



SHRP2 SOLUTIONS
STRATEGIC HIGHWAY RESEARCH PROGRAM

Chloride-Induced Corrosion Modeling

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Federal Highway Administration

American Association of State Highway and Transportation Officials
AASHTO

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

Agenda

- Introduction
- *fib* Bulletin 34 Model Code for Service Life Design
- Conclusion

How is service life currently considered?

- Structural design standards:
  - Do not specifically account for service life
  - Fail to quantify durability limit states

- Codes and standards as design basis:
  - Assumed life is typically 75 years
  - Take no account of specific environment
  - Take no account of specific material properties
  - Make no use of deterioration models
  - No metric to quantify durability
  - Knowledge base is 10-30+ years
  - "Deemed to satisfy rules"

Solutions?

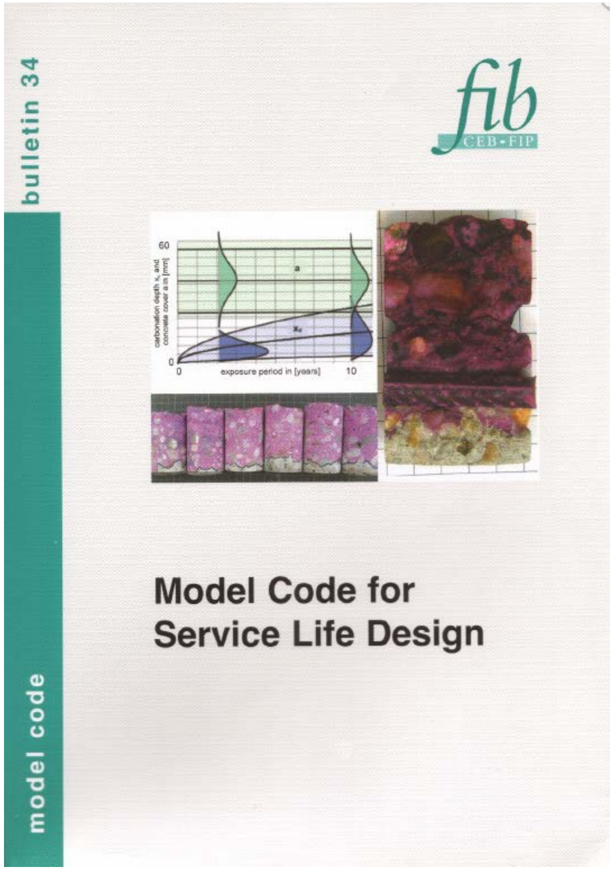
- Performance and design requirements that owners and designers can use
- Service life design using a rational probabilistic approach
- Transform subjective concept of "durability" into a actual design methods and tools for designers that permit optimization of design for service life

fib Bulletin 34 Model Code for Service Life Design

- Written and distributed by the International Federation of Structural Concrete (*fib*)

- A reliability-based service life design methodology for concrete structure
  - Similar to Load-Resistance Factor Design

- ISO 16204:2012 Service Life Design of Concrete Structures

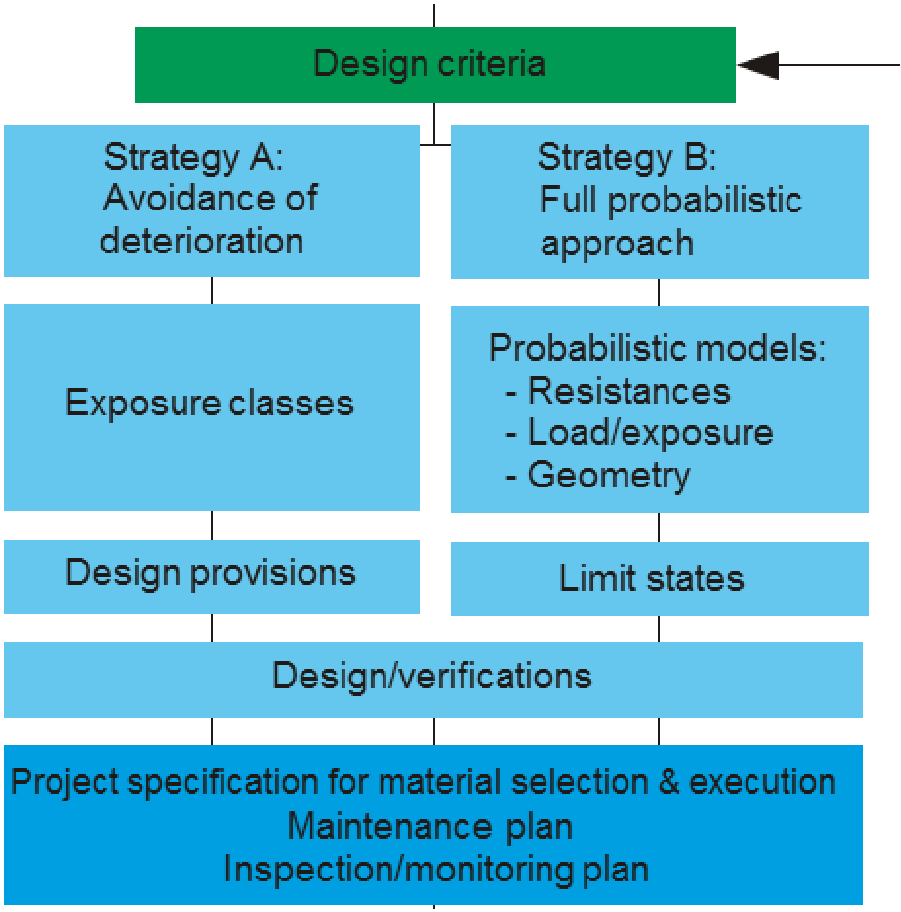


fib Bulletin 34 Model Code for Service Life Design

- 1 of 2 strategies

- Avoidance approach applied for:
  - Carbonation-induced corrosion
  - Sulfate attack
  - DEF
  - AAR
  - Freeze/thaw degradation

