


SHRP2 SOLUTIONS
STRATEGIC HIGHWAY RESEARCH PROGRAM

Service Life Design of Concrete Elements

IBC Workshop: W-8 Service Life Design

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U.S. Department of Transportation
Federal Highway Administration

American Association of State Highway and Transportation Officials
AASHTO

Presentation Overview

- This part of the worked example covers:
  - Concrete deterioration mechanisms for different bridge components;
  - Service life design of concrete elements:
    - Mitigation methods for concrete components;
    - Full probabilistic service life design for chloride-induced corrosion;
    - Requirements for concrete mix designs;
    - Development of concrete specifications.

Concrete Deterioration

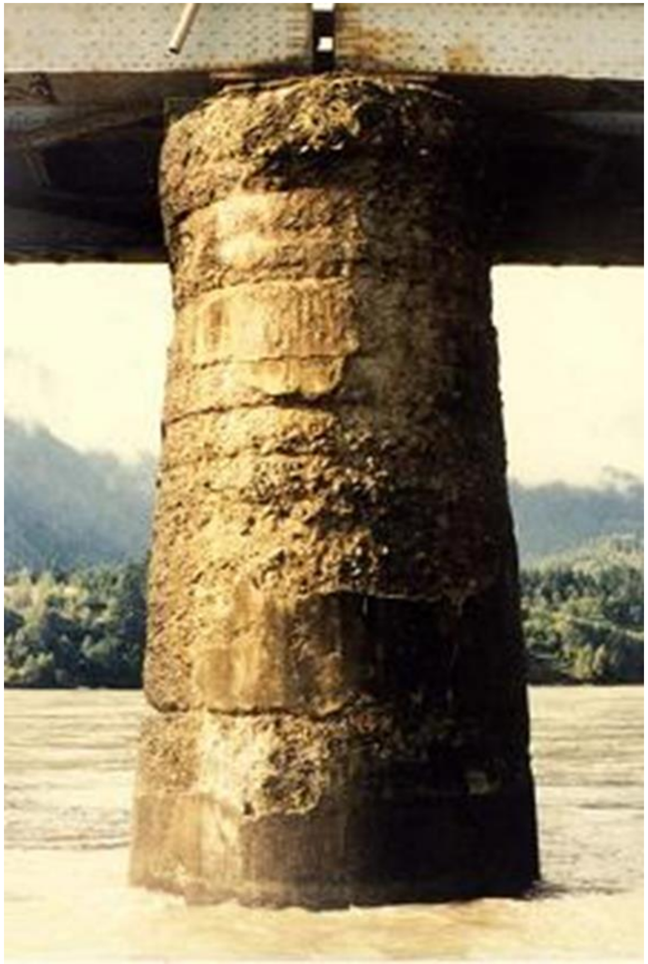
- Concrete deterioration mechanisms considered:

  - **Alkali-Aggregate Reaction (AAR)**

  - **Sulfate attack**

Concrete Deterioration

- Concrete deterioration mechanisms considered:
  - **Freeze-thaw damage**
  - **Salt scaling**



Concrete Deterioration

- Concrete deterioration mechanisms considered:
  - **Chloride-induced corrosion**
  - **Carbonation-induced corrosion**
  - **Delayed Ettringite Formation (DEF)**

Concrete Deterioration for Bridge Components

Exposure zone	Examples of elements for piers	Exposure conditions	Steel corrosivity category ISO 12944-2	Potential concrete deterioration mechanisms: Exposure zones	Materials			Environmental		
				ACI 318-14	AAR	Sulfate	Freeze-thaw	Scaling	Carbonation-induced corrosion	Chloride-induced corrosion
Buried	Pile cap, wing wall, abutment wall.	Limited chloride exposure in soil. Limited O_2. Freeze-thaw above frost line. Sulfates.		S1, C1, F1	X	X	X			X
	Face of steel casing for tangent piles permanently buried, piles.		Im3: soil							
Atmospheric	Cast-in-place deck bottom surface, wing wall.	Atmospheric O_2 and CO_2. Some airborne chlorides. Temperature and humidity variations, including freeze-thaw.		F2	X		X		X	X
	Face of steel casing for tangent piles facing the precast concrete full height wall.		C3: Temperate zone, atmosphere with low salinity							
Indirect Deicing Salts	Areas under or within 10 ft. horizontally of expansion joints, zone within 6-20 ft. vertically of a roadway: upper part of pier columns, pier cap, abutment wall.	Alternating wetting and drying. Atmospheric O_2 and CO_2. Freeze/thaw with indirect exposure to de-icing salts, leakage from deck joints, temperature and humidity variations.		C2, F3	X		X		X	X
	Girders.		C4: Temperate zone, atmosphere with moderate salinity							
Direct Deicing Salts	Top surface of decks, barriers, pier columns within 6 ft. vertically of a roadway.	Alternating wetting and drying. Atmospheric O2 and CO_2. Freeze/thaw with direct exposure to de-icing salts applications, temperature and humidity variations.		C2, F3	X		X	X	X	X
	Decorative fence.		C5-I: Temperate zone, aggressive atmosphere							
No Exposure	Infill concrete for steel piles.	No exposure to external environment.								

Exposure Categories According to ACI 318-14

- Exposure categories of concrete according to ACI 318-14:

Category	Class	Condition	
Freezing and thawing (F)	F0	Concrete not exposed to freezing-and-thawing cycles	
	F1	Concrete exposed to freezing-and-thawing cycles with limited exposure to water	
	F2	Concrete exposed to freezing-and-thawing cycles with frequent exposure to water	
	F3	Concrete exposed to freezing-and-thawing cycles with frequent exposure to water and exposure to deicing chemicals	
Sulfate (S)		Water-soluble sulfate (SO_4^{2-}) in soil, percent by mass[1]	Dissolved sulfate (SO_4^{2-}) in water, ppm[2]
	S0	$SO_4^{2-} < 0.10$	$SO_4^{2-} < 150$
	S1	$0.10 \leq SO_4^{2-} < 0.20$	$150 \leq SO_4^{2-} < 1500$ or seawater
	S2	$0.20 \leq SO_4^{2-} \leq 2.00$	$1500 \leq SO_4^{2-} \leq 10{,}000$
	S3	$SO_4^{2-} > 2.00$	$SO_4^{2-} > 10{,}000$
In contact with water (W)	W0	Concrete dry in service Concrete in contact with water and low permeability is not required	
	W1	Concrete in contact with water and low permeability is required	
Corrosion protection of reinforcement (C)	C0	Concrete dry or protected from moisture	
	C1	Concrete exposed to moisture but not to an external source of chlorides	
	C2	Concrete exposed to moisture and an external source of chlorides from deicing chemicals, salt, brackish water, seawater, or spray from these sources	

[1]Percent sulfate by mass in soil shall be determined by ASTM C1580.

[2]Concentration of dissolved sulfates in water, in ppm, shall be determined by ASTM D516 or ASTM D4130.

