SHRP2 SOLUTIONS
STRATEGIC HIGHWAY RESEARCH PROGRAM

Service Life – Testing & Documentation

Oregon DOT Workshop – Portland, OR

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January 17, 2018

U.S. Department of Transportation
Federal Highway Administration

American Association of State Highway and Transportation Officials
AASHTO

Discussion Topics

- Introduction
- Design Issues
  - Environmental Loading
  - Material Properties / Component Dimensions
- Construction Monitoring & Testing Issues
  - Concrete Tests for Durability
  - Concrete Cover Dimension Verification
- In-Service Issues
  - Verification of Actual Performance vs. Planned Performance
- Summary

Introduction

- Owners are specifying Service Life Design, particularly for projects using alternative project delivery
  - Design-Build (DB)
  - Design-Build-Operate-Maintain (DBOM)
  - Public Private Partnership (P3)
- Service Life Design is not just about design for durability
- It’s about management of durability issues throughout the life of the structure
- Designers & Contractors need to be aware of new design, construction, and operations requirements

Through-Life Stages

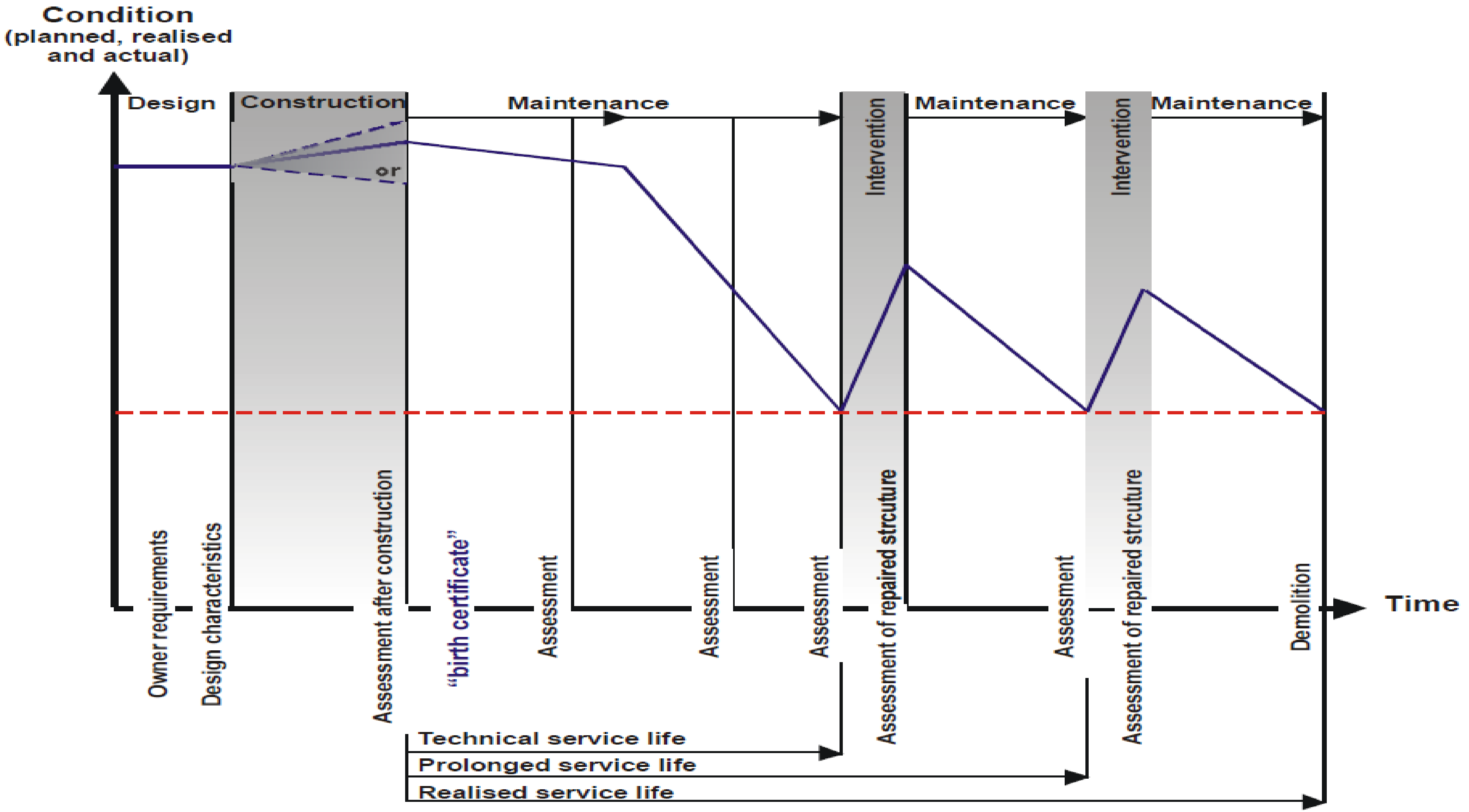


Fig. 2-1: Complete service life from birth to death, adapted from [28]

