Duracrete/fib Bulletin 34 Service Life Model and AASHTO Guide Specification for Service Life Design of Highway Bridges

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Agenda

- History of Service Life Design Development
- Chloride-Induced Corrosion Model from fib Bulletin 34
- Review Workshop Modelling Cases vs Model Limitations
- Modeled Cases & Input Parameters
- Application of AASHTO Guide Specification
- Results & Conclusions

History of SLD

1915 Çanakkale Bridge Caissons (2019)

2022	**FHWA Service Life Design Reference Guide** https://www.fhwa.dot.gov/bridge/preservation/docs/hif22052.pdf
2020	**AASHTO Guide Specification for Service Life Design**
2019	**CSA S6:19 (2019) introduces fib Bulletin 34 based modelling in commentary**
2015-2019	**SHRP2 R19A Project, Service Life Design for Bridges - Summary Guide (2019)** https://shrp2.transportation.org/Pages/ServiceLifeDesignforBridges.aspx
2013	**fib Bulletin 34 approach applied to Gov. Mario Cuomo & Abraham Lincoln Bridge**
2012	**ISO 16204 "Durability – Service Life Design of Concrete Structures"**
2002-2006	**International Federation for Structural Concrete (fib) Task Group 5.6 developed fib Bulletin 34**
1996-1999	**DuraCrete project - Framework for a probabilistic based durability design of concrete structures**
1980's-90's	**CEB (now fib) General Task Group No. 20: Durability and Service Life of Concrete Structures**

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fib Bulletin 34 Chloride-Induced Corrosion Model

- Chloride Ingress – Fick's 2nd Law of Diffusion to Corrosion Initiation

- **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 (NT Build 492)
  - α is the Aging Exponent
  - a is the Concrete Cover
  - Δx is the Transfer Function

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

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

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

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

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fib Bulletin 34 Input Parameters

Variable	Symbol	Short description	*fib* Bulletin 34 recommendations	Distribution	Unit
Cover	a	Concrete thickness measured from concrete surface to the surface of the outermost steel reinforcement.	Distribution function for large cover depths typically a normal distribution whereas for small cover depths, distributions excluding negative values should be chosen, such as the lognormal function.	Normal	mm (in)
Temperature	T_{real}	Temperature of the structural element or the ambient air.	T_{real} can be determined by using available data from a weather station nearby the structure.	Normal	^{o}C (^{o}F)
Initial chloride concentration	C_o	Initial chloride content in concrete at time t = 0.	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
Surface concentration	$C_{s,\Delta x}$	Chloride content at the depth Δx.	Surface concentration depends on material properties and on geometrical and environmental conditions. Ideally, data is gathered from similar structures.	Lognormal	Mass-% of total cementitious materials
Chloride migration coefficient	$D_{RCM,0}$	Chloride migration coefficient measured from NT Build 492 at 28 days.	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	x 10^{-12} m^2/s

fib Bulletin 34 Input Parameters

<table>
<tr><th>Variable</th><th>Symbol</th><th>Short description</th><th>fib Bulletin 34 recommendations</th><th>Distribution</th><th>Unit</th></tr>
<tr><td>Ageing factor</td><td>α</td><td>Time-dependent change of the migration coefficient as concrete matures.</td><td>Recommended values for ageing factors for concrete with an equivalent water-cement ratio between 0.40-0.60:
<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></tr>
<tr><td>Transfer function</td><td>Δx</td><td>Consideration of capillary action causing rapid transport of chlorides to a depth Δx</td><td>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></tr>
<tr><td>Critical chloride concentration</td><td>C_{cr}</td><td>Chloride concentration required to depassivate reinforcement</td><td>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></tr>
</table>

