (m*m/s)	L365 Init (yrs)	ERF Init (yrs)	Avg. Diff (%wt)
0	200.0	10.0	1.000	0.050	8.870E-12	0.1	0.1	0.02641412
1	200.0	20.0	1.000	0.050	8.870E-12	0.2	0.2	0.00321595
2	200.0	30.0	1.000	0.050	8.870E-12	0.5	0.5	0.00143871
3	200.0	40.0	1.000	0.050	8.870E-12	0.8	0.8	0.00137160
4	200.0	50.0	1.000	0.050	8.870E-12	1.2	1.2	0.00138123
5	200.0	60.0	1.000	0.050	8.870E-12	1.8	1.8	0.00139729
6	200.0	70.0	1.000	0.050	8.870E-12	2.3	2.3	0.00140854
7	200.0	80.0	1.000	0.050	8.870E-12	3.1	3.1	0.00148045
8	200.0	90.0	1.000	0.050	8.870E-12	3.8	3.8	0.00146977
9	200.0	100.0	1.000	0.050	8.870E-12	4.8	4.8	0.00150216
10	200.0	110.0	1.000	0.050	8.870E-12	5.8	5.8	0.00152166
11	200.0	120.0	1.000	0.050	8.870E-12	6.8	6.8	0.00154075
12	200.0	130.0	1.000	0.050	8.870E-12	8.0	8.0	0.00161298
13	200.0	140.0	1.000	0.050	8.870E-12	9.3	9.2	0.00198084
14	200.0	150.0	1.000	0.050	8.870E-12	10.8	10.7	0.00325238
15	200.0	160.0	1.000	0.050	8.870E-12	12.7	12.1	0.00693507
16	200.0	170.0	1.000	0.050	8.870E-12	15.5	13.7	0.01761402

[1] The Crank Nicolson finite difference approach used in Life-365 v2.2 1-D slab and wall calculation is an approximation to the Fick's Second Law solution and thus an approximation to the error function direct solution. To make the comparison, a particular set of Life-365 v2.2 parameters must be held constant, including the surface concentration over time, the diffusion coefficient over time, and the external temperature over time.

[2] The values shown may not exactly match the current version of Life-365, due to continual refinements being made to the codebase.

#	Slab Depth (mm)	Rebar Depth (mm)	Surface Conc. (%wt)	Init Conc (%wt)	D28 (m*m/s)	L365 Init (yrs)	ERF Init (yrs)	Avg. Diff (%wt)
17	200.0	180.0	1.000	0.050	8.870E-12	22.2	15.3	0.05659158
18	200.0	190.0	1.000	0.050	8.870E-12	500.0	17.1	0.68549250

From left to right, the table lists the depth of slab, depth of reinforcing, constant surface concentration, concentration to initiate corrosion, the constant diffusion coefficient, and then the estimates of initiation period by the two techniques, and the average differences in the values in the graphs exemplified by Figure 2.9. This figure specifically plots the 60 Life-365 point estimates of concentration (one for each 'slice' in the finite difference mesh) against the 'continuous' error function estimates. Finally, it lists whether the ERF value computed is valid, specifically, whether the error function computed a zero concentration at the depth of the bottom of the slab. If it does not, then the error function estimate is not directly comparable to the Life-365 estimate.

The table illustrates how for many of the comparisons done, the Life-365 v2.2.3 estimates are nearly identical to the error function estimates. When the error function is not valid, however, some of the estimates do not compare well at all. This is due to the fact that the error function is not reporting a zero concentration at the bottom of the slab, when by assumption and design the Life-365 finite difference approach specifically does.
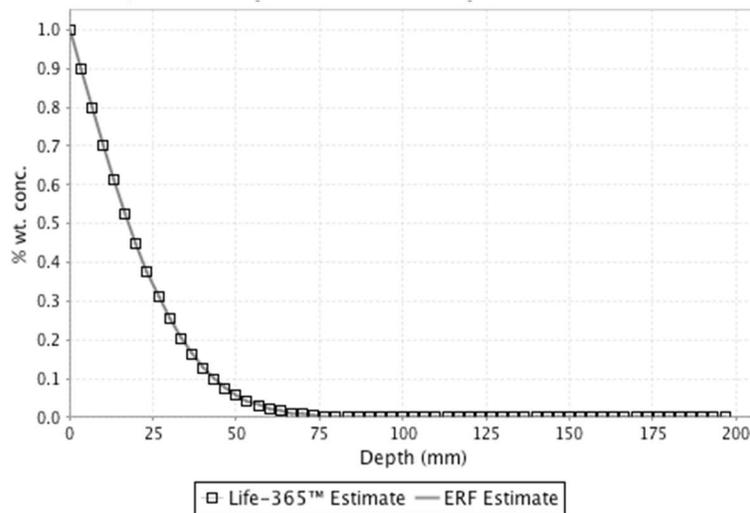

Figure 2.9. Life-365™/ERF Comparison: Over Depth at Time of Initiation

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 user can change the propagation period to reflect local expertise.

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 corrosion protection strategy, and the environmental exposure. The user needs to estimate the cost and extent of this first repair (i.e., the percentage of area to be repaired) and the fixed interval over which future repairs are conducted.

2.4   Probabilistic Predictions of Initiation Period

Life-365 includes probabilistic predictions of the initiation period, based on Bentz (2003). These predictions are calculated using the following steps:

a) Estimate time to first corrosion for the "best guess" or average values of the inputs, that is, the values input by the user.

b) For each of five specific input variables (D_{28}, C_s, m, C_t, x_d), estimate five additional time to first corrosions, where each is individually adjusted by 10 percent.

c) Use the results of steps b) and step a) to estimate the derivative of corrosion initiation time with respect to each of the five variables. This determines the sensitivity of initiation period to variations in each of the input variables.

d) Use the results from step c) to estimate a single parameter of variability, similar to a standard deviation, for a log-normal assumed variation of time to corrosion initiation (shown by Bentz to work well), where the average value of this distribution is taken from the deterministic analysis in step a) and the variability of this assumed distribution is determined from the results of steps b) and c).

2.5   Estimating Life-Cycle Cost

To estimate life-cycle cost, Life-365 follows the guidance and terminology in ASTM E-917 Standard Practice for Estimating the Life-Cycle Cost of Building Systems. This includes the process of

1. Defining a base year, study period, rates of inflation and discount, project requirements, and alternatives that meet project requirements;
2. Calculating the present value of future costs;
3. Reporting results in present value (constant dollar) and current dollar terms; and
4. Conducting uncertainty and sensitivity analysis.

User Input Parameters

The user is responsible for providing the following cost information needed for the life-cycle cost analysis:

- Cost of concrete mixtures (including corrosion inhibitors) for the various corrosion protection strategies under consideration,

- Cost, coverage (percent of surface area), and timing of repairs,

- Inflation rate, i, and

- Real discount rate, r.

Life-365 provides the following default costs for the included rebars:

- 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 user should review and if necessary, change the costs of these materials to better reflect actual project costs in his area.

2.6   Calculating Life-Cycle Cost

Present Worth Calculations

Life-cycle cost is 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 calculated as the sum of concrete costs, steel (or other reinforcement) costs, and any surface protection (membrane or sealer) costs. Life-cycle cost is expressed in either total dollars or dollars per unit area of the structure (e.g. dollars per square meter). 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 in year t is calculated as

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

All future repair costs over the entire design life of the structure are calculated in this manner.

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3   Life-365™ Computer Program User 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 project, structure, 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 describes how to install, start, and use the Life-365 Computer Program, and then describes additional optional features designed for experienced practitioners.

3.1   Installing Life-365

To install Life-365 from the Life-365 website (http://www.life-365.org):

- **On Windows computers:**
  - o Uninstall any previous versions of Life-365 v2.0 or higher that are installed on the computer, by going to the Windows Control Panel, accessing the "Add or Remove Programs" application, and removing these versions of Life-365.
  - o Once removed, access the new version of Life-365 and then double-click your mouse on the downloaded Windows install file; this will run through a quick installation program that, among other things, puts a program-start icon in your Programs folder.

- **On Apple OS X computers:**
  - o Double-click your mouse on the Apple install file; this will mount a disk drive on your desktop. Open the disk drive and drag the Life-365 program into your Applications Folder.
  - o Different versions of Life-365 can run simultaneously on Mac OS X, although we recommend the user only use the most recent version.

3.2   Starting Life-365

Installing Life-365 puts a start menu item labeled "Life-365" in your Windows Programs folder (accessible from the Start button in the lower left-hand corner of your screen) and an icon on your desktop; on Apple computers there should be a Life-365 icon in your Applications folder. (Other, UNIX platforms may not, depending on your Java settings). To start Life-365, simply select this menu item or the desktop icon.

When Life-365 starts for the first time, it will ask you to select the base units of measure for your projects, either in **SI metric**, **US units**, or **Centimeter metric**. This selection will determine whether all of your inputs need to be expressed in, for example, meters or yards. If you decide later to change these base units, go to the Default Settings and Parameters tab at the bottom of the screen, change the selection in the **Base Units** field, and then press the **Save** button; all future projects will use this new base unit.

When Life-365 starts in general, your screen should look similar to Figure 3.1. This screen has two components: on the left-hand side there is a navigation menu, under the **Navigator** section, that lets you open new or existing Life-365 project files; under the **Settings** section, it lets you

change the default settings and get help with particular screens; and under the **Tips** section, it displays text that gives you information and tips on using the software.

Figure 3.1. Startup Screen

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

1. The **Current Analysis** tab, which contains the current project on which you are working (on startup, this tab shows the opening banner in Figure 3.1);

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 offers detailed explanations of the key windows and features in the Life-365 Computer Program.

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 baseline concrete mixture. 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 has a list of chronological **Steps** that divides your Life-365 analysis into logical analytical components:

1. **Define project**: e.g., input the title, description, structure type, units of measure, and economic values.

2. **Define alternatives**: e.g., input the titles and descriptions of the alternatives that meet the project requirements.

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3. **Define exposure**: input the location and type of structure (so as to set the chloride and temperature exposure conditions).

4. **Define mix designs**: input the concrete mixture and corrosion protection strategy for each alternative.

5. **Compute service life**: calculate the service life of each alternative.

6. **Define project costs**: input the initial construction, barrier, and repair costs and repair schedule.

7. **Compute life-cycle cost**: calculate and sum the present value of all costs, for each alternative, and compare.

Each of the software tabs that execute these steps is discussed in turn.

3.3   Project Tab

The **Project** tab allows you to complete Steps 1 and 2 above, specifically, 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 3.2).
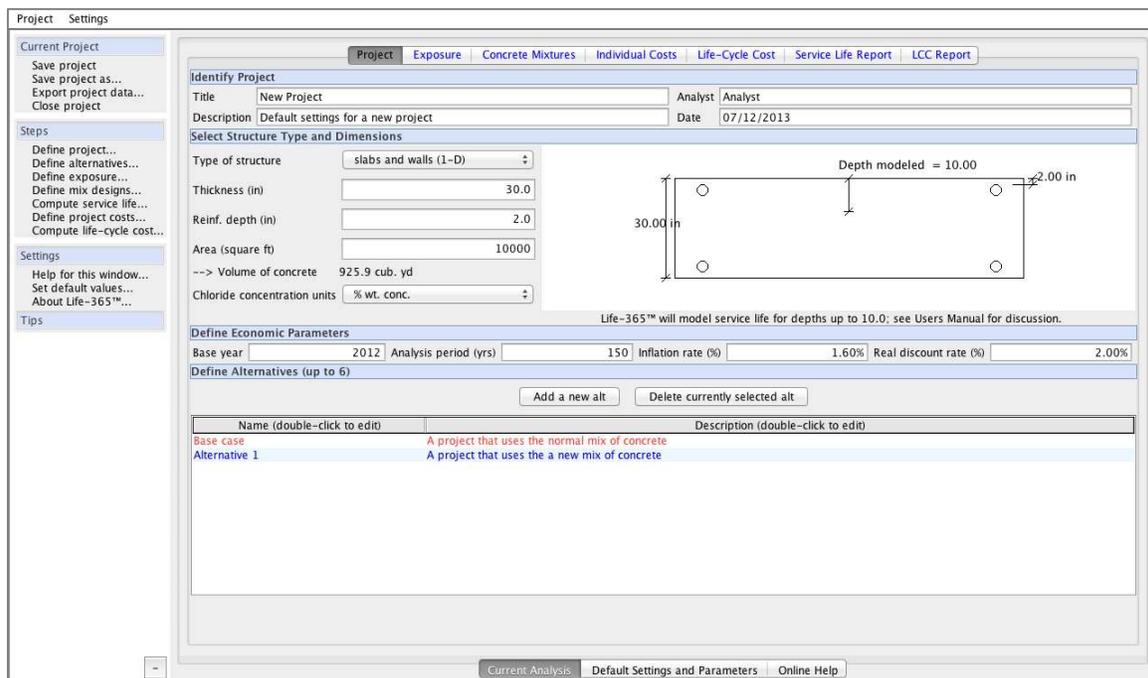

Figure 3.2. Project Tab

Identify Project

In this section you can set the project **Title**, **Description**, **Analyst**, and **Date**, most of which are used to simply document the project, but also are part of the report displayed in and printed from the **LCC Report** tab (Figure 3.15).

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, which also sets the means of chloride ingress,

e.g., 1-D (one dimensional). Use the **Thickness** (for 1-D structures) or **Width (**for 2-D structures), and **Area or Total Length** 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 reinforcement. Finally, use the **Chloride concentration units** drop-down box to select 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

Four parameters are used to set the period and interest rates over which life-cycle cost is computed. Set the **Base year** to be the current year or other initial year that is relevant to your analysis. Set the **Analysis period** to be the period of time over which life-cycle cost should be calculated; 75 years is a common period and Life-365 allows the user to select up to 200 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 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).[3]

Define Alternatives

Use this section to set the number, names, and descriptions of alternatives to be analyzed and compared. Use the **Add a new alt** and **Delete currently selected alt** buttons to create and delete alternatives, respectively, and double-click the mouse on the alternative's **Name** or **Description** fields to change them.

3.4   Exposure Tab

The **Exposure** tab (Figure 3.3) is used to set the exposure of the concrete to external chlorides, and to set the monthly temperatures to which the concrete is exposed.