Mitigation Methods for Concrete Components

- Alkali-Aggregate Reaction (AAR):

Deterioration mechanism	Alkali-Aggregate Reaction (AAR)
Design strategy	Avoidance of deterioration or deemed to satisfy.
Considerations	Use non-reactive aggregates. Local non-reactive aggregates may not be available or long-term test data may not be available.
General mitigation methods	Mitigation methods include: - Avoidance: Use non-reactive aggregate - Deemed to satisfy: Limit the alkali contribution by the Portland cement to the concrete; and/or - Use a sufficient amount of effective supplementary cementitious materials
Requirements in U.S. codes and standards	Guidance from AASHTO R80-17 can be used.
Required testing	The following testing is required based on AASHTO R80-17: - Petrographic analysis per ASTM C295. - Expansion testing in accordance with ASTM C1260 or ASTM C1293 in order to determine aggregate-reactivity class. If aggregates are shown to be reactive, additional mitigation measures as per AASHTO R80-17 can be implemented.

Mitigation Methods for Concrete Components

- Delayed Ettringite Formation (DEF):

Deterioration mechanism	Delayed Ettringite Formation (DEF)
Design strategy	Avoidance of deterioration.
Considerations	Only applicable if there are high temperatures during curing: precast or mass concrete components.
General mitigation methods	Mitigation methods include: - Application of a maximum temperature of 160°F during curing. - Use of fly ash (FA) or ground granulated blast furnace slag (GGBS).
Requirements in U.S. codes and standards	N.A. (Guidance in ACI 207)
Required testing	If precast or mass concrete is used: - Limit curing temperatures to 160°F. - To be measured using temperature sensors. - Thermal control plan needed.

Mitigation Methods for Concrete Components

- Sulfate attack:

Deterioration mechanism	Sulfate attack
Design strategy	Deemed to satisfy.
Considerations	Geotechnical measurements indicate that the soil surrounding the abutments is contaminated and has a sulfate content of 0.14%. ACI 318-14 states that sulfate attack is not applicable when the sulfate content is below 0.1% in soil - therefore sulfate mitigation methods must be identified.
General mitigation methods	Mitigation methods include: - Using Portland cement with a low alkali content and C_3A-content (sulfate resistant cement, Type II or V); - Providing a concrete with low permeability and a low water-cement ratio; and - The use of supplementary cementitious materials.
Requirements in U.S. codes and standards	Requirements according to ACI 318-14 for concrete classified as S1: - Maximum water-cementitious ratio of 0.50 and a minimum compressive strength of 4000 psi (28 MPa). - ASTM C150 Type II or V cement is allowed. Types I and III are also allowed if the C_3A content is less than 8%.
Required testing	No testing required. Implement limits on cementitious materials as per ACI 318-14.

Mitigation Methods for Concrete Components

- Freeze-thaw and scaling:

Deterioration mechanism	Freeze-thaw and scaling
Design strategy	Deemed to satisfy.
Considerations	All parts of the concrete structure except the infill for the tangent piles will be exposed to freeze-thaw cycles. In addition, concrete exposed to both freeze-thaw cycles and de-icing salts is subject to scaling.
General mitigation methods	Mitigation methods include: - Using freeze-thaw resistant aggregates; and - Providing air-entrainment in the concrete. - The supplementary cementitious materials content should be limited for concrete with a risk of scaling. For decks and barriers, a limit of 25% fly ash by total mass of cementitious is typically used.
Requirements in U.S. codes and standards	Requirements according to ACI 318-14: - F1: w/cm $\leq$ 0.55; f'c $\geq$ 3500 psi (24 MPa). Plastic air content = 4.5% for max aggregate size of 1''. - F2: w/cm $\leq$ 0.45; f'c $\geq$ 4500 psi (31 MPa). Plastic air content = 6% for maximum aggregate size of 1''. - F3: w/c $\leq$ 0.40; f'c $\geq$ 5000 psi (35 MPa). Plastic air content of 6% for maximum aggregate size of 1''.
Required testing	The following testing is required (includes more than required by ACI 318-14 to demonstrate that the concrete has sufficient resistance): - Plastic air content of freshly mixed concrete tested. ACI requirement: see above. - Air-void system of hardened concrete in accordance with ASTM C457. ACI guideline: spacing factor $\leq$ 0.008 inch. - Freeze-thaw resistance per ASTM C666. Recommendation: minimum durability factor of 90 after 300 cycles. - Resistance to scaling for deck and barrier concrete in per ASTM C672. Requirement: visual rating $\leq$ 3 after 50 cycles, this means that moderate scaling (visible coarse aggregate) is allowed at the end of the test. Alternatively: test CSA A23.2-22C can be used, a maximum mass loss of 0.16 psf (0.8 kg/m^2) can be used as a passing criterion.

Mitigation Methods for Concrete Components

- Carbonation-induced corrosion:

Deterioration mechanism	Carbonation-induced corrosion
Design strategy	Deemed-to-satisfy.
Considerations	Mitigation methods for chloride-induced corrosion also prevent carbonation-induced corrosion and will govern.
General mitigation methods	Mitigation methods for carbonation-induced corrosion include low concrete permeability and adequate concrete cover.
Requirements in U.S. codes and standards	N.A.
Required testing	N.A.

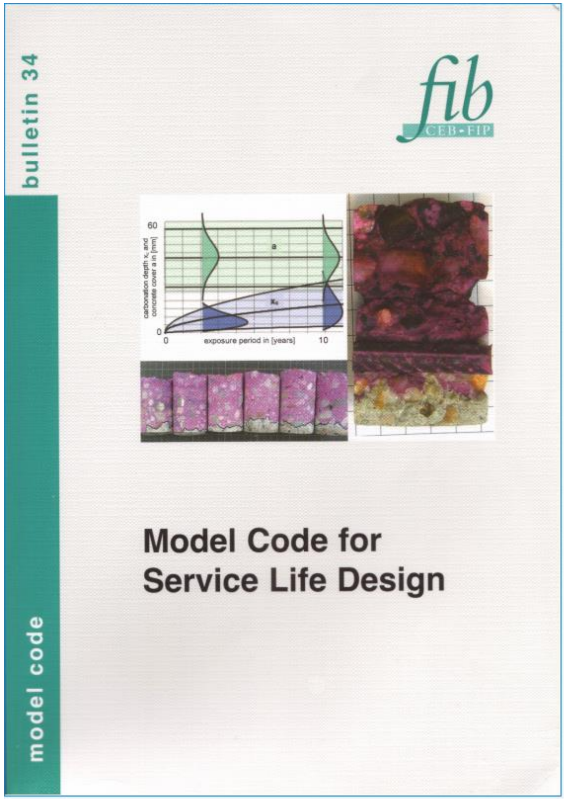
Mitigation Methods for Concrete Components

- Chloride-induced corrosion:

Deterioration mechanism	Chloride-induced corrosion
Design strategy	Full probabilistic modelling approach following fib Bulletin 34.
Considerations	The probabilistic model in fib Bulletin 34 is based on Fick's second law of diffusion and contains improvements to yield a good approximation of chloride distribution in concrete.
General mitigation methods	Mitigation methods include: - Use of low permeability concrete; - Adequate concrete cover thickness; - Use of corrosion-resistant reinforcing (not used in this example); and - Effective control of cracking per applicable structural design code and construction specifications.
Requirements in U.S. codes and standards	Requirements according to ACI 318-14 for concrete classified as C2: - w/cm $\leq$ 0.40 and f'c $\geq$ 5000 psi (35 MPa). - Maximum water-soluble chloride content in concrete of 0.15 mass-% of cement (this limit is reduced to 0.1 mass-% of total cementitious materials for acid-soluble chloride).
Required testing	The following testing is required: - The chloride migration coefficient per NT Build 492 at 28 days. - Water-soluble chloride (ASTM C1218) or acid-soluble chloride (ASTM C1152) Test criteria will be determined by the modeling.