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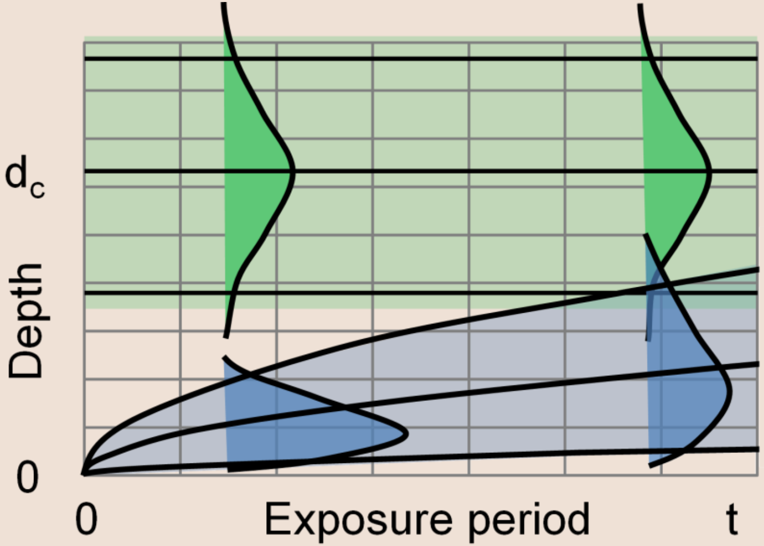
fib Bulletin 34 Chloride-Induced Corrosion Model

- Influential inputs are probabilistic distributions
- **Fick's 2nd law-based model provides time, depth where critical chloride threshold reached**
- **Probabilistic consideration of cover thickness (d_c)**
- Overlap indicates increasing probability for critical chloride content at reinforcement depth



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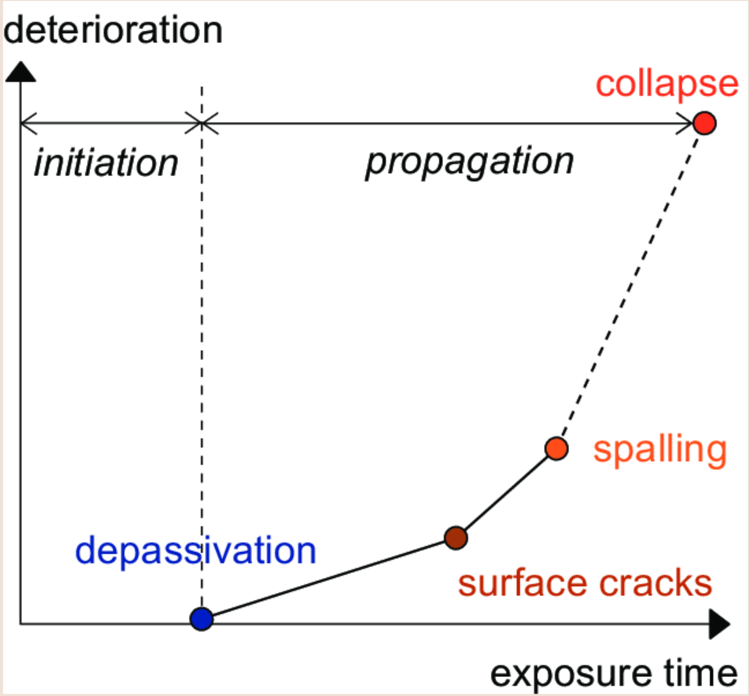
fib Bulletin 34 Chloride-Induced Corrosion Model

- Service life limit state is defined as a 10% probability for depassivation
  - Reliability index, β of ~1.30
  - 90% probability that corrosion will not initiate during service life
- Similar to serviceability limit state
  - Reaching limit state ≠ immediate failure



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Model Cases & Parameters

Table 4. Modeling Cases and Parameters

	Case 1	Case 2	Case 3
Location	Boston, MA		
Element	Bridge Deck	Marine Pile	Marine Wall
Thickness/Diameter	8 in	36 in	8 in
Exposure	Deicing Salt	Submerged	Splash
Target Initiation Time with 90% Confidence	100 years		
Cover	2.5 in	3.0 in	3.0 in
Maximum Surface Concentration	5500 ppm	8000 ppm	10000 ppm
Black Bar Initiation Threshold	735 ppm		
Enhanced Initiation Threshold	2500 ppm		
Hydration Time	8 years		

