
**TUTORIAL FOR
PROBABILISTIC CHLORIDE ATTACK ANALYSIS TOOL**

**PROCAAT
FULL-PROBABILISTIC DESIGN TOOL**

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April 2017

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Abstract

This report provides the background and tutorial for Probabilistic Chloride Attack Analysis Tool (ProCAAT), a Microsoft Excel (2016) based tool. The tool has been developed to perform the full-probabilistic design approach detailed in *fib* Bulletin 34 - Model Code for Service life Design (2006), for the chloride-induced corrosion in uncracked concrete. Service life design of the concrete is based on the solution to a mathematical model for initiation of corrosion in the reinforcing steel in a concrete section exposed to chlorides. The model uses Fick's 2nd law to compare the chloride content in the concrete at the depth of the reinforcement at a desired time, to the critical chloride content for the reinforcing steel. Monte Carlo simulation is used to solve the problem repeatedly, by changing the value of each of the random variables in the equation based on their predefined probability distribution.

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General Description

This tool has been developed to perform the full-probabilistic design approach detailed in *fib* Bulletin 34 - Model Code for Service life Design (2006), for the chloride-induced corrosion in uncracked² concrete. Service life design of the concrete is based on the solution to a mathematical model for initiation of corrosion in the reinforcing steel in a concrete section exposed to chlorides. The model uses Fick's 2nd law, defined in Eqs. (B2.1-1) to (B2.1-4), to compare the chloride content in the concrete at the depth of the reinforcement at a desired time, to the critical chloride content for the reinforcing steel. The method uses Monte Carlo simulation to solve Eq. B2.1-1 repeatedly, by changing the value of each of the random variables in the equation based on their predefined probability distribution.

$$C_{\text{crit}} = C(x = a, t) = C_0 + (C_{S,\Delta x} - C_0) \cdot \left[1 - \text{erf} \left(\frac{a - \Delta x}{2 \sqrt{D_{\text{app},C} \cdot t}} \right) \right] \quad (\text{B2.1-1})$$

$$D_{\text{app},C} = k_e \cdot D_{\text{RCM},0} \cdot k_t \cdot A(t) \quad (\text{B2.1-2})$$

$$k_e = \exp \left(b_e \left(\frac{1}{T_{\text{ref}}} - \frac{1}{T_{\text{real}}} \right) \right) \quad (\text{B2.1-3})$$

$$A(t) = \left(\frac{t_0}{t} \right)^\alpha \quad (\text{B2.1-4})$$

This tool is in the form of a Microsoft Excel spreadsheet consisting of three sheets: *instructions*, *input parameters*, and *output results*. In the instructions a description of the general problem and a brief explanation on how to use the tool is provided. In input parameter sheet all the input data must be entered by the analyst, and in the output results sheet all the output data are both presented for review and printing.

In assessment of performance the following terminology is used. Failure occurs when the chloride concentration is greater than the critical chloride concentration at the location of the reinforcement at the service life of interest. The probability of failure is the probability of this event occurring. The reliability index is defined as minus the inverse of the standard Gaussian cumulative distribution function computed at the probability of failure. According to *fib* 34 an acceptable probability of failure is 10% which corresponds to a reliability index of 1.3. A calculated reliability index greater than 1.3 at the reinforcement at the service life of interest is deemed satisfactory performance. A calculated reliability index less than 1.3 at the reinforcement at the service life of interest is deemed unsatisfactory performance.

¹ This tool has been validated in Microsoft Excel 2013.

² According to SHRP2 Solutions, uncracked concrete is defined as concrete in which the ordinary crack width is less than 0.3 mm or 0.012 in.