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[3] 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.
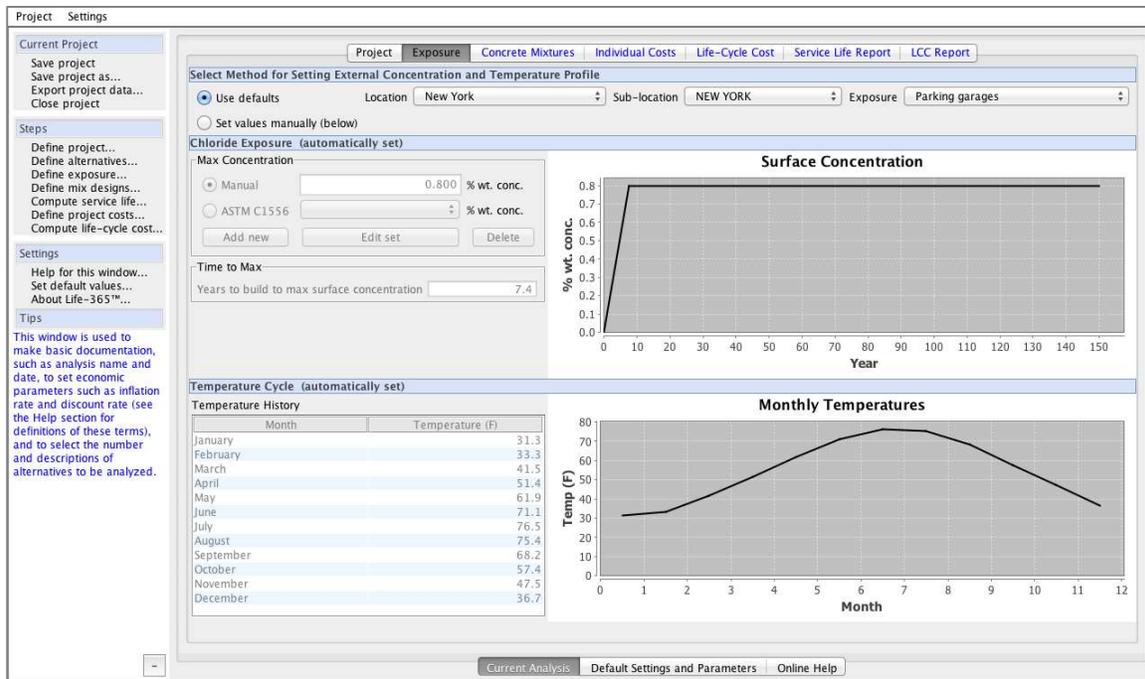
Figure 3.3. Exposure Tab

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 and **Time to build to max** in the upper panel and the **Temperature History** in the lower panel. When the **Use defaults** button is not checked, then the user must manually input these concentration and temperature values. In Life-365 v2.2.3, the user can manually input their own maximum chloride level by also using values measured in accordance with ASTM C1556 (see Section 4 for details).

Define Chloride Exposure

The 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 the 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**

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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 Mixtures Tab

The **Concrete Mixtures** tab (Figure 3.4) is used to define the concrete mixtures for each project alternative defined in the **Project** tab.
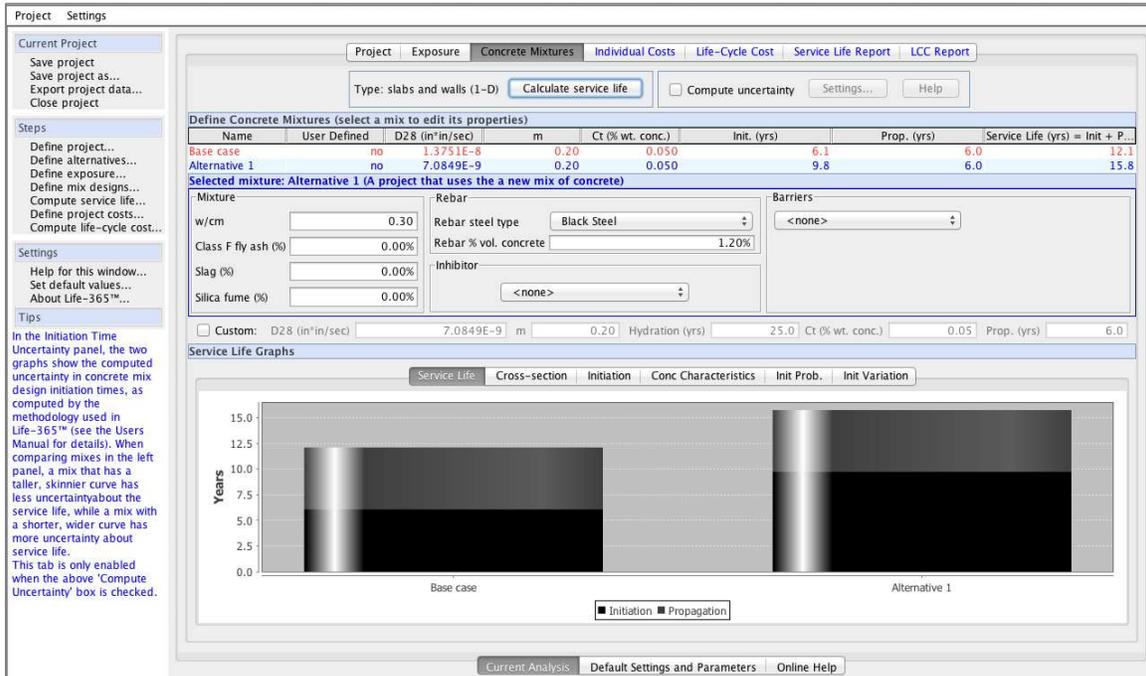

Figure 3.4. Concrete Mixtures Tab

Define Concrete Mixtures

This section allows the user to input the concrete mixtures and corrosion protection strategies of each alternative. Because the calculation of concrete service life is computationally intensive, you need to press the **Calculate service lives** button after inputting the mixtures and strategies to make the calculations.

Check-mark the **Compute uncertainty** box if you want Life-365 to compute the uncertainty of service life for each concrete mixture. In general, this is a calculation reserved for advanced users of Life-365; to understand Life-365 uncertainty analysis, press the **Help** button to the right, and see Section 3.10 (pg. 38) of this manual for details on how to use service life uncertainty in your analysis. For now, leave the **Compute uncertainty** unchecked.

Selected mixture

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

Mixture group – use this section to set the water-cementitious materials ratio (**w/cm**) of your concrete mixture, and whether and to what level you are using SCMs (**Slag**, **Class F fly ash**, or **Silica fume**). Enter the SCM amounts in percent substitution.

Rebar and **Inhibitors** groups – use these sections 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, where the costs of the steels are set in (1) the **Individual Costs** tab, under the **Default Concrete and Repair Costs** tab), and (2) the **Default Settings and Parameters** tab at the bottom of the Life-365 window. Use the **Inhibitor** drop-down to include in your mixture any corrosion inhibitors that will be used. 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 include a membrane or sealant application on the concrete. If the **Use defaults** box is checked, then you simply select membrane or sealant; if not checked, then you must input the values of **Initial efficiency (%)**, **Age at failure (yrs)**, and **# times reapplied** for the particular one selected.

Custom Mixture Properties

In addition to inputting the constituent physical concrete mixture and other corrosion protection strategies, Life-365 allows the user to input directly the model properties used to calculate service life. (Doing so will potentially generate results that override one or more of the basic Life-365 modeling assumptions, so check-marking the **Custom** button the first time will cause a pop-up window to appear asking that the user confirm he is aware of this.) The set of **Custom** input fields together override the model, in the following ways.

Initial diffusion coefficient, D28. Inputting the initial diffusion coefficient directly overrides the calculation of D28 based on w/cm ratio and the level of silica fume.

Diffusion decay index, m. Inputting this index directly overrides the calculation of m based on the levels of slag and fly ash. The value of m, however must still be between 0.2 and 0.6.

Hydration years. By default, Life-365 models hydration taking 25 years, where the effects of hydration on concrete diffusivity are modeled by **m**; if under these default settings the modeled concrete's diffusivity continues to decline past 25 years, Life-365 holds the concrete's diffusion coefficient constant after 25 years. Inputting a custom hydration value here changes the number of years after which hydration stops; if you set the **Hydration (yrs)** field to 5, then hydration will stop after 5 years and the diffusion coefficient will no longer decline (it may, however, still change monthly due to the monthly changes in temperature).

Chloride concentration necessary to initiate corrosion, C_t. Inputting this value overrides the initiation corrosions based on the type of reinforcing steel used (black steel = 0.05 % wt. concrete, epoxy-coated = 0.05 %, and stainless steel = 0.5 %).

Propagation period. Inputting this value overrides the propagation periods based on the type of reinforcing steel used (black = 6 years, epoxy-coated = 20 years, and stainless steel = 6 years).

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

Service Life. The Service Life tab (Figure 3.5) shows the service life of each alternative concrete mixture alternative, in terms of the component initiation period and propagation period.
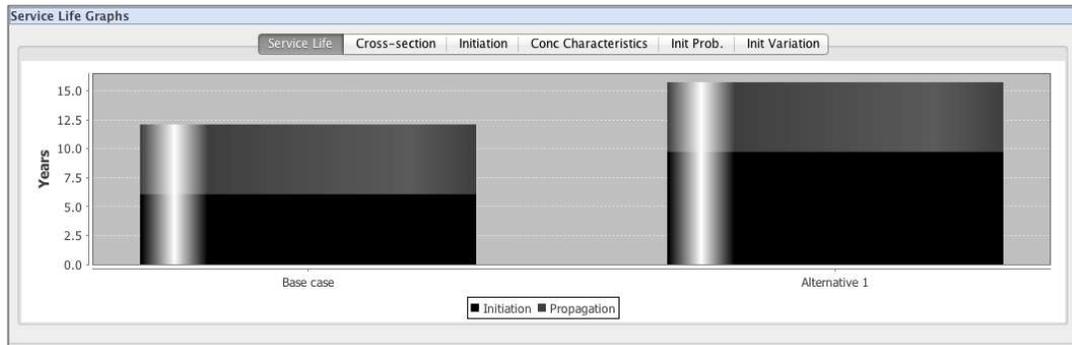

Figure 3.5. Service Life Tab

Cross-section. The cross-section tab (Figure 3.6) shows a cross-section of the chloride concentration of the concrete mixture at the point of initiation of corrosion. The alternative shown is selected from the left-hand-side **Select:** drop-down box.
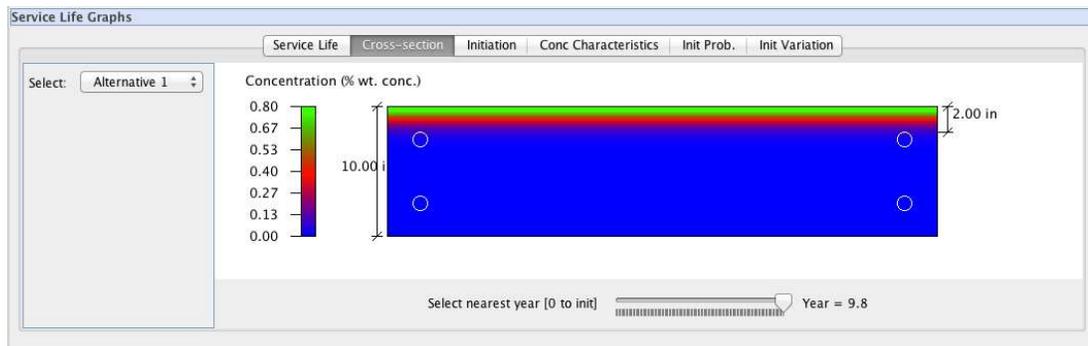

Figure 3.6. Cross-section Tab

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 have a color that reflects the level of chloride concentration at initiation, which in this graph is 0.05 % wt of concrete.

Initiation. This tab (Figure 3.7) shows two graphs: 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.

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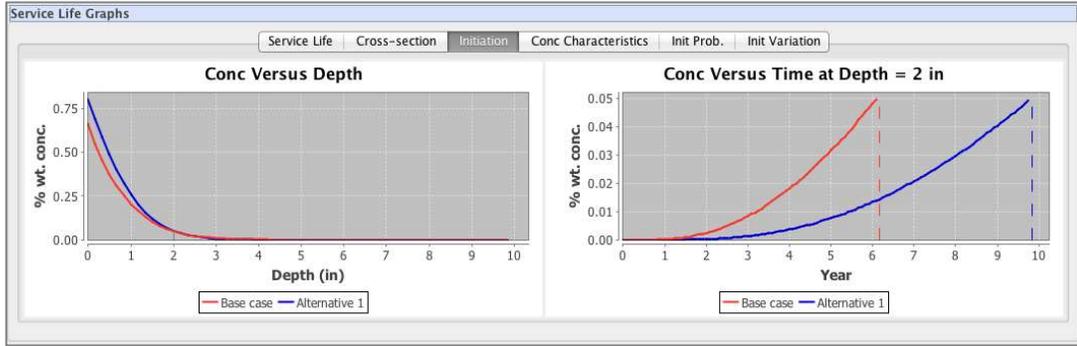
Figure 3.7. Concrete Initiation Graphs

The right graph shows that the Base case mixture hits initiation in 5 years at a rebar chloride concentration of about 0.05 % weight of concrete, while the Alternative 1 mixture hits initiation in 17 years with a rebar concentration of 0.05 % weight of concrete.

Concrete Characteristics. Finally, the **Conc Characteristics** tab (Figure 3.8) displays two additional graphs that help interpret the performance of the concrete mixtures. The left-hand-side graph, **Diffusivity Versus Time**, shows how the calculated concrete chloride diffusivity changes over the initiation periods, by mixture. The right-hand-side graph, **Surface Concentration Versus Time**, shows how the concrete surface conditions change over the same period.
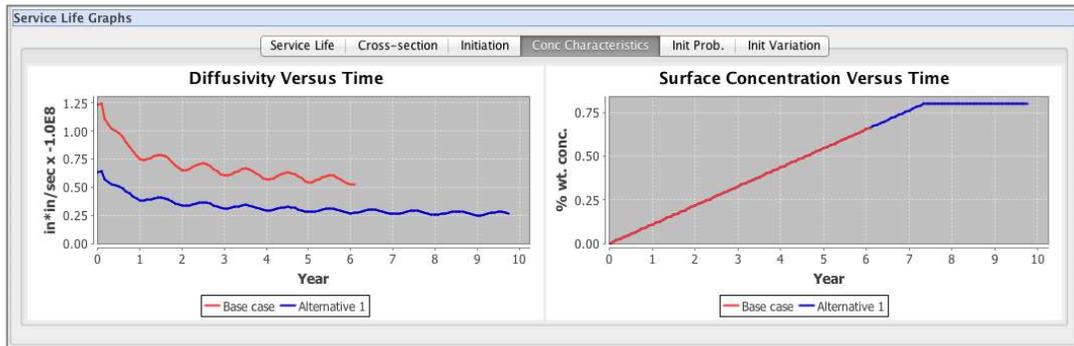

Figure 3.8. Concrete Characteristics Tab

For this particular graph, the left panel indicates that both mixtures have the same chloride diffusivity characteristics (different mixtures 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 mixtures have the same surface concentrations; this would not be true if the mixtures had membrane or sealant applications.