- Full probabilistic approach for:
  - Chloride-induced corrosion

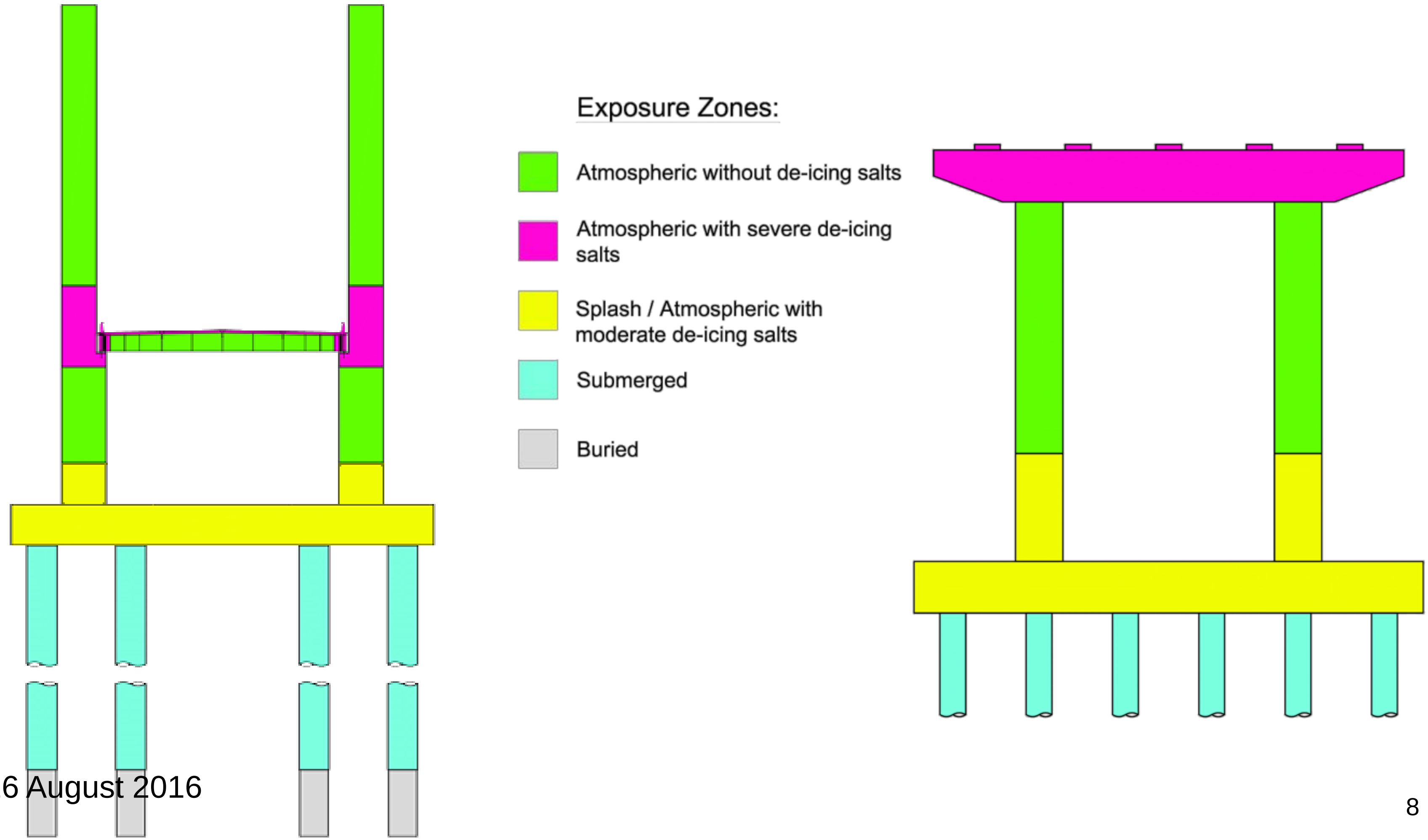


fib Bulletin 34 Model Code for Service Life Design Strategy - Probabilistic Analysis

1. Define exposure zones and degradation mechanisms
2. Select limit state
3. Design Parameters
   - Materials
   - Concrete quality
   - Concrete cover
4. Project Specifications
5. Construction → pre-testing and production testing

