Life-365™ v2.2

Adding user estimates of chloride exposure

by Mark A. Ehlen and Anthony N. Kojundic

Over the past 15 years, Life-365™ has been widely used to estimate the service lives of concrete structures exposed to environmental chlorides. Its development started in 1998, when the Strategic Development Council (SDC) of the American Concrete Institute (ACI), responding to concern by the engineering community over disparate existing models, identified the need for a "standard model" of concrete service life. Later that year, the National Institute of Standards and Technology (NIST), ACI, and ASTM International sponsored a concrete service life workshop, where a decision was made to develop such a model. Based on sponsorship through a consortium of industry stakeholders, the Life-365 Service Life Prediction Model was released. Subsequent consortia, with guidance by industry and user feedback, have since added uncertainty analysis[1,2] and verification and validation processes to the Life-365 model and software.

Perhaps the most difficult and time-consuming task in developing Life-365 v1.0 was estimating surface chloride concentration (C_s). Exposure levels were known to vary by locale, environment, and type of structure, but there were limited data on which to base assumed values. However, salt-loading information from the Salt Institute and the few U.S. states that had sufficient data were used to create a map with the anticipated chloride buildup rates for North America (Fig. 1).[3] The maximum chloride exposure expected for parking structures in the most heavily salted areas (in some urban areas near the Great Lakes) was 1% by weight of the concrete (% wt. conc.). The minimum chloride buildup rate was 0.015% wt. conc./year. As the map indicates, about 75% of North America (the yellow region) was assigned this minimum buildup rate. While that rate may be reasonable for southern states such as Georgia, it is unlikely that the minimum rate is appropriate for the northern and western mountainous regions of the United States.

As a further complication in providing reasonable estimates for C_s, international users now represent half of all downloads of Life-365 (**www.life-365.org**). Given the lack of representative salt-loading values for most of the world, the User's Manual for Versions 1.0 through 2.1 directed users to "use chloride data from local sources where available" and to "compare the output using the values selected by Life-365 against output generated from user-defined chloride buildup rates and maximum surface concentrations." Users ultimately chose a wide range of values for C_s to make service-life calculations. The resulting predictions were probably not representative of the actual service lives of similar structures in comparable environments.

Estimating C_s with ASTM C1556

To address these issues, the current version of Life-365 (v2.2) includes a module that can provide an estimate of C_s using information obtained through ASTM C1556, "Standard Test Method for Determining the Apparent Chloride Diffusion Coefficient of Cementitious Mixtures by Bulk Diffusion." ASTM C1556 was released in 2003 to aid

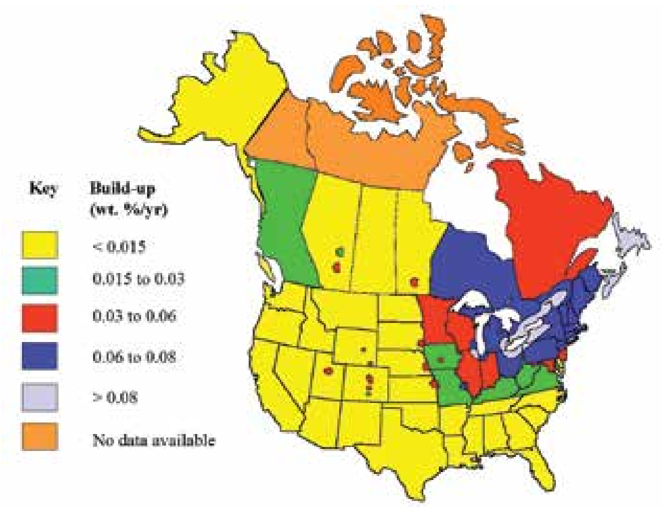


Fig. 1: Rate of chloride buildup (wt. %/year) in North America by region[3]

practitioners in accurately measuring the chloride content in concrete samples, and to use these measurements to estimate the apparent diffusion coefficient and maximum surface chlorides of concrete using Fick's second law of diffusion.[4] ASTM C1556 is very similar to the NT Build 443 method[5] used by many prior to the release of ASTM C1556. In fact, Life-365 uses the method in NT Build 443 to estimate the relationship between the water-cementitious material ratio (*w/cm*) and the 28-day apparent diffusion coefficient D_{28}.[3]

ASTM C1556 can be used to make estimates for the:

- Initial apparent diffusion coefficient for a concrete mixture;
- Average diffusion coefficient over the life of an existing concrete structure;
- Changes over time in the diffusivity of a particular concrete (sampled or in place); and
- Maximum surface chloride exposures for a concrete structure.

Regarding diffusion coefficients, ASTM C1556 diffusion concepts are very different than those used in Life-365. To illustrate, Fig. 2 shows the diffusivity of a concrete mixture, as represented by a red line. Three points in time are highlighted: day 28, year 1, and year 5.