3.6   Individual Costs Tab

The **Individual Costs** tab (Figure 3.9) allows you to edit the different constituent cost and cost parameters, and view the effects they have on the constituent costs that make up life-cycle cost.
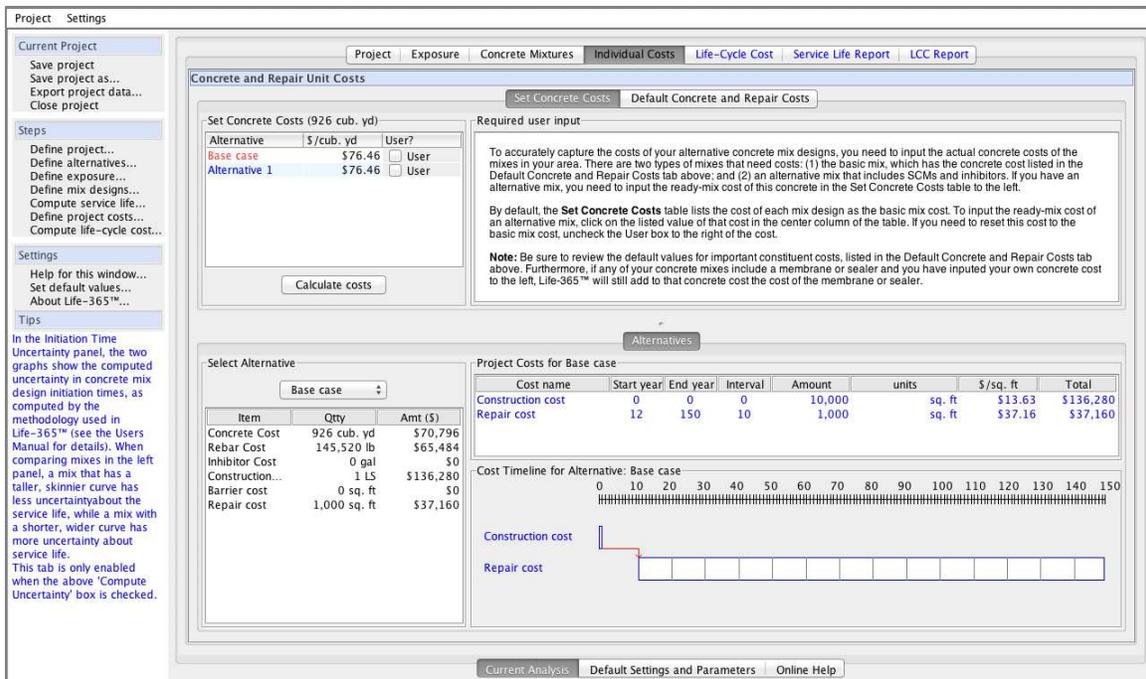
Figure 3.9. Individual Costs Tab

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 mixture costs. Initially, this table displays the default concrete cost that is listed in **Concrete & Steel** section of the **Default Settings and Parameters** tab (located at the bottom of the Life-365 screen); this default cost should represent the cost of concrete only, without inhibitors, barriers, or steel (these costs are all used later, when calculating the initial construction cost). If, however, a particular mixture uses, for example, SCMs or other materials that cause concrete costs to be different than the default cost, enter that cost in this table, by double-clicking on the cost itself; doing so will cause the **User?** box to be check-marked. If you enter a cost and need to return that cost to the default cost, simply uncheck the **User?** box.

Default Concrete and Repair Costs

This section (Figure 3.10) lists the costs associated with three categories of project 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 (located 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 <u>project</u> values of cost.) If you would like to make the values currently shown in <u>this project</u> to be the default values <u>for all future projects</u>, press the **Set as defaults** button.

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Figure 3.10. Default Concrete and Repair Costs

Costs for Each Alternative Mix Design

Based on these costs, the **Project Costs** section lists up to three costs: (1) the **Construction cost**, or 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 project costs. The graph in Figure 3.9 shows in particular the initial construction cost occurring between year 0 and year 1, and then the repair costs starting after construction (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 see the different cost timelines of your different alternative mixtures.

3.7   Life-Cycle Cost Tab

Once the project, exposure, concrete mixtures, and individual costs data have been entered, the resulting life-cycle cost of the alternative mixtures are computed and can be viewed and compared in the **Life-cycle Cost** tab (Figure 3.11).
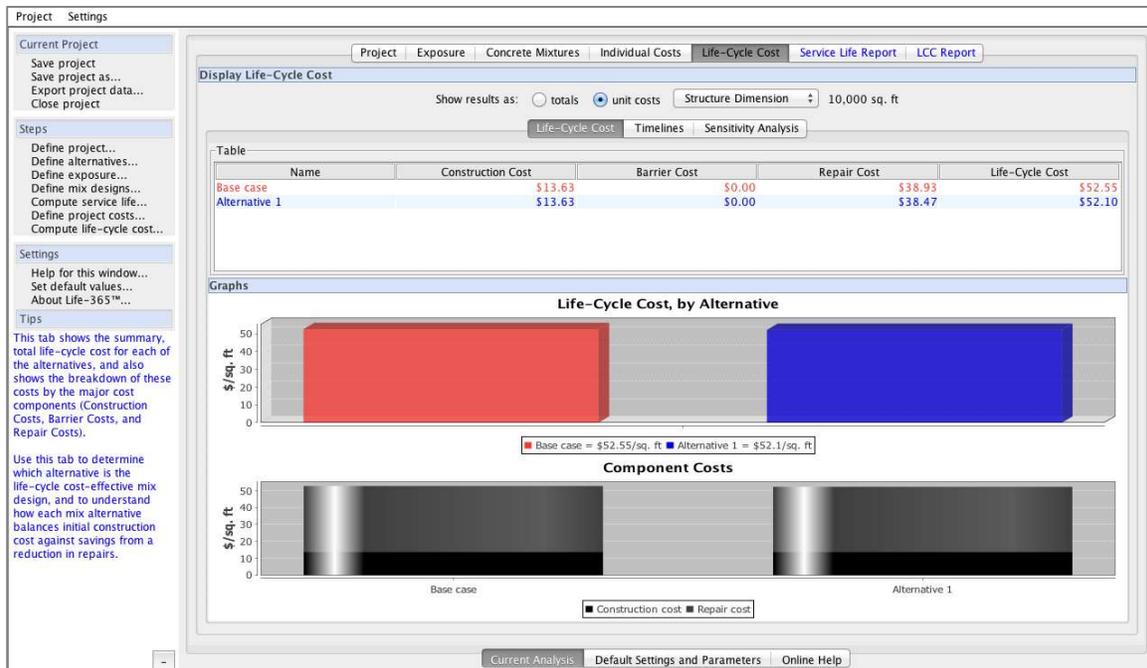
Figure 3.11. Life-Cycle Cost Tab

Life-Cycle Cost

This first tab displays the life-cycle cost of each alternative, in tabular form, as a total (the colored bars) and by component cost (the black and gray bars).

Timelines

The **Timelines** tab (Figure 3.12) shows the constituent costs over time. This tab will initially show just one of the four timeline figures but can show all four together when the user checks the **Show all four time series 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 materials and labor (the inflation rate) and time-value of money (the real discount rate), and that are summed to compute life-cycle cost.
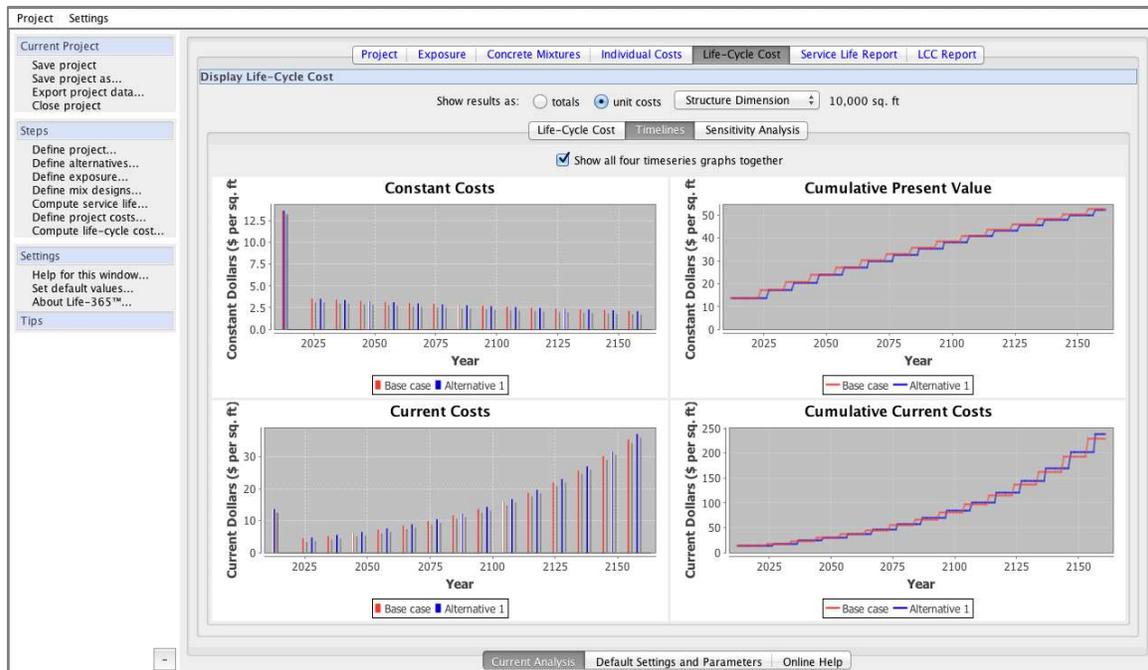
Figure 3.12. Life-Cycle Cost: Timelines Tab

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 cost, but is a useful estimate of the actual dollars that are estimated to be spent over the study period.

For these particular alternatives, the upper-right **Cumulative Present Value** gives a good explanation of why Alternative 1 (the blue line in the graph) has lower life-cycle cost: while it does have a slightly higher cost at initial construction and identical repair costs, it has fewer repairs due to the longer service life (specifically, its first repair occurs later), resulting in a total level in the last year of the study period that is lower than the Base case (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 assumptions or inputs for economic, concrete, constituent-material, or repair 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 cost. For example, you can easily change the environmental conditions of the mixtures (e.g., switching location from New York, NY to Philadelphia, PA) or some of the properties of your mixtures.

A second, efficient way to conduct sensitivity analysis on a subset of all parameters is to use the **Sensitivity Analysis** tab (Figure 3.13). In this tab, you select one of the predefined parameters listed in the left-hand tree (**Discount rate (%)** is selected in the figure) and then 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 percent variation of an discount rate of 3 percent will create discount rates of between 0 percent and 6 percent). Life-365 will then compute the life-cycle cost of each alternative across this range of parameters and compare them

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in the right-hand graph. The vertical dashed line is positioned at the value of the parameter you selected as your "best guess" estimate.
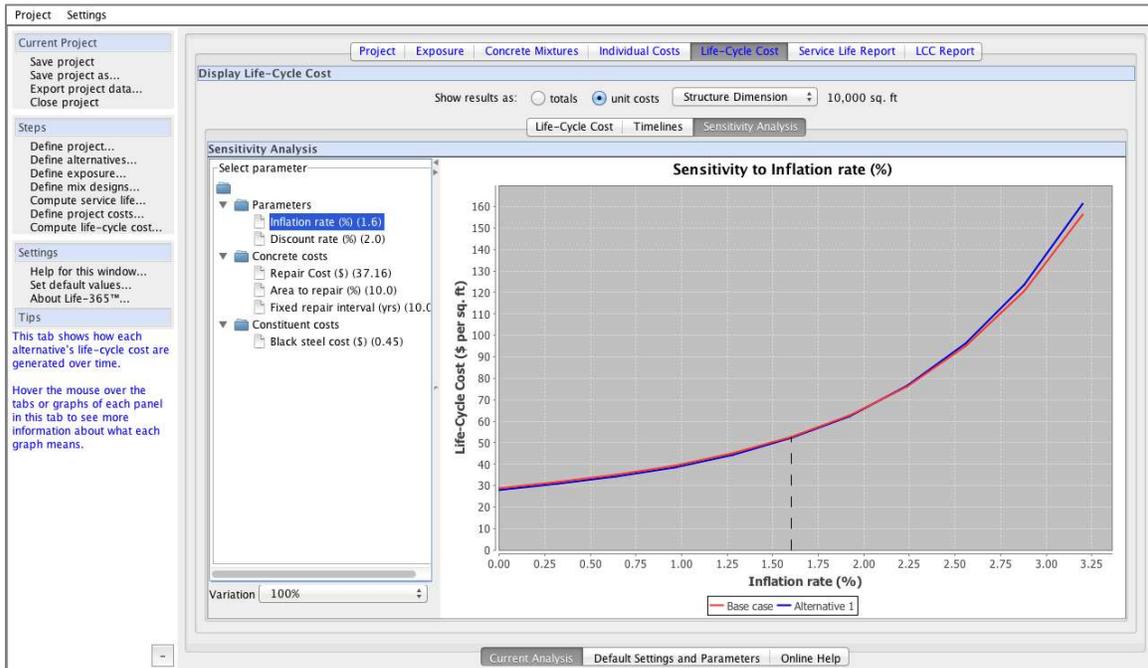

Figure 3.13. Life-Cycle Cost: Sensitivity Analysis Tab

The graph in Figure 3.13 shows the effects of varying the discount rate between 0 percent and 6 percent (as indicated by the graph's horizontal axis). The graph shows that Alternative 1 has lower life-cycle cost than the Base case, regardless of the (reasonable) real discount rate selected, that is, the life-cycle cost effectiveness of Alternative 1 is insensitive to (reasonable) changes in the real discount rate. Sequentially working through all of the parameters in the tree will allow the user to determine if the results are sensitive to any of these input parameters.

3.8   Service Life and Life-Cycle Cost Reports Tabs

Finally, Life-365 provides two pre-defined reports of your project: an **SL Report** (for "Service Life Report"; Figure 3.14) and an **LCC Report** (or "Life-Cycle Cost Report"; Figure 3.15). These two reports list most but not all of the parameters used in your analysis (your saved project file contains all of the parameters used). Each report can be printed by pressing the printer icon in the upper-left corner of the window. If you want to save the report as a PDF file, click on the disk-drive icon in the upper-left corner, select "*.pdf" as the filetype, enter a file name, and save.
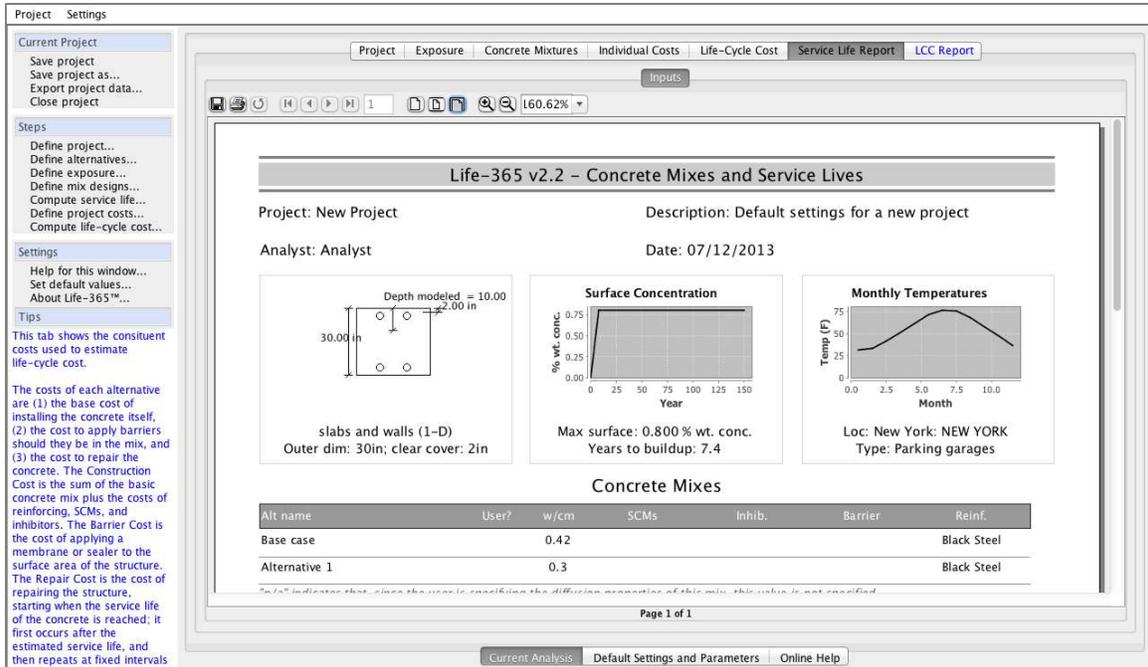
Figure 3.14. Service Life (SL) Report Tab
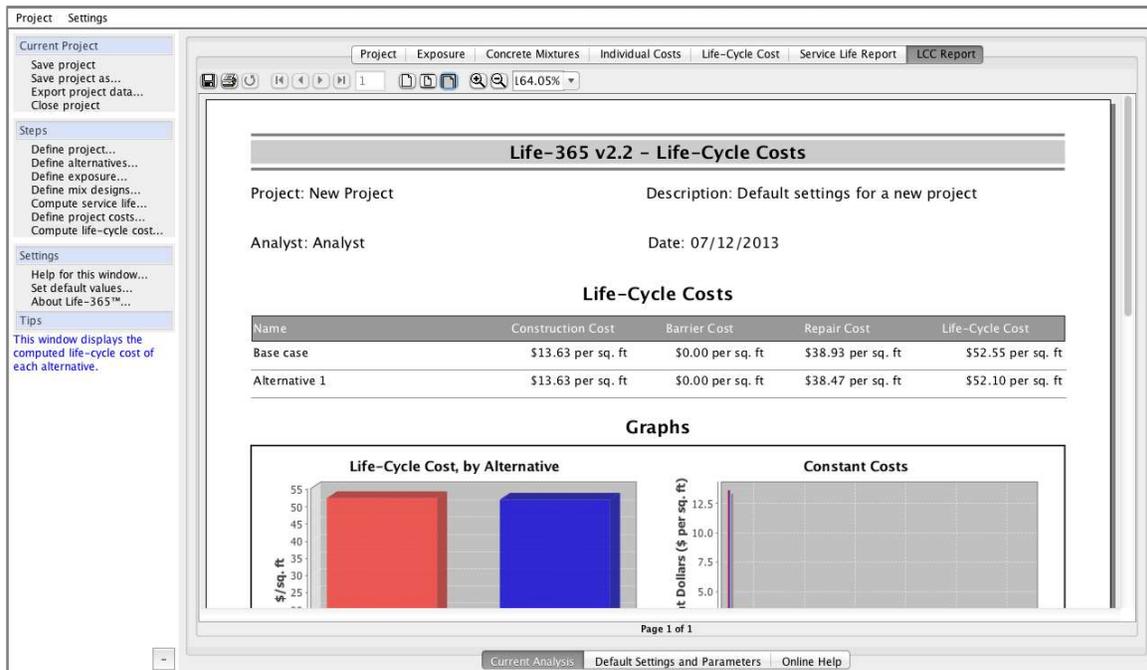
Figure 3.15. LCC Report Tab