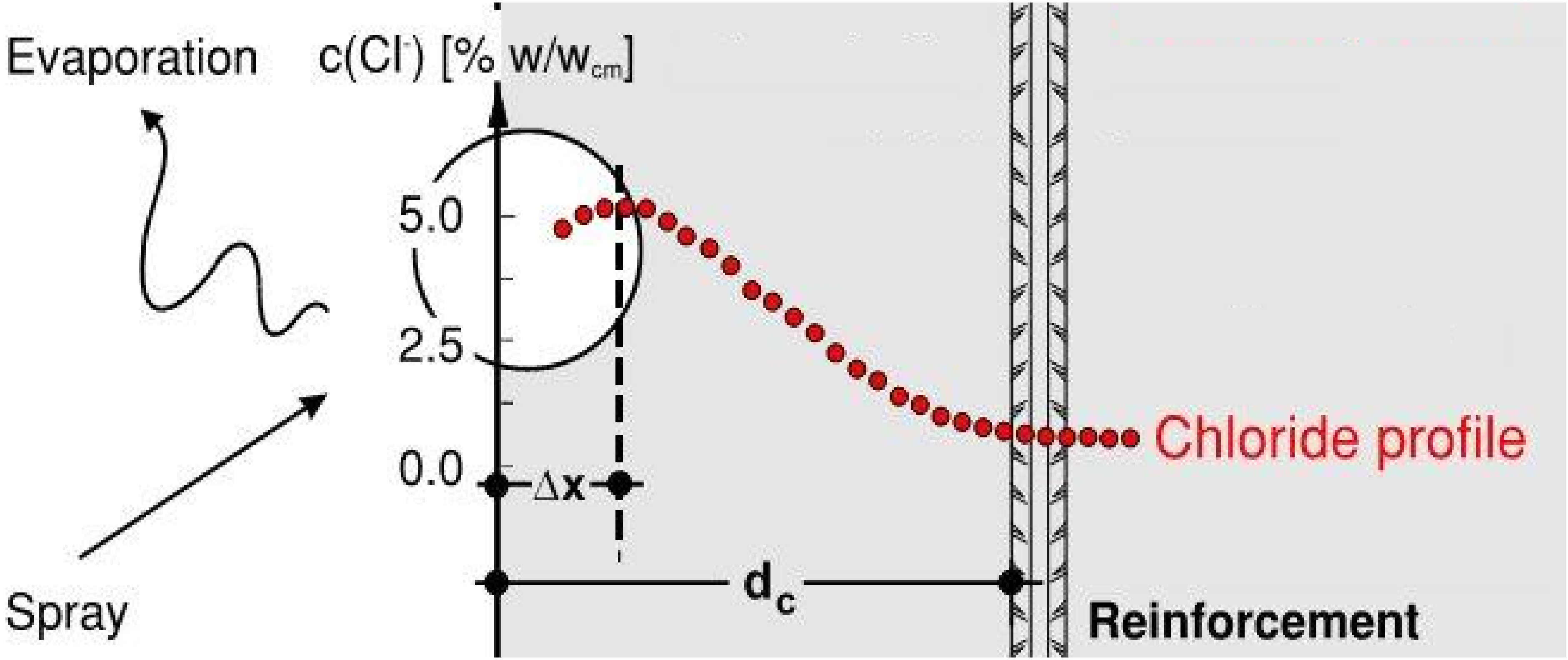
Service Life Assessment

1. Define exposure zones and degradation mechanisms



Assessment *(continued)*

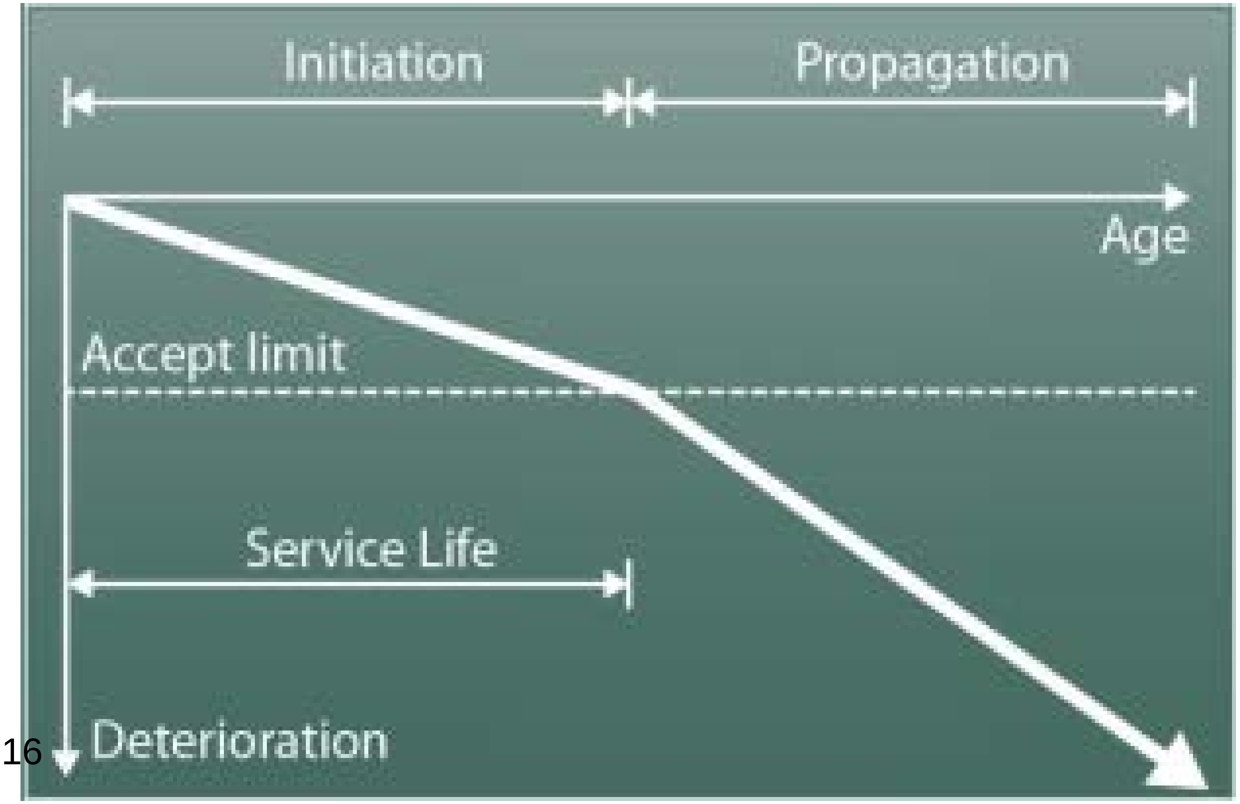
2. Select limit state



Modelling Chloride-Induced Corrosion

2. Select limit state

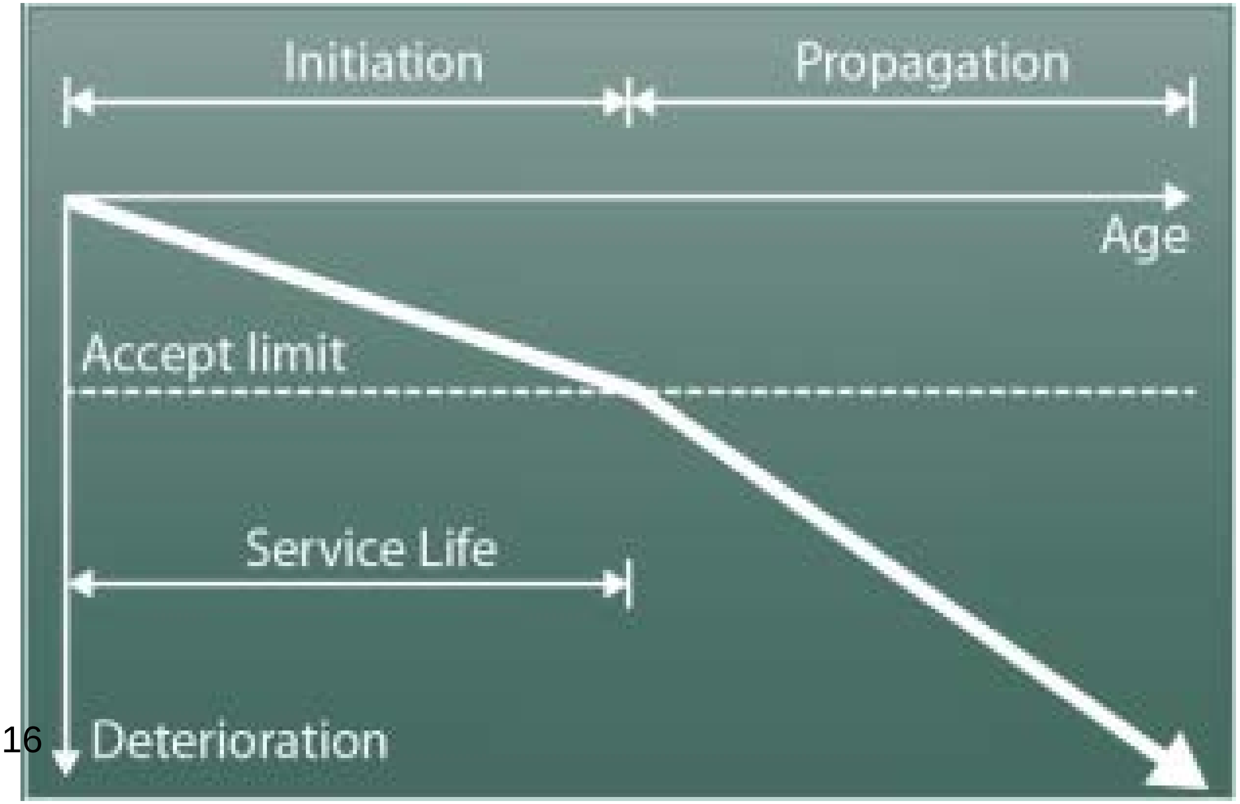
- Depassivation of reinforcement marks end of service life
- Occurs when critical chloride threshold is reached at reinforcement