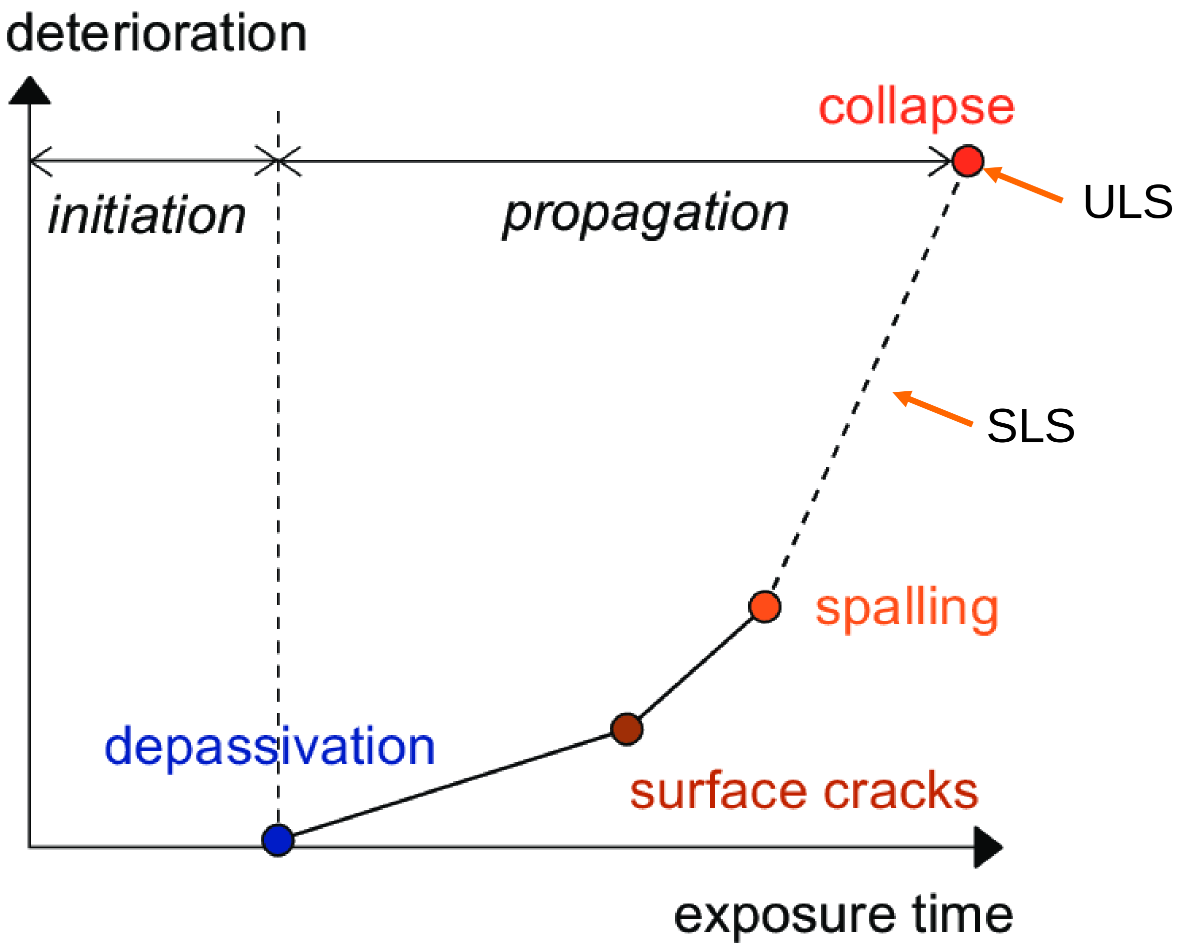
Modelling of Chloride-Induced Corrosion

- Chloride-induced corrosion:
  - For non-replaceable components, the limit state is to achieve 75-year service life with a target confidence level of 90% (reliability index of 1.3). The confidence level is based on guidance from *fib*.
  - Parameters are modelled in accordance with guidance and algorithm provided by *fib* Bulletin 34.



Modeling of Chloride-Induced Corrosion

- Service life is considered equal to corrosion initiation time:



fib Bulletin 34 Chloride-Induced Corrosion Model

- Chloride ingress – Fick's 2nd law of diffusion to corrosion initiation:

$$C_{crit} \geq C(x = a, t) = C_o + (C_{s,\Delta x} - C_o) \cdot \left[1 - \operatorname{erf}\left(\frac{a - \Delta x}{2\sqrt{D_{app,C} \cdot t}}\right)\right]$$

$$D_{app,C} = k_e \cdot D_{RCM,0} \cdot k_t \cdot A(t)$$

$$k_e = \exp\left(b_e\left(\frac{1}{T_{ref}} + \frac{1}{T_{real}}\right)\right)$$

$$A(t) = \left(\frac{t_o}{t}\right)^{\alpha}$$

- **Red – Environmental Loading**
  - C_o & C_s are the Chloride Background and Surface Concentrations
  - T_{real} is the annual mean Temperature at the project site
- **Green – Material Resistance**
  - $D_{RCM,0}$ is the Chloride Migration Coefficient, α is the Aging Exponent, both are functions of the concrete mix design
  - a is the Concrete Cover thickness
- Δx is the Transfer Function