For each point in time, the estimate provided per ASTM C1556 is the average diffusivity over the period from day zero to the target date, while the estimate provided per Life-365 is the instantaneous diffusion on the target date. Given the declining nature of diffusivity over time (due primarily to ongoing hydration of the binder), the ASTM C1556 estimates are always greater than the Life-365 estimates.

While the ASTM C1556 and Life-365 diffusion estimates are not comparable, the estimates for C_s are. In fact, Life-365 v2.2 now estimates C_s using the ASTM C1556 approach. For a fully ASTM C1556-compliant procedure conducted in a controlled laboratory environment, C_s is manually set and therefore is known exactly. For in-place core sampling and other chloride-concentration tests, however, the value of this surface concentration is unknown but needed by Life-365. Figure 3 illustrates how the ASTM C1556 method is used to estimate the surface chloride concentration (the blue dot in the figure). Concrete chloride levels are measured and plotted as a function of the associated sample depths. A curve (based on Fick's second law of diffusion) is fitted to the data, and the C_s value is estimated as the concentration where the fitted curve crosses the vertical axis (where sample depth is zero).

Given that field data introduce uncertainty to derived parameters such as surface concentration, ASTM C670, "Standard Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials," can be used for estimating the coefficient of variation (COV) and the standard deviation for surface chloride concentration. These statistics are not directly used by Life-365 in its automated calculations of service life uncertainty. If, however, the user applies ASTM C670 to calculate the COV from multiple ASTM C1556 estimates, they can be directly input using the Life-365 "Uncertainty Settings" window, accessed via the "Settings" button in the "Concrete Mixtures" tab.

Incorporation of Field Data into Life-365

Life-365 uses surface chloride concentration over time and monthly average temperatures to capture how the environment affects the corrosion-initiation period. Life-365 v2.2 allows users to input chloride concentrations determined from field-extracted cores following ASTM C1556. The "Exposure" tab (Fig. 4) contains a section titled, "Chloride Exposure (user defined)." The Max Concentration (C_s) can be input manually as a single value, or by using the new ASTM C1556 feature.

The user inputs the chloride concentration values determined by the ASTM C1556 test method, and the program displays the input values and performs a regression analysis to fit a curve to the data and determine the C_s at the surface (Fig. 5).

Although the model uses only the determined C_s in the service life calculations, the model does follow the entire ASTM C1556 method and provides calculated results as well (Fig. 6). The calculated diffusion results, in particular, are not used by the model for service life predictions, and as described previously are average diffusion values for that particular specimen. The diffusion estimates used by the model for the service-life calculation are based on the user-selected alternatives chosen to mitigate chloride diffusion and subsequent corrosion and propagation.[3]

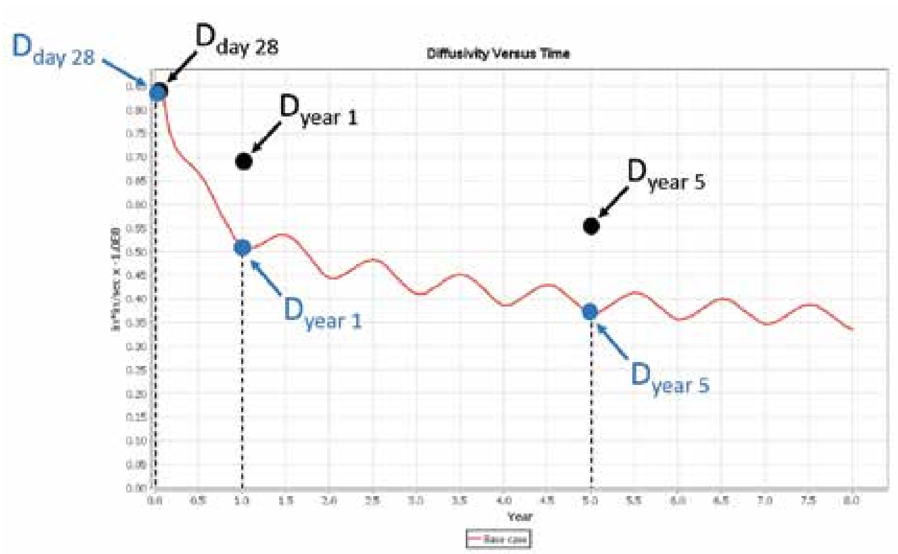


Fig. 2: ASTM C1556 (black) and Life-365 (blue) diffusion coefficient estimates (D) at three ages: day 28, year 1, and year 5