Example Deterioration Model

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

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

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

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

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

- **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

New Design Issues

- Determining Properties and Finding Data for Deterioration Models
  - Environmental Loading
  - Material Resistances
    - Chloride Diffusion/Migration Coefficients
    - Critical Chloride Content
    - Concrete Cover Depth

New Design Issues

- 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

New Design Issues

- Deterioration other than from chlorides
- Environmental exposure from Carbonation (CO_2)
  - CO_2 (C_s) concentration from the atmosphere (known)
  - Data collected for CO_2 concentration from emission sources in industrial areas

Durability Tests – Design

Objective	Potential Testing Specifications	Information Obtained
Determine design chloride loading from concrete cores taken from existing/nearby structures	Nordtest Method NT Build 443 / Accelerated Chloride Penetration (Bulk Diffusion Test)	C_S or $C_{S,\Delta x}$ and Δx Chloride Surface Concentration, used in chloride deterioration model
	ASTM C1543 / Determining the Penetration of Chloride Ion into Concrete by Ponding (Salt Ponding Test)	
	ASTM C1556 / Determining the Apparent Chloride Diffusion Coefficient of Cementitious Mixtures by Bulk Diffusion	

Durability Tests – Design

Objective	Potential Testing Specifications	Information Obtained
Determine design chloride loading in brackish water	ASTM D512 / Chloride Ion in Water	C_{eqv} , Natural Chloride Content of Sea Water used in chloride deterioration model
Determine presence of chemicals (sulfates) in soil and water	ASTM D516 / Sulfate Ion in Water	Sulfate content (% mass $S0_4$ in sample)
	ASTM C1580 / Water-Soluble Sulfate in Soil	

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

Determining Chloride Loading

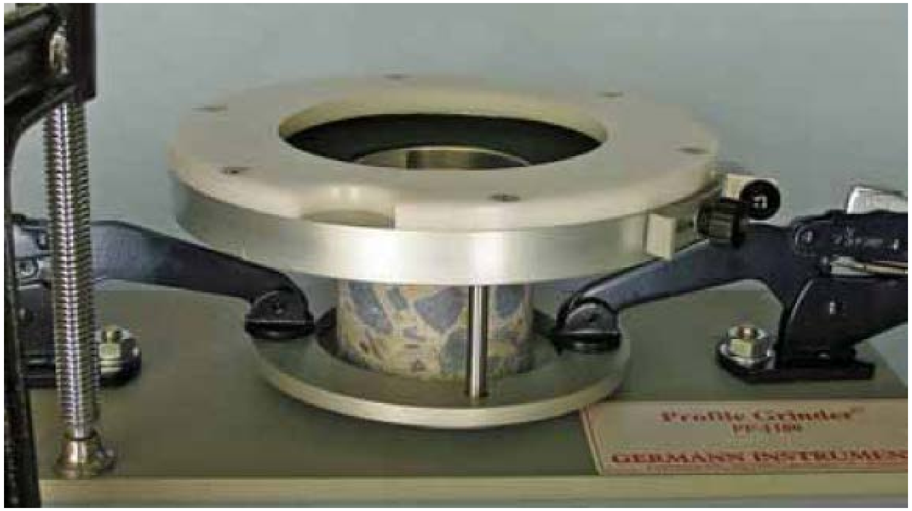
nordtest method

NT BUILD 443
Approved 1995–11

Concrete Hardened: Accelerated Chloride Penetration

- Known as the Bulk DiffusionTest
- 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