A is the Age Factor

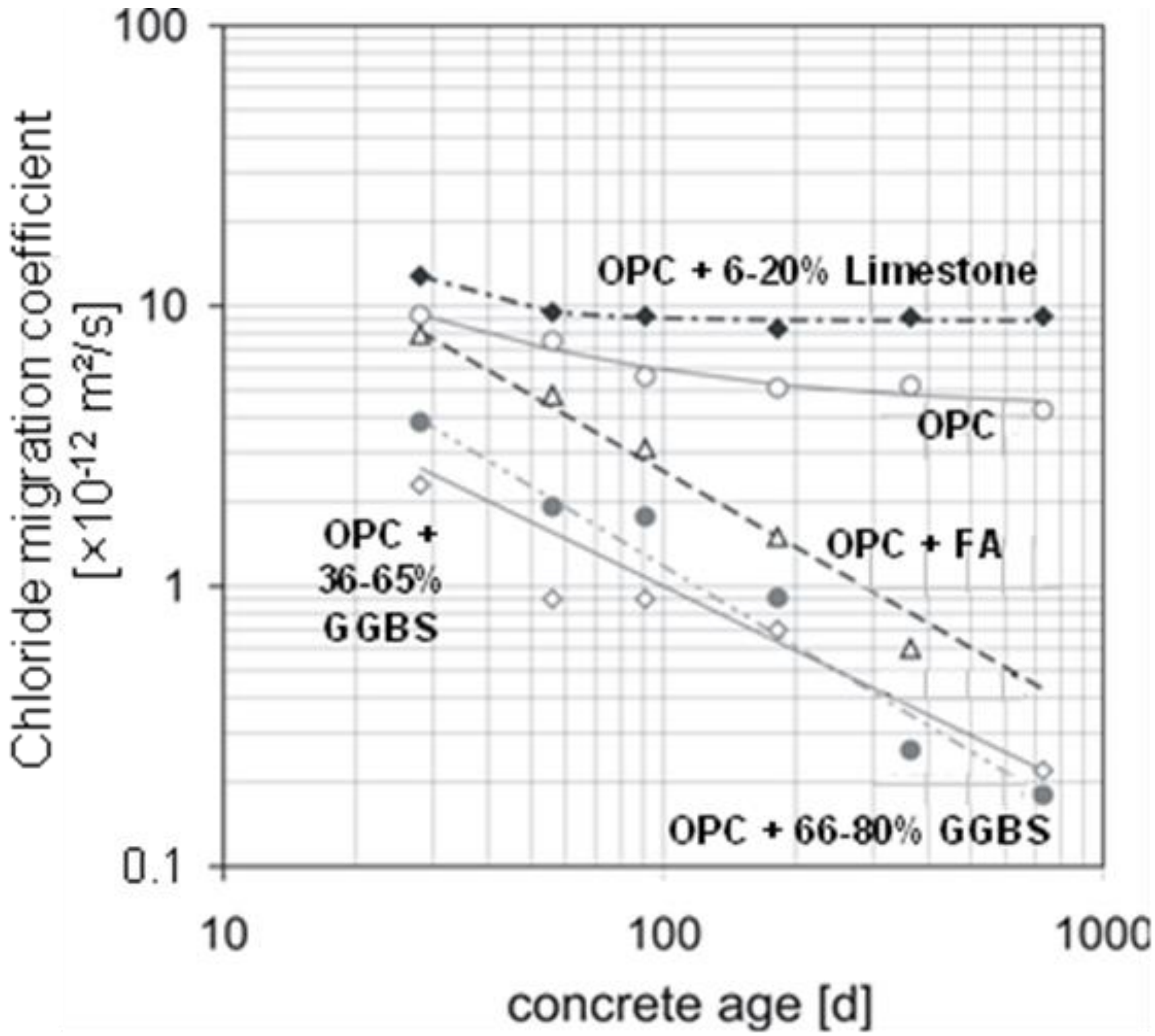
fib Bulletin 34 Input Parameters

Variable	Symbol	Short description	Fib Bulletin 34 recommendations	Used in example for direct de-icing salt exposure zone			
				Distribution	Unit	Mean	Standard deviation and function parameters
Cover	a	Concrete thickness measured from concrete surface to the surface of the outermost steel reinforcement.	Fib Bulletin 34 recommends that the distribution function for large cover depths be typically chosen as a normal distribution whereas for small cover depths, distributions excluding negative values should be chosen, such as the lognormal function. For this example, covers from AASHTO LRFD are used as starting point. It is assumed that 90% of the cover is within the construction tolerance of ±0.5 inches. For a normal distribution, this means that the standard deviation is found by dividing the tolerance by a z-value of 1.645.	Normal	mm (in)	70 (2.75)	7.6 (0.3)
Temperature	T_{real}	Temperature of the structural element or the ambient air.	Fib Bulletin 34 recommends that T_{real} can be determined by using available data from a weather station nearby the structure. The data used for this example is based on public data for monthly averages for New York City. A mean value of 11.5°C is determined as the annual average temperature. The standard deviation is estimated from the expected value over a period of 100 years. A value of 2°C is assumed. Can be calculated if sufficient data are available.	Normal	°C (°F)	11.5 (52.7)	2 (35.6)
Initial chloride concentration	C_0	Initial chloride content in concrete at time t = 0.	Fib Bulletin 34 states that the initial chloride content in the concrete is not only caused by chloride ingress from the surface, but can also be due to chloride contaminated aggregates, cements or water used for the concrete production. The total amount of chlorides present in the concrete mix will be determined during the construction phase and will be specified to be less than the assumed value.	Deterministic	Mass-% of total cementitious materials	0.1	-
Surface concentration	$C_{S,\Delta x}$	Chloride content at the depth Δx.	Fib Bulletin 34 states that it depends on material properties and on geometrical and environmental conditions. Ideally, data is gathered from similar structures. In this example, the surface concentration is based on interpretation of measured in-situ chloride surface concentration of bridge decks from the literature.	Lognormal	Mass-% of total cementitious materials	4	2
Chloride migration coefficient	$D_{RCM,0}$	Chloride migration coefficient measured from NT Build 492 at t = 28 days.	Fib Bulletin 34 recommends the standard deviation of the chloride migration coefficient to be 0.2 times the mean value. The mean value is assumed in the model such that the desired reliability index is obtained.	Normal	$\times 10^{-12}$ m^2/s	7	1.4