Modelling Chloride-Induced Corrosion

2. Select limit state

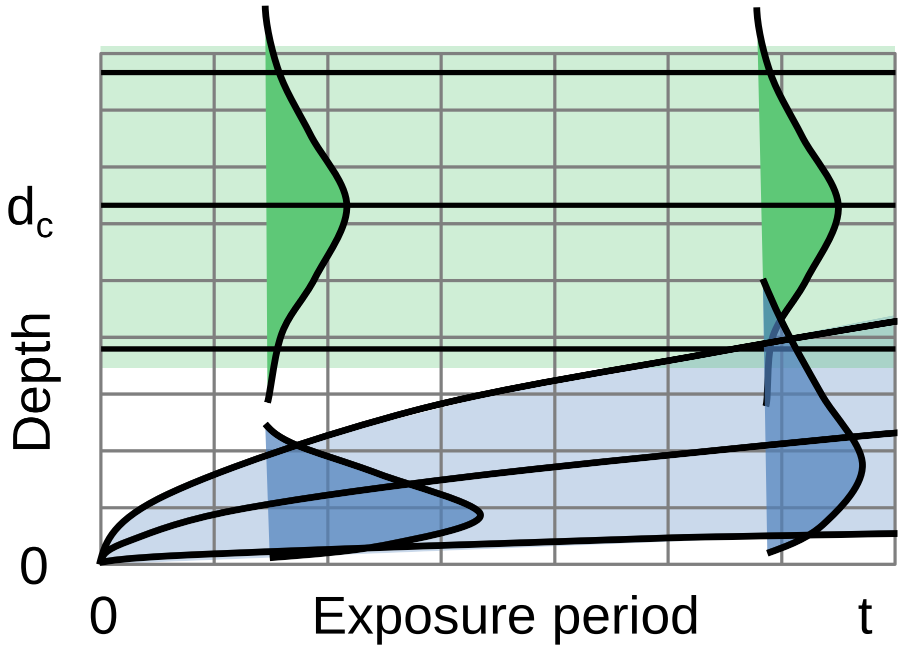
- Serviceability limit state:
  - 10% probability that corrosion will initiate within the service life
  - 90% probability that it will not!



Modeling Chloride-Induced Corrosion

3. Design Parameters

- Depassivation of reinforcement marks end of service life
- **Fick's 2nd law-based model provides time, depth where critical chloride threshold reached**
- **Probabilistic consideration of cover thickness (d_c), critical chloride threshold**
- All input are probabilistic variables.



Modeling Chloride-Induced Corrosion

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

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

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

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

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

- **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
  - a is the Concrete Cover

Modeling Chloride-Induced Corrosion

- Environmental exposure of coastal marine bridges
  - Chloride loading (C_s) based on natural salinity of sea water
  - Data collected from existing documentation or perform salinity tests
- Environmental exposure from de-icing chemicals
  - Chloride loading (C_s) much more difficult to assess
  - Best source of data is from test coring existing structures in similar environment

Determining Chloride Loading

Designation: C1543 – 10

Standard Test Method for
Determining the Penetration of Chloride Ion into Concrete by Ponding[1]

- Known as the Salt Ponding Test
- Used to develop chloride profiles in test specimens or existing concrete taken from cores
- Results include Surface Chloride Concentration (C_s) and Concrete Apparent Coefficient of Diffusion ($D_{app,C}$) at age of core