Chloride Profile Grinding



Source: Germann Instruments

Determining Chloride Loading

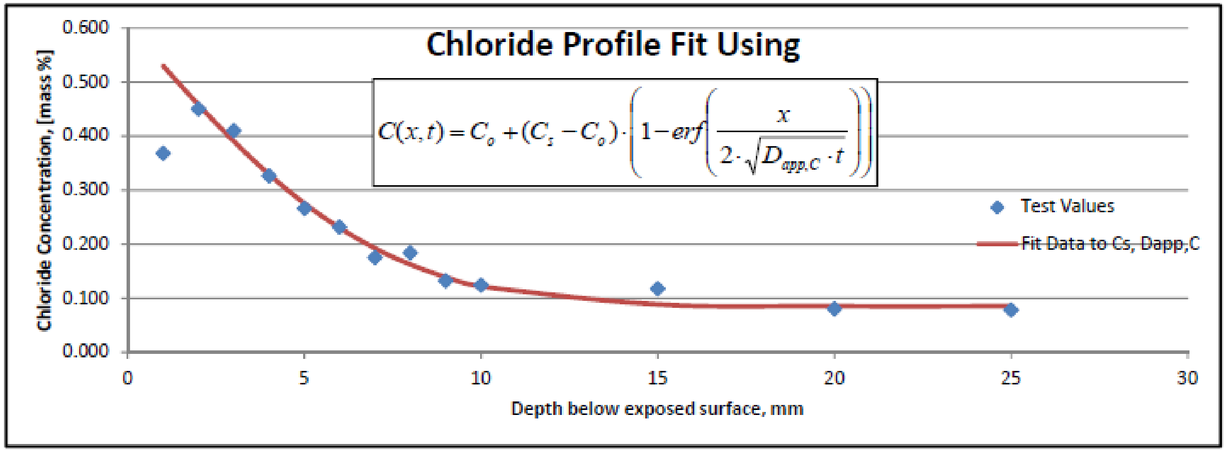
Designation: C 1556 – 04

INTERNATIONAL

Standard Test Method for
Determining the Apparent Chloride Diffusion Coefficient of Cementitious Mixtures by Bulk Diffusion[1]

d	depth from surface	[mm]	1	2	3	4	5	6	7	8	9	10	15	20	25	
C_m	Test Values	[mass %]	0.368	0.450	0.410	0.326	0.266	0.231	0.175	0.183	0.132	0.124	0.117	0.080	0.078	
C_c	Fit Data to C_s, $D_{app,C}$	[mass %]	0.530	0.458	0.391	0.329	0.275	0.230	0.192	0.162	0.139	0.122	0.089	0.085	0.085	$\sum (C_m-C_s)^2$
$(C_m - C_s)^2$	Sum of least squares			6.72E-05	3.76E-04	1.10E-05	9.01E-05	1.55E-06	2.93E-04	4.34E-04	5.00E-05	4.66E-06	8.12E-04	2.66E-05	4.90E-05	2.22E-03

C_o	Initial chloride content (measured)	[mass %]	0.085
t	Exposure time	[yr]	1
C_s	Chloride content at exposed face	[mass %]	0.605
$D_{app,C}$	Apparent coefficient of chloride diffusion	[mm^2/yr]	15.324



New Design/Construction Issues

- **Resistance to Chloride Ingress by Diffusion** is a function of the:
  - Concrete Chloride Migration Coefficient ($D_{RCM,0}$)
  - Cover Depth (a)

- **Resistance to Carbonation is a function** of the:
  - Inverse Carbonation Resistance ($R_{ACC,0}^{-1}$)
  - Cover Depth

New Design/Construction Issues

- Resistance to both Chloride Ingress and Carbonation 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)

Durability Tests – Design

Objective	Potential Testing Specifications	Information Obtained
Determine design chloride durability resistance properties from trial batch mix designs	Nordtest Method NT Build 492 / Chloride Migration Coefficient from Non-Steady-State Migration Experiments (Rapid Chloride Migration, RCM)	$D_{RCM,0}$, Chloride Migration Coefficient used in chloride deterioration model
Determine initial chloride content of concrete from trial batch mix designs	Nordtest NT Build 208 / Chloride Content by Volhard Titration	C_O , Initial Chloride Content used in chloride deterioration model
	ASTM C1152 / Acid Soluble Chloride in Mortar and Concrete	

Chloride Migration Test
NT Build 492

nordtest method

NT BUILD 492

Approved 1999–11

- **Chloride Migration Coefficient** from Non-Steady State Migration Experiments
  - Known as the Rapid Chloride Migration (RCM) Test
  - Determines Concrete Chloride Migration Coefficient, $D_{RCM,0}$ used directly in fib Bulletin 34 deterioration model
  - 28 day cure, test duration usually 24 hours

