WJE

SOLUTIONS FOR THE BUILT WORLD

Probabilistic Service Life Modeling Implemented Through WJE CASLE

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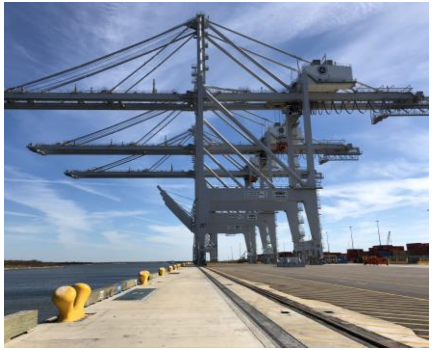
ACI Fall Convention 2023

aci

WJE CASLE

Corrosion Assessment and Service Life Evaluation

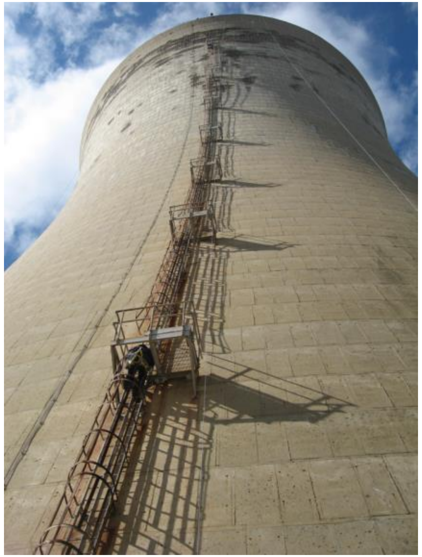
- **In-house service life modeling software**
- **Probabilistic Modeling**
- **Existing and New Structures**


WJE CASLE

Corrosion Assessment and Service Life Evaluation

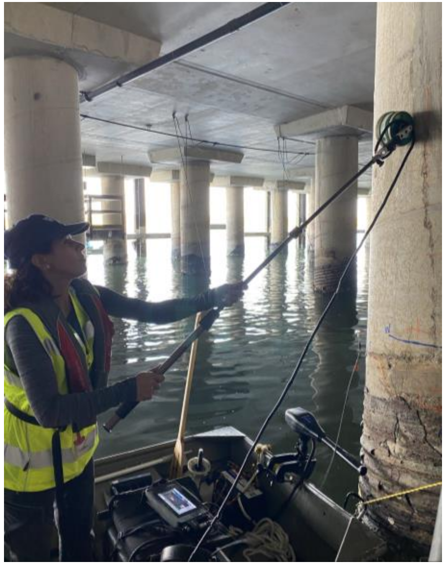
- Developed/adapted per project needs



WJE CASLE

Corrosion Assessment and Service Life Evaluation

- *We continuously refine our knowledge through field investigations and evaluation of existing infrastructure*



Corrosion Assessment and Service Life Evaluation

- *A customizable approach to consider the circumstances and exposure conditions unique to the modeled structure*
  - *Cracking*
  - *Sealer and coatings*
  - *Changing exposure with time*
  - *Multilayer systems (overlays):*
    - *Concrete overlays*
    - Thin polymer overlay
    - Premixed polymer concrete overlay

Corrosion Assessment and Service Life Evaluation

- *Foundation of CASLE:*
  - *fib Bulletin No. 34 -Model Code for Service Life Design*
  - *Concrete Society Technical Report No. 61-Enhancing reinforced concrete durability: Guidance on selecting measures for minimizing risk of corrosion of reinforcement in concrete*
  - *ACI 365.1R-00 Service-Life Prediction— State-of-the-Art Report*
  - *Life-365 service life prediction model*
  - *Others*

Corrosion Assessment and Service Life Evaluation

New Structures

- What is modeled: Probability of exceeding service life limit versus time
- Assumed: cover, rebar, exposure

(more conservative)

- Tested: concrete performance

Existing Structures

- What is modeled: Level of corrosion-related deterioration versus time
- Tested:
  - Core samples (chloride profile for concrete performance & exposure)
  - GPR survey (cover)
  - Damage (model verification)

WJE

Methodology

Chloride –Induced corrosion

Modeling Chloride Transport

- Mathematical representation of transport:
  - Finite difference solution

Fickean Diffusion (Apparent Diffusion)