Service Life Assessment

3. Design Parameters
4. Input in Project Specification

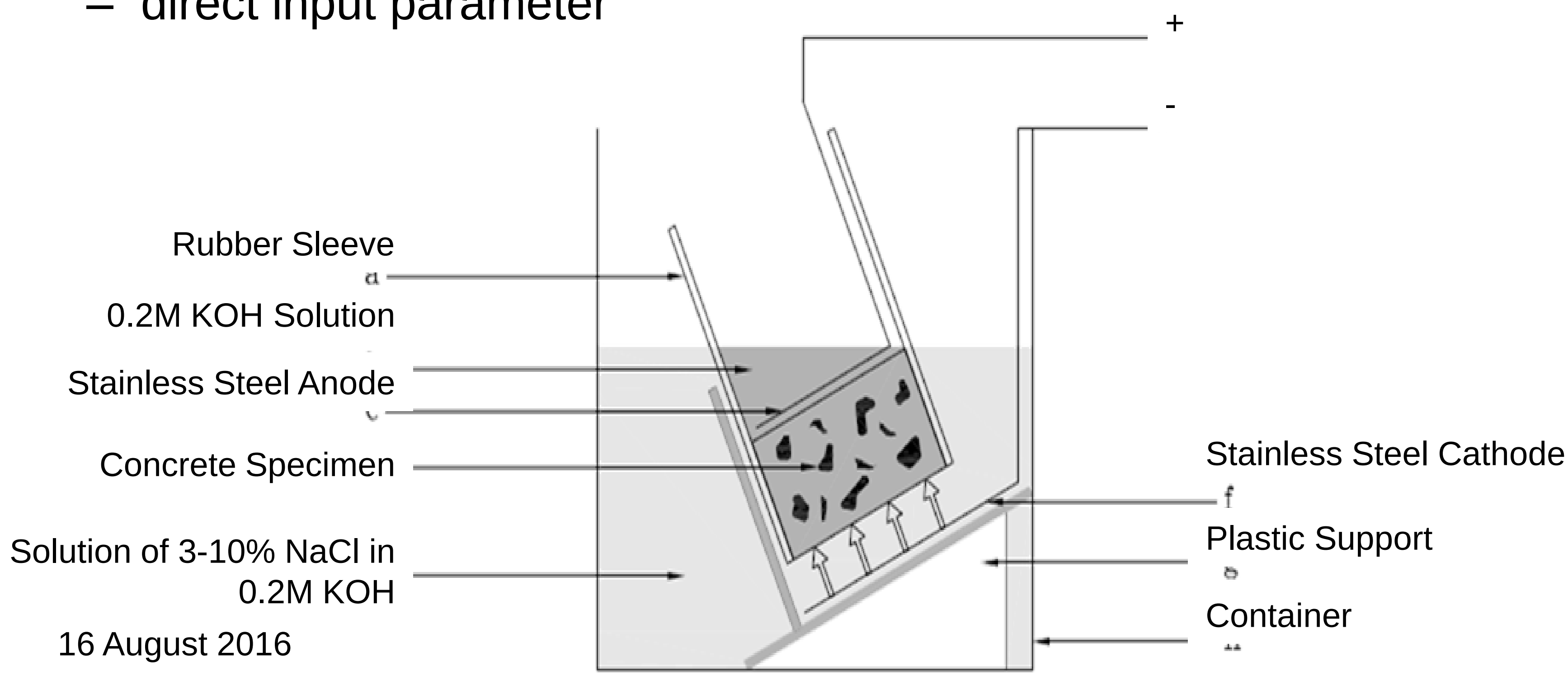
Exposure Zone	Structural Element	Nominal cover [in]	Max. w/cm [-]	Max. mean Chloride Migration Coefficient $D_{28} \times 10^{-9}$ [in^2/s] Mix 1	Mix 2	Mix 3
De-icing salt spray	Towers, pier caps, abutments	3.0	0.40	14.1	3.4	4.9
	Deck			11.3	2.7	4.0
	Concrete barriers	2.75		12.4	3.4	4.6
Atmospheric	Towers, pier caps, pier columns	3.0	0.40	15.0	11.0	12.0
Splash	Towers, pier caps, pier columns	3.0	0.40	15.0	5.1	7.1
	Pile caps	4.0			9.9	12.0
Submerged	Concrete plug for piles	2.5	0.40	15.0	5.8	8.3

Service Life Assessment

5. Construction → Pre-testing and production testing

fib Model Code is based on NT Build 492: Rapid Chloride Migration Test

- measure the migration coefficient of concrete at 28 days
- direct input parameter



NT Build 492 – Test Setup

NT Build 492

- Split specimen axially into 2 pieces
- Spray silver nitrate solution on broken surface
- Measure chloride penetration depth
- Calculate Chloride Migration Coefficient, $D_{RCM,0}$

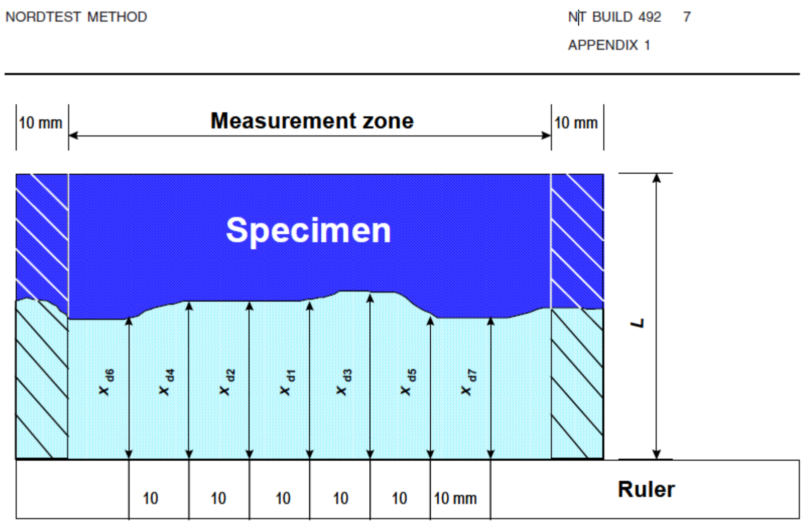


Fig. 5. Illustration of measurement for chloride penetration depths.

Modeling Chloride-Induced Corrosion

- **Resistance to Chloride Ingress** influenced by concrete mix proportions:
  - Type of Cement
  - Water/Cement Ratio
  - Supplemental Cementitious Materials
    - Fly Ash (FA)
    - Ground Granulated Blast Furnace Slag (GGBFS)
    - Silica Fume (SF)
  - Aggregates

NT Build 492 Test Summary

- Important to perform test at 28 days
- Test takes 24 hours
- One test includes 3 specimens
- Cost of a single test is approximately $1,000