Acknowledging Model Limitations

- *fib* Bulletin 34 probabilistic model was developed for concrete cast in formwork
  - Not developed/appropriate for modeling concrete cast immediately against soil
  - Cannot be used for retaining walls not cast in formwork (e.g., secant pile walls)
  - Case 2 not applied
  - Case 3 is assumed to be cast in formwork, backfilled or similar

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Model Cases & Parameters – Concrete Types

100% Type I/II Cement (CTRL)

- 658 lb/cy Type I/II Cement
- 0.38 w/cm ratio
- 14.0 x 10^{-12} m²/s Chloride Migration Coefficient

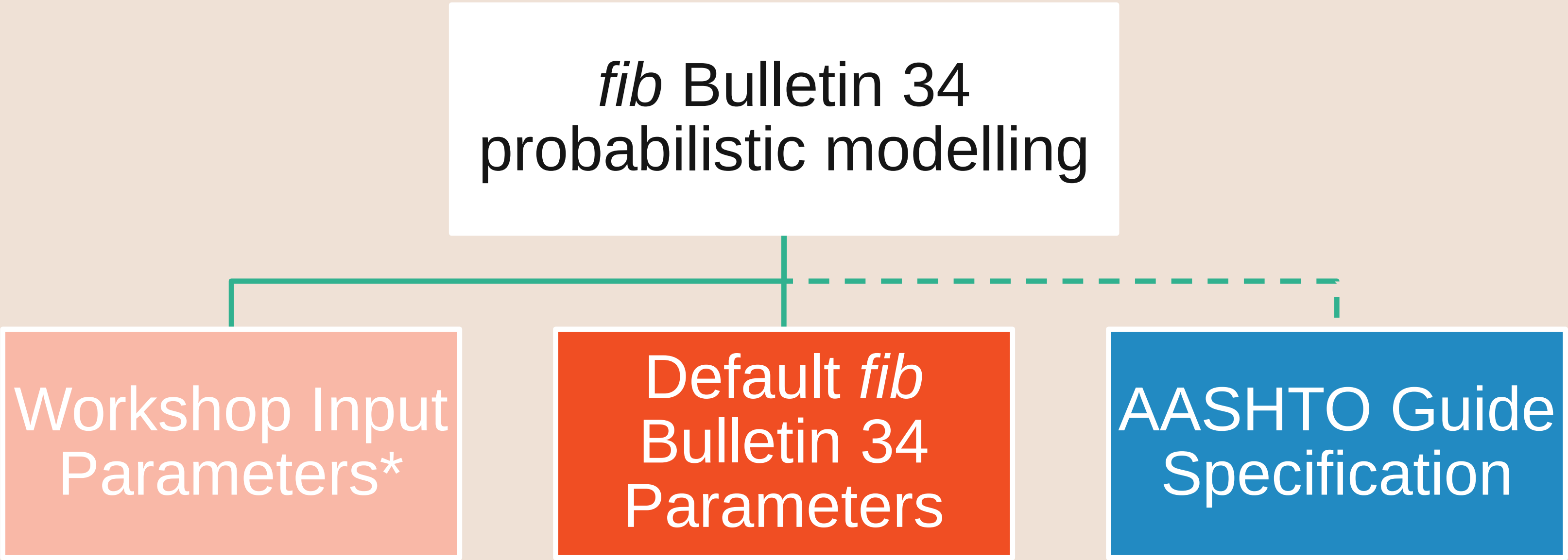
8% Silica Fume (SF-8)

- 605 lb/cy Type I/II Cement
- 53 lb/cy Silica Fume
- 0.38 w/cm ratio
- 3.6 x 10^{-12} m²/s Chloride Migration Coefficient

20% Hyaloclastite Pozzolan (HP-20)

- 526 lb/cy Type I/II Cement
- 132 lb/cy Hyaloclastite Pozzolan, Class N/F ASTM C618
- 0.38 w/cm ratio
- 9.6 x 10^{-12} m²/s Chloride Migration Coefficient

Assessments Performed



* To facilitate discussions, modelling was completed using workshop input parameters. Certain inputs are not standard values as supported by fib Bulletin 34 and various other references.