$$\frac{dC}{dt} = D_a \times \frac{d^2C}{dx^2}$$

Modeling Chloride Transport

Time →

Δt

Δx

Depth ↓

← Concrete surface

4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
0	3169	3436	3536	3593	3631	3657	3679	3696	3709	3722	3732	3741	3749	3756	3763	3768	3774	3779	3784	3788	3792	3796	3799	3803
0	2421	2918	3111	3221	3295	3346	3390	3424	3450	3475	3495	3513	3529	3543	3556	3567	3579	3589	3598	3607	3615	3622	3629	3636
0	1767	2429	2701	2860	2967	3042	3107	3156	3195	3231	3261	3287	3311	3332	3351	3368	3385	3400	3413	3426	3438	3450	3460	3470
0	1233	1980	2314	2514	2650	2747	2830	2894	2944	2992	3031	3065	3096	3123	3149	3171	3193	3213	3231	3248	3264	3278	3292	3306
0	821	1580	1955	2187	2348	2463	2563	2640	2701	2759	2806	2848	2885	2919	2950	2977	3004	3028	3051	3072	3091	3109	3127	3143
0	524	1234	1629	1882	2062	2192	2306	2395	2465	2532	2587	2636	2679	2719	2755	2787	2819	2847	2874	2898	2921	2943	2963	2982
0	320	943	1337	1603	1796	1937	2063	2161	2239	2314	2376	2430	2480	2524	2565	2601	2638	2670	2700	2728	2755	2779	2803	2825
0	188	704	1082	1350	1550	1699	1833	1938	2024	2105	2173	2232	2287	2336	2381	2421	2462	2498	2531	2562	2592	2619	2645	2670
0	106	514	863	1124	1326	1480	1619	1729	1820	1906	1978	2043	2101	2154	2204	2247	2291	2330	2367	2401	2433	2463	2492	2519
0	58	367	677	926	1124	1278	1420	1534	1628	1718	1794	1862	1924	1980	2033	2079	2126	2168	2207	2244	2278	2311	2342	2371
0	30	256	524	754	944	1096	1237	1353	1448	1541	1620	1690	1754	1814	1869	1917	1967	2011	2053	2092	2129	2164	2196	2228
0	15	175	399	606	786	932	1071	1186	1282	1376	1456	1528	1594	1656	1712	1763	1815	1861	1905	1946	1984	2021	2056	2088
0	8	117	299	482	648	786	921	1033	1128	1222	1303	1376	1443	1506	1564	1616	1670	1717	1763	1805	1845	1883	1919	1954
0	4	76	221	379	529	658	786	895	988	1080	1160	1233	1301	1365	1424	1476	1531	1580	1627	1670	1712	1751	1788	1824
0	2	49	160	294	428	546	666	770	860	950	1029	1101	1169	1232	1292	1345	1400	1450	1497	1542	1584	1624	1663	1699
0	1	30	115	226	343	450	561	659	745	832	908	979	1046	1109	1168	1221	1276	1327	1374	1419	1462	1503	1542	1580
0	0	19	81	171	272	367	469	560	641	724	798	867	932	994	1052	1105	1160	1210	1258	1303	1346	1388	1427	1465
0	0	11	56	128	213	298	389	473	549	628	698	764	827	887	945	996	1051	1101	1148	1193	1237	1278	1318	1356
0	0	7	38	95	166	239	321	397	467	541	608	671	731	789	845	896	949	998	1045	1090	1133	1174	1214	1252
0	0	4	26	70	128	190	262	331	395	464	526	586	644	700	753	803	855	903	949	993	1035	1076	1116	1154
0	0	2	17	50	98	150	213	275	333	396	454	510	565	618	669	717	767	814	859	902	944	984	1023	1061
0	0	1	11	36	74	118	172	226	278	336	389	442	493	543	592	638	687	731	775	817	858	898	936	973
0	0	1	7	25	55	91	138	185	232	283	333	381	429	476	523	566	612	655	698	738	778	817	854	890
0	0	0	5	18	41	70	109	150	191	238	283	327	371	416	459	500	544	586	626	665	704	741	778	813
0	0	0	3	12	30	54	86	121	157	199	239	280	320	361	402	440	482	522	560	598	635	671	706	741
0	0	0	2	8	22	41	68	97	129	165	201	238	275	313	351	387	426	463	500	536	571	606	640	673
0	0	0	1	6	16	31	52	78	104	136	168	201	235	270	305	338	375	410	444	479	512	546	578	610
0	0	0	1	4	11	23	40	61	84	112	140	170	200	232	264	295	329	362	394	427	459	490	521	552
0	0	0	0	2	8	17	31	48	68	92	116	142	170	198	228	256	288	318	349	379	409	439	469	498
0	0	0	0	2	5	12	24	38	54	75	96	119	143	169	196	222	251	279	307	336	364	393	421	449
0	0	0	0	1	4	9	18	29	43	60	79	99	121	144	168	191	218	244	270	297	323	350	376	403
0	0	0	0	1	3	6	13	23	34	48	64	82	101	121	143	164	189	212	237	261	286	311	336	361
0	0	0	0	0	2	5	10	17	26	39	52	67	84	102	121	141	163	185	207	230	253	276	299	323
0	0	0	0	0	1	3	7	13	21	31	42	55	70	86	103	120	140	160	180	201	222	244	266	288
0	0	0	0	0	1	2	5	10	16	24	34	45	58	72	87	102	120	138	156	176	195	215	236	256
0	0	0	0	0	1	2	4	7	12	19	27	37	47	60	73	86	102	119	135	153	171	189	208	227
0	0	0	0	0	0	1	3	6	9	15	22	30	39	49	61	73	87	102	117	133	149	166	183	201
0	0	0	0	0	0	1	2	4	7	12	17	24	32	41	51	61	74	87	101	115	130	145	161	178
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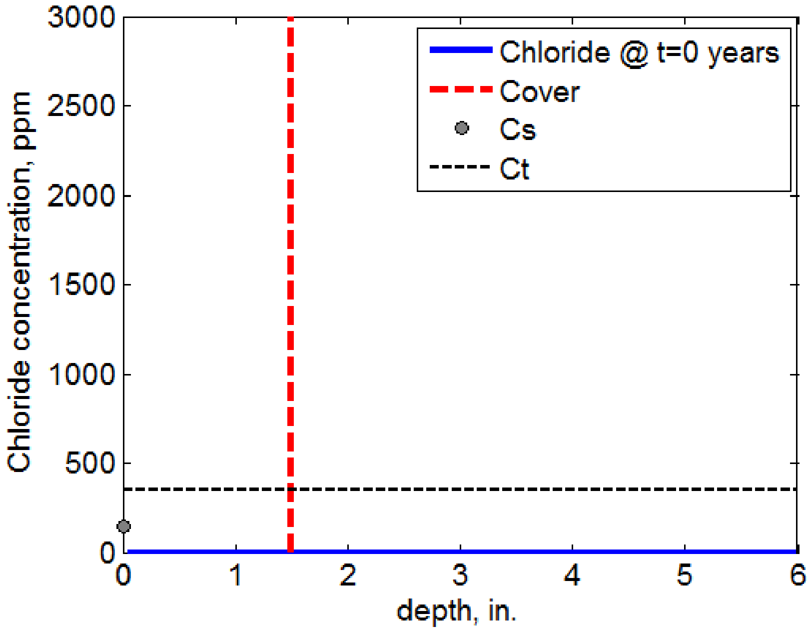
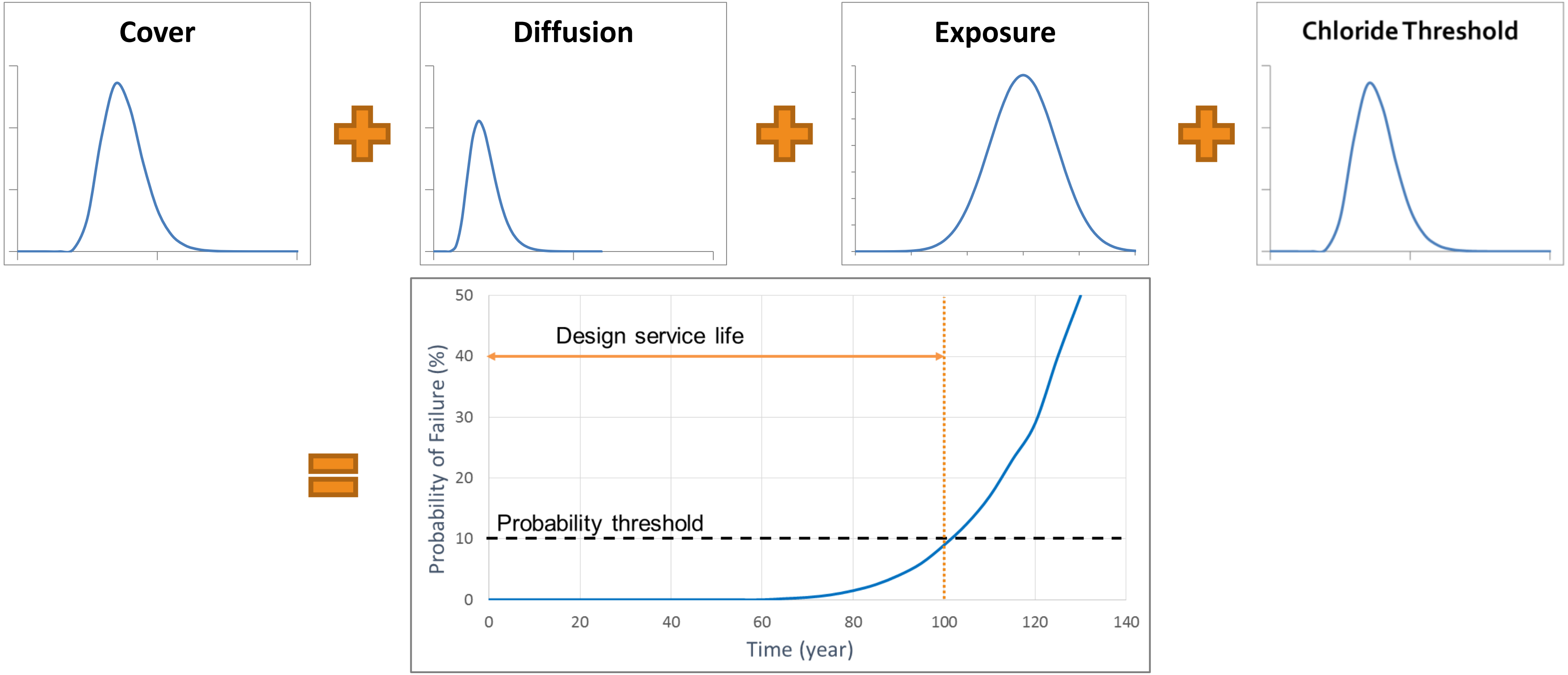
0	0	0	0	0	0	0	0	0	0	1	1	2	3	5	7	9	12	15	19	23	28	33	39	45