NT Build 492 – Test Setup

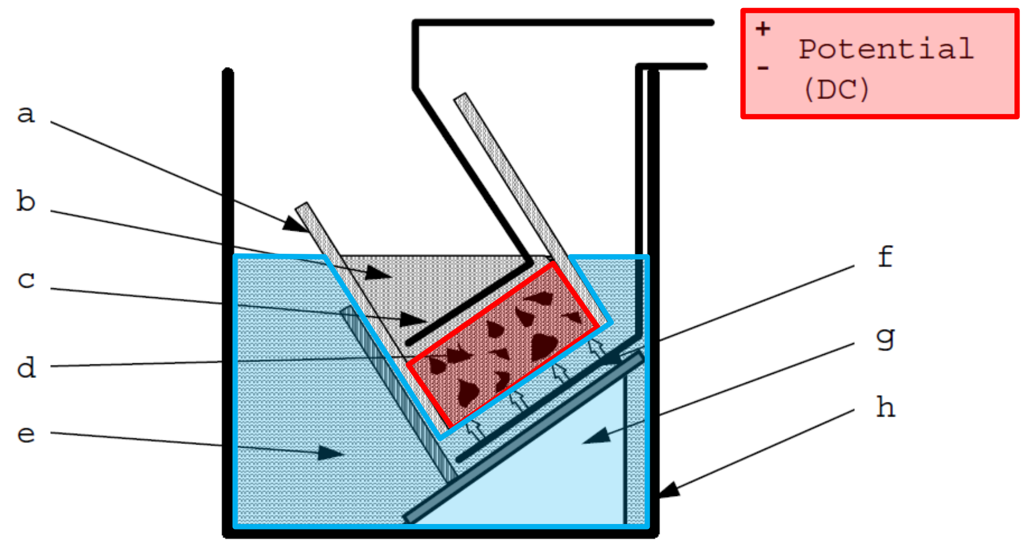
NT Build 492

- Schematic Test Setup
  - 4” diameter x 2” thick specimen sliced from concrete test cylinder
  - 10% Solution of NaCl in water
  - Subjected to electrical current to accelerate chloride ingress

NORDTEST METHOD

NT BUILD 492 5

APPENDIX 1



a. Rubber sleeve
b. Anolyte
c. Anode
d. Specimen
e. Catholyte
f. Cathode
g. Plastic support
h. Plastic box

Fig. 1. One arrangement of the migration set-up.

NT Build 492

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

NORDTEST METHOD

NT BUILD 492 7

APPENDIX 1

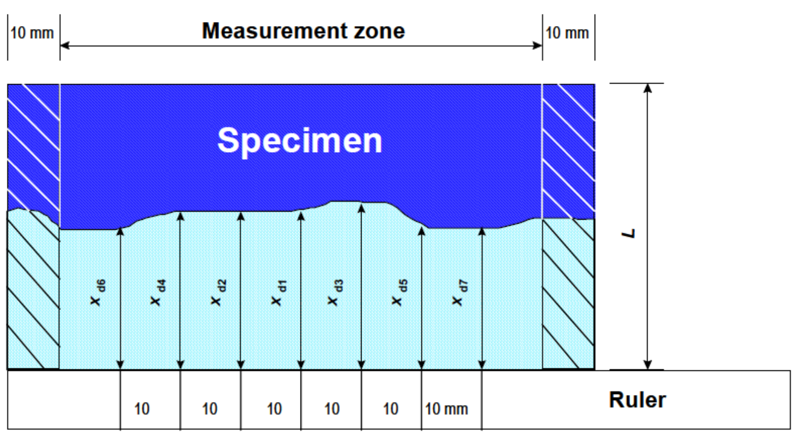


Fig. 5. Illustration of measurement for chloride penetration depths.

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

Other Rapid Chloride Tests

- **The RCM Test (NT Build 492)** is not to be confused with:

  - **ASTM C1202/AASHTO T 277** – Standard Test Method for Electrical Indication of Concrete’s Ability to Resist Chloride Ion Penetration

  - **AASHTO TP-64** – Predicting Chloride Penetration of Hydraulic Cement Concrete by the Rapid Migration Procedure

ASTM C1202

- Known as the Rapid Chloride Permeability Test (RCPT)
- Measures electrical charge (Coulombs) passed through concrete specimen
- Specimens are not split/measured for chloride depth

ASTM C1202 Results

- Qualitative not Quantitative

Table: Chloride Permeability Based on Charge Passed

Charge Passed (Coulombs)	Chloride Permeability	Typical of
>4,000	High	High W/C ratio (>0.60) conventional PCC
2,000–4,000	Moderate	Moderate W/C ratio (0.40–0.50) conventional PCC
1,000–2,000	Low	Low W/C ratio (<0.40) conventional PCC
100–1,000	Very Low	Latex-modified concrete or internally-sealed concrete
<100	Negligible	Polymer-impregnated concrete, Polymer concrete

Source: Grace Technical Bulletin TB-0100

AASHTO TP-64

- Test procedures appear similar to NT Build 492, but there are subtle differences
- Uses different
  - Duration of test (18 hours)
  - Preconditioning
  - Temperature
  - Voltage
- *fib* Bulletin 34 calibrated to NT Build 492 only

Durability Tests – Design

Objective	Potential Testing Specifications	Information Obtained
Determine carbonation durability resistance properties from trial batch mix designs	RILEM CPC-18 / Measurement of Hardened Concrete Carbonation Depth	$R_{ACC,0}^{-1}$, Inverse Effective Carbonation Resistance used in carbonation deterioration model
	Accelerated Carbonation Test (ACC) / DARTS: Durable and Reliable Tunnel Structures: Data European Commission, Growths 2000, Contract G1RD-CT-2000-00476, Project GrD1-25633, 2004	
	Nordtest Method NT Build 357 / Concrete, Repairing Materials and Protective Coating: Carbonation Resistance	