Input Parameters Sheet

In the *Input parameters* sheet, all the input data required for the tool must be entered by the analyst. Below, a brief description of all the parameters and the probabilistic features of the random variables are explained, and it is shown how and from where those input data can be obtained. The input parameter sheet is reproduced in Figure 1. Some of these parameters are constants and some are random variables. In case of the random variables, each is defined by its specific parameters (mean value, standard deviation, etc.) and its probability distribution (Normal, Lognormal, Beta, etc.). All input values that need to be entered by the analyst are shown with the light green filled color, and are described below. For some cases, the unit of measure can be selected by the analyst. Other parameters such as b_e , T_{ref} , and t_0 are predefined by *fib* and should not be altered.



 													
<i>Input Parameters</i>													
Parameter	Description	FIB reference	Units	Distribution function	Normal distribution parameters			Lognormal distribution parameters		Beta distribution parameters			
					Mean (μ)	Standard deviation (σ)	Coeff. of variation (cov)			Lower bound (a)	Upper bound (b)	α	β
C_{crit}	Critical chloride content	Chapter B2.2.6	wt-%c	Beta	0.60	0.15				0.20	2.00	5.31	18.58
C_a	Initial chloride content	Chapter B2.2.4	wt-%c	Constant	0.10								
C_a or $C_{a,dep}$	Chloride content at surface or at substitute surface at depth x	Chapter B2.2.5	wt-%c	Lognormal	3.00	1.50	0.50	0.99	0.47				
s	Concrete cover	Chapter B1.2.1	in	Lognormal	2.50	0.25	0.10	0.91	0.10				
αx	Transfer function - Submerged/epoxy conditions	Chapter B2.2.5	mm	Constant	0.0								
k_e	Environmental transfer variable	Equation B2.1-3	N/A	N/A									
$D_{Cl,H}$	Chloride migration coefficient	Chapter B2.2.1	E-12 m ² /yr	Normal	7.567	0.182	0.02						
k_1	Transfer parameter	Chapter B2.2.2	N/A	Constant	1.0								
$A(t)$	Aging function	Equation B2.1.4	N/A	N/A									
k_p	Regression variable	Chapter B2.2.3	K	Normal	4800	700	0.15						
T_{ref}	Standard test temperature	Chapter B2.2.3.4	K	Constant	293								
$T_{ref,1}$	Temperature of the structural element or the ambient air	Chapter B2.2.3.3	°F	Normal	55.9	15.7	0.28						
t_0	Reference point of time	Chapter B2.2.2	year	Constant	0.0767								
α	Aging exponent - Blast furnace slag cement concrete	Chapter B2.2.2	N/A	Beta	0.45	0.20				0	1	2.33	2.85
t_{SL}	Design service life	Chapter B1.2.2	year	Constant	100								
β	Target reliability index	Chapter A2.2	N/A	Constant	1.30								

Figure 1 - Input parameters sheet

C_{crit} is the total critical chloride content at the location of the reinforcement that would initiate corrosion, expressed in mass percentage of the cement (or the total mass of all binders). Beta distribution is used for this parameter. Per *fib* 34, a mean value of 0.6, standard deviation of 0.15, and lower and upper bounds of 0.2 and 2.0 are recommended. It should be mentioned here that currently, there is no available data for epoxy coating of reinforcement.

C_0 is the initial chloride content of the concrete caused by chloride contaminated aggregates, cements, or the water used for production. This parameter has a constant value equal to the maximum chloride content allowed by the standard specifications. As stated in ACI 318 Commentary, this maximum value is 0.10 percent by mass of cement. According to *fib* 34, in contrast to chloride profiles resulting from chloride ingress from the surface, the distribution of the initial chloride content can be assumed to be uniform over the whole cross section. This distribution should not be confused with the probabilistic distribution of the variable C_0 since by the term distribution, *fib* 34 refers to the variation of the parameter over a field regardless of its probabilistic distribution.