Corrosion Initiation

Initiation when concentration exceeds threshold

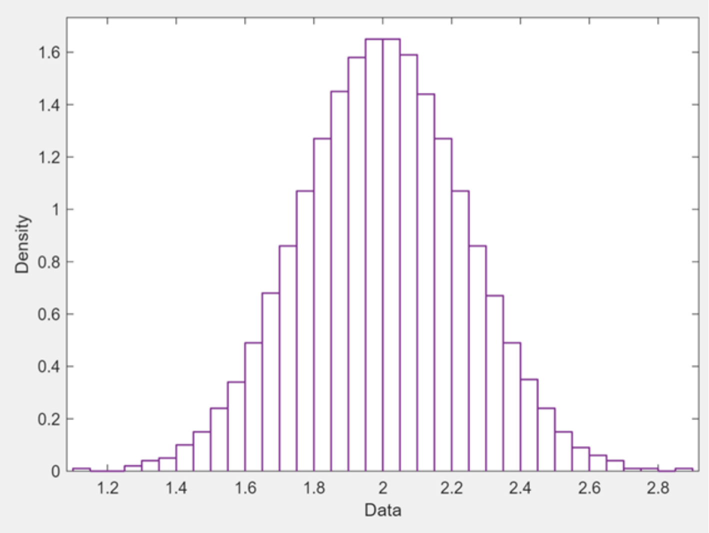


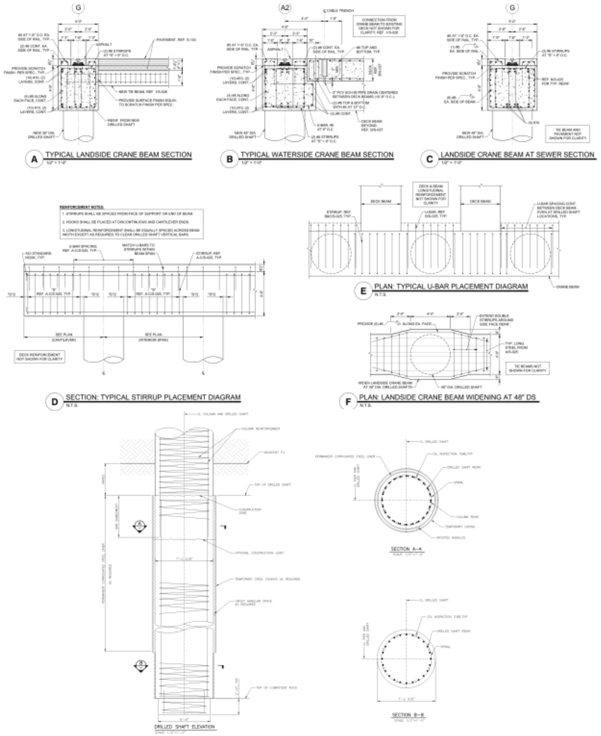
Modeling Concepts - Probabilistic



Modeling Concepts - Probabilistic

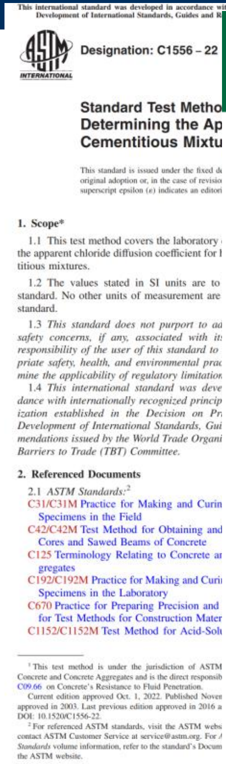
- *Inputs:*
  - *Cover*





Modeling Concepts - Probabilistic

- *Inputs:*
  - *Diffusion coefficient*
    - *Lab testing*
    - *Literature*


This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and R

Designation: C1556 – 22

Standard Test Metho
Determining the Ap
Cementitious Mixtu

This standard is issued under the fixed d
original adoption or, in the case of revisio
superscript epsilon (ε) indicates an editori