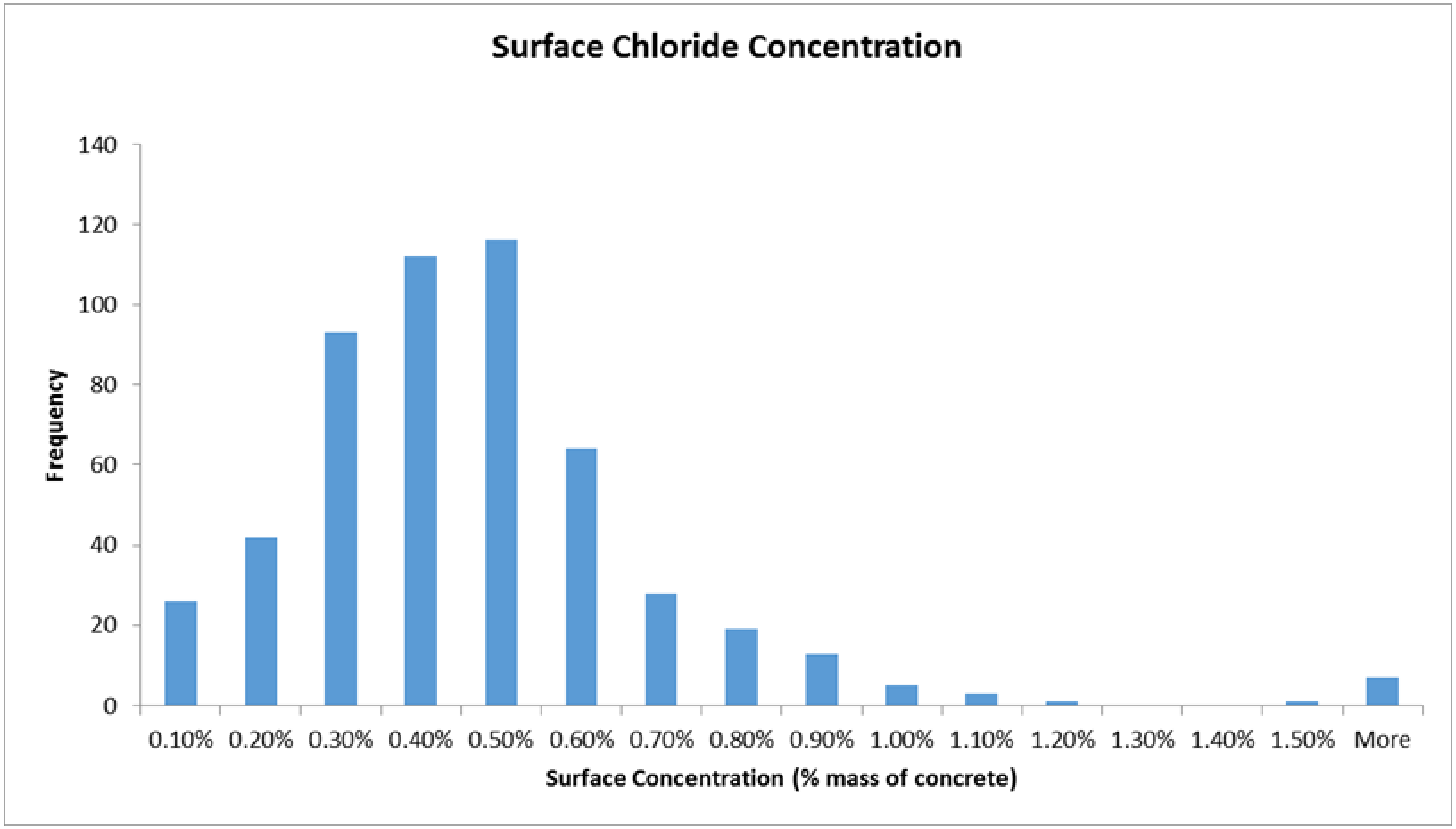
fib Bulletin 34
Input Parameters

<table>
<tr><th rowspan="2">Variable</th><th rowspan="2">Symbol</th><th rowspan="2">Short description</th><th rowspan="2">Fib Bulletin 34 recommendations</th><th colspan="4">Used in example for direct de-icing salt exposure zone</th></tr>
<tr><th>Distribution</th><th>Unit</th><th>Mean</th><th>Standard deviation and function parameters</th></tr>
<tr><td>Ageing factor</td><td>α</td><td>The age factor describes the time-dependent change of the migration coefficient as concrete matures.</td><td>Fib Bulletin 34 and fib Bulletin 76 recommend the following ageing factors for concrete
<table>
<tr><th rowspan="2">Concrete mixes</th><th rowspan="2">Distr.</th><th colspan="2">Submerged/buried, water level, de-icing salts zones</th><th colspan="2">Atmospheric zone</th></tr>
<tr><th>Parameters</th><th>Mean (μ)</th><th>Parameters</th><th>Mean (μ)</th></tr>
<tr><td>Portland Cement + 20-35% FA</td><td>Beta</td><td>σ=0.15, a=0; b=1</td><td>0.60</td><td>σ=0.15, a=0; b=1</td><td>0.65</td></tr>
<tr><td>Portland Cement</td><td>Beta</td><td>σ =0.12, a=0; b=1</td><td>0.30</td><td>σ=0.15, a=0; b=1</td><td>0.65</td></tr>
</table>
μ = mean value; σ = standard deviation; a and b are the upper and lower bounds.</td><td>Beta</td><td>-</td><td>0.6</td><td>0.15
a=0; b=1</td></tr>
<tr><td>Transfer function</td><td>Δx</td><td>Capillary action leads to a rapid transport of chlorides into the concrete up to a depth Δx from the surface. Beyond this depth, chloride ingress is controlled by diffusion.</td><td>Fib Bulletin 34 recommends the following values for the transfer function:
- For water level, direct and indirect de-icing salts zones: beta distribution with a mean value of 8.9 mm, standard deviation of 5.6 mm with parameter a = 0.0 and b = 50.0.
- For buried, submerged, and atmospheric zones: deterministic value of 0.</td><td>Beta</td><td>mm
(in)</td><td>8.9
(0.35)</td><td>5.6
a=0; b=50</td></tr>
<tr><td>Critical chloride concentration</td><td>C_{cr}</td><td>Concentration required to break down the passive layer protecting the steel reinforcement.</td><td>Fib Bulletin 34 recommends using a beta distribution with a mean value of 0.6% by mass of cementitious materials (based on uncoated carbon steel reinforcement), a standard deviation of 0.15, a lower bound of 0.2, and an upper bound of 2.0.</td><td>Beta</td><td>Mass-% of total cementitious materials</td><td>0.6</td><td>0.15
a=0.2; b=2</td></tr>
<tr><td>Transfer parameter</td><td>k_t</td><td>-</td><td>Fib Bulletin 34 assumes k_t as a constant value equal to 1.</td><td>Deterministic</td><td>-</td><td>1</td><td>-</td></tr>
<tr><td>Regression variable</td><td>b_e</td><td>-</td><td>Fib Bulletin 34 recommends using a normal distribution with a mean value of 4800K and a standard deviation of 700K.</td><td>Normal</td><td>K</td><td>4800</td><td>700</td></tr>
<tr><td>Reference time</td><td>t_0</td><td>-</td><td>Fib Bulletin 34 assumes t_0 as a constant value equal to 28 days = 0.0767 years.</td><td>Deterministic</td><td>years</td><td>0.0767</td><td>-</td></tr>
<tr><td>Standard test temperature</td><td>T_{ref}</td><td>-</td><td>Fib Bulletin 34 defines T_{ref} to be constant with a value of 293K (= 20°C).</td><td>Deterministic</td><td>°C
(°F)</td><td>20
(68)</td><td>18</td></tr>
</table>