Finally, you can copy and paste results from Life-365 to your own Word- and PowerPoint-based reports, one of two ways. First, you can take "screenshots" of the current window that are by default put in your clipboard for pasting. In Microsoft Windows, a screenshot is taken by pressing the "Shift" and then "PrtSc" keys; on Apple Computers, press "Shift," "Apple," and "3"

simultaneously to take the screenshot. To paste what is now in your clipboard to the Word or PowerPoint document, press "Ctrl+v" in Windows or "Command+v" on Apple computers.

The second way to copy information from Life-365 is to hover the mouse over graphs or tables, and right-click the mouse; a pop-up menu will appear (e.g., Figure 3.16) with options to copy the information to the clipboard, or to export the raw data from the figure or table.
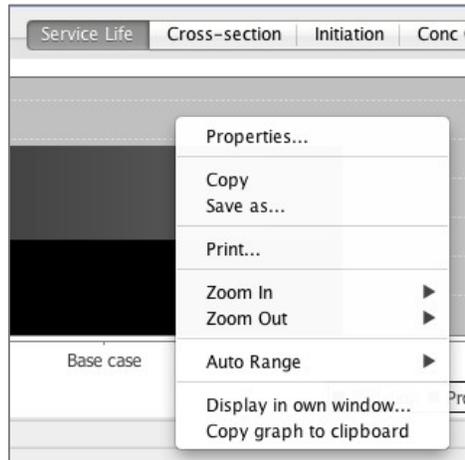
Figure 3.16. Pop-up Menu for Copying a Graph to Clipboard

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 window offering context-sensitive help.

3.9.1   Default Settings and Parameters

The **Default Settings and Parameters** tab, shown in Figure 3.17, allows the user to edit the parameters that are common across the different analyses, such as the units of measure, location of project, economic conditions, and concrete costs.
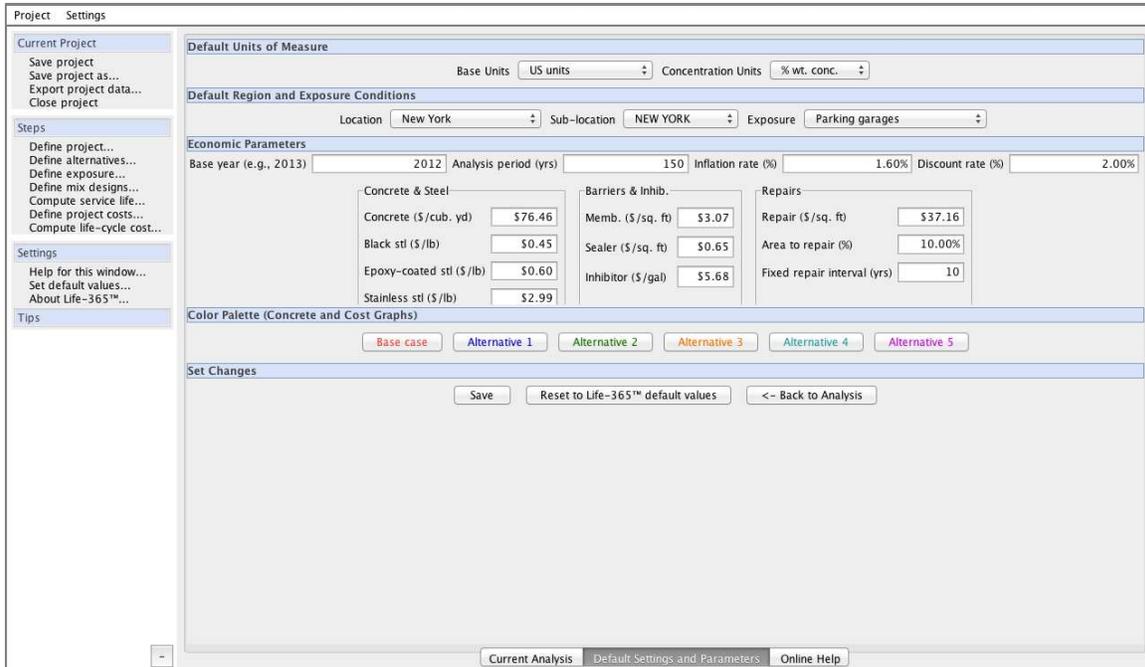
Figure 3.17. Default Settings and Parameters Tab

Before conducting even your first analysis, it is recommended that you access this tab and set the default settings to reflect your own conditions, particularly your concrete, steel, and repair costs, and then press the **Save** button. Your first project, then, will use your best estimates of these parameters.

3.9.2 Online Help

The **Online Help** tab (Figure 3.18) lists a series of pages describing the functionality of and tips on using each window.

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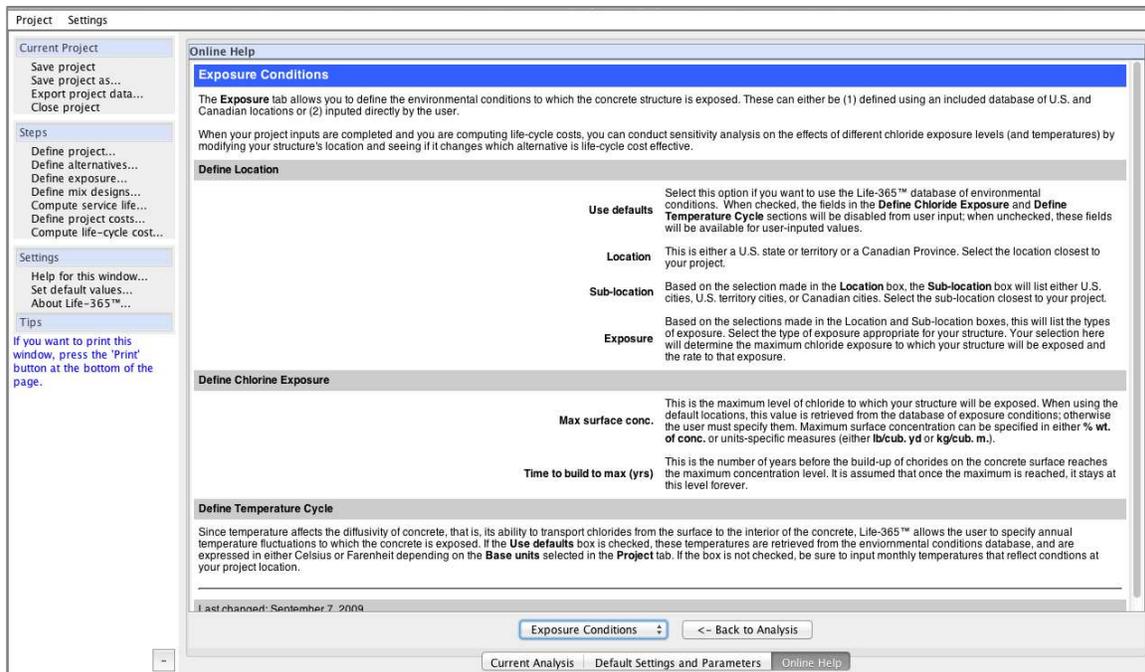
Figure 3.18. Online Help

Individual pages can be accessed by selecting from the drop-down box at the bottom of the panel (in Figure 3.18, this box displays "Concrete Mixtures"). 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; where available, a help window will display with information for the help you need.

3.10 Advanced Analysis: Service Life Uncertainty

The analysis described in Section 3.2 through Section 3.8 is, in and of itself, generally sufficient: it calculates service life and life-cycle cost, given the "best-guess" estimates of economic conditions, environmental conditions, concrete mixture 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 3.13) is an example. Formal uncertainty analysis would include many of the above parameters and procedures.

Model of Initiation Period Uncertainty

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 mixture'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 mixture 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 initiation-period uncertainty (only) on life-cycle cost. As shown in Figure 3.19, the user activates Life-365 to compute initiation period uncertainty by checking the **Compute uncertainty** box in the upper part of the **Concrete Mixtures** tab.
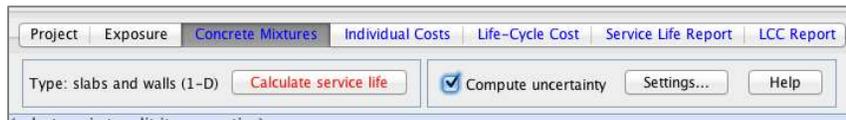
Figure 3.19. Concrete Mixtures Tab: Initiation Time Uncertainty Tab

When selected, Life-365 will display a small window (Figure 3.20) describing this process and then asking for verification that the user wants to conduct this analysis. Selecting **Yes** in this window and then pressing the **Recalculate service lives** button will invoke the uncertainty calculations, thereby adding some new panels to the **Concrete Mixtures** and **Life-Cycle Cost** tabs. If you do select **Yes**, you can later turn the uncertainty calculations off by un-checking the same **Compute uncertainty** checkbox.
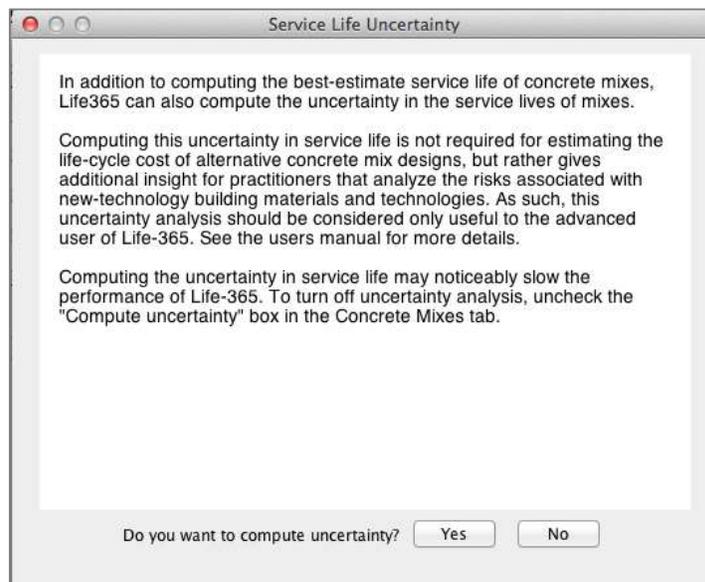
Figure 3.20. Service Life Uncertainty Prompt

Initiation Period Probabilities

When the **Yes** button is pressed (and then the **Recalculate service lives** button), the uncertainty in service life is computed for each concrete mixture listed in the **Concrete Mixtures** 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 necessary tools to interpret these graphs, let's examine in detail the two figures more closely.
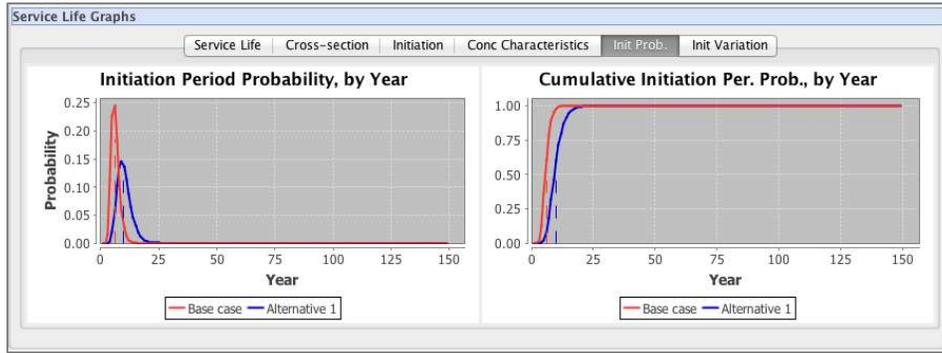
Figure 3.21. Initiation Probability Graphs

Consider the two alternatives shown in Figure 3.22. The Base case (the red line) is from a basic mixture with no additives or corrosion protection strategies 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 10 years and Alternative 1 an initiation period of 15 years (with associated service life of 16 and 21 years, respectively).
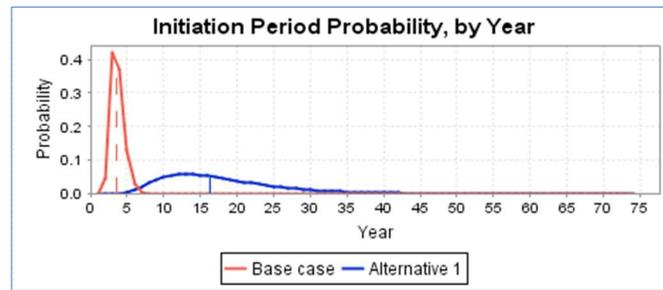
Figure 3.22. Initiation Period Probability, by Year

Several important points can be made with this graph: first, it is hard if not impossible to interpret anything about the probabilistic service lives of each alternative (16 and 21 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 average initiation period (the expected value of service life). Note that this average value is equal to the deterministic value of initiation period calculated when uncertainty analysis is turned off. Second, peak of the Base case (red line) is higher than the peak of 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 mixtures has the longest service life in a probabilistic sense, that is, across the range of initiation periods each mixture can experience.