Concrete Cover Depth

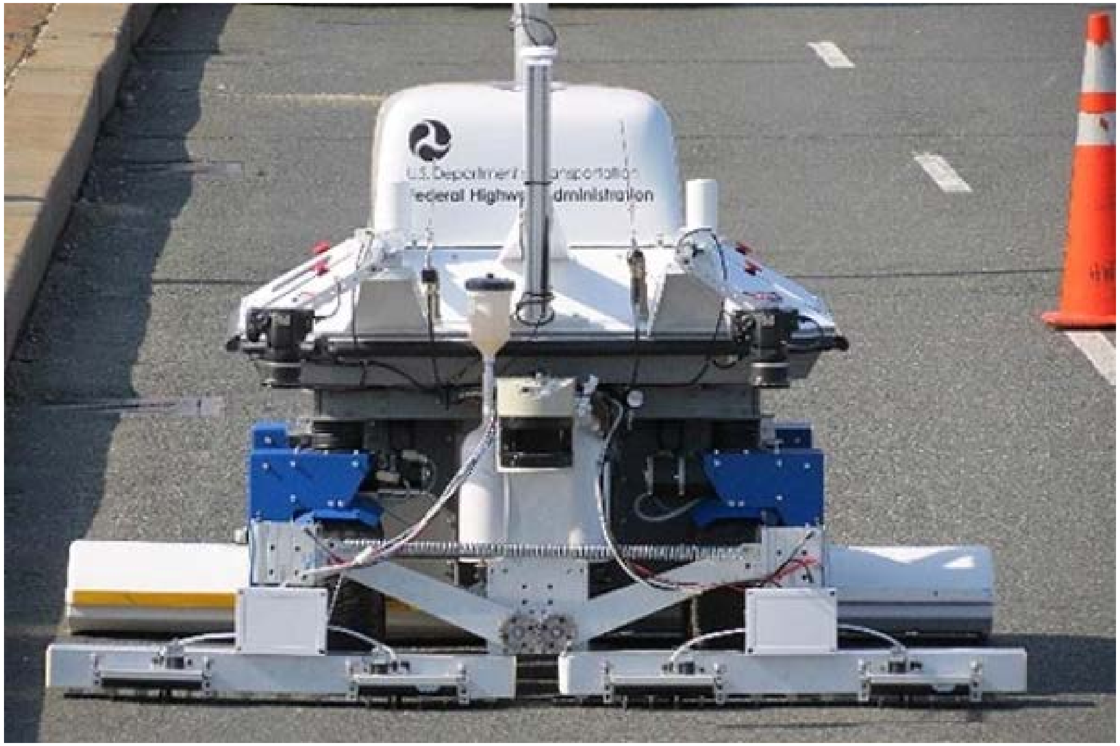
- Lack of U.S. standards for measuring cover depth in hardened concrete
- Service Life goal is for complete mapping
  - Min/Max Depths
  - Used to calculate mean & standard deviations
- International Standard
  - British Standard 1881-204:1988 – Testing Concrete. Recommendations on the use of electromagnetic covermeters

Covermeters

- Sources: Proceq Elcometer

Concrete Cover Depth

- FHWA's Robotic Assisted Bridge Inspection Tool (RABIT) with Ground Penetrating Radar (GPR)



How does this concrete durability study affect the structural design?

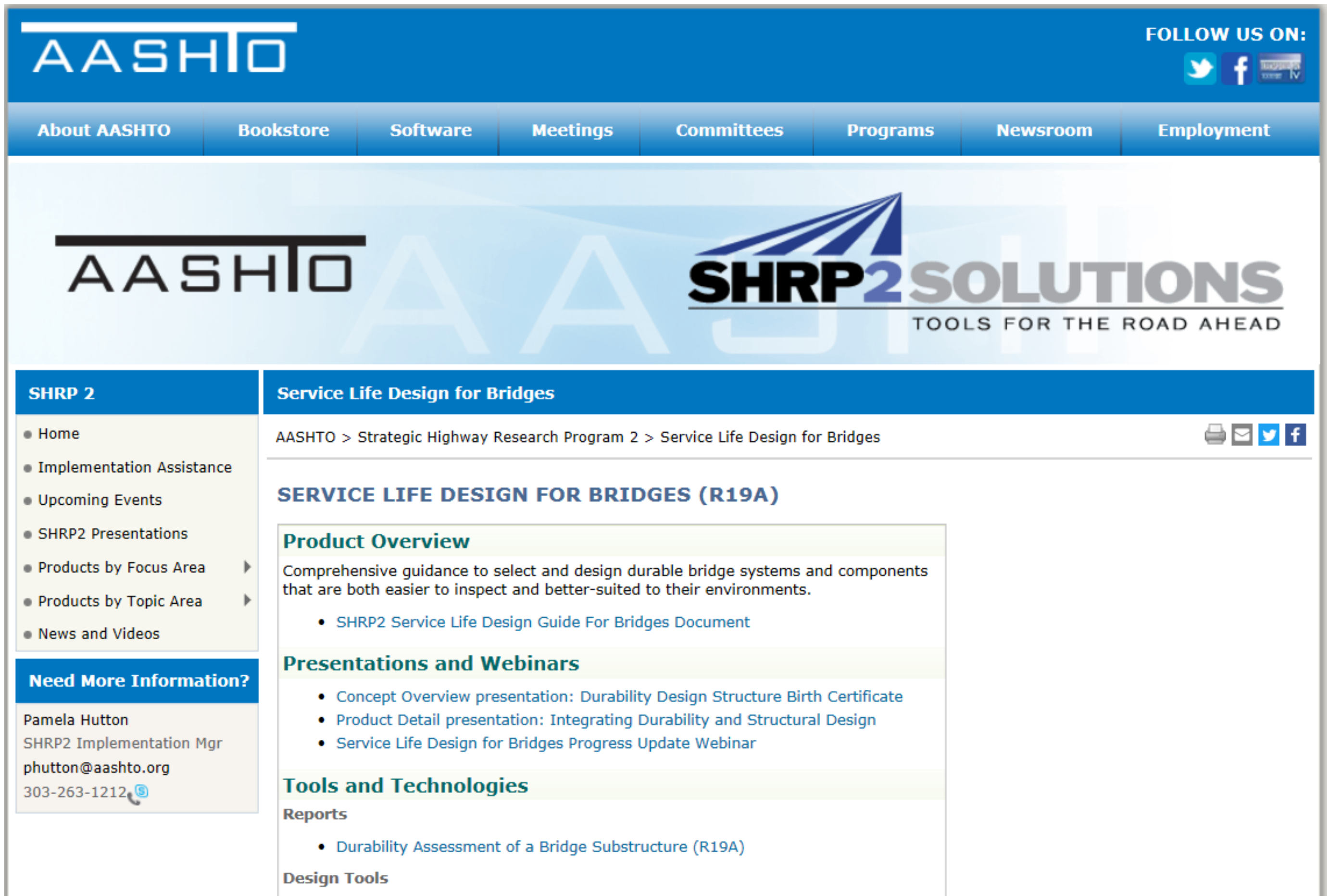
- Quantifiable requirements for the concrete quality
- Concrete cover
- Type of reinforcing steel

Design Tools

- SHRP2 R19A: Design tools for fully probabilistic model for chloride-induced corrosion
  - Excel spreadsheet
  - Design charts