1. Scope*

1.1 This test method covers the laboratory
the apparent chloride diffusion coefficient for h
titious mixtures.

1.2 The values stated in SI units are to
standard. No other units of measurement are
standard.

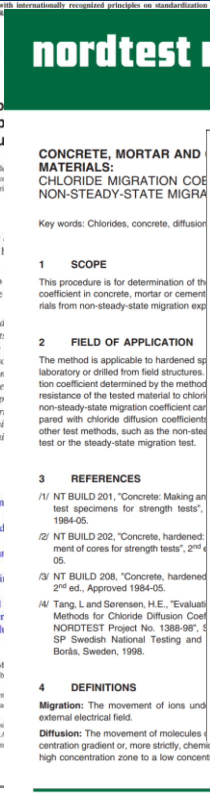
1.3 *This standard does not purport to ad
safety concerns, if any, associated with it
responsibility of the user of this standard to
priate safety, health, and environmental prac
mine the applicability of regulatory limitation*

1.4 *This international standard was deve
dance with internationally recognized princip
ization established in the Decision on Pr
Development of International Standards, Gui
mendations issued by the World Trade Organi
Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]
C31/C31M Practice for Making and Curin
Specimens in the Field
C42/C42M Test Method for Obtaining and
Cores and Sawed Beams of Concrete
C125 Terminology Relating to Concrete ar
gregates
C192/C192M Practice for Making and Curi
Specimens in the Laboratory
C670 Practice for Preparing Precision and
for Test Methods for Construction Mater
C1152/C1152M Test Method for Acid-Solu

[1] This test method is under the jurisdiction of ASTM
Concrete and Concrete Aggregates and is the direct responsib
C09.66 on Concrete's Resistance to Fluid Penetration.
Current edition approved Oct. 1, 2022. Published Noven
approved in 2003. Last previous edition approved in 2016 a
DOI: 10.1520/C1556-22.
[2] For referenced ASTM standards, visit the ASTM webs
contact ASTM Customer Service at service@astm.org. For A
Standards volume information, refer to the standard's Docum
the ASTM website.


nordtest method

NT BUILD 492
Approved 1999–11

1(8)

CONCRETE, MORTAR AND
MATERIALS:
CHLORIDE MIGRATION COE
NON-STEADY-STATE MIGRA

Key words: Chlorides, concrete, diffusion

1 SCOPE

This procedure is for determination of th
coefficient in concrete, mortar or cement
rials from non-steady-state migration exp

2 FIELD OF APPLICATION

The method is applicable to hardened sp
laboratory or drilled from field structures.
tion coefficient determined by the method
resistance of the tested material to chlori
non-steady-state migration coefficient ca
pared with chloride diffusion coefficients
other test methods, such as the non-stea
test or the steady-state migration test.

3 REFERENCES

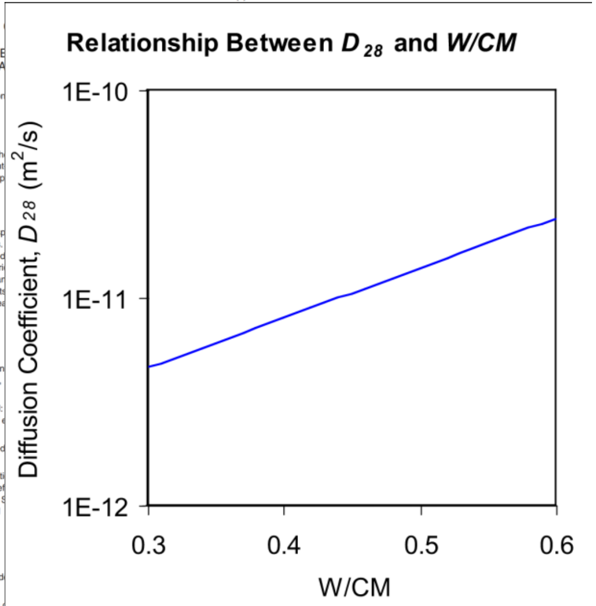
/1/ NT BUILD 201, "Concrete: Making an
test specimens for strength tests",
1984-05.
/2/ NT BUILD 202, "Concrete, hardened:
ment of cores for strength tests", 2nd e
05.
/3/ NT BUILD 208, "Concrete, hardened
2nd ed., Approved 1984-05.
/4/ Tang, L and Sørensen, H.E., "Evaluati
Methods for Chloride Diffusion Coef
NORDTEST Project No. 1388-98", S
SP Swedish National Testing and
Borås, Sweden, 1998.

4 DEFINITIONS

Migration: The movement of ions und
external electrical field.

Diffusion: The movement of molecules
centration gradient or, more strictly, chemical potential, from a
high concentration zone to a low concentration zone.

- Vacuum pump: capable of maintaining a pressure of less
than 50 mbar (5 kPa) in the container.