To do this, we need the cumulative probability density functions, shown in Figure 3.23, which simply add each year's individual probability to create cumulative probabilities.
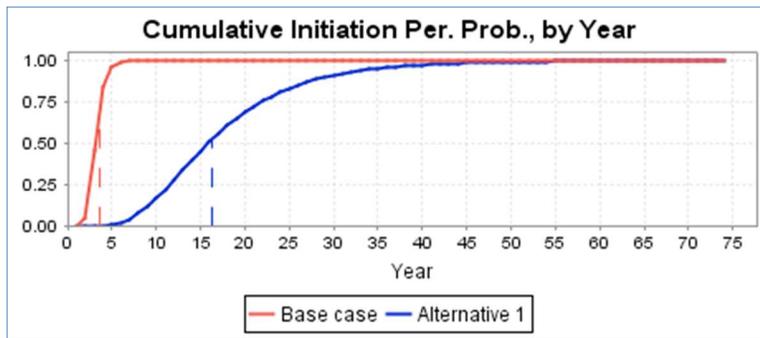
Figure 3.23. Cumulative Initiation Per. Prob., by Year

Using this graph, it can be difficult to determine which, if either, concrete mixture 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 lines at Year 16 on the horizontal axis. Given that the blue line is below the red line at this year, the probability graph specifically states:

The blue line (Alternative 1) has a lower probability of being 16 years (or less) than the red line (Base case).

Said differently, Alternative 1 is less likely to have a service life of 16 years or less than the Base case. If, instead, we say the converse of the above, italicized statement, we get a more understandable statement:

Alternative 1 has a higher probability than the Base case of having a service life longer than 16 years.

That is, Alternative 1, by being below the Base case, has a higher probability of having an initiation period longer than that many years. Since it is below the Base case line for all values above 12 years, it is a reasonable conclusion that Alternative 1 has a longer service life in a probabilistic sense.[4]

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 alternative has the statistically longest initiation period.

Sources of Initiation Period Uncertainty

To understand how the concrete mixture factors influence the uncertainty in initiation period, the **Service Life Results** section also includes an **Init Variation** graph, shown in Figure 3.24. This graph shows, by alternative, the level of uncertainty in each initiation period and the components of this uncertainty. For example, in the figure, Alternative 1 has much higher uncertainty than the

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[4] 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.

Base case and this uncertainty is primarily due to *m* (which represents the effects of hydration on decreases in concrete diffusivity), followed by uncertainties in cover depth and D28.
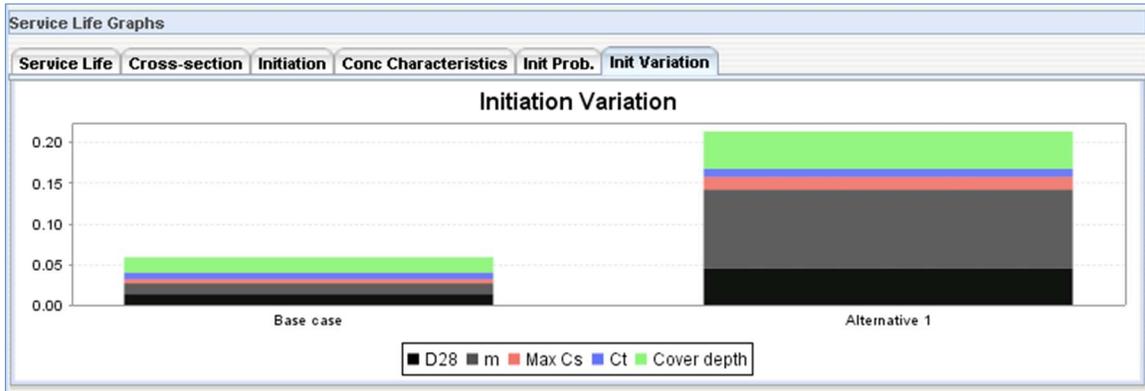
Figure 3.24. Initiation Variation Graph

Impacts on Life-Cycle Costs

In cases where there is not clear statistical dominance of one service life over the other(s), for example, when there are many alternatives and the CDF lines cross each other over different years, we can still calculate the effects of different outcomes of initiation periods (and thus service lives) on life-cycle cost, using the following technique: when conducting service life probabilistic analysis, a new **Modify Uncertainty** panel appears in the lower portion of the **Life-Cycle Cost: Life-Cycle Cost** tab (Figure 27 and Figure 3.26).

Figure 3.25. Life-Cycle Costs Tab with Modify Uncertainty Panel

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When first created, this panel sets the **Probability** slider to "50," which means that there is a 50-percent probability that each concrete mixture's initiation period will be less than the indicated value and a 50-percent probability that it will be more than the indicated value. In Figure 3.25, the initiation periods are displayed as 4 and 16 years.
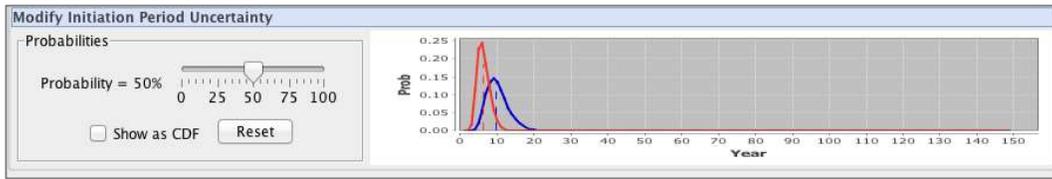
Figure 3.26. Modify Uncertainty Panel

At the 50-percent values, all of the 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 3.26 is to allow the user to modify the uncertainty values for each alternative and see what effect the new values have on life-cycle cost. Since the 50-percent values represent the "best guess" of each mixture'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 mixtures will be changed to 75 percent. Given that the concrete mixtures have different probability functions, a change to 75 percent, for example, will create different service lives.

To summarize, the probability slider shown in Figure 3.26 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 cost to uncertainty in the economic, environmental, concrete, and cost parameters.

3.11 Special Applications: Epoxy-Coated Rebar, 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 mixed 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 accurately captured.

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 3.27. 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 Figure 3.27) and Life-365 will use this average price for all slabs that use Epoxy-coated steel on top and black steel on the bottom.

Concrete & Steel		Concrete & Steel	
Concrete ($/cub. yd)	$76.46	Concrete ($/cub. yd)	$76.46
Black stl ($/lb)	$2.20	Black stl ($/lb)	$2.20
Epoxy–coated stl ($/lb)	$2.93	Epoxy–coated stl ($/lb)	$2.57
Stainless stl ($/lb)	$14.55	Stainless stl ($/lb)	$14.55

Default Costs   Hybrid Costs

Figure 3.27. 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 mixtures 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 all-epoxy-coated steel.

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

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4 Module for Estimating Maximum Surface Concentration

Life-365 v2.2.3 includes a module that allows users to estimate the maximum surface chloride concentration and for obtaining a more accurate estimate of the apparent diffusion coefficient of concrete mixtures proposed for use on new projects using the measurements of samples from structures or standard specimens exposed to chlorides, respectively, in accordance with ASTM C1556. This section describes the ASTM test method and how these measurements are used in the Life-365 model.

4.1 ASTM C1556 Method

4.1.1 Definition

ASTM C1556, *Standard Test Method for Determining the Apparent Chloride Diffusion Coefficient of Cementitious Mixtures by Bulk Diffusion,* (ASTM [2011a]) aids practitioners by using the chloride content of concrete samples to estimate the apparent chloride diffusion coefficient D and the maximum surface concentration c_s of the concrete. These estimates of diffusion coefficient and surface concentration are based on Fick's second law of diffusion:

$$c(x,t) = c_s - (c_s - c_i)erf\left[\frac{x}{\sqrt{4Dt}}\right],$$

<div align="right">Eq. 1</div>

where

x = depth from the top surface,

t = time since the exposure to the surface chlorides,

c_s = the constant chloride concentration at the surface of the concrete,

c_i = the constant initial chloride concentration of the concrete, and

D = the constant chloride diffusion coefficient of the concrete.

ASTM C1556 is very similar to methods described in earlier publications such as AASHTO T260 (1994), Weyers (1983; 1992), and NT Build 443 Method (NORDTEST [1995]). In fact, Life-365 uses the NT Build Method to estimate the relationship between the water-cementitious-material ratio w/cm and the 28-day diffusion coefficient D_{28} (see pg. 75 in this User Manual). Since then, many publications describe how to use ASTM C1556 to estimate the diffusion coefficient and/or maximum surface concentration.

Diffusion Coefficient

There are at least three general cases where ASTM C1566 is used to estimate the diffusion coefficient:

1. For estimating the <u>initial</u> diffusion coefficient of a concrete mixture, most commonly the twenty-eight day apparent diffusion coefficient, D_{28}.

2. For estimating the <u>average</u> diffusion coefficient of concrete in an existing structure, such as a 15-year-old bridge deck.

3. For estimating how the diffusivity of a particular concrete (standard specimens or sampled from a structure) changes over time; a sample can be measured and curve fitted at, say, Day-28, Year-1, and Year-5 values of average diffusion coefficient.

Concrete field samples do not directly meet the sample requirements in ASTM C1556, but can still be used to estimate diffusion and surface concentration by "fitting" the data to Fick's second law of diffusion. The result estimates the <u>average</u> diffusion coefficient over, say, the 15-year life of a concrete field sample, as opposed to the <u>instantaneous</u> diffusion coefficient in the 15th year.

4.1.2   Maximum Surface Concentration

In addition to estimating average diffusion coefficients, ASTM C1566 can be used to estimate the maximum surface concentration of chlorides to which the concrete has been exposed to over its lifetime. Figure 4.1 illustrates how the ASTM method directly estimates the average surface chloride concentration as the intersection of the Fick's second law-based grey line and the horizontal access, that is, the estimated chloride concentration at depth = 0 (the blue dot in the figure).
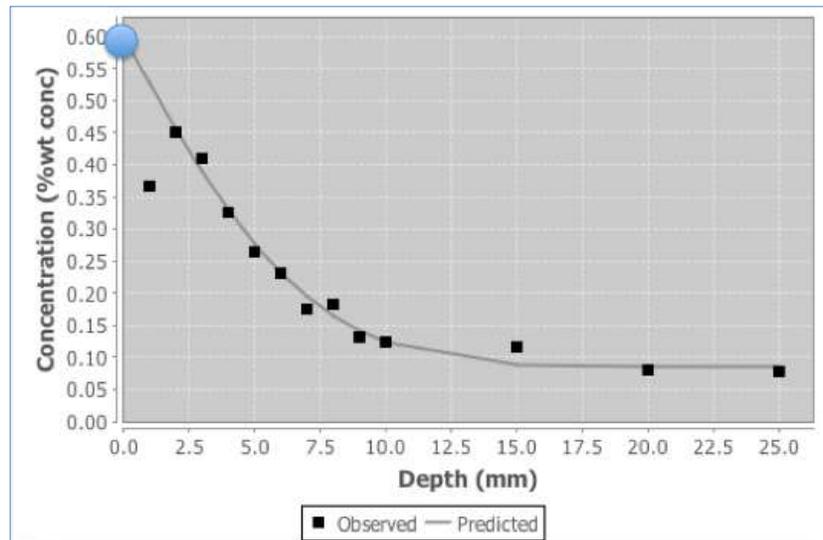
Figure 4.1. ASTM Estimate of Surface Chloride Concentration

When ASTM C1556 is performed on standard molded samples prepared and conditioned in a controlled laboratory environment, this surface concentration is known exactly.[5] For in-situ core sampling and other chloride-concentration tests, however, the value of this surface concentration is unknown – and this input is needed by Life-365. This provides better input information than the default values of Life-365. This update to Life-365 ASTM C1556 module allows for the input of a better estimate a maximum surface chloride concentration of a structure for the typical exposure conditions it is exposed to in service. To improve the reliability of the estimate, core samples should be taken from similar types of structures in the same type of exposure anticipated for new construction – for example parking garage structures, marine exposure, etc.

4.2   How Life-365 Uses the ASTM C1556 Method

Life-365 uses two types of exposure conditions, surface chloride concentration that build up over time and monthly average temperatures, to capture how the environment affects the corrosion

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[5] Section 7 of ASTM C1556-11 (2011) Method calls for "An aqueous NaCl solution prepared with a concentration of 165 ± 1 g NaCl per L of solution."

initiation period. The surface chloride concentration over time is modeled as a constant initial maximum concentration, with a linear increase to that maximum from time zero. The defaults estimates of maximum chloride concentration are based on data from the Salt Institute and the time to buildup to maximum are based on data in Weyers (1993).

Life-365 now also includes a module that uses measurements obtained using ASTM C1556 for generating an estimate of the maximum surface chloride concentration (C_s), and the time to build (t) up to that maximum.

4.2.1   Data Required for Maximum Surface Concentration Calculations

When creating a new ASTM C1556 concrete sample data set, the analyst needs to have the following "inputs" or required data:

- The concrete chloride concentration, by depth, of a concrete sample, following ASTM C1556. Note: the ASTM C1556 specifically discards the first, or top-most layer for the chloride concentration measurement.

- Life-365 uses three units of measure – SI-mm, SI-cm, and US – and for each chloride concentration – %wt concrete, kg/m3, or lb/y3 respectively. The concrete sample data will need to be converted to one of these three units of measures. For example, chloride concentration data expressed in parts per million will need to be converted to, say, %wt concrete (by dividing the values by 1,000,000 and then multiplying by 100, so that a number such as 10,000 ppm is expressed as 1%).

- The initial chloride concentration of the concrete, expressed in the same units as the depth/concentration data.

- The time duration of the concrete exposure to chlorides, in days.

4.2.2   Inputting the Data

To input chloride concentration data into a Life-365 project, access the **Exposure** tab in the project (Figure 4.2), select **Set values manually**, and then select **ASTM C1556**.
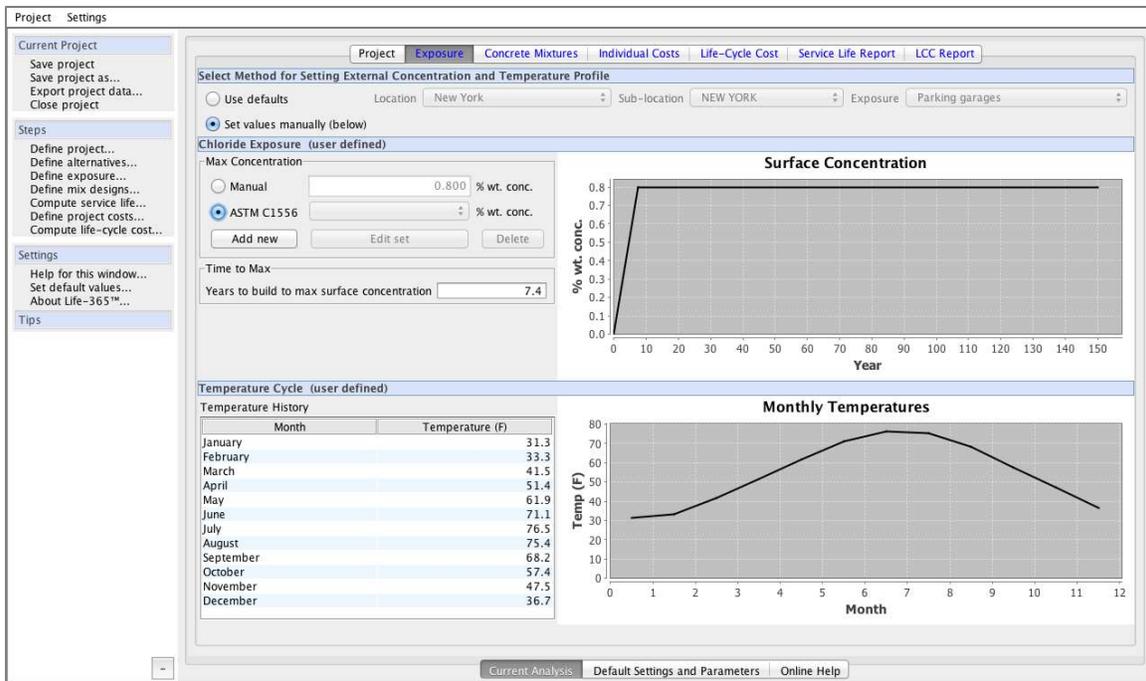
Figure 4.2. New Life-365 Exposure Tab