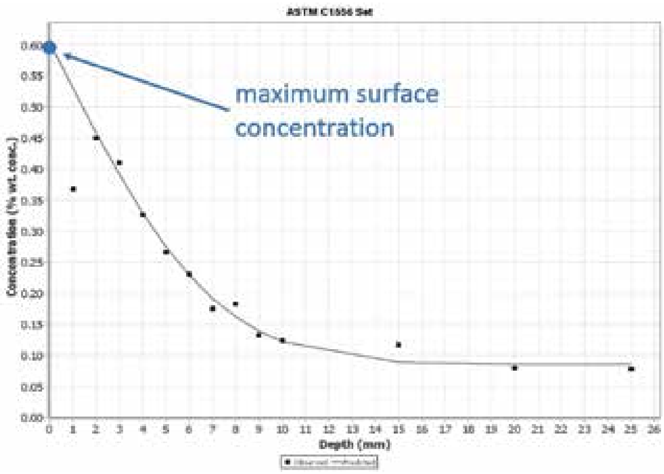


Fig. 3: ASTM C1556 estimate of surface chloride C_s (% wt. conc.)

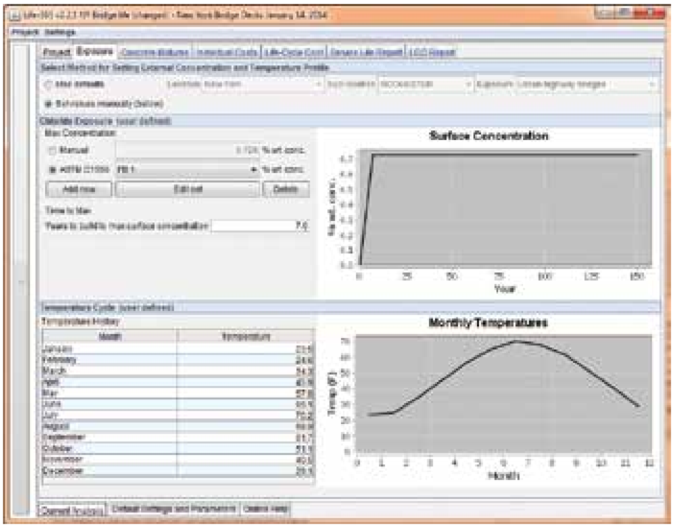


Fig. 4: New Life-365 "Exposure" tab with ASTM C1556 option to input local chloride concentrations

Years to Corrosion Initiation Comparison

In an earlier Life-365 validation study by Hooton, et al.,[6] concrete cores were extracted from a set of high-performance concrete structures in the United States. A group of samples from the New York State Department of Transportation included cores from a project in the Rochester, NY, area. A Class HP bridge deck and the adjacent approaches of Class H conventional concrete, all constructed under the same contract by the same construction team and concrete producer were studied (Table 1). A comparison was made of the model's default value of C_s for Rochester, NY, to the C_s value calculated using Life-365 v2.2 based on the ASTM C1556 chloride-profile data determined from both Class HP and Class H concrete cores under the same exposure conditions.

As seen in Table 1, this analysis demonstrates that the service-life predictions made by the model using the default C_s for Rochester, NY, are only minimally affected by the properties of the concrete used for the chloride profile inputs. It suggests that the Class HP concrete cores had much lower chloride contents than the Class H concrete cores. In fact, the Class H concrete approach slabs contained chloride concentrations well above the corrosion threshold value. However, the curve fitted to the chloride profiles of both the Class H and the Class HP concrete cores yields a very similar C_s, as one would expect from concrete under identical exposure conditions. Service-life results are therefore predicted for either class of concrete (Table 1).

Conclusions

Life-365 was originally developed to provide an industry-consensus service-life model for concrete when exposed to external sources of chlorides. In some regions of the United States, Life-365 gives default values for the model parameters that affect service life, including the maximum surface chlorides to which the concrete is exposed. In all cases, the software allows the user to override these values based on local and more precise data.

One of the most influential parameters affecting service life estimates is the C_s value, which can be estimated using field samples of existing concrete structures. Life-365 v2.2 has integrated the estimating method provided in ASTM C1556