Design Tools

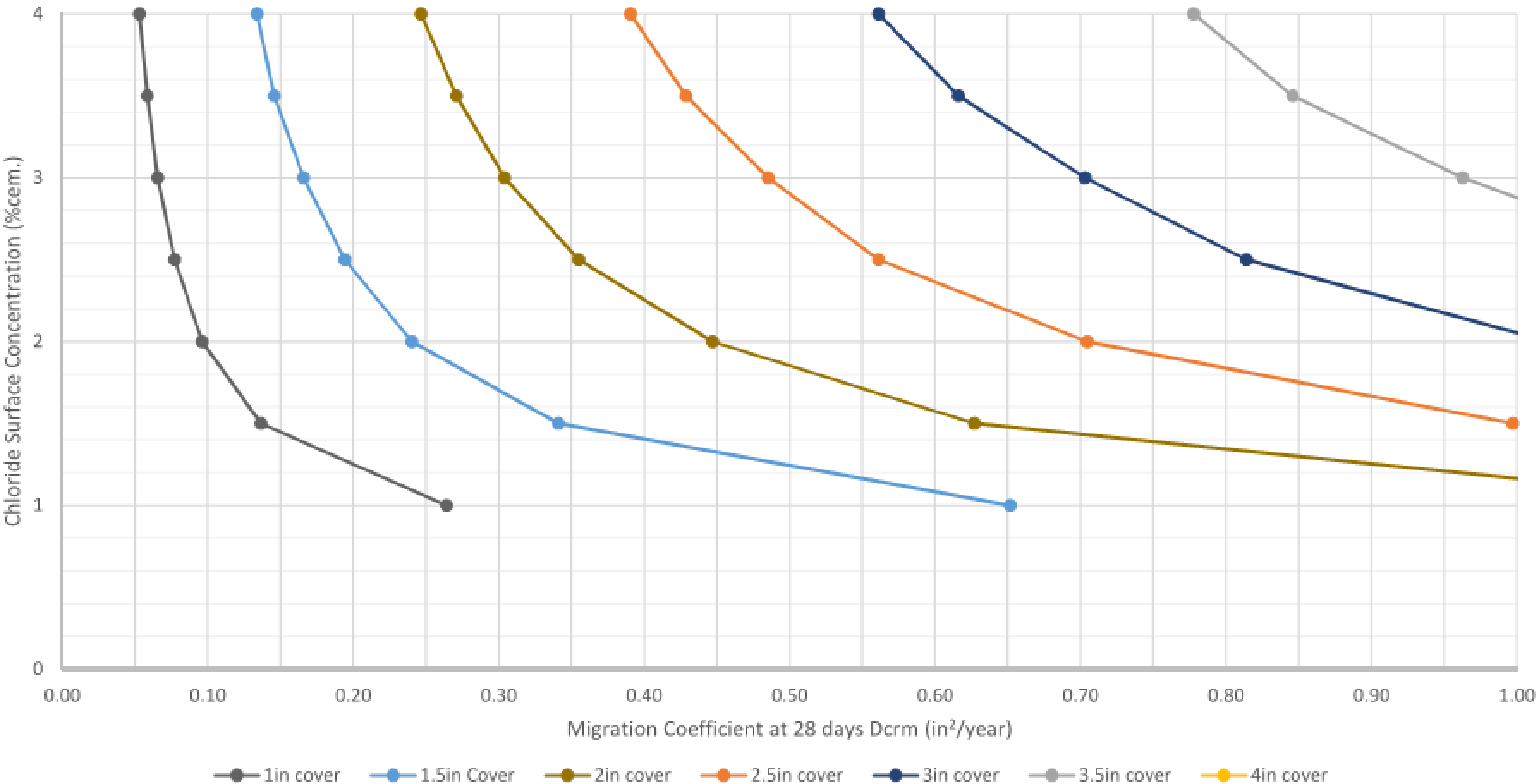
- SHRP2 Website:
- http://shrp2.transportation.org/Pages/ServiceLifeDesignforBridges.aspx



SERVICE LIFE DESIGN - GRAPHICAL SOLUTION

Calculations as per fib Bulletin 34 - fully probabilistic design
Service Life = 100 years
Beta = 1.3, Probability of failure = 10%
Critical chloride concentration: black bars - 0.6%cem.
Initial chloride concentration : 0.1%cem.

Temperature: mean = 49.1F, std = 12.1F
Exposure Zones: Buried/Submerged
Concrete Type: OPC + >20%FA



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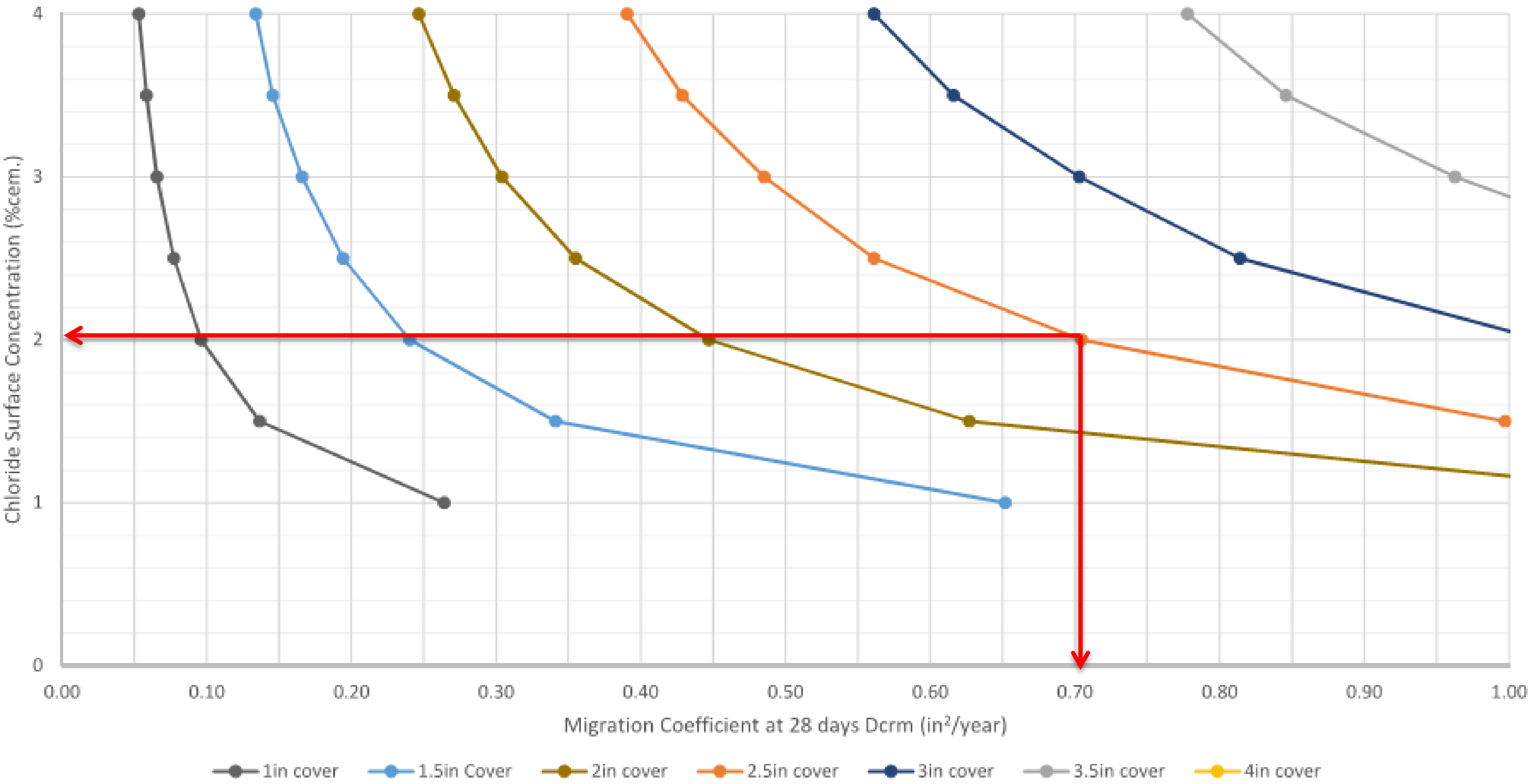