To create a new ASTM set, press the **Add new** button in the panel. After prompting for a set name, a new empty data set will display in an ASTM data panel (Figure 4.3).
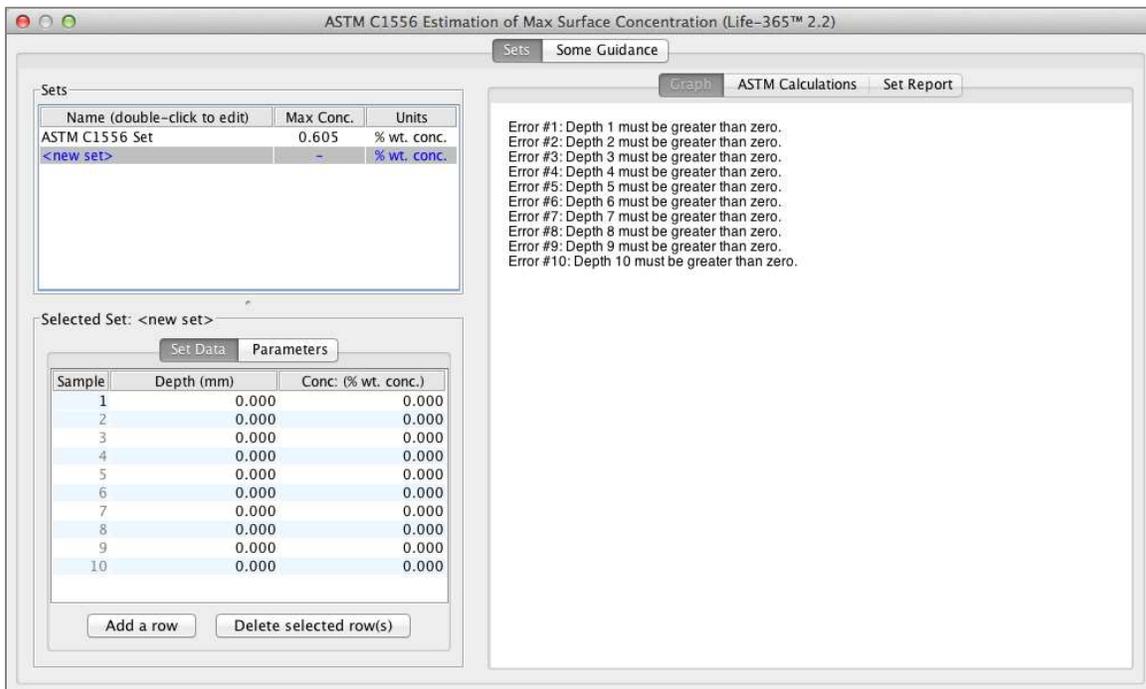
Figure 4.3. ASTM New Set Data Entry Panel

To enter a C1556 chloride data set, select the depth field, e.g., **Sample 1**, and enter the depth value. Do the same for the chloride concentration value, and then repeat these two inputs for all of the

remaining sample data. If you have more than 10 rows of data, select the **Add a row** button at the bottom of the screen to add a row. When complete, if you have extra, empty rows, select them and then press the **Delete selected row(s)** button on the bottom of the screen to delete them. When completed with entering the depth/concentration data, select the Parameters tab and input the Days and **Initial Conc** (concentration) values for your data set.
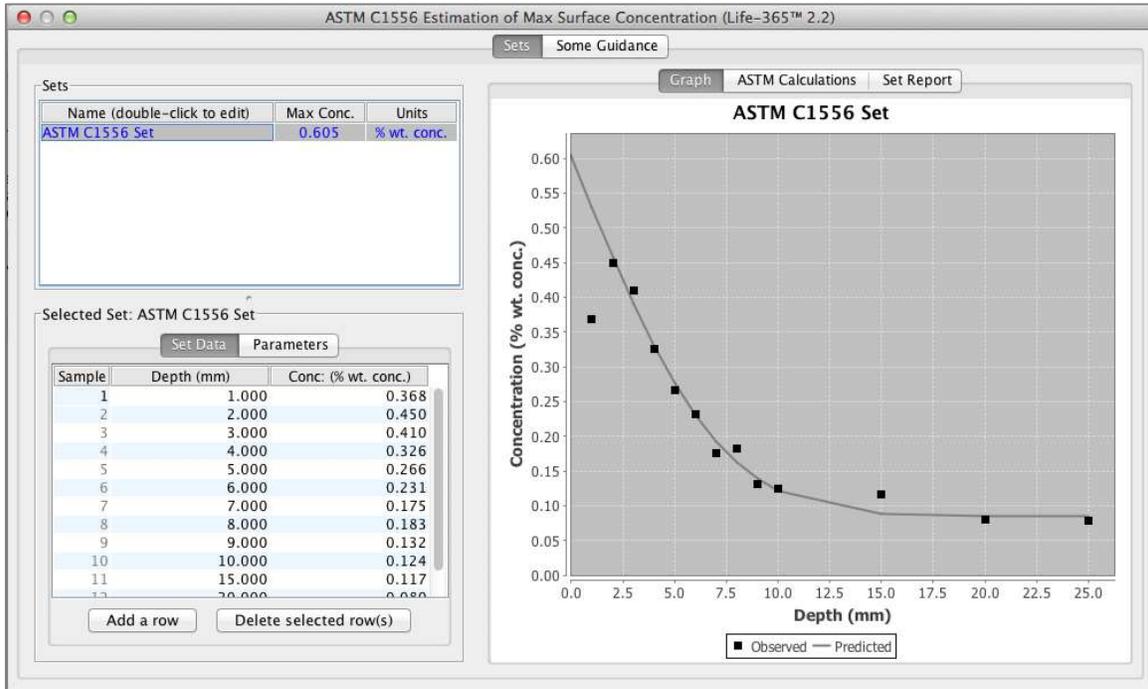
Figure 4.4. ASTM C1556 Data

When done, the ASTM C1556 panel should look something like Figure 4.5.

Showing the Data

Parameters Panel
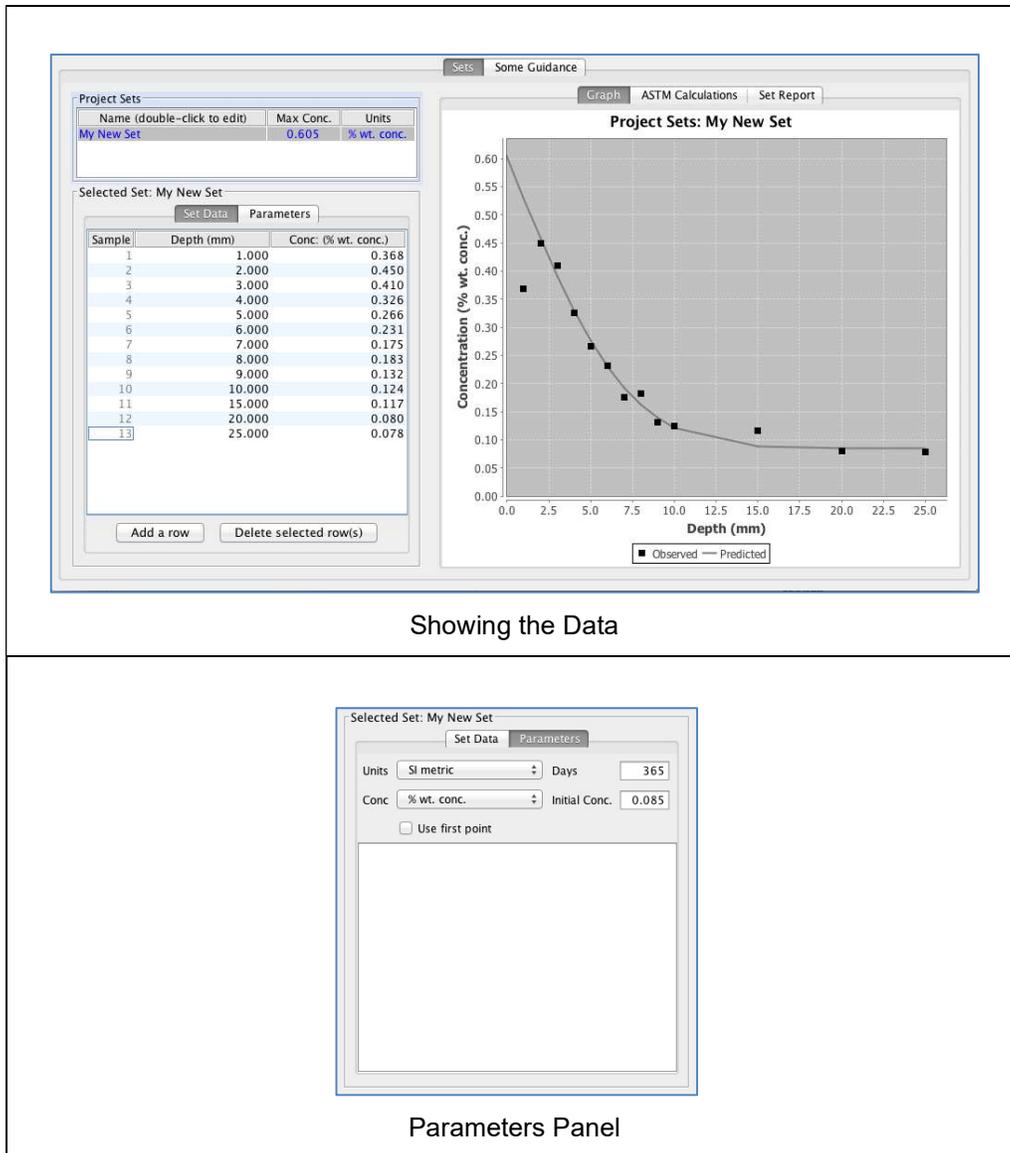
Figure 4.5. ASTM Panel with Data Entered

4.2.3 Viewing the Results

Once the data has been entered, the data can be viewed in a number of ways.

1. The Sets panel now lists the new data set, the maximum surface chloride concentration and their units of measure. The maximum surface chloride concentration value listed in the table is the value that can be used in a Life-365 project analysis.

2. As shown in Figure 4.6, the ASTM Calculations tab lists all of the calculations used (and specified by ASTM C1556) for fitting the concrete data to Fick's second law.
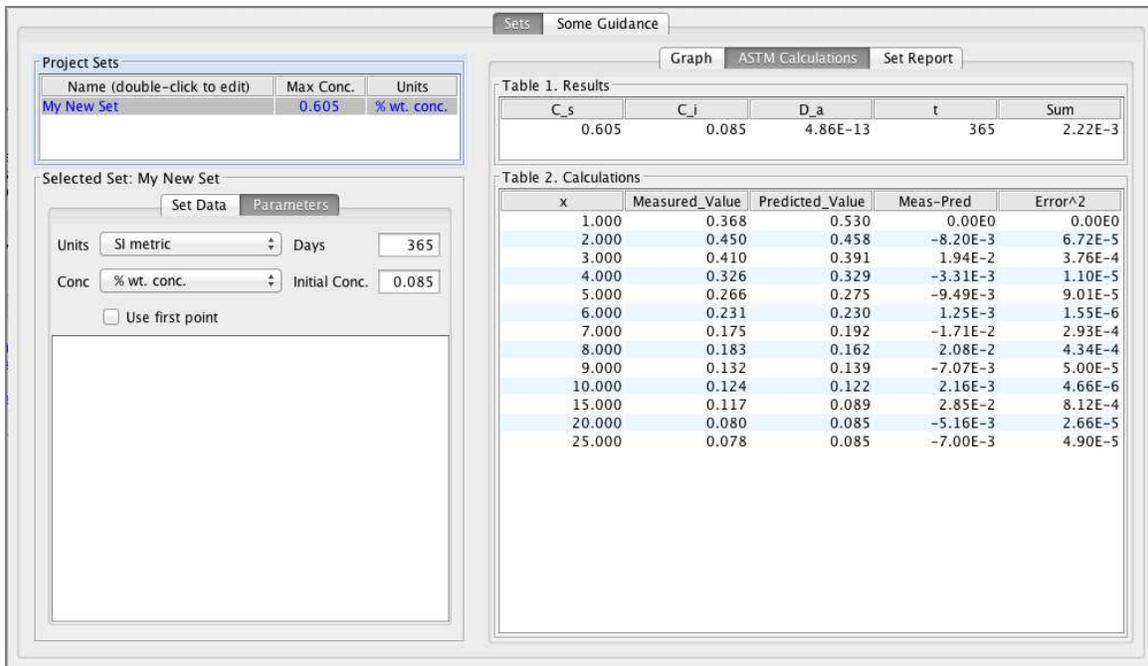
Figure 4.6. ASTM Panel: ASTM Calculations Tab

4.2.4 Using the Surface Concentration Estimate in the Life-365 Project

Once the concrete data has be entered and verified, the set can be used in a Life-365 project. As shown in Figure 4.7, the new set can be used by first selecting **Set values manually**, then selecting **ASTM C1556**, and then selecting the new set from the drop-down **<import>** list.

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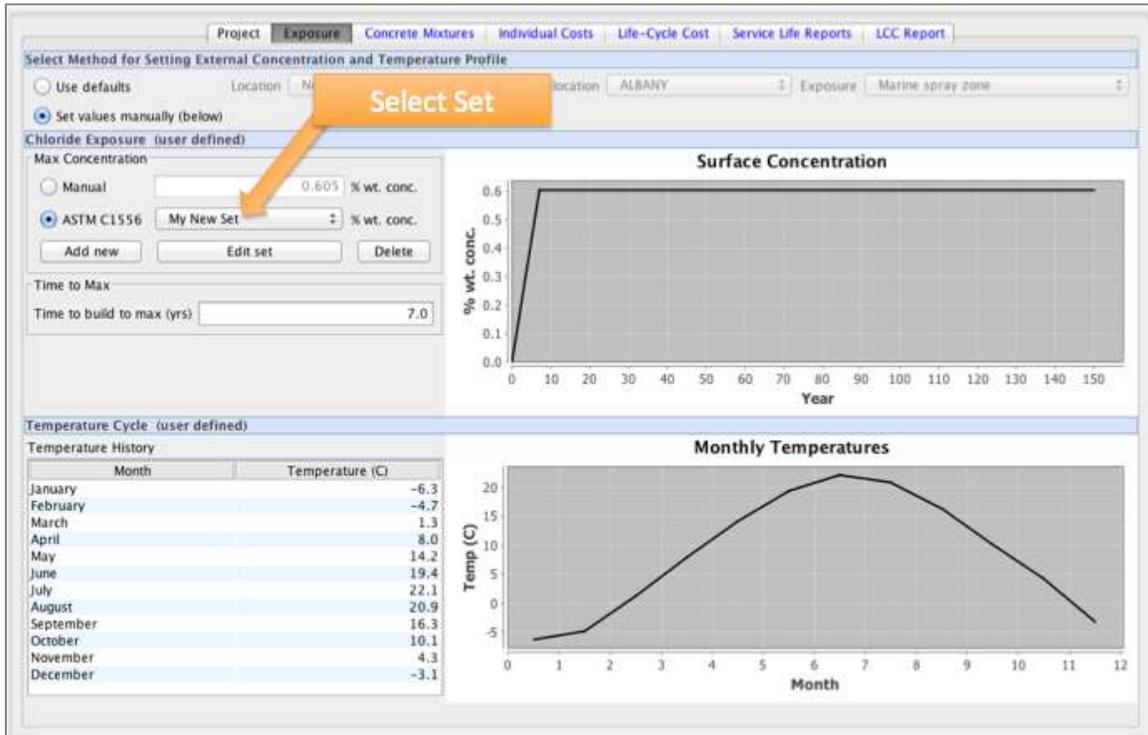
Figure 4.7. Accessing an ASTM Dataset in a Life-365 Project

To edit a set in the **ASTM C1556** dropdown list, select the set and then press the **Edit set** button. To delete the currently selected set, press the **Delete** button.