Modeling Concepts - Probabilistic

- *Inputs:*
  - *Exposure*
    - *Historical data*
    - *Testing samples from adjacent structures*

Modeling Concepts - Probabilistic

- *Inputs:*
  - *Chloride Threshold:*
    - *Type of Reinforcement*
    - *Cement and SCM content*
    - Chloride threshold distributions are derived based on literature and WJE's previous projects

Modeling Cases

Inputs

Modeling Cases - Inputs

- *Three cases*
- *Three mix design*
- *Two types of reinforcing steel*

ACI Convention Fall 2023 – Boston, MA
Comparison of Corrosion Service Life Models
Modeling Parameters

Table 3. Laboratory Testing Results

	CTRL	SF-8	HP-20
ASTM C642 – Volume of Permeable Voids (%)			
28-Day	8.8	11.8	12.8
90-Day	11.4	11.8	12.2
ASTM C1556 – Apparent Diffusion Coefficient ($\times10^{-12}$ m^2/s)	4.6	1.2	2.1
ASTM C1585 – Capillary Absorption ($mm/s^{1/2}$)			
Initial Absorption	0.0004	0.0003	0.0008
Secondary Absorption	0.0003	0.0002	0.0002
ASTM C1760 – Bulk Electrical Conductivity (mS/m)			
28-Day	11.0	3.3	6.5
56-Day	9.1	2.5	3.9
90-Day	8.3	2.3	2.4
NT Build 492 – Non-Steady-State Migration Coefficient ($\times10^{-12}$ m^2/s)	14.0	3.6	9.6
STADIUM® IDC OH^- Diffusion Coefficient ($\times10^{-11}$ m^2/s)			
28-Day	17.47	3.11	4.99
90-Day	12.85	2.41	1.91
STADIUM® MTC Permeability ($\times10^{-22}$ m^2)			
28-Day	23.26	3.35	15.59
90-Day	11.50	2.71	5.76

**Unless otherwise specified, the tests were performed on 28-day wet-cured samples.*

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		
Black Bar Initiation Threshold	735 ppm		
Enhanced Initiation Threshold	2500 ppm		
Hydration Time	8 years		

ACI Convention Fall 2023 – Boston, MA
Comparison of Corrosion Service Life Models
Modeling Parameters

Table 1. Mix Design Proportions

	CTRL	SF-8	Hyaloclastite Pozzolan-20
Cement, Type I/II (lb/yd^3)	658	605	526
Silica Fume (lb/yd^3)	0	53	0
Hyaloclastite Pozzolan (lb/yd^3)	0	0	132
Fine Aggregate (lb/yd^3)	1279	1263	1273
3/4" Crushed Coarse Aggregate (lb/yd^3)	1815	1815	1680
Total Water (lb/yd^3)	250	250	250
w/cm	0.38	0.38	0.38
Design Air (%)	6	6	6

Table 5. Annual Temperature Profile of Boston (°F)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Ave.
29	31	38	48	58	68	73	72	65	55	45	34	51

Table 6. Variation of Input Parameters

	CoV (%)
Cover	8
Maximum Surface Concentration	30
[illegible]	25
[illegible]	25
[illegible]	30
Enhanced Threshold	20

Modeling Cases - Inputs

- *Diffusion Coefficient:*

aci CONCRETE CONVENTION

ACI Convention Fall 2023 – Boston, MA
Comparison of Corrosion Service Life Models
Modeling Parameters

Table 3. Laboratory Testing Results

	CTRL	SF-8	HP-20
ASTM C642 – Volume of Permeable Voids (%)			
28-Day	8.8	11.8	12.8
ASTM C1556 – Apparent Diffusion Coefficient ($\times 10^{-12}$ m^2/s)	4.6	1.2	2.1
Initial Absorption	0.0004	0.0003	0.0008
Secondary Absorption	0.0003	0.0002	0.0002
ASTM C1760 – Bulk Electrical Conductivity (mS/m)			
28-Day	11.0	3.3	6.5
56-Day	9.1	2.5	3.9
NT Build 492 – Non-Steady-State Migration Coefficient ($\times 10^{-12}$ m^2/s)	14.0	3.6	9.6
28-Day	17.47	3.11	4.99
90-Day	12.85	2.41	1.91
STADIUM® MTC Permeability ($\times 10^{-22}$ m^2)			
28-Day	23.26	3.35	15.59
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Table 4. Modeling Cases and Parameters

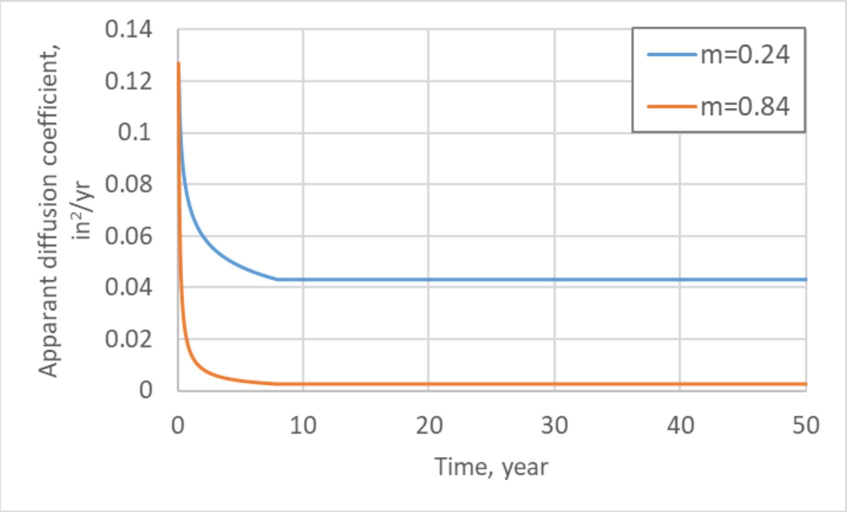
	Case 1	Case 2	Case 3
Location	Boston, MA		
Element	Bridge Deck	Marine Pile	Marine Wall
Thickness/Diameter	8 in	36 in	8 in
Exposure	Deicing Salt	Submerged	Splash
Target Initiation Time with 90% Confidence	100 years		
Cover	2.5 in	3.0 in	3.0 in
Maximum Surface Concentration	5500 ppm	8000 ppm	10000 ppm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

Modeling Cases - Inputs

- *Aging factor*
  - *Provided info - Bulk Electrical conductivity*
  - *8 years hydration time*