C_S or $C_{S,\Delta x}$ is the chloride content at the surface or at the substitute surface of the concrete and represents the environmental loading on the structural element. The chloride content should be taken at the depth of Δx below the surface (substitute surface) for elements intermittently exposed to chlorides and at the surface for atmospheric or submerged zones. According to SHRP2 Solutions³, lognormal distribution is used for this variable, and the coefficient of variation of 0.5. For more information regarding how to determine the mean value, refer to SHRP2 Solutions.

a is the concrete cover thickness. Depth of cover batched over the reinforcement is a major parameter in design for durability. Lognormal probability distribution is used for this parameter. The mean value should be the value considered for design, and the standard deviation should be the tolerance allowed by the standard specifications.

Δx is the transfer function and should be formulated in structural elements that are intermittently exposed to constant or varying concentration chloride solutions. For splash conditions, Δx is described as a random variable with a Beta distribution, a mean value of 8.9 mm, a standard deviation of 5.6 mm, and lower and upper bounds of 0 and 50 mm. For submerged or spray conditions, Δx is a constant and equals 0. For tidal conditions, Δx is a Beta distributed random variable and the four parameters must be determined. In this tool, the analyst must choose between the three in the drop-down list. In case of selecting tidal conditions, the mean value, standard deviation, lower and upper bounds must also be entered. Otherwise, the analyst does not need to enter any further input parameters.

$D_{RCM,0}$ is the chloride migration coefficient and is a governing parameter in the chloride-induced corrosion model. This parameter shows durability of the concrete and is a normally distributed variable. The mean value of the parameter could be determined from the test results in the lab described in Nordtest NT Build 492, the Rapid Chloride Migration Method (RCM). In case of not having test data available, the data in

³ Durability assessment of a bridge substructure (R19A)

table B2-1 in *fib* 34 or any similar literature can be used. *fib* 34 also recommends a coefficient of variation of 0.2. Note that the units of the input for this parameter must be the same as in Nordtest NT Build 492. For convenience of the analyst the unit used in the tool is E-12 m²/s.

T_{real} is the temperature of the structural element or the ambient air. Normal distribution is used for this parameter. The mean value and the standard deviation could be extracted from an evaluated weather station data. The right units for the input parameter must also be selected by the analyst. This data should be extracted from an evaluated weather station data near the site. If no data is available at the site, one can refer to the National Oceanic and Atmospheric Administration (NOAA).

α is the ageing exponent and depends on the constituents of the concrete mix used. Beta distribution is used for this variable. For type I Portland cement concrete, a mean value of 0.3 and a standard deviation of 0.12 are used. For concrete with 20% or more fly ash, a mean value of 0.6 and a standard deviation of 0.15 are used. For Type III cement including blast furnace slag, a mean value of 0.45 and a standard deviation of 0.20 are used. All of these mix designs are assumed to have w/c (w/c_{eqv}) ratios between 0.4 and 0.6. In the tool, analyst must choose among the three cases in the drop-down list.

t_{SL} is the design service life expected for the structure. The unit must be in [years].

β is the target reliability index. The recommended value by *fib* 34 is 1.3, which is approximately equivalent to a probability of failure of 10%, or a probability of survival of 90%. (The actual reliability index equivalent to probability of failure of 10% is slightly different and is 1.282).

Output Results Sheet

On top of this sheet, two command buttons are provided for the analyst to click on and get two set of results (Figure 2). The first button called *Quick run* only gives, in shorter time, the reliability information of the design and whether it passes the design requirements or not. The second button called *Run full analysis* adds more detailed results on the previous results which is explained in details below. While either of those analysis running, a window will show up and show the progression of the operations.

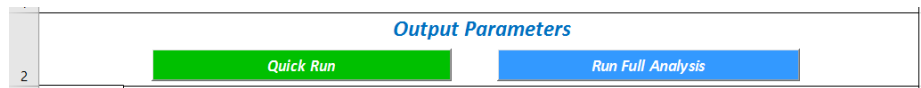


Figure 2 – Sample section 1 from Output Result sheet

As previously mentioned, the main method used in this tool is Monte Carlo simulation. What is done in this method is that for each iteration we have either pass performance or failure based on the comparison of the critical chloride content and the chloride content at time t at the reinforcement depth. At the end, the total number of times that the critical chloride content is exceeded is compared to the total number of trials and final results are given in form of a probability of failure and reliability index. The reliability index recommended by *fib* Bulletin 34 is 1.3. Other reliability indices can be considered as well by changing the value in its corresponding cell in *Input parameters* sheet.