4.2.5   Guidance Tab

The second, **Some Guidance** tab at the top provides information how to correctly use this Life-365 application of ASTM C1556. Important guidance includes:

- Be sure that a particular data set has the correct setting for **Unit** (base units), **Conc** (concentration units), **Days** (the age of the sample when measured), and **Initial conc.** (the initial chloride concentration of the sample). If significantly incorrect, any one of these parameters could cause significant deviations in the estimated surface concentration of chlorides used in Life-365.

- The precision of the ASTM estimate of surface chloride concentration is sensitive to the number of samples. While the ASTM C1556 Method does not specify a minimum number of samples of depth and concentration, the user should attempt to see how sensitive their estimates are to this number.
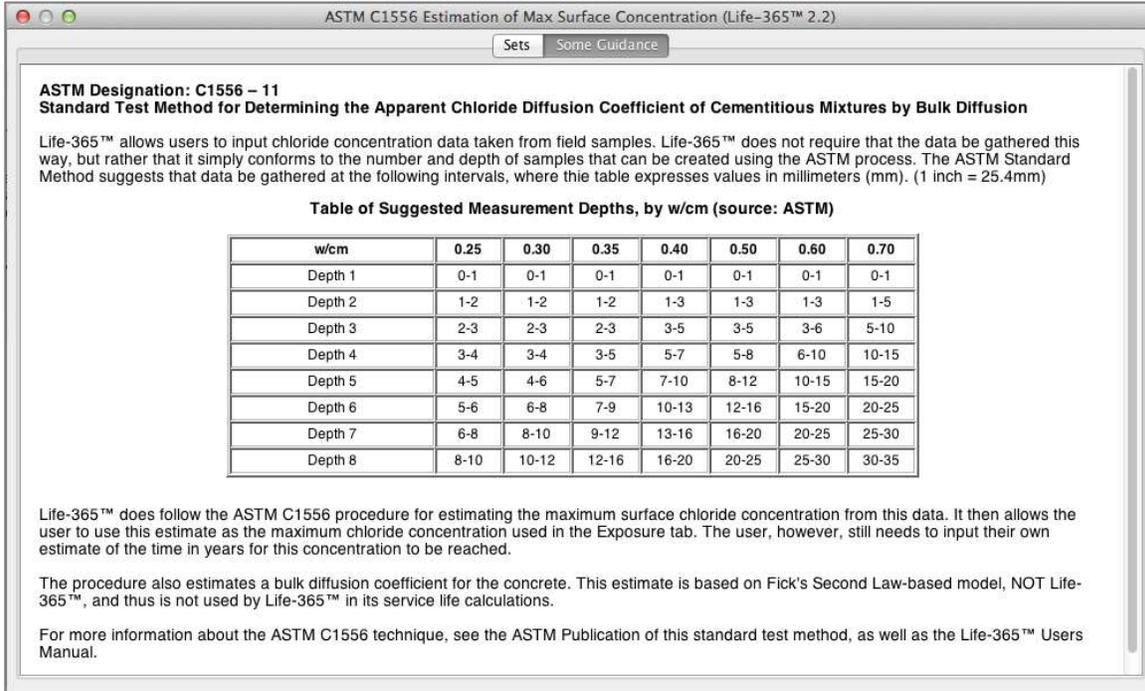
Figure 4.8. Life-365 ASTM Guidance Tab

4.3   Software Algorithm

The ASTM C1556 procedure requires an algorithm to fit the laboratory data to a diffusion and surface concentration curve that reflects Fick's second law of diffusion:

$$c(x,t) = c_s - (c_s - c_i)erf\left[\frac{x}{\sqrt{4Dt}}\right],$$

Eq. 2

where

x = depth from the top surface,

t = time since the exposure to the surface chlorides,

c_s = the constant chloride concentration at the surface of the concrete,

c_i = the constant ambient chloride concentration of the concrete, and

D = the constant chloride diffusion coefficient of the concrete.

The specific requirement stated in ASTM C1556 is to select the values of c_s and D that minimize the function

$$\sum \left(c_x^t - c(x,t)\right)^2,$$

Eq. 3

where the variables are c_s and D, and the parameters (or the information taken as <u>given</u> in this equation are x, t, c_t, and c_x^t, the last of which is the observed value of concentration at depth x and time t. We instead use a Levenberg-Marquardt nonlinear least squares algorithm that will find the

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values of c_s and D.[6] The solver needs a gradient of this function, in particular the first derivatives of $c(x,t)$ with respect to c_s and D. These derivatives are:

$$\frac{\partial c(x,t)}{\partial c_s} = \left(1 - erf\left[\frac{x}{\sqrt{4Dt}}\right]\right), \text{ and}$$ Eq. 4

$$\frac{\partial c(x,t)^2}{\partial D} = -(c_s - c_i)\frac{2}{\sqrt{\pi}}e^{-\left[\frac{x}{\sqrt{4Dt}}\right]^2}\left(\frac{x}{\sqrt{4t}}\right)\left(-\frac{1}{2}D^{-\frac{3}{2}}\right).$$ Eq. 5

Implementing these in Life-365™, our verification test is that this Levenberg-Marquardt algorithm produces the same estimate of surface concentration and diffusion as those obtained from ASTM C1556, as illustrated in Figure 4.9.
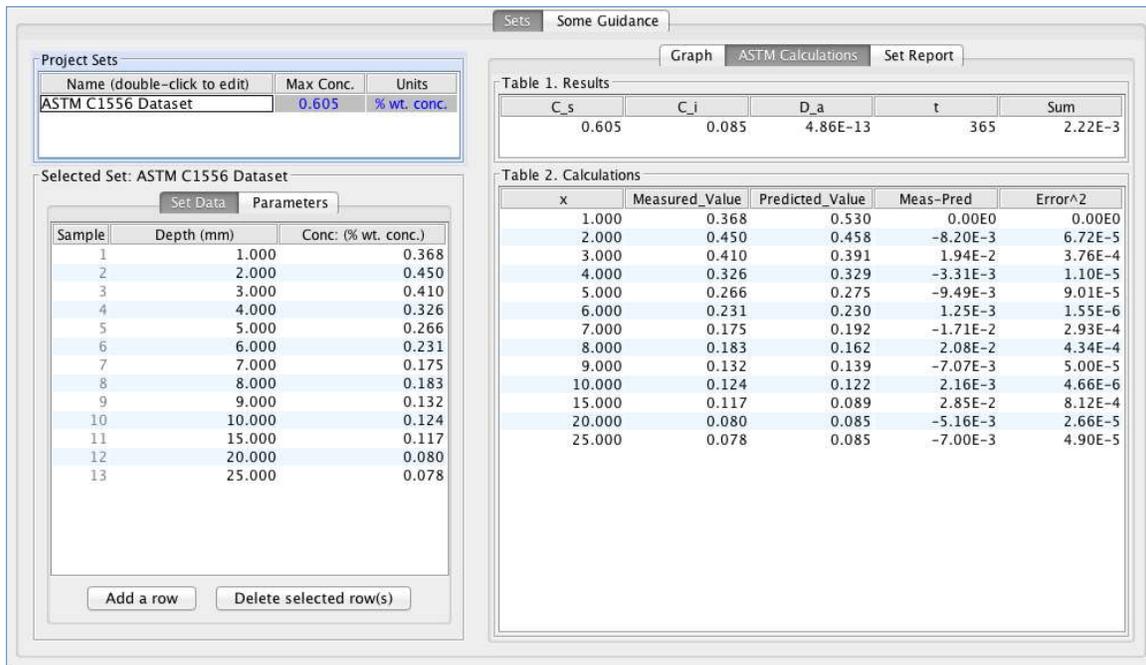
Figure 4.9. Verification of Results for Levenberg-Marquardt Algorithm

The Levenberg-Marquardt algorithm requires initial guesses of c_s and D. In the model, the default initial guesses are $c_s = 1.0$ percent-weight concrete, and $D = 1\times10^{-12}$ meters-squared per second. A more detailed grid evaluation of ranges of values for these initial guesses, $c_s \in [0.01, 2.0]$ and $D \in [1\times10^{-15}, 1\times10^{-10}]$, yields the same solution values of c_s and D.

4.4   ASTM C1556 References

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5 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 cost 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 researched and understood. Consequently it is necessary to simplify the 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 that users of the model are made aware of important 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. Validation of estimates from the model to the service life of actual structures is also an important activity that can further improve the model's output.

5.1 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 5.1.
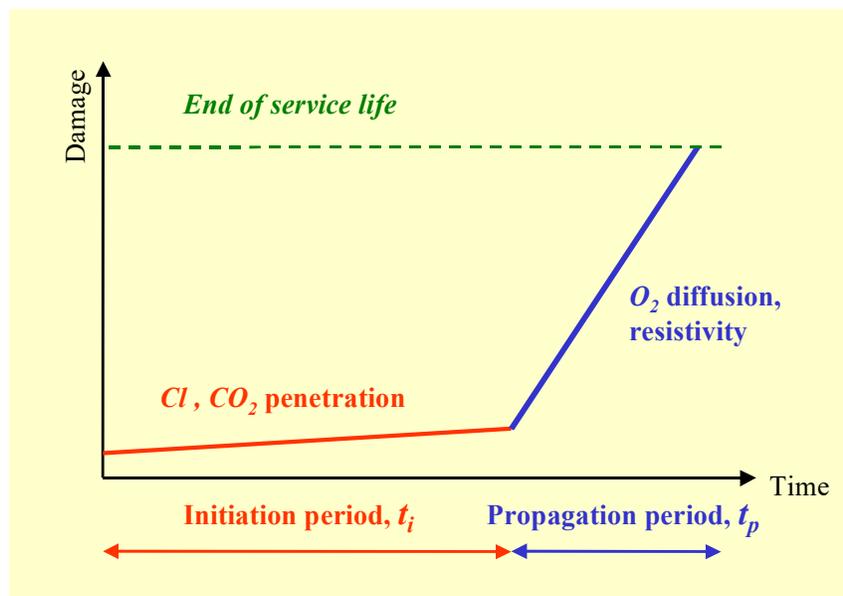
Figure 5.1. Components of Concrete Service Life

5.1.1 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, the 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 that is completely saturated. Although there are relatively simple numerical solutions to Fickean 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 (under the assumption of uncracked concrete).

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 (developed by Evan Bentz of the University of Toronto), 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.

5.1.2   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 structural member 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 buildup 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 of time to the propagation period based on empirical observations. This approach has been adopted by Life-365.

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

Life-365 requires the following data to calculate the time to first repair, t_r:

C_s   Surface concentration (kg/m^3, lb/yd^3, %)

This is the chloride concentration at the surface 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 buildup and maximum value can be default values within Life-365 based on the geographic location and nature of the structure, or can be input by the user. This version of the model includes user input for ASTM C1556 data that can impact this input value.

D   Diffusion coefficient (m^2/s, in^2/s)

This is a material property that is either default values set by Life-365 on the basis of concrete mixture proportions provided by the user, or inputted directly by the user in the **Set own concrete properties** section of the **Concrete Mixtures** tab. This version of the model includes user input for ASTM C1556 data that can impact this input value.

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 Eq. 2 and Eq. 8). It is either default value set by Life-365 on the basis of concrete mixture proportions provided by the user, or inputted directly by the user in the **Set own concrete properties** section of the **Concrete Mixtures** tab. In all cases, Life-365 assumes that hydration of cementitious materials is complete after 25 years, at which point the time-varying effects of *m* no longer apply and Life-365 holds the diffusion coefficient constant.

C_t   Chloride threshold (kg/m^3, lb/yd^3, % - is the same units as *C_s*)

This is the concentration of chloride required to initiate corrosion of the embedded steel reinforcement. The value is either a default value set by Life-365. The value changes based the basis of the type and quantity of corrosion inhibitor and the nature of the reinforcement. Alternatively, the user can input a different value in the **Set own concrete properties** section of the **Concrete Mixtures** tab.

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 a default value set by Life-365 on the basis of the type of reinforcement, or inputted directly by the user in the **Set own concrete properties** section of the **Concrete Mixtures** tab.

T   Temperature (°C, °F)

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 by un-checking the **Use defaults** box in the **Exposure** tab.

5.2.1 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. Life-365 includes the following exposure conditions:

- 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 are only available for coastal regions. 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 values in Table 4:

Table 4. Build-up Rates and Maximum Surface Concentration, Various 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 percent per year to greater than 0.1 percent per 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 5.2, which shows how the chloride build-up rates vary across North America.
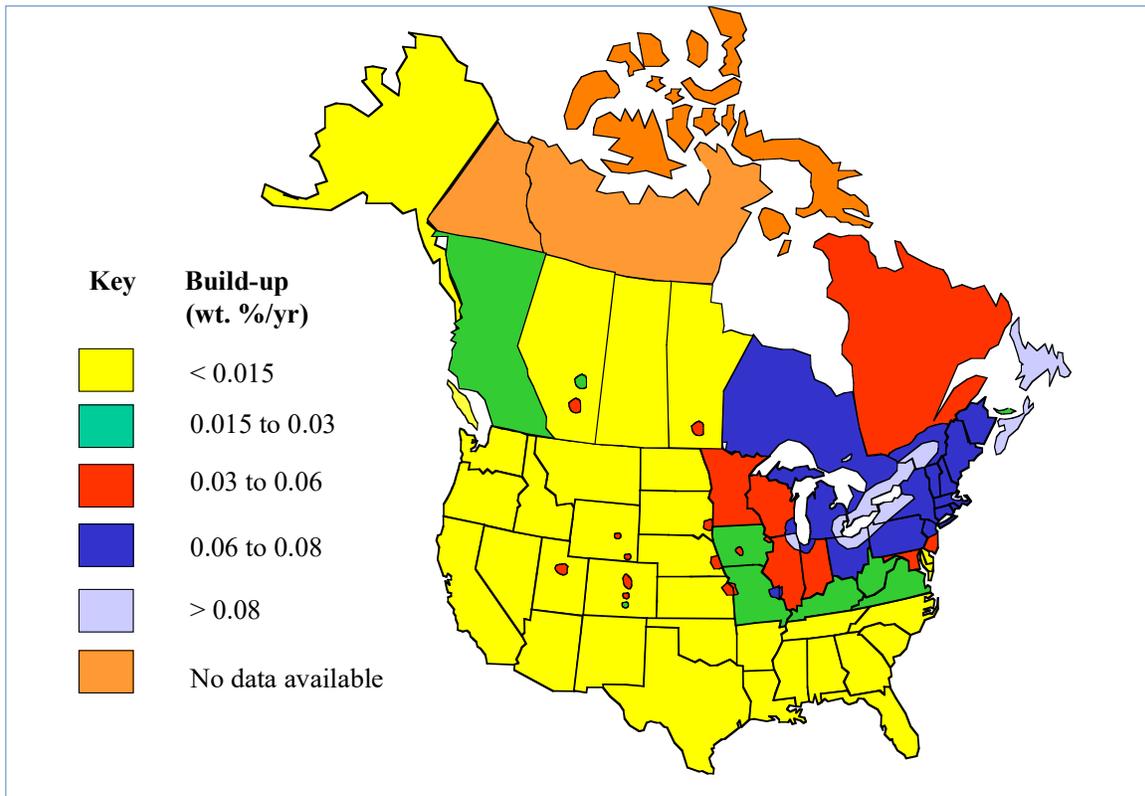
Figure 5.2. Chloride Levels, by Region of North America

The maximum surface concentration for parking structures located in the regions where deicing salt use is the greatest (light blue in Figure 5.2) is assumed to reach 1.0 % wt. of concrete. Elsewhere, the maximum surface concentration for parking structures is assumed to reach 0.8 percent. Life-365 applies the factors listed in Table 5 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 5. 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 percent of value in Fig. 31	0.85/0.68
Rural Bridges	70 percent 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 by un-checking the **Use defaults** box in the **Exposure** tab.