Model Cases

Case	Concrete Type	Key Differing Details/Assumptions: Workshop defined inputs	Key Differing Details/Assumptions: fib Bulletin 34 recommended inputs
Case 1 – Bridge Deck 2.5” Cover	CTRL	- Hydration time = 8 yrs - Age factor from test data (not per fib Bulletin 34) - C_{crit} Values: - Black bar – 0.45% - ”Enhanced” – 1.5%	- Aging factor ‘on’ for duration of target service life, set based on published values - C_{crit} Values: - Black bar – 0.60% - ”Enhanced” – 1.5%
	SF-8		
	HP-20		
Case 3 – Marine Wall 3” Cover	CTRL		
	SF-8		
	HP-20		

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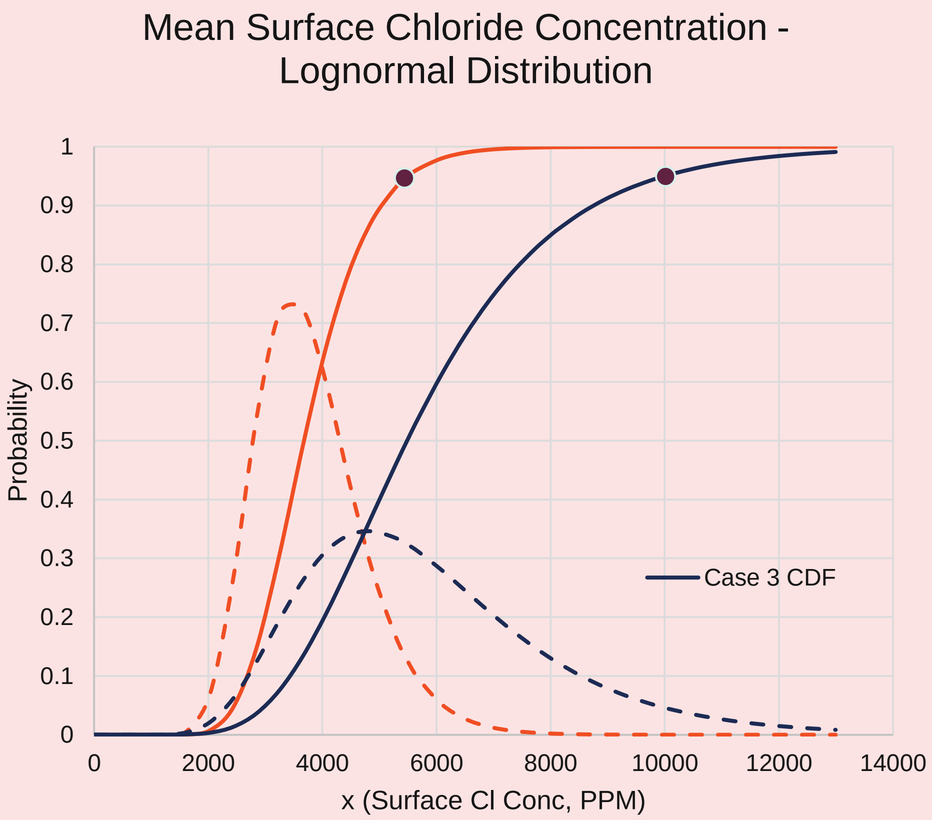
Interpretation of Parameters

Maximum surface concentrations prescribed:

Table 4. Modeling Cases and Parameters

	Case 1	Case 2	Case 3
Maximum Surface Concentration	5500 ppm	8000 ppm	10000 ppm

"Maximum" concentration set as 95% quantile & mean concentration determined



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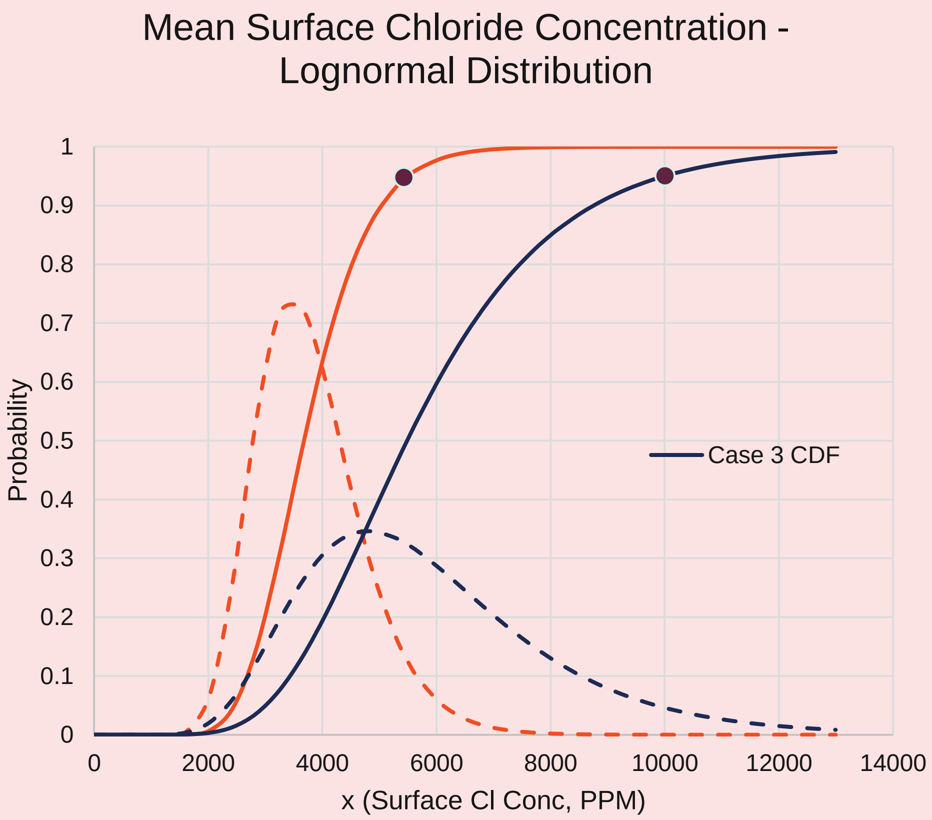
Interpretation of Parameters

Exposure Cases	Mean Surface Concentration (% by mass cem)	
	Mean, μ	**Std Dev, σ**
Case 1 – Bridge Deck	2.3	0.7
Case 3 – Marine Wall	3.4	1.0

Concentrations conversions used 658 lbs/cy (390 kg/m³) cementitious materials content & 4050 lbs/cy (2400 kg/m³) unit weight of concrete