Calculations based on Monte Carlo simulation in this tool are performed for 500,000 samples, wherein each, a unique random number between 0 and 1 is generated to be used along with the specific probability distribution of each of the variables given in the *Input Parameters* sheet to determine the value for each variable. After each iteration all the values for random variables are plugged in Eq. (B2.1-1), and finally the comparison is made between the actual and critical chloride contents. Parameter values used are in *mm* and *years* to match those in the *fib* Bulletin 34.

Below, it is explained how the results produced and shown in different sections of the *Output results* sheet can be interpreted and used.

Sec. 1 Information given in this section is the main results and they are used to determine whether the reliability requirements of the design are satisfied or not. The probability of failure/survival is calculated by counting the number of failures/passes and dividing them by the total number of samples. The target reliability is the value entered on the input sheet and is defaulted to 1.3 based on *fib* Bulletin 34. The reliability index β is the opposite of the inverse Gaussian distribution function of the probability of failure (based on the common assumption of Gaussianity of the safety margins). The calculated reliability index is compared to the target reliability index to determine whether the design parameters are meeting the requirements or not.

Sec. 2 What is provided in this section is regarding the variation of the probabilities of failure and reliability indices over time up to the design service life. Hence, it can be observed here for instance, in what year the permitted probability of failure is violated or the reliability index of the design is crossing the threshold of target reliability. Also it can be observed that for a certain target reliability index, what would be the expected design service life. A sample of section 2 is illustrated in Figure 3.

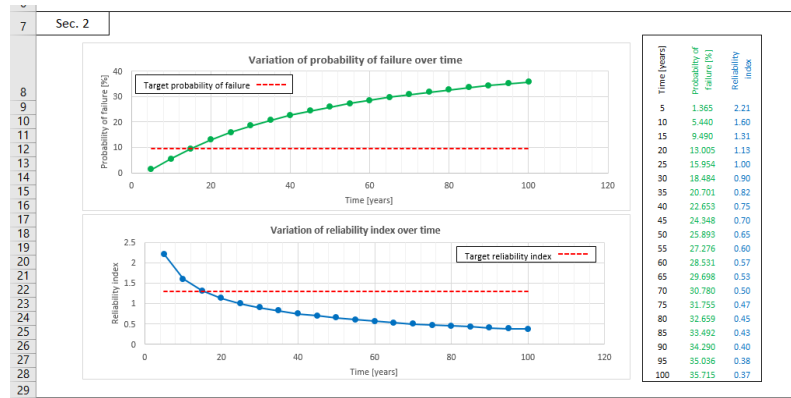


Figure 3 – Sample Section 2 from Output Result sheet

Sec. 3 In this section, it can be observed first, how the chloride content is changing over time at the location of the reinforcement, and second, how the critical chloride content is advancing through the cover concrete toward the location of reinforcement in time (Figure 5). In each plot the middle line shows the median value of the two parameters mentioned above, while the two lines on its sides show the 1st and 3rd quartile of the values generated for that parameter in the calculations. The two colored areas between each two lines are representatives of the dispersion of the parameters over time, so that it can be observed how much uncertainty exists around the median at each time step. There is also a red line in the second plot, showing the average depth at which reinforcement are placed, so one can see how the critical chloride content is approaching that point in time.