Carbonation Tests

- Accelerated Carbonation Test (ACC) – DARTS – Durable And Reliable Tunnel Structures: Deterioration Modelling, 2004
  - Documented in *fib* Bulletin 34, pages 50-53
  - Specimens cured 28 days in water
  - Placed in carbonation chamber for 28 days and exposed to CO2 concentration of Cs = 2.0 vol.-%
  - Tests performed at 56 days
  - Specimens split, exposed surfaces treated with phenolphthalein and measured for penetration depth
  - Inverse Carbonation Resistance ($R_{ACC,0}^{-1}$) is calculated

Carbonation Test Chamber

Carbonation Tests

- Sample showing carbonated concrete in purple

Critical Chloride Content

Reinforcing Type	Trade Name	Specification	Alloy Type	UNS Designation	Compositional Requirements (min %)				C_{cr} - mass % by weight cement	C_{cr} - Ratio to Carbon Steel
					Cr	Mo	N	PREN*		
Carbon steel		ASTM A615/ ASTM A706/ AASHTO M31							0.6	1
Epoxy-coated carbon steel									0.9	1.5
Galvanized carbon steel									1.0	1.67
	MMFX ChrōmX 2100 and 2120		CL	K23050	2		0.05	2.8		
	MMFX ChrōmX 4100 and 4120		CM	K42050	4		0.05	4.8	1.2	2
	MMFX ChrōmX 9100 and 9120 (formerly MMFX$_2$)	ASTM A1035	CS	K81550	9.2		0.2	12.4	2.4	4
Low-carbon chromium steel		ASTM A1035/ AASHTO M334	CS		9.2		0.05	10	2.4	4

Critical Chloride Content

Reinforcing Type	Trade Name	Specification	Alloy Type	UNS Designation	Compositional Requirements (min %)				C_{cr} - mass % by weight cement	C_{cr} - Ratio to Carbon Steel
					Cr	Mo	N	PREN*		
Stainless steel-clad carbon steel		AASHTO M329		Cladding S31600 or S31603	16	2		22.6		
Austenitic Stainless Steel		ASTM A955/ AASHTO M334	XM-28	S24100	16.5		0.2	19.7	2.4	4
			XM-29	S24000	17		0.2	20.2		
			304	S30400	18			18		
			304L	S30453	18		0.1	19.6		
			316L	S31603	16	2		22.6	3.6	6
			316L	S31653	16	2	0.1	24.2		
Duplex (Austenitic-Ferritic) Stainless Steel	2101LDX	ASTM A955/ AASHTO M334		S32101	21	0.1	0.2	27.33		
			2204	S32304	21.5	0.05	0.05	23.165		
			2205	S31803	21	2.5	0.08	31.65	6	10

Durability Tests – Design or Construction

Objective	Potential Testing Specifications	Information Obtained
Determine freeze-thaw and salt scaling susceptibility	CEN/TS 12390-9 / Testing hardened concrete – Part 9: Freeze-thaw resistance – Scaling	Scaling % by weight or mass per volume
	RILEM TC 176-IDC / Recommendation: CIF Test, Test method of frost resistance of concrete	
	ASTM C457 / Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete	Air/void spacing and percentage
	ASTM C231 (or C173)/ Air Content of Freshly Mixed Concrete by the Pressure (or Volumetric) Method	Air content of concrete sample and/or air content of mortar portion

Durability Tests – Design or Construction

Objective	Potential Testing Specifications	Information Obtained
Determine potential for reactivity of aggregates in concrete	RILEM TC 191-ARP / Alkali-reactivity and prevention – Assessment, specification and diagnosis of alkali-reactivity.	Expansion % of aggregates for classification of reactivity / Class 1 very unlikely / Class 2 uncertain / Class 3 very likely
	AASHTO R80 / Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction	Determine risk of ASR from reactivity of aggregates and exposure, and determination of supplemental cementitious materials (SCMs) to provide various levels of prevention
	ASTM C1260 / Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)	Average length change in concrete specimens

Durability Tests – Construction

Objective	Potential Testing Specifications	Information Obtained
Verify chloride durability resistance properties during production	Nordtest Method NT Build 492 (Rapid Chloride Migration, RCM)	As constructed $D_{RCM,0}$, Chloride Migration Coefficient used in chloride deterioration model
Determine initial chloride content of concrete during production	Nordtest NT Build 208 ASTM C1152	As constructed C_O, Initial Chloride Content used in chloride deterioration model
Verify concrete carbonation durability resistance properties during production	RILEM CPC-18 Accelerated Carbonation Test (ACC) / DARTS Nordtest Method NT Build 357	As constructed $R_{ACC,0}^{-1}$, Inverse Effective Carbonation Resistance used in the carbonation deterioration model