Full Probabilistic Tool - Input

				Normal Distr Coefficients		
Parameter	**Description**	**Units**	**Distribution Function**	**Mean, μ**	**Std Dev, σ**	**Coeff of Variation, σ/μ**
$D_{RCM,0}$	Chloride Migration Coefficient (from Nordtest NT Build 492 - results are given in m^2/sec)	in^2/yr	Normal	0.420	0.084	0.20
		mm^2/yr		271.0	54.2	
		m^2/sec		8.59E-12	1.72E-12	
b_e	Regression variable, (limited to 3500 °K to 5500 °K)	°K	Normal	4800	700	
T_{real}	Temperature (from Local Weather Data)	°F	Normal	49.1	12.06	
		°C		9.5	6.70	
		°K		282.65	6.70	
T_{ref}	Standard test temperature	°F	Constant	67.6		
		°C		19.8		
		°K		292.9		
k_e	Environmental transfer variable	n/a	n/a			
k_t	Transfer parameter	n/a	Constant	1.0		
α	Aging exponent - All types in atmospheric zone	n/a	Beta	0.65	0.15	
t_o	Reference point of time (28 days = 0.0767 yrs)	yrs	Constant	0.0767		
A(t)	Aging 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	3.00	1.50	0.50

Monte Carlo Trial Results

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

Trial	$D_{RCM,0}$ (mm^2/yr) rand 0-1	$D_{RCM,0}$ RESULT	b_e (°K) rand 0-1	b_e RESULT	T_{real} (°K) rand 0-1	T_{real} RESULT	k_e	α rand 0-1	α RESULT	$A(t_{SL})$	cover (mm) rand 0-1	cover RESULT	C_{crit} (mass% of binder) rand 0-1	C_{crit} RESULT	$C(x=cov,t_{SL})$ RESULT	Pass (1) /Fail (0)
1	0.392	256.08	0.117	3967	0.918	292.0	1.0	0.921	0.853	0.0022	0.528	50.9	0.788	0.716	0.10	1
2	0.924	348.42	0.607	4990	0.690	286.0	0.7	0.236	0.541	0.0207	0.411	49.0	0.372	0.538	0.46	1
3	0.547	277.42	0.325	4482	0.682	285.8	0.7	0.473	0.650	0.0094	0.005	36.5	0.666	0.654	0.55	1
4	0.510	272.31	0.118	3970	0.025	269.5	0.3	0.094	0.439	0.0430	0.432	49.3	0.240	0.486	0.27	1
5	0.422	260.27	0.379	4585	0.203	277.1	0.4	0.757	0.766	0.0041	0.172	44.8	0.517	0.592	0.10	1
6	0.995	412.47	0.158	4099	0.160	276.0	0.4	0.935	0.864	0.0020	0.520	50.7	0.623	0.635	0.10	1
7	0.965	369.00	0.104	3920	0.320	279.5	0.5	0.398	0.619	0.0118	0.336	47.8	0.511	0.590	0.15	1
8	0.654	292.43	0.844	5500	0.626	284.8	0.6	0.102	0.447	0.0406	0.782	55.5	0.296	0.509	0.71	0
9	0.899	340.12	0.979		0.223	277.5	0.4	0.136	0.475	0.0330	.266	46.6	0.112	0.424	0.43	0
4999	0.892	338.07	0.897	5500	0.238	277.9	0.4	0.610	0.705	0.	0.116	43.4	0.279	0.502	0.10	1
5000	0.911	344.10	0.347	4524	0.702	286.2	0.7	0.865	0.819	0.00	0.805	56.1	0.669	0.655	0.10	1

SUMMARY

	$D_{RCM,0}$	b_e	T_{real}	k_e	α	$A(t_{SL})$	cover	C_{crit}
Computed Mean	270.47	4740	282.6	0.6	0.65	0.0	50.76	0.60
Input Mean	270.97	4800	282.7		0.65		50.80	0.60
Max	469.64	5500	309.08	2.41	1.00	0.	76.30	1.21
Min	92.56	3500	259.46	0.10	0.09	0.0	32.65	0.24

Total Passing	4526	
Total # of Trials	5000	
Reliability	0.91	
P_f, Probability of failure	0.09	
β, Reliability Index (calculate	1.312	Passes
β, Target Reliability Index	1.3	

Conclusion

- Scientific approach to quantify service life
  - fib Bulletin 34 / Probability-based mathematical modelling
  - Environmental loads and materials resistances
  - Defined durability requirements

Questions?

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AASHTO SHRP2 R19A Website:
http://shrp2.transportation.org/Pages/ServiceLifeDesignforBridges.aspx

FHWA GoSHRP2 Website:
www.fhwa.dot.gov/GoSHRP2/