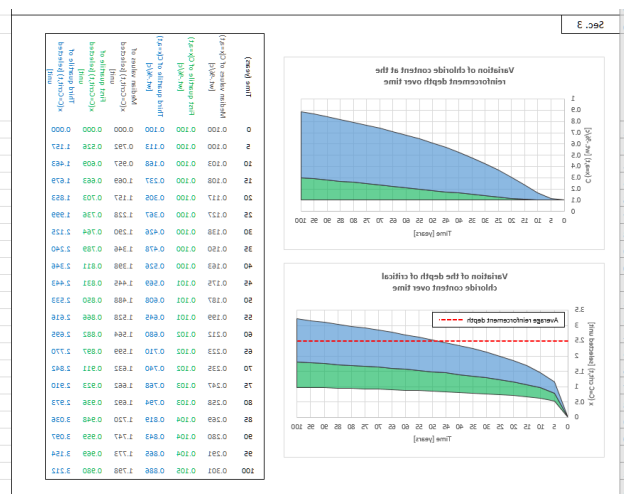


Figure 4 – Sample section 3 from Output Result sheet

Sec. 4 In the light green filled cell, the analyst may enter the year of interest for which the probability distribution of chloride content at reinforcement depth and the location of the critical chloride content are to be displayed (Figure 5). The two plots show these probability distributions. Comparing these distributions with the associated threshold values can give a visual idea of how close the system is to failure.

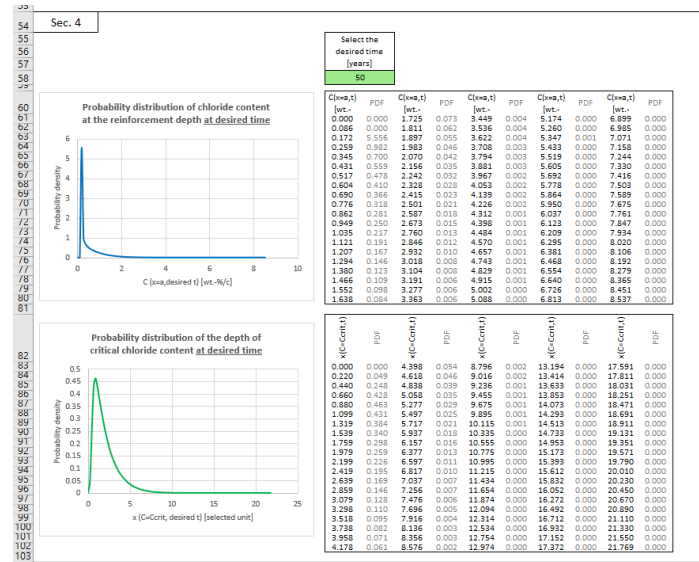


Figure 5 – Sample section 4 from Output Result sheet

Sec. 5 Chloride migration coefficient is one of the governing parameters that is measured in the lab for the concrete specimens that are going to be used in design. Here in this section (Figure 6), one can find that having all the input parameters the same as what they were described before, what values of chloride migration coefficient is required to achieve the target reliability index or any other indices. Using the information in this section, different mixes of concrete can be batched and tested in the lab to ensure that the concrete mix used for a given project has a chloride migration coefficient less than the maximum value allowed.

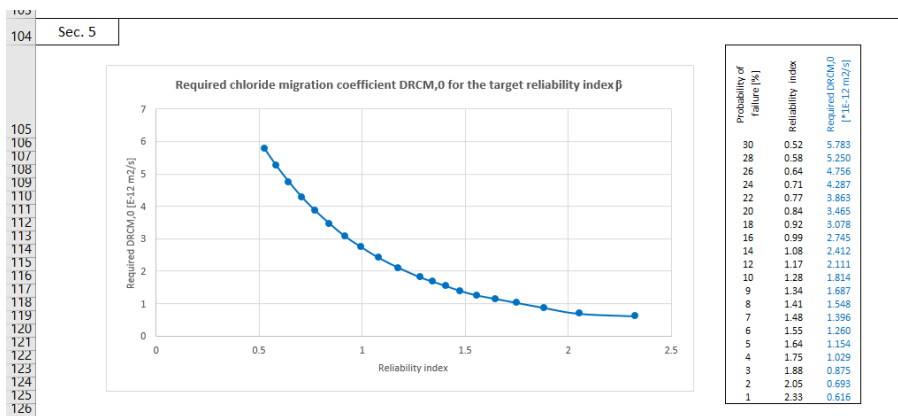


Figure 6 – Sample section 5 from Output Result sheet

Illustrative Example

In this part, an illustrative example is brought to show step by step how the tool works.