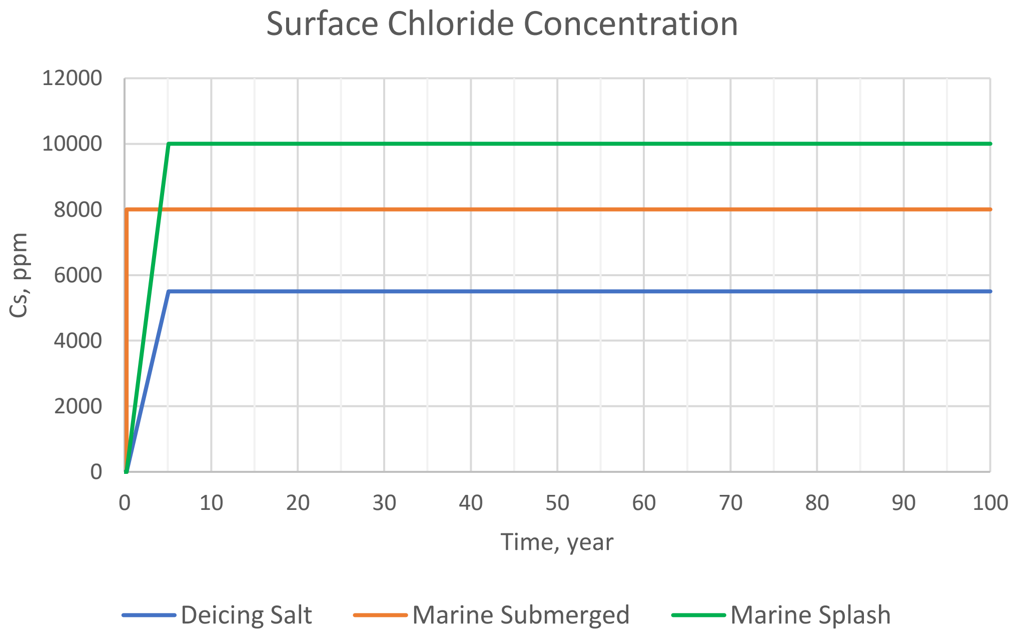
$$D(t,m) = D_{28}\left(\frac{28\ days}{t}\right)^{m}$$

	CTRL	SF-8	HP-20
ASTM C1760 – Bulk Electrical Conductivity (mS/m)			
28-Day	11.0	3.3	6.5
56-Day	9.1	2.5	3.9
90-Day	8.3	2.3	2.4
Calculated aging factor	*0.24*	*0.32*	*0.84*