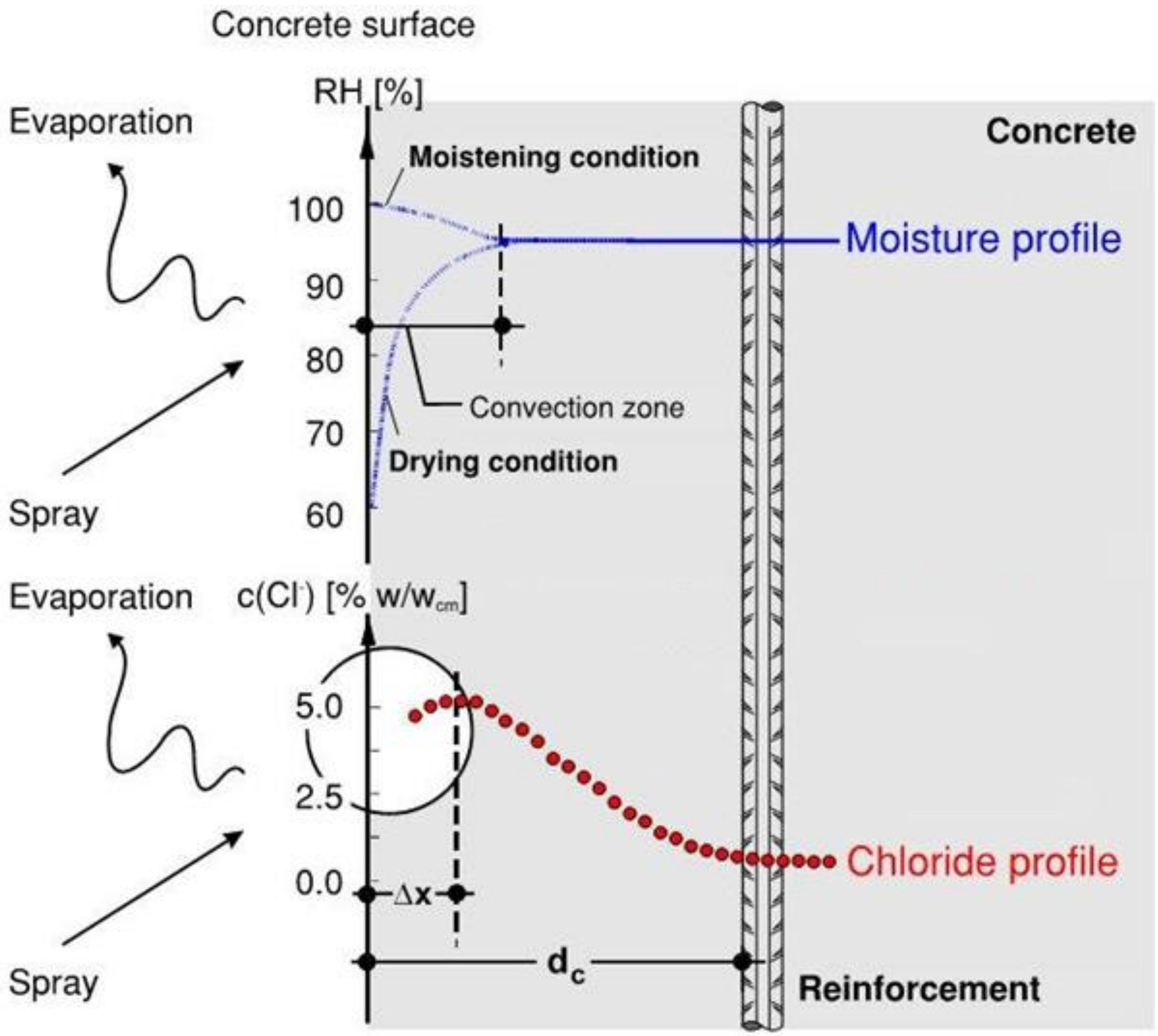
Ageing Factor



Chloride Surface Concentration



Transfer Function



Concrete Mix Designs

- Concrete mix designs:
  - Two types of mix designs, both containing 590 lbs/yd^3 (350 kg/m^3) of cementitious materials, are assumed based on availabilities of local materials:
    - OPC: Portland Cement Type I or Type II only.
    - OPC+20-35%FA: Portland Cement Type I or Type II with 20%-35% Type F fly ash by mass of total cementitious materials.

Concrete Mix Designs

- Input parameters for the chloride-induced corrosion model for all structural elements and all exposure zones for both types of concrete mix design (OPC and OPC+20-35% FA):

Structural element	Descrip-tion	Exposure zone	Cover			Surface concentration, $C_{S,\Delta x}$ [mass-% of cem. mat.l]			Ageing factor, a					Transfer function, Δx [mm]		
									Distr.	OPC		OPC+20-35%FA				
			Distr.	Mean	Std. dev.	Distr.	Mean	Std. dev.		Mean	Std. dev.	Mean	Std. dev.	Distr.	Mean	Std. dev.
Piers	Pile cap	Buried	Normal	76 mm (3.0 in)	15.2 mm (0.6 in)	Lognormal	0.5	0.25	Beta	0.3	0.12 a=0; b=1.0	0.6	0.15 a=0; b=1.0	Deterministic	0	-
	Bottom part of column	Direct de-icing salts	Normal	76 mm (3.0 in)	15.2 mm (0.6 in)	Lognormal	4	2	Beta	0.3	0.12 a=0; b=1.0	0.6	0.15 a=0; b=1.0	Beta	8.9	5.6 a=0; b=50
	Column and pier cap	Indirect de-icing salts	Normal	76 mm (3.0 in)	15.2 mm (0.6 in)	Lognormal	2	1	Beta	0.3	0.12 a=0; b=1.0	0.6	0.15 a=0; b=1.0	Beta	8.9	5.6 a=0; b=50
Abut-ments	Wing wall	Buried	Normal	64 mm (2.5 in)	15.2 mm (0.6 in)	Lognormal	0.5	0.25	Beta	0.3	0.12 a=0; b=1.0	0.6	0.15 a=0; b=1.0	Deterministic	0	-
	Abutment wall	Indirect de-icing salts	Normal	76 mm (3.0 in)	15.2 mm (0.6 in)	Lognormal	2	1	Beta	0.3	0.12 a=0; b=1.0	0.6	0.15 a=0; b=1.0	Beta	8.9	5.6 a=0; b=50
Cast-In-Place Deck	Top of the deck	Direct de-icing salts	Normal	70 mm (2.75 in)	7.6 mm (0.3 in)	Lognormal	4	2	Beta	0.3	0.12 a=0; b=1.0	0.6	0.15 a=0; b=1.0	Beta	8.9	5.6 a=0; b=50
	Underside of the deck	Atmosphe ric	Normal	44 mm (1.75 in)	7.6 mm (0.3 in)	Lognormal	1.5	0.75	Beta	0.65	0.15 a=0; b=1.0	0.65	0.15 a=0; b=1.0	Deterministic	0	-

Example of Time to Corrosion Modelling

- Example of chloride-induced modelling for concrete in deck:
  - This example considers the concrete used for the deck exposed directly to deicing salts.
  - Two combinations of cementitious materials are considered: ‘OPC’ and ‘OPC+20-35%FA’.
  - A Monte Carlo simulation with 50,000 runs is performed to determine the required chloride mitigation coefficient for both mix designs to obtain a reliability index of 1.3.
  - A spreadsheet for the performance of such full probabilistic modelling with 5,000 runs can be downloaded from the SHRP2 website:
    https://www.fhwa.dot.gov/goshrp2/Solutions/Renewal/R19A/Service_Life_Design_for_Bridges

Example of Time to Corrosion Modelling

- Concrete mix **OPC+20-35%FA** used in deck exposed to direct de-icing salts:
  - Input to spreadsheet based on values previously defined
  - Output is calculated values to obtain a reliability index greater than 1.3:

INPUT PARAMETERS

Parameter	Description	Units	Distribution Function	Normal Distr Coefficients: Mean, μ	Std Dev, σ	Coeff of Variation, σ/μ	Log-Normal Distr Coeffs: $\ln\mu - \ln((\sigma/\mu)^2+1)/2$	$\sqrt{\ln((\sigma/\mu)^2+1)}$	Beta Distr Coeffs: Lower Bound, a	Upper Bound, b	α	β
		in^2/yr		0.340	0.068	0.20						
	Chloride Migration Coefficient (from Nordtest NT	mm^2/yr		219.4	43.9							
$D_{RCM,0}$	Build 492 - results are given in m^2/sec)	m^2/sec	Normal	6.95E-12	1.39E-12							
b_e	Regression variable, (limited to 3500 °K to 5500 °K)	°K	Normal	4800	700							
		°F		52.7	3.60							
		°C		11.5	2.00							
T_{real}	Temperature (from Local Weather Data)	°K	Normal	284.65	2.00							
		°F		67.6								
		°C		19.8								
T_{ref}	Standard test temperature	°F	Constant	292.9								
k_e	Environmental transfer variable	n/a	n/a									
k_t	Transfer parameter	n/a	Constant	1.0								
α	Ageing exponent - PCC w/ ≥ 20% Flyash	n/a	Beta	0.6	0.15				0	1	5.80	3.87
t_o	Reference point of time (28 days = 0.0767 yrs)	yrs	Constant	0.0767								
A(t)	Ageing function	n/a	n/a									
C_o	Initial Chloride Content of Concrete	mass% of binder	Normal	0.10	0.00	0.001						
C_s or $C_{s,\Delta x}$	Chloride Concentration at surface, or at substitute surface Δx	mass% of binder	Log-Normal	4.00	2.00	0.50	1.3	0.47				
		in		0.35	0.22	0.629			0	1.97		
Δx	Transfer function - splash/spray zone	mm	Beta	8.90	5.60				0	50	1.90	8.77
		in		2.75	0.30							
cover, a	Concrete cover	mm	Normal	69.85	7.62							
C_{crit}	Critical chloride content (plain reinforcing)	mass% of binder	Beta	0.60	0.15	0.25			0.2	2	5.31	18.58
t_{SL}	Design service life	yrs	n/a	75								
β	Target Reliability	n/a	n/a	1.3								

Example of Time to Corrosion Modelling

- Concrete mix **OPC+20-35%FA** used in deck exposed to direct de-icing salts:
  - Output from spreadsheet showing the last six simulations:

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Trial Results of Randomly Generated Values of Input Parameters to Fick's 2nd Law

Trial	$D_{RCM,0}$ (mm^2/yr)		b_e (°K)		T_{real} (°K)		k_e	α		$A(t_{SL})$	$D_{app,C}$ (mm^2/yr)	C_o (mass% of binder)		$C_{s,\Delta x}$ (mass% of binder)		Δx (mm)		cover (mm)		C_{crit} (mass% of binder)		$C(x=cov,t_{SL})$	Pass (1)
	rand 0-1	RESULT	rand 0-1	RESULT	rand 0-1	RESULT		rand 0-1	RESULT			rand 0-1	RESULT	rand 0-1	RESULT	rand 0-1	RESULT	rand 0-1	RESULT	rand 0-1	RESULT	RESULT	/Fail (0)
49995	0.882	271.33	0.368	4564	0.195	282.9	0.6	0.164	0.446	0.0463	7.25	0.25	0.10	0.850	5.836	0.394	6.437	0.835	77.3	0.530	0.598	0.28	1
49996	0.059	150.90	0.449	4710	0.241	283.2	0.6	0.300	0.521	0.0277	2.41	0.07	0.10	0.047	1.626	0.009	0.647	0.547	70.8	0.263	0.495	0.10	1
49997	0.767	251.27	0.036	3540	0.348	283.9	0.7	0.600	0.648	0.0116	1.98	0.71	0.10	0.590	3.983	0.395	6.456	0.037	56.2	0.746	0.693	0.12	1
49998	0.501	219.47	0.440	4694	0.406	284.2	0.6	0.087	0.385	0.0705	9.45	0.04	0.10	0.909	6.721	0.768	12.575	0.620	72.2	0.951	0.870	0.85	1
49999	0.504	219.82	0.466	4740	0.084	281.9	0.5	0.012	0.255	0.1722	20.10	0.97	0.10	0.859	5.947	0.285	5.046	0.513	70.1	0.754	0.697	1.48	0
50000	0.461	215.11	0.318	4468	0.573	285.0	0.7	0.311	0.526	0.0267	3.76	0.69	0.10	0.803	5.356	0.220	4.205	0.946	82.1	0.742	0.690	0.11	1

SUMMARY

	$D_{RCM,0}$	b_e	T_{real}	k_e	α	$A(t_{SL})$	$D_{app,C}$	C_o	$C_{s,\Delta x}$	Δx	cover	C_{crit}
Computed Mean	219.31	4749	284.6	0.6	0.60	0.03	3.83	0.10	4.01	8.87	69.83	0.60
Input Mean	219.35	4800	284.7		0.60			0.10	4.00	8.90	69.85	0.60
Max	405.53	5500	293.18	1.01	0.99	0.67	109.29	0.10	23.19	36.94	101.73	1.44
Min	12.32	3500	276.10	0.34	0.06	0.00	0.03	0.10	0.37	0.03	41.14	0.24

Total Passing	45872	
Total # of Trials	50000	
Reliability	0.92	
P_f, Probability of failure	0.08	
β, Reliability Index (calculated)	1.388	Passes
β, Target Reliability Index	1.3	

  - The reliability index is greater than 1.3 for a maximum allowable chloride migration coefficient of 7 x 10^{-12} m^2/s.

Example of Time to Corrosion Modelling

- Concrete mix **OPC** used in deck exposed to direct de-icing salts:
  - Input to spreadsheet based on values previously defined
  - Output is calculated values to obtain a reliability index greater than 1.3:

INPUT PARAMETERS

Parameter	Description	Units	Distribution Function	Normal Distr Coefficients: Mean, μ	Std Dev, σ	Coeff of Variation, σ/μ	Log-Normal Distr Coeffs: $\ln\mu - \ln((\sigma/\mu)^2+1)/2$	$\sqrt{\ln((\sigma/\mu)^2+1)}$	Beta Distr Coeffs: Lower Bound, a	Upper Bound, b	α	β
$D_{RCM,0}$	Chloride Migration Coefficient (from Nordtest NT Build 492 - results are given in m^2/sec)	in^2/yr	Normal	0.064	0.013	0.20						
		mm^2/yr		41.0	8.2							
		m^2/sec		1.30E-12	2.60E-13							
b_e	Regression variable, (limited to 3500 °K to 5500 °K)	°K	Normal	4800	700							
T_{real}	Temperature (from Local Weather Data)	°F	Normal	52.7	3.60							
		°C		11.5	2.00							
		°K		284.65	2.00							
T_{ref}	Standard test temperature	°F	Constant	67.6								
		°C		19.8								
		°F		292.9								
k_e	Environmental transfer variable	n/a	n/a									
k_t	Transfer parameter	n/a	Constant	1.0								
α	Ageing exponent - Type I Portland Cement (PCC)	n/a	Beta	0.3	0.12				0	1	4.08	9.51
t_o	Reference point of time (28 days = 0.0767 yrs)	yrs	Constant	0.0767								
A(t)	Ageing function	n/a	n/a									
C_o	Initial Chloride Content of Concrete	mass% of binder	Normal	0.10	0.00	0.001						
C_s or $C_{s,\Delta x}$	Chloride Concentration at surface, or at substitute surface Δx	mass% of binder	Log-Normal	4.00	2.00	0.50	1.3	0.47				
Δx	Transfer function - splash/spray zone	in	Beta	0.35	0.22	0.629			0	1.97		
		mm		8.90	5.60				0	50	1.90	8.77
cover, a	Concrete cover	in	Normal	2.75	0.30							
		mm		69.85	7.62							
C_{crit}	Critical chloride content (plain reinforcing)	mass% of binder	Beta	0.60	0.15	0.25			0.2	2	5.31	18.58
t_{SL}	Design service life	yrs	n/a	75								
β	Target Reliability	n/a	n/a	1.3								