Concrete Cover Depth

- Lack of U.S. standards for measuring cover depth in hardened concrete

- Service Life goal is for complete mapping
  - Measurements Taken on Each Surface
  - Minimum Sample Size – 20 per Surface
  - Used to Calculate Mean & Standard Deviations
  - Perform Statistical Evaluation for Acceptance Purposes

Durability Tests – Construction

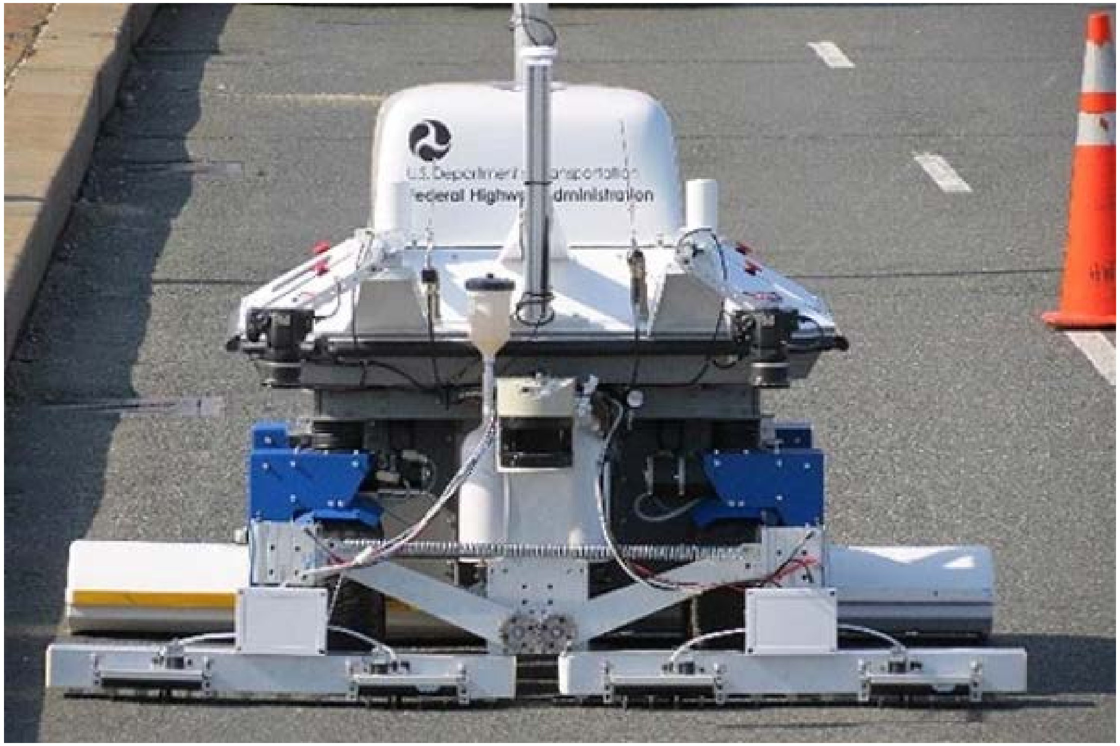
Objective	Potential Testing Specifications	Information Obtained
Verify clear concrete cover in completed structure	BS1881:204 Testing concrete. Recommendations on the use of electromagnetic covermeters	Calibration of covermeters
	ACI 228.2R-2.51 / ACI Concrete Practices Non Destructive testing: Covermeters	
	The German Concrete and Construction Association (DBV), Technical Report, Concrete Cover and Reinforcement per Eurocode 2. (in German)	Statistical evaluation of measured cover dimensions, a, in hardened concrete