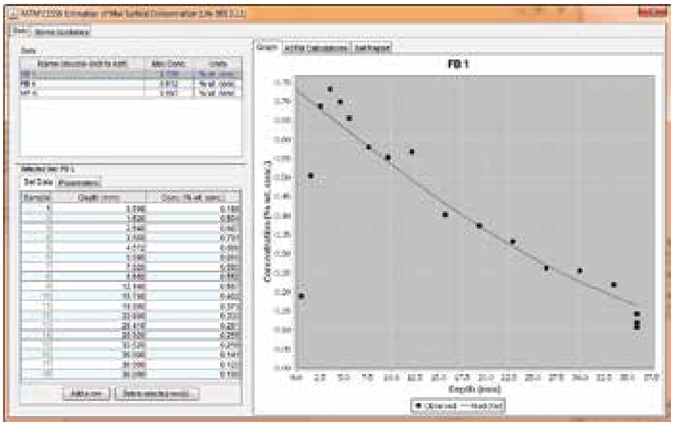


Fig. 5: ASTM C1556 Input/Edit panel for C_s determination

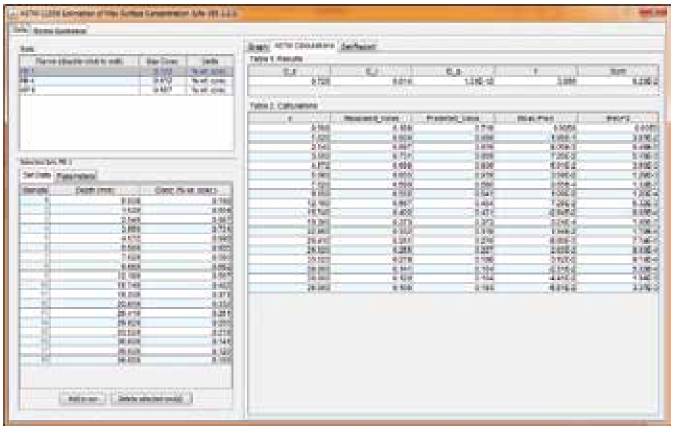


Fig. 6: ASTM C1556 tab in Life-365 v2.2 for maximum surface chloride concentration calculations

into the software, allowing users to develop more accurate predictions of chloride exposure and thus service life. Furthermore, the ASTM C670 methods for estimating uncertainty in C_s can be input into Life-365, providing better approximations of the range of service life for a given region and structure type. It's anticipated that industry feedback on these new capabilities will be used to further improve the Life-365 software.

References

1. Bentz, E.C., "Probabilistic Modeling of Service Life for Structures Subject to Chlorides," *ACI Materials Journal*, V. 100, No. 5, Sept.-Oct. 2003, pp. 391-397.

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

3. *Life-365 v2.2.1 User's Manual*, the Life-365 Consortium III, The Silica Fume Association, Lovettsville, VA, Dec. 2013, 86 pp.

4. Fick, A., "Ueber Diffusion," *Annalen der Physik*, V. 170, No. 1, 1855, pp. 59-86. (http://onlinelibrary.wiley.com/doi/10.1002/andp.18551700105/pdf)

5. NT Build 443, "Concrete, Hardened: Accelerated Chloride Penetration," NORDTEST, Espoo, Finland, 1995, 5 pp.

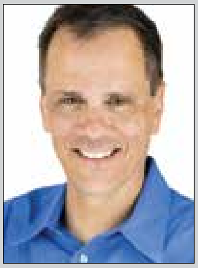
Table 1:
Predicted years to corrosion initiation using default C_s for Rochester, NY, and C_s obtained from Class H and Class HP concrete core samples following ASTM C1556

Sample used for profile inputs	Class H core	Class HP core
Default	5.6	27.8
Class AA approach cores	6.3	31.1
HPC deck cores	7.1	36.1

6. Hooton, R.D.; Bentz, E.C.; and Kojundic, T., "Long-Term Chloride Penetration Resistance of Silica Fume Concretes Based on Field Exposure," *Second International Symposium on Service Life Design for Infrastructures*, K. van Breugel, G. Ye, and Y. Yuan, eds., RILEM Publications SARL, 2010, pp. 503-512.

Note: Additional information on the ASTM standards discussed in this article can be found at **www.astm.org**.

Selected for reader interest by the editors.



Mark A. Ehlen is an engineer and economist with 15 years of experience in developing and applying life-cycle costing techniques to new technology construction materials. With degrees in structural engineering and economics from Cornell University, Ehlen previously worked at the National Institute of Standards and Technology, where he received the Department of Commerce Bronze Medal, and now works at Sandia National Laboratories and separately as a consultant to the construction industry.

Anthony N. Kojundic, FACI, is Director of the Silica Fume Association, and for the past 30 years, Business Manager of Elkem Materials Inc., the largest silica fume (microsilica) supplier in the world. Kojundic is a member of ACI Committees 234, Silica Fume in Concrete; 239, Ultra-High Performance Concrete; 362, Parking Structures; 363, High-Strength Concrete; 365, Service Life Prediction; and 522, Pervious Concrete. He also serves on ASTM International technical committees. He is a member of the Transportation Research Board (TRB), the National Concrete Bridge Council, Concrete & Masonry Related Associations (CAMRA), and the Concrete Industry's Joint Sustainability Initiative. Kojundic served as Chair of the Life-365 Consortium III overseeing the development of the Life-365 v2.2.1 service-life and life-cycle cost model.