Step 1. First, you must open the *Input Parameters* sheet (Figure 1). There are some light green filled cells and some with no fill. The light green filled cells are the ones their value must be determined by the analyst. The numbers observe in the other cells are calculated automatically when the tool runs.

Step 2. The first parameter that must be entered is the critical chloride content. Per *fib* 34, recommended values are 0.6 for mean, 0.15 for standard deviation, 0.2 for lower bound, and 2.0 for upper bound. These may be modified as needed. The corresponding cells are shown in Figure 7.

6	C_{crit}	Critical chloride content	Chapter B2.2.6	wt.-%/c	Beta	0.60	0.15				0.20	2.00	5.31	18.58
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Figure 7 - Inputs for critical chloride content

Step 3. Next is to enter the inputs for initial chloride content of the concrete. According to ACI 318 the value must be 0.1 which must be entered in the cell under *mean value* column as shown in Figure 8.

7	C_o	Initial chloride content	Chapter B2.2.4	wt.-%/c	Constant	0.10								
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Figure 8 - Inputs for initial chloride content

Step 4. For the chloride content at surface a mean value of 3.0 and a coefficient of variation of 0.50 is considered as recommended by SHRP2 Solutions.

8	C_s or $C_{s,\Delta x}$	Chloride content at surface or at substitute surface at depth Δx	Chapter B2.2.5	wt.-%/c	Lognormal	3.00	1.50	0.50	0.99	0.47				
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Figure 9 - Inputs for chloride content at surface or at substitute surface at depth Δx

Step 5. Depending on design criteria, the appropriate values for mean value and standard deviation of the concrete cover must be chosen (Figure 10). Here, a mean value of 2.5 in. and a standard deviation of 0.25 in. is used. The right unit must also be selected in the drop-down list.

9	a	Concrete cover	Chapter B1.2.1	in	Lognormal	2.50	0.25	0.10	0.91	0.10				
10	Δx	Transfer function - Submerged/spray c		mm	Constant	0.0								

Figure 10 - Inputs for concrete cover

Step 6. From the drop-down list the exposure zone must be selected (Figure 11). Unless the exposure zone is considered as tidal conditions, there is no need to enter any value in other light green color filled cells for the input since the predefined values would be entered and taken into calculations automatically. In case of having tidal conditions for the exposure zone, make sure that all the 4 required parameters are defined in their corresponding cells. In this example, a spray zone exposure condition is chosen.

10	Δx	Transfer function - Submerged/spray conditions	Chapter B2.2.5	mm	Constant	0.0								
11		Transfer function - Splash conditions Transfer function - Submerged/spray conditions Transfer function - Tidal conditions	Equation B2.1-3	N/A	N/A									

Figure 11 - Inputs for transfer function

Step 7. From experiments, the mean value and coefficient of variation should be entered. These values can be determined in accordance with NT Build 492 (1999). As an example a mean value of $7.567E-12$ m²/s is used in Figure 12 with a coefficient of variation of 0.024 as measured in the lab. Note to enter the mean value in the correct units [E-12 m²/s].

12	$D_{cm,0}$	Chloride migration coefficient	Chapter B2.2.1	E-12 m ² /s	Normal	7.567	0.182	0.02						
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Figure 12 - Inputs for chloride migration coefficient

Step 8. Temperature of the structural element or the ambient air must be entered here. This can be determined from local weather data. In this example (Figure 13), a mean value of 55.9 °F and standard deviation of 15.7 °F is used as the average temperature and its standard deviation among different months in Pennsylvania. Make sure that the right unit is also selected from the drop-down list in the unit column.