Example of Time to Corrosion Modelling

- Concrete mix **OPC** used in deck exposed to direct de-icing salts:
  - Output from spreadsheet showing the last six simulations:

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Trial Results of Randomly Generated Values of Input Parameters to Fick's 2nd Law

Trial	$D_{RCM,0}$ (mm^2/yr) rand 0-1	$D_{RCM,0}$ (mm^2/yr) RESULT	b_e (°K) rand 0-1	b_e (°K) RESULT	T_{real} (°K) rand 0-1	T_{real} (°K) RESULT	k_e	α rand 0-1	α RESULT	$A(t_{SL})$	$D_{app,C}$ (mm^2/yr)	C_o (mass% of binder) rand 0-1	C_o (mass% of binder) RESULT	$C_{s,\Delta x}$ (mass% of binder) rand 0-1	$C_{s,\Delta x}$ (mass% of binder) RESULT	Δx (mm) rand 0-1	Δx (mm) RESULT	cover (mm) rand 0-1	cover (mm) RESULT	C_{crit} (mass% of binder) rand 0-1	C_{crit} (mass% of binder) RESULT	$C(x=cov,t_{SL})$ RESULT	Pass (1) /Fail (0)
49995	0.813	48.24	0.984	5500	0.939	287.7	0.7	0.768	0.386	0.0699	2.40	0.05	0.10	0.980	9.396	0.852	14.885	0.019	54.0	0.925	0.832	0.46	1
49996	0.891	51.05	0.080	3815	0.037	281.1	0.6	0.059	0.127	0.4169	12.28	0.54	0.10	0.251	2.606	0.207	4.040	0.057	57.8	0.249	0.490	0.63	0
49997	0.749	46.46	0.364	4557	0.059	281.5	0.5	0.012	0.079	0.5796	14.35	0.01	0.10	0.019	1.347	0.822	13.953	0.871	78.5	0.649	0.646	0.30	1
49998	0.990	59.95	0.472	4750	0.314	283.7	0.6	0.244	0.209	0.2371	8.38	0.09	0.10	0.556	3.822	0.553	8.650	0.187	63.1	0.006	0.306	0.56	0
49999	0.621	43.50	0.835	5483	0.448	284.4	0.6	0.776	0.390	0.0681	1.69	0.41	0.10	0.874	6.153	0.759	12.373	0.646	72.7	0.975	0.929	0.10	1
50000	0.378	38.41	0.131	4015	0.011	280.1	0.5	0.177	0.185	0.2806	5.74	0.72	0.10	0.327	2.894	0.402	6.550	0.345	66.8	0.764	0.703	0.21	1

SUMMARY

	$D_{RCM,0}$	b_e	T_{real}	k_e	α	$A(t_{SL})$	$D_{app,C}$	C_o	$C_{s,\Delta x}$	Δx	cover	C_{crit}
Computed Mean	40.99	4749	284.6	0.6	0.30	0.17	4.43	0.10	3.98	8.93	69.87	0.60
Input Mean	~~40.97~~	4800	284.7		0.30			0.10	4.00	8.90	69.85	0.60
Max	73.13	5500	293.34	1.03	0.79	0.88	32.43	0.10	26.44	37.47	102.79	1.41
Min	10.19	3500	276.67	0.34	0.02	0.00	0.07	0.10	0.44	0.05	33.48	0.23

Total Passing	45271	
Total # of Trials	50000	
Reliability	0.91	
P_f, Probability of failure	0.09	
β, Reliability Index (calculated)	1.313	Passes
β, Target Reliability Index	1.3	

  - The reliability index is greater than 1.3 for a maximum allowable chloride migration coefficient of 1.3 x 10^{-12} m^2/s. It is, however, not possible to design an OPC concrete mix which such low chloride migration coefficient and therefore this concrete mix design will not be allowed for deck concrete.

Normally Anticipated Migration Coefficients

- *fib* Bulletin 34 provides a summary of normally anticipated values for the chloride migration coefficient, $D_{RCM,0}$, for different types of cement:

$D_{RCM,0}$ [x 10^{-12} m²/s]	Equivalent water-cement ratio*					
Cement type	0.35	0.4	0.45	0.5	0.55	0.6
OPC	N.A	8.9	10	15.8	19.7	25
OPC + FA (k = 0.5)	N.A	5.6	6.9	9	10.9	14.9
OPC + SF (k = 2.0)	4.4	4.8	N.A	N.A	5.3	N.A
OPC+66-80% GGBS**	N.A	1.4	1.9	2.8	3	3.4

* Equivalent water cement ratio, considering FA (fly ash) or SF (silica fume) with the respective k-value (efficiency factor). The considered contents were: FA: 22 wt.-%/cement; SF: 5 wt.-%/cement.

** GGBS = ground granulated blast-furnace slag.

Requirements for Concrete Mixes

- Requirements for concrete mixes based on the full probabilistic service life design:

Structural element	Description	Cover		Governing exposure zones	Min. compressive strength (psi)	Cement (ASTM C150)	Type of concrete and max. allowable chloride migration coefficient NT BUILD492 at 28 days ($\times 10^{-12}$ m^2/s)		Plastic air content (%)	Freeze-thaw tests		
		Specified (in)	Construction tolerance (in)				OPC	OPC+20-35%FA		Spacing factor (ASTM C457)	Durability factor (ASTM C666)	Resistance to scaling (ASTM C672)
Piles	With permanent steel casings	3	0.5	-	As per design	No Requirement						
Piers	Pile cap	3	1	Buried	3500	Type II	15	10	4.5	≤0.008 in.	≥90	-
	Bottom part of column	3	1	Direct de-icing salts	5000	Type I-II	Not allowed	7	6	≤0.008 in.	≥90	-
	Upper part of column and pier cap	3	1	Indirect de-icing salts	5000	Type I-II	Not allowed	10	6	≤0.008 in.	≥90	-
Abutments	Wing wall	2.5	1	Buried/ Atmospheric	4500	Type II	15	10	6	≤0.008 in.	≥90	-
	Abutment wall	3	1	Buried/ Indirect de-icing salts	5000	Type I-II	Not allowed	10	6	≤0.008 in.	≥90	-
Cast-In-Place Deck	Top of the deck	2.75	0.5	Direct de-icing salts	5000	Type I-II	Not allowed	7	6	≤0.008 in.	≥90	≤3
	Underside of the deck	1.75	0.5	Atmospheric								