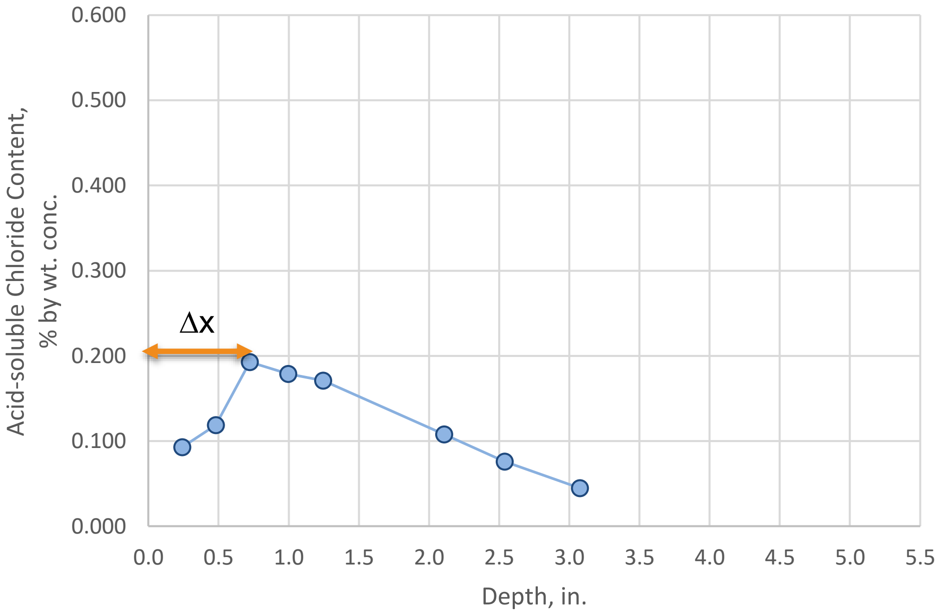
Modeling Cases - Inputs

- *Exposure:*
  - *Buildup time*



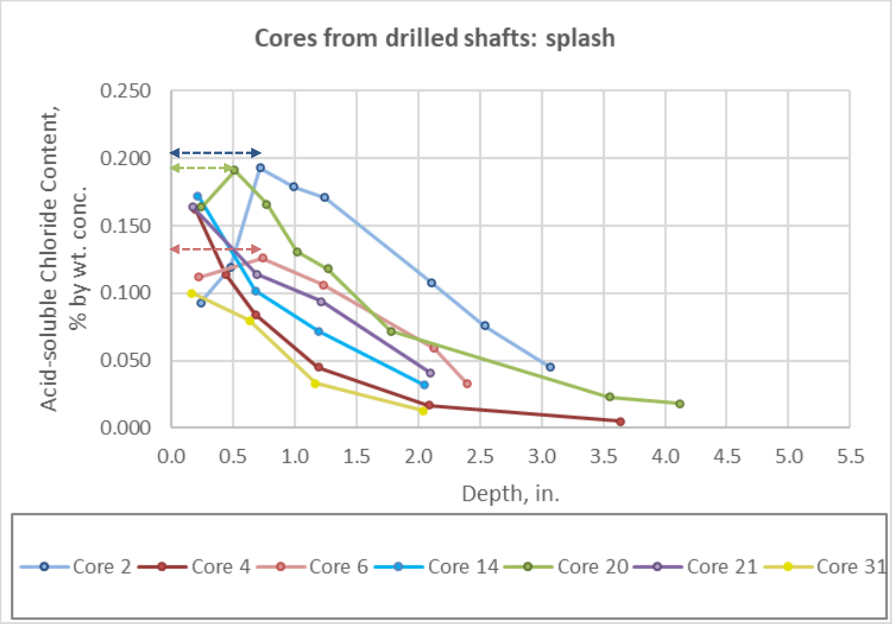
Modeling Cases - Inputs

- *Transfer Depth:*
  - *Marine Wall*
    - *Splash*



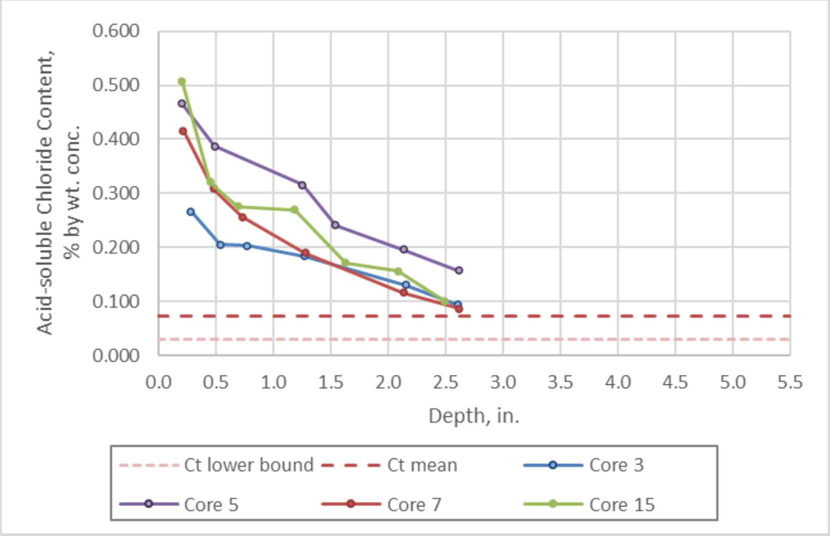
Modeling Cases - Inputs

- *Transfer Depth:*
  - *Marine Wall – Splash:*
    - *Based on Fib 34*
    - *Beta distribution*
      - *m=0.35 in.*
      - *s=0.22 in.*
      - *a= 0.0 in.*
      - *b=2.0 in.*



Modeling Cases - Inputs

- *Transfer Depth: 0 in.*
  - *Bridge Deck – Deicing Salt*
  - *Marine Wall – Submerged*



Modeling Cases

Results

Results

- Black bars

	Initiation time, yr. (10% probability)		
Element/Mix ID	CTRL	SF-8	HP-20
Bridge Deck - Deicers	16	73	>110
Pile-Submerged	15	83	>110
Wall-Splash	13	56	>110

- Enhanced bars

	Initiation time, yr. (10% probability)		
Element/Mix ID	CTRL	SF-8	HP-20
Bridge Deck - Deicers	48	>110	>110
Pile-Submerged	41	>110	>110
Wall-Splash	28	>110	>110

Discussion – Aging Factor

- *Provided data- Electrical conductivity*
  - *8 years hydration time*
- *Preferred basis- NT Build 492 or ASTM C1556 at later ages*
- *Literature (Life 365)*
  - *25 years hydration time*

$$m = 0.2 + 0.4(\%FA/50 + \%SG/70).$$

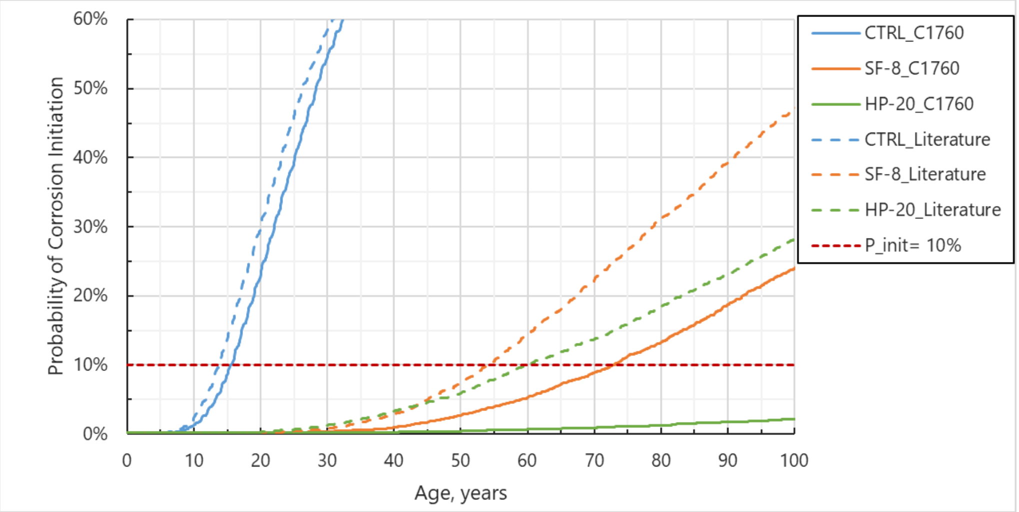
	CTRL	SF-8	HP-20
ASTM C1760 – Bulk Electrical Conductivity (mS/m)			
28-Day	11.0	3.3	6.5
56-Day	9.1	2.5	3.9
90-Day	8.3	2.3	2.4
Calculated aging factor	0.24	0.32	0.84
Literature (Life 365) estimates	0.20	0.20	0.36?

Discussion – Aging Factor

- Bridge Deck – Deicing Salt
- Black bar

Aging factor source	CTRL	SF-8	HP-20	
Given data	0.24	0.32	0.84	8-year hydration
Literature (Life 365)	0.20	0.20	0.36	25-year hydration

	Initiation time, yr. (10% probability)		
Aging Factor/Mix ID	CTRL	SF-8	HP-20
Given (ASTM C1760)	16	73	>110
Literature (Life 365)	14	54	60
%Reduction	*12%*	*26%*	*>50%*