Covermeters

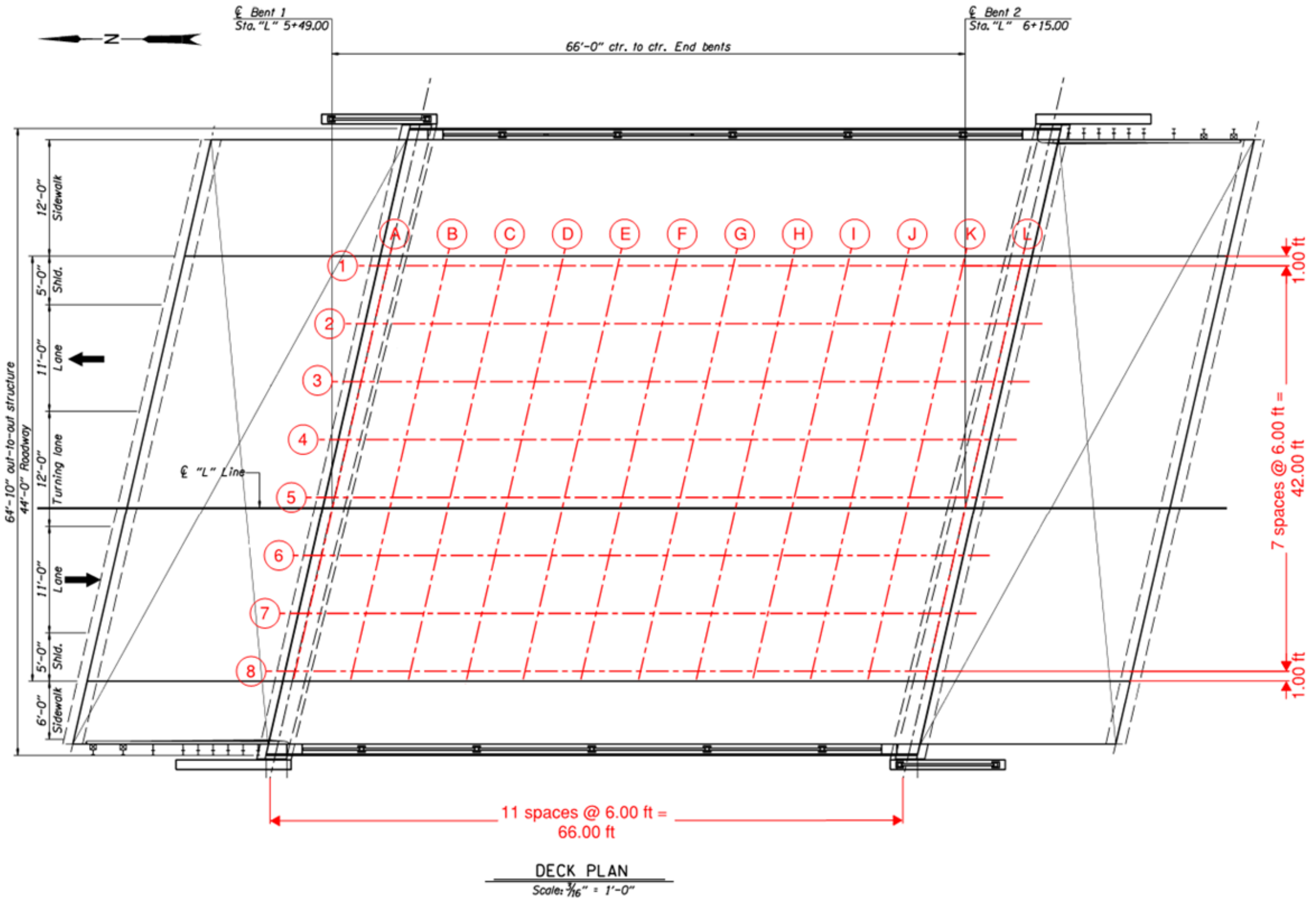
- Sources: Proceq Elcometer

Concrete Cover Depth

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



Cover – Grid Sampling Method



Cover Measurements

As-Constructed Cover Dimensions at Grid Points [in]												
	A	B	C	D	E	F	G	H	I	J	K	L
1	2.52	2.20	2.60	2.99	2.05	2.87	2.72	2.80	3.11	2.99	3.11	2.83
2	2.40	2.20	2.48	2.72	2.72	2.76	2.91	2.99	2.17	2.83	2.99	2.09
3	2.24	2.24	***1.46***	***1.57***	2.52	2.20	2.36	2.20	2.20	***1.89***	***1.85***	2.24
4	1.93	2.01	***1.65***	2.01	2.24	2.28	2.24	2.13	2.32	2.48	2.52	2.80
5	2.28	2.40	2.09	1.93	2.01	***1.89***	2.17	1.97	***1.81***	1.93	2.56	2.32
6	2.99	3.11	2.48	2.09	3.15	2.91	2.83	2.56	2.83	2.72	2.83	2.28
7	2.24	2.99	3.15	***1.10***	2.60	2.91	2.44	2.99	2.24	2.48	2.24	2.40
8	2.13	***1.85***	2.20	2.20	2.13	2.83	2.52	2.40	2.20	***1.77***	2.32	2.48

Statistical Evaluation of Measured Cover Depths, all units [in]

Target threshold %		5%
Nominal cover	c_{nom}	2.5
Safety margin	Δc	0.6
Req'd minimum cover	c_{min}	1.9
Sample size	N	96
Median	X_M	2.34
Min	X_{min}	1.10
Mean	X	2.40
Std. Dev.	s	0.42