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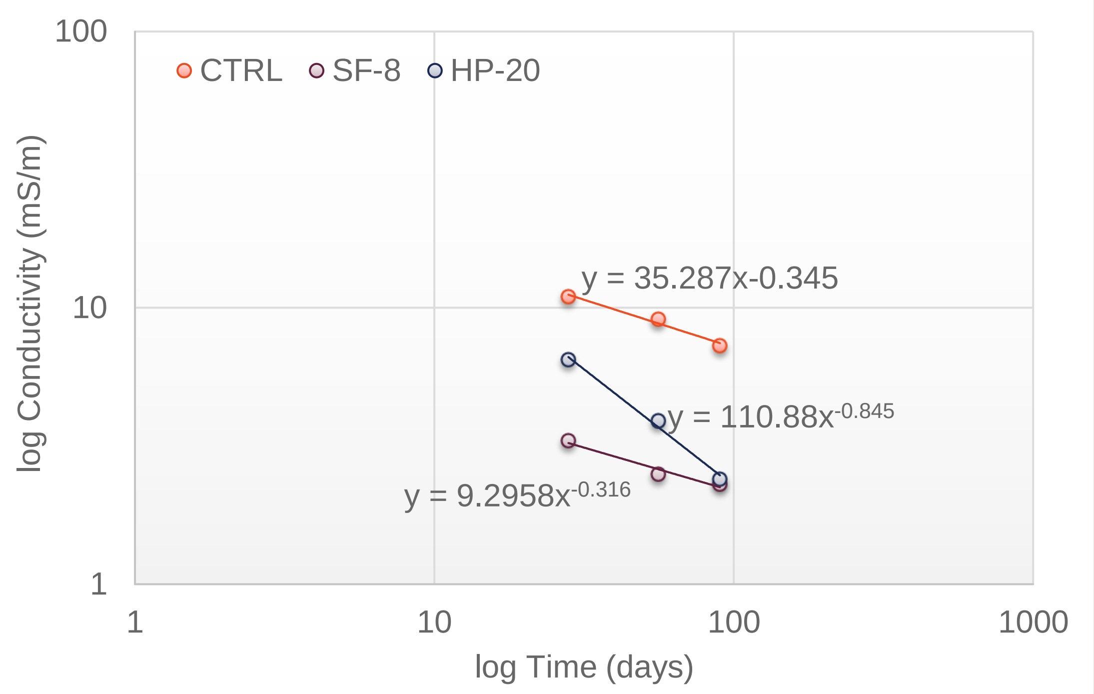
Interpretation of Parameters – Age Factors

- Workshop Input Parameters included ASTM C1760 Bulk Electrical Conductivity results at 28, 56, 90 days
- Workshop approach was to determine age factors as best fit on log-log plot



Interpretation of Parameters – Age Factors

Workshop Approach	fib Approach
• Calculated by plotting Bulk Electrical Conductivity test results (ASTM C1760) against time on a logarithmic scale • Results only available at 28, 56, and 90-day period • Instructions to workshop provided this methodology to calculate age factors for each mix design	• Relies on published results in fib Bulletin 34, 76, etc. • With new materials, age factors are calculated by plotting apparent chloride diffusion, D_{app} against time on a logarithmic scale – *fib* 76 recommends collecting data for 2 years • D_{app} calculated using chloride migration coefficient (NT Build 492 test)

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Interpretation of Parameters – Age Factors

Concrete Type	Workshop approach			fib Bulletin 34 approach		
	Mean, μ	Std Dev, σ	Duration, yrs	Mean, μ	Std Dev, σ	Duration, yrs
CTRL	0.35	0.09	8	0.30	0.12	100
SF-8	0.32	0.08	8	0.30	0.12	100
HP-20	0.85	0.21	8	0.60	0.15	100

- Age factor modeled as a beta distribution
- Bounds of beta distribution for HP-20 for workshop approach: a = 0, b = 1.5
- Age factor for SF-8 equal to CTRL for fib Bulletin 34 approach
- HP-20 treated as Class F fly ash for selection of age factor for fib bulletin 34 approach