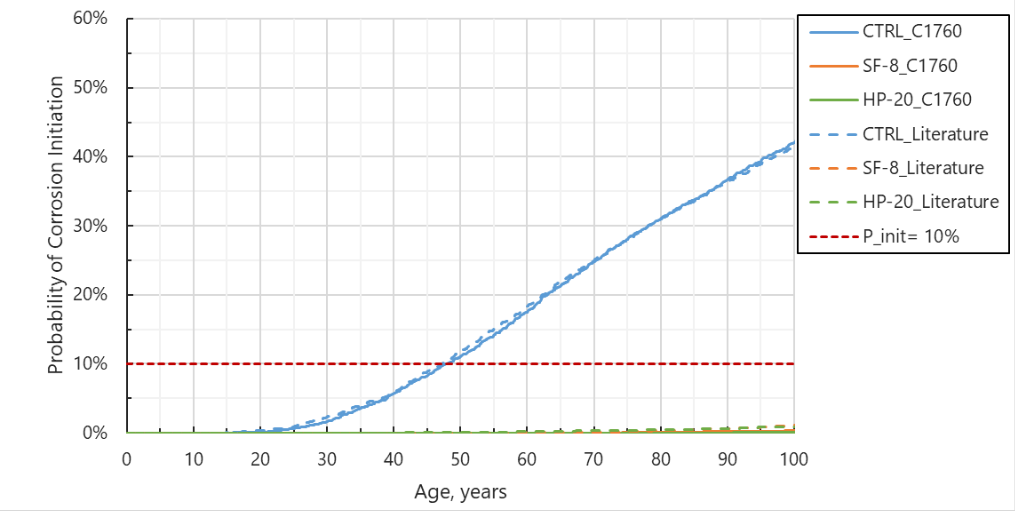


Discussion – Aging Factor

- Bridge Deck - Deicing salt
- Enhanced bar

Aging factor source	CTRL	SF-8	HP-20	
ASTM C1760	0.24	0.32	0.84	8-year hydration
Life 365	0.20	0.20	0.36	25-year hydration

	Initiation time, yr. (10% probability)		
Aging Factor/Mix ID	CTRL	SF-8	HP-20
Given (ASTM C1760)	48	>110	>110
Literature (Life 365)	47	>110	>110
%Reduction	*2%*	-	-



Results

- Black bars

	Initiation time, yr. (90% probability)		
Element/Mix ID	CTRL	SF-8	HP-20
Bridge Deck - Deicers	16	73	>110
Pile-Submerged	15	83	>110
Wall-Splash	13	56	>110

- Enhanced bars

	Initiation time, yr. (90% probability)		
Element/Mix ID	CTRL	SF-8	HP-20
Bridge Deck - Deicers	48	>110	>110
Pile-Submerged	41	>110	>110
Wall-Splash	28	>110	>110

Discussion – Threshold (black bars)

- Provided values:
  - Average =735 ppm
  - COV=30%
- CASLE threshold

Reinforcement Type	Distribution	Parameters (% by wt. cement)
Uncoated	Beta	lower bound: 0.20 upper bound: 2.00 mean: 0.48 std. deviation: 0.15

Source: Adapted from (Broomfield 2007), based on data from (Breit 1997)

$$Cement_{eqv} := CM \cdot [1 - max[0.010(\%FA - 10), 0] - max[0.005 \cdot (\%SG - 20), 0] - 0.025 \cdot \%SF]$$

Where:

CM = weight of total cementitious
%FA = proportion of fly ash (applicable for up to 50%)
%SG = proportion of slag cement (applicable for up to 80%)
%SF = proportion of silica fume (applicable for up to 20%)

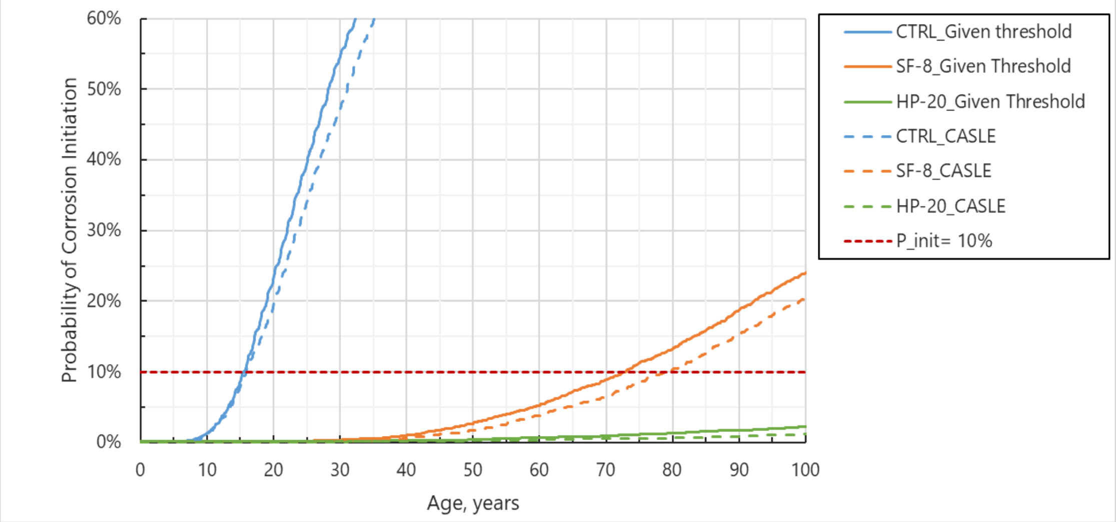
Source: Concrete Society Technical Report No. 61

Discussion – Threshold

- Marine Pile - submerged
- Black bar

	Chloride Threshold (ppm)				
	Distribution	average	stand. dev.	lower bound	upper bound
Given - All mixes	Normal	735	221	-	-
CASLE - CTRL	Beta	807	252	336	3361
CASLE - SF-8	Beta	644	201	268	2685
CASLE - HP-20	Beta	726	227	302	3023

	Initiation time, yr. (10% probability)		
Threshold/Mix ID	CTRL	SF-8	HP-20
Given Threshold	15	83	>110
WJE CASLE	16	79	>110
%Change	*+7%*	*-5%*	-



Conclusions

- Black bars

Element/Mix ID	Initiation time, yr. (10% probability) CTRL	SF-8	HP-20
Bridge Deck - Deicers	16	73	>110
Pile-Submerged	15	83	>110
Wall-Splash	13	56	>110

Adjusting aging factor

Literature (Life 365)	14	54	60

Adjusting Threshold

WJE CASLE	16	79	>110

- Enhanced bars

Element/Mix ID	Initiation time, yr. (10% probability) CTRL	SF-8	HP-20
Bridge Deck - Deicers	48	>110	>110
Pile-Submerged	41	>110	>110
Wall-Splash	28	>110	>110

Adjusting aging factor

Literature (Life 365)	47	>110	>110

Representative and accurate characterization of input distributions is vital