17	T_{real}	Temperature of the structural element or the ambient air	Chapter B2.2.3.3	°F	Normal	55.9	15.7	0.28						
18	t_0	Reference point of time		°F °C K	Constant	0.0767								

Figure 13 - Inputs for temperature of the structural element or the ambient air

Step 9. Here the concrete mix must be selected in the drop-down list for the sake of defining the parameters of ageing exponent (Figure 14). From the concrete mix design sheet, blast furnace slag cement concrete is chosen here.

19	α	Ageing exponent - Blast furnace slag cement concrete	Chapter B2.2.2	N/A	Beta	0.45	0.20			0	1	2.33	2.85
20		Ageing exponent - Portland cement concrete Ageing exponent - Portland fly ash cement concrete Ageing exponent - Blast furnace slag cement concrete	Chapter B1.2.2	years	Constant	100							

Figure 14 - Inputs for ageing exponent

Step 10. Design service life expected for the structure must be entered next. For instance, 100 can be entered if the desired service life of the structural component is 100 years (Figure 15).

20	t_{SL}	Design service life	Chapter B1.2.2	years	Constant	100							
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Figure 15 - Inputs for design service life

Step 11. Lastly, the target reliability index must be entered. *fib* 34 recommend a value of 1.3 (Figure 16).

21	β	Target reliability index	Chapter A2.2	N/A	Constant	1.30							
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Figure 16 - Inputs for target reliability index

Step 12. Now that all the input data are entered, the analysis is ready to run. To do so, the *Output Results* sheet must be selected. There are two yellow buttons provided for the analyst to run the analysis as described before (Figure 2). While running either of the analyses, a progress bar will show up. (Figure 17). After the analysis is complete, the window will disappear, and the results could be examined (Figure 18).

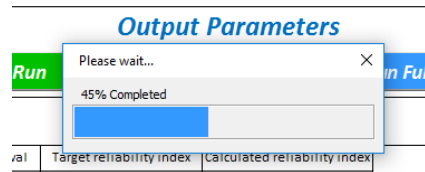


Figure 17 – loading window indicating analysis is running

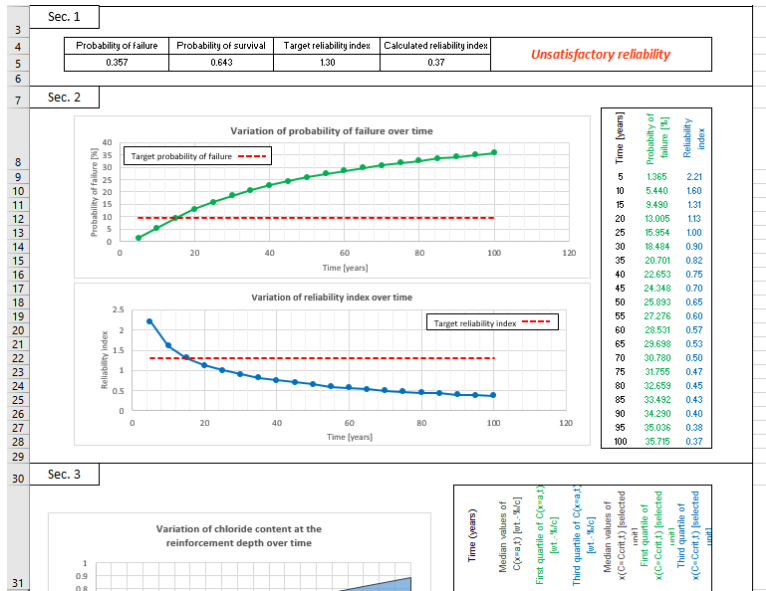


Figure 18 – Results

References

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- [2] NT BUILD 492 (1999). Concrete, mortar and cement-based repair materials: Chloride migration coefficient from non-steady-state migration experiments. NORDTEST method 492. NORDTEST, Espoo, Finland.
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- [5] Microsoft Excel (Version 2016)