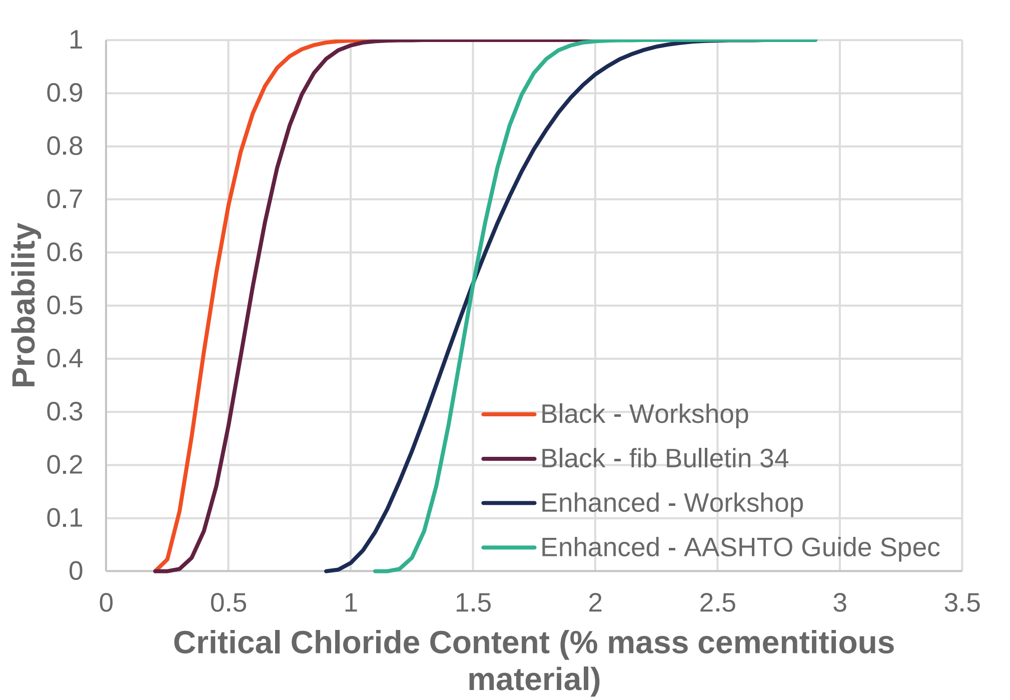
Interpretation of Parameters – Chloride Threshold

	Workshop Chloride Threshold				fib/AASHTO Chloride Threshold			
	Mean, μ	**Std Dev, σ**	**a**	**b**	**Mean, μ**	**Std Dev, σ**	**a**	**b**
Black rebar	0.45	0.14	0.2	2	0.60	0.15	0.2	2
Enhanced rebar	1.50	0.30	0.9	2.9	1.50	0.15	1.1	2.9

- Beta distribution bounds (a and b) for Workshop input parameters adjusted to obtain S- shaped curve
- Other values were applied based on *fib* Bulletin 76 or AASHTO Guide Spec recommendations

Interpretation of Parameters – Chloride Threshold

- Beta distributions used to model critical chloride content
  - Includes upper and lower bounds
- Important to verify all distribution curves are rational



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Interpretation of Parameters – Initial Chloride Content

- Workshop input parameter: 85 ppm in concrete
  - Calculated to be 0.05% by mass of binder (based on 658 lbs/yd^3 cementitious material)

- fib Bulletin 34 input parameter: 0.10% by mass of binder

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Comparison of Results – Black Bar

Case	Concrete Type	Model Outputs			
		Workshop defined inputs		fib Bulletin 34 inputs	
		t @ β = 1.30	β @ 100 years	t @ β = 1.30	β @ 100 years
Case 1 – Bridge Deck 2.5” Cover	CTRL	5 to 10 yrs	-2.2	5 to 10 yrs	-0.93
	SF-8	20 to 25 yrs	-0.82	35 to 40 yrs	0.29
	HP-20	55 to 60 yrs	0.81	85 to 90 yrs	1.20
Case 3 – Marine Wall 3” Cover	CTRL	5 to 10 yrs	-2.4	10 to 15 yrs	-0.94
	SF-8	25 to 30 yrs	-0.72	40 to 45 yrs	0.35
	HP-20	65 to 70 yrs	0.94	95 to 100 yrs	1.28

Comparison of Results – Enhanced Bar

Case	Concrete Type	Model Outputs			
		Workshop defined inputs		fib Bulletin 34 inputs	
		t @ β = 1.30	β @ 100 years	t @ β = 1.30	β @ 100 years
Case 1 – Bridge Deck 2.5” Cover	CTRL	35 to 40 yrs	0.35	45 to 50 yrs	0.74
	SF-8	>100 yrs	1.53	>100 yrs	1.88
	HP-20	>100 yrs	2.25	>100 yrs	2.43
Case 3 – Marine Wall 3” Cover	CTRL	25 to 30 yrs	-0.22	30 to 35 yrs	0.26
	SF-8	95 to 100 yrs	1.28	>100 yrs	1.61
	HP-20	>100 yrs	2.07	>100 yrs	2.22