5.2.2 Diffusion Coefficient

PC Concrete

Life-365 assumes a time-dependent diffusion coefficient as defined by Eq. 2 through Eq. 5 of this document. The value of D_{28} is dependent on the water-cementitious material ratio (*w/cm*) of the concrete (Eq. 4), 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 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 second law of Diffusion to the experimental data.

Figure 5.3 shows the relationship between D_{28} and *w/cm* for concrete at 20°C based on data from this test. The data shown represent portland cement concretes (without supplementary cementitious materials) 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).
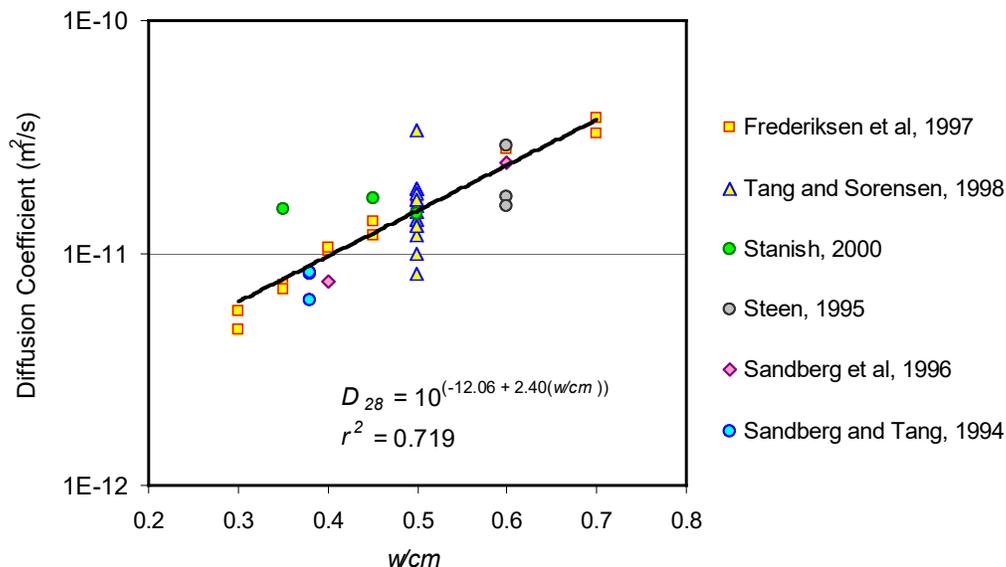

Figure 5.3. Effects of w/cm on Diffusion Coefficient

Based on this relationship, the predicted early-age diffusion coefficient for a portland cement concrete with $w/cm = 0.40$ is $D_{28} = 7.9$ x 10^{-12} m^2/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 x 10^{-12} m^2/s in northern states to 6.7 x 10^{-12} m^2/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 Eq. 2 and Eq. 3. For example, the calculated diffusion coefficient at 10 years for a portland cement concrete with $w/cm = 0.40$ is $D_{10y} = 2.5$ x 10^{-12} m^2/s at 10°C. This is not inconsistent with the range of values presented by Weyers (1998).

Effects of Supplementary Cementitious Materials

Besides the w/cm, the composition of cementitious materials also makes a significant impact to the diffusion coefficient of concrete.

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 5.4 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 mixture without silica fume (D_{PC}).
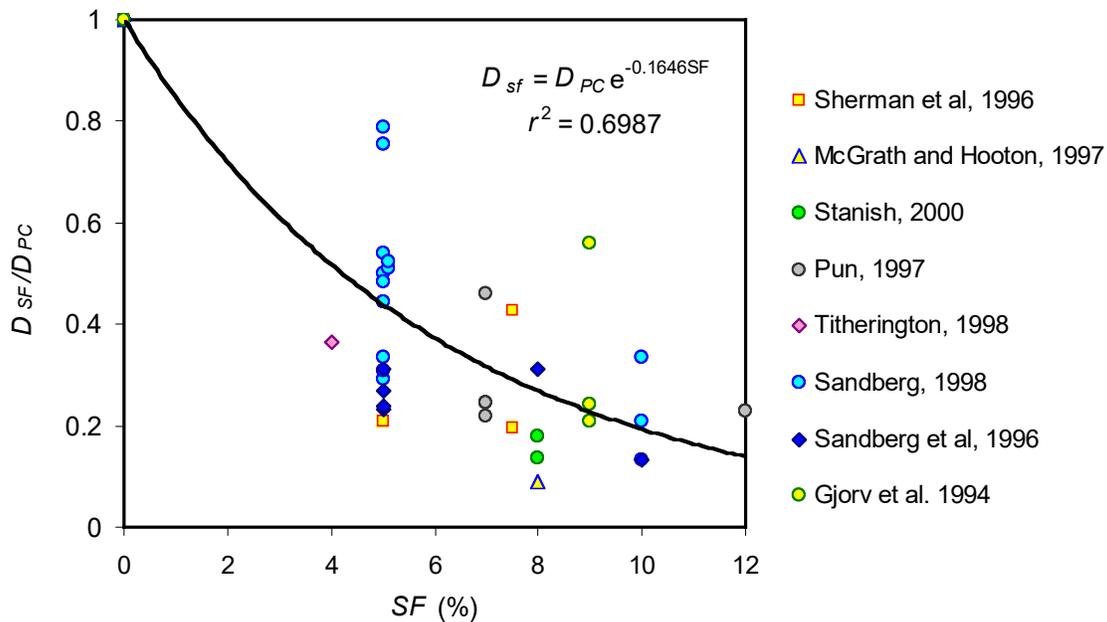

Figure 5.4. Effects of Silica Fume on Diffusion Coefficient

Results showing the effect of slag cement 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.

Due to the limitations of the default diffusion coefficient values for concrete mixtures with supplementary cementitious materials, the module that allows the input of data obtained from C1556 measurements can provide a better input to the model.

5.2.3   Diffusion Decay Index (*m*)

A number of studies 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. mixture proportions) and the environment (e.g. temperature and humidity). The following equation has frequently been suggested in the literature:

$$D(t) = D_{ref} \cdot \left(\frac{t_{ref}}{t}\right)^{m},$$

where $D(t)$ =   diffusion coefficient at time t,

          D_{ref} =   diffusion coefficient at some reference time t_{ref}, and

          m =   constant (depending on mixture proportions).

Bamforth (1999) recently proposed the values in Table 6 for m based on a review of published diffusion coefficients from more than 30 sources:

Table 6. Values of m, Various Concrete Mixtures

Concrete Mixture	*m*
PC Concrete	0.264
Fly Ash Concrete	0.700
Slag cement 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 percent) and slag cement (e.g. 50 to 70 percent). 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 cement (*%SG*) in the mixture. The relationship used is

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

Other researchers have proposed relationships between m and other parameters such as the *w/cm* ratio and silica fume content of the mixture (Mangat and Molloy, 1994; Maage et al., 1995). These are not considered in the current version of Life-365, but may be incorporated in future versions. The user is encouraged to examine the influence of m by comparing different values in user-defined scenarios.
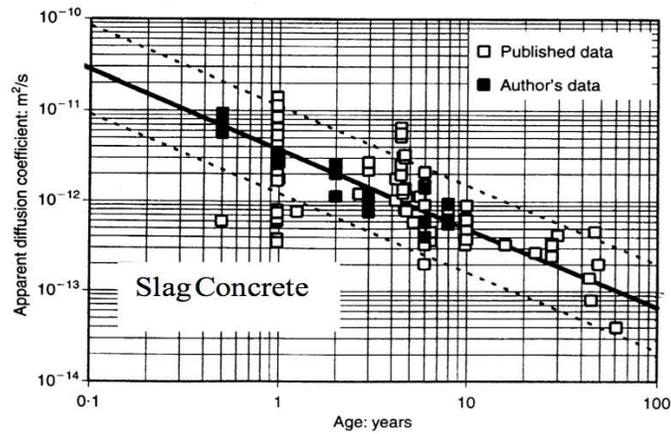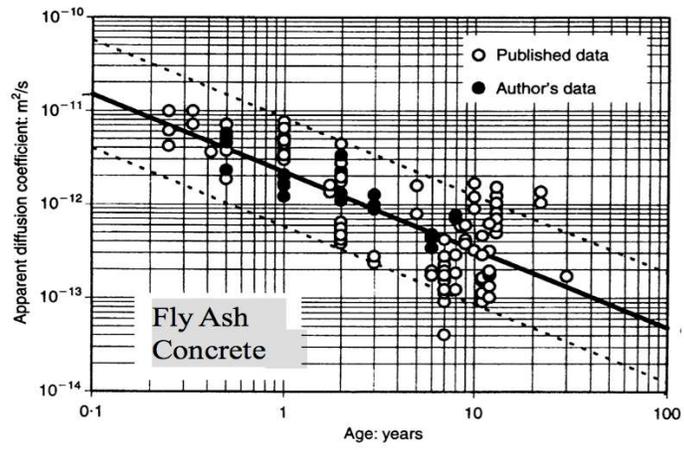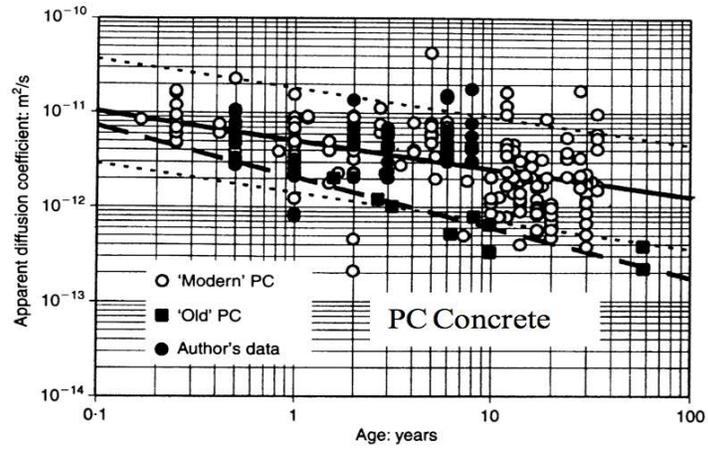
Figure 5.5. Effects of Age on Diffusivity

To reflect the completion of hydration, it is reasonable to assume that there is some limiting value of diffusion coefficient of the concrete mixture. In Life-365 the diffusion coefficient decays with time according to Eq. 2 until the concrete reaches the age of 25 years, at which point the diffusion coefficient remains constant for the rest of the analysis period (i.e., $D_t = D_{25y}$ for $t \geq 25$ years).

5.2.4 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 percent 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 percent for buildings exposed to a temperate European climate and 0.2 percent 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 percent by mass of cement is equivalent to a range of 0.03 to 0.07 percent by mass of concrete (for typical concretes with cement contents in the range 350 to 400 kg/m^3). Consequently a value of C_t = 0.05 percent 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 7. Doses and Thresholds, Various Inhibitors

Dose		Threshold, C_t
litres/m³	gal/cy	% wt. conc.
Rheocrete 222+[7]		
5	1	0.12
Calcium Nitrite Inhibitor		
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.

The use of an organic inhibitor (Rheocrete 222+) also causes a reduction of the initial diffusion coefficient to 90 percent 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 $C_t = 0.50$ percent (i.e., ten times black steel). This value was taken from the FHWA study conducted by MacDonald et al (1998).

5.2.5   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 (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;

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

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.

5.2.6   Temperature

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

5.3   Input Parameters for Calculating Life-cycle cost

All the input parameters related to calculating the initial construction, barrier, 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.

5.4   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_t, 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.

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Appendix A. Test Protocols for Input Parameters

Background

Life-365 is a concrete service-life tool that contains algorithms to determine "best guess" default 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 Computer Program.

The limitations of this default-value approach were recognized by the model developers, so the Program allows allow users to evaluate alternative strategies by entering their own, custom project or product-specific data. This appendix is intended to guide the individual in selecting these custom values. 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 initiation of corrosion in Life-365 (and their location in the Computer Program) are shown in Table A1-1.

Table A1- 1. User Definable Input Parameters

Parameter	Where it is Input in the Computer Program
Maximum surface chloride content, C_{max}	**Exposure** tab: **Max surface conc**.
Rate of surface chloride build-up, k	**Exposure** tab: **Time to build to max (yrs)**
Sealer efficiency factor, e	**Concrete Mixtures** tab: **Initial efficiency (%)**
Concrete temperature monthly history	**Exposure** tab: **Temperature History**
Concrete cover, x_d	**Project** tab: **Thickness** (1D) or **Width** (2D)
Apparent chloride diffusion coefficient, D_{28}	**Concrete Mixtures** tab: **D₂₈**
Diffusion decay index, m	**Concrete Mixtures** tab: **m**
Critical chloride threshold for corrosion initiation, C_t	**Concrete Mixtures** tab: **C_t**
Corrosion propagation time, t_p	**Concrete Mixtures** tab: **Prop. period**

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 user values in the **Max surface conc.** field in the **Exposure** tab of the Computer Program. 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 percent chloride by mass and has a density of approximately 1.01 kg/L. If the concrete porosity is 15 percent by volume, and has a density of 2.30 kg/L, the theoretical maximum is:

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

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 percent. 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 percent 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 5.2 (pg. 61). Changes to k affect the time to reach C_{max}. Users can change k by changing the **Time to build to max (years)** field in the **Exposure** tab of the Computer Program, or the sealer **Initial efficiency** field in the **Concrete Mixtures** tab. (Note that this estimation of the build-up rate is separate from specification of the maximum surface chloride concentration, the latter of which can be done in Life-365 through lookup tables, ASTM C1556, or manual input.)

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 percent NaCl solution.

For example, the data from NCHRP 244 Table B-30 indicates the reference concrete gained 0.235 percent and silane-treated concrete had gained 0.050 percent. 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 affects 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 in the **Exposure** tab, by un-checking the **Use defaults** box and then entering data in the **Temperature History** table.

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. At the time of Life-365's first development, there was no ASTM C1556 standard, so the model developers adopted the Norwegian standard method, NT BUILD 443. This laboratory procedure calculates D_{28} directly from a chloride content profile. Both methods should generate similar if not identical estimates of D_{28}.

The procedure for obtaining obtain this D_{28} reference value is as follows:

1. After 28 days of 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; or the web http://www.vtt.fi/nordtest.

Diffusion decay index, 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 but diminishing hydration in Eq. 2 by using the diffusion decay index, *m*, and assuming that hydration completes in 25 years, after which point the diffusion coefficient stays constant at its computed 25-year value. 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_t

The corrosion threshold concentration of chloride is influenced by numerous variables, and is therefore not a singular value. The C_t 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 percent 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 8. 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 ft2 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