AASHTO Guide Specification – Calibrated Deemed to Satisfy Approach

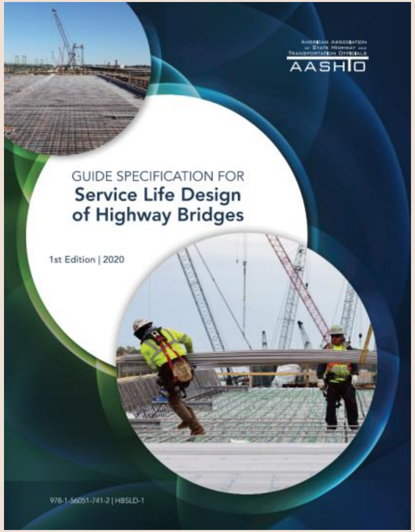

Table 4.2.4.2.2-1—Nominal Concrete Cover Requirements (continued)

Exposure Class				Concrete Type[2]	Reinforcement Class[3]	Service Life Category		
						Normal	Enhanced	Maximum
Class	Condition	Description	Examples			Cover (in)[1,4]		
C-M3	Marine - Tidal or Splash/Spray Zone	Surfaces in contact with salt water either in the tidal zone or splash/spray zone	Substructures within tidal zone or splash/spray	Any	D	1.0	1.0	1.0
				OPCFA+SF	C	1.5	1.5	1.5
				OPCFA	C	1.5	1.5	2.0
				GGBS+SF	C	1.5	2.0	2.0
				GGBS	C	2.0	2.0	2.5
				OPC	C	3.5	4.0	
				OPCFA+SF	B	2.0	2.0	2.5
				OPCFA, GGBS+SF	B	2.5	2.5	3.0
				GGBS	B	3.5	3.5	4.0
				OPCFA+SF	A	3.0	3.0	3.5
				OPCFA	A	3.5	4.0	4.0
				GGBS+SF	A	3.5	4.0	

AASHTO Guide Specification – Calibrated Deemed to Satisfy Approach

Case	Concrete Type	AASHTO Guide Specification Required Cover	
		Black Bar	Enhanced Bar
Case 1 – Bridge Deck 2.5” Cover	CTRL	N.A.	N.A.
	SF-8	N.A.	N.A.
	HP-20	3” Required	2” Required
Case 3 – Marine Wall 3” Cover	CTRL	N.A.	N.A.
	SF-8	N.A.	N.A.
	HP-20	4” Required	2.5” Required

Summary of Results

Case	Concrete Type	Viable Option for 100 Year Service Life?					
		Black Bar			Enhanced Bar		
		Workshop	fib 34	AASHTO	Workshop	fib 34	AASHTO
Case 1 – Bridge Deck 2.5" Cover	CTRL						
	SF-8				☺	☺	
	HP-20			3"	☺	☺	2"
Case 3 – Marine Wall 3" Cover	CTRL						
	SF-8				☺	☺	
	HP-20		😐 (β = 1.28)	4"	☺	☺	2.5"

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Summary & Conclusions

- Care is needed with available modeling tools:
  - Know the limitations, fundamental assumptions of the modeling tools used
  - Modify default input parameters with caution
  - Expert involvement required with complex models to yield reliable results
- Similar conclusions found using workshop and fib Bulletin 34 input parameters in terms of viable combinations of concrete and reinforcement types to achieve 100 year service life
  - Maintaining aging for duration of service life resulted in slight increases in time @ $\beta = 1.30$ and β at 100 years
- Use of rebar with enhanced corrosion-resistance is effective and can permit use of concrete with reduced durability performance
- Use of calibrated deemed-to-satisfy method from AASHTO Guide Specification provided similar conclusions, offers a solution avoiding improper use of input parameters but with limited mix design currently considered

Questions