Qualitative Procedure				
# measurements < c_{min}	10	# allowed per N	7	NG
Quantitative Procedure				
Outlier cover	X_{OG}	$= 2.5X_M - 1.5X_{min}$	4.20	
Location parameter	r	$= (X + X_M)/2$	2.37	
Form parameter	k	$=1.8\ r/s$	10.21	
Threshold value	c(5%)	$= r/(19^{1/k})$	1.78	
Parameter p(x)	p(x)	$= c_{min}/r$	0.80	
% of cover depth <c_{min}	F(x)	$= p(x)^k/(1+p(x)^k)$	9%	>5% NG

In-Service Issues

- Monitoring actual performance vs. design
- Monitoring tests are often destructive (taking cores)
- Alternative to coring is to cast additional test specimens and store on project site in same environmental exposure
- Frequency of testing – suggest 10-20 year intervals

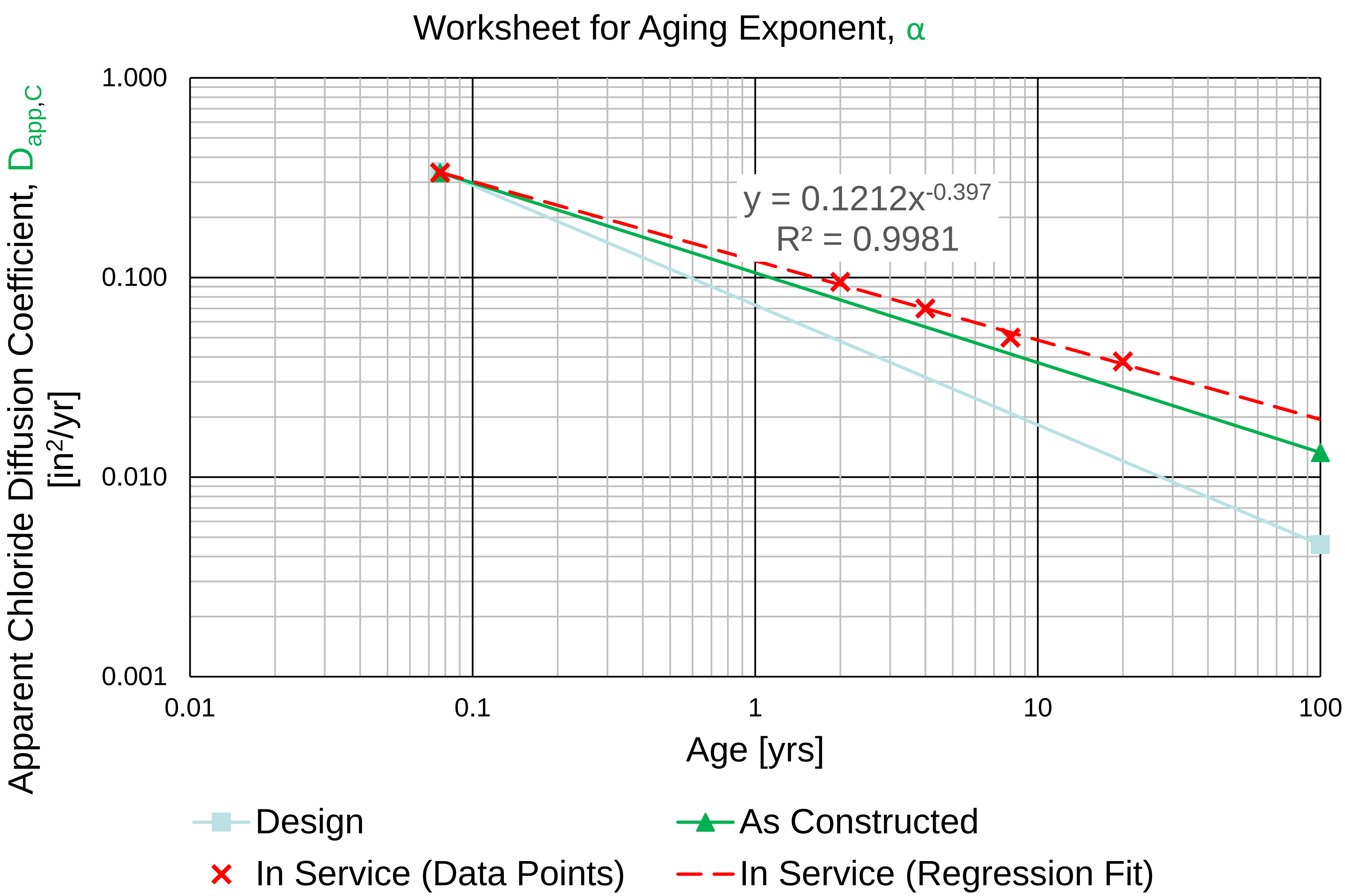
In-Service Monitoring & Testing

Objective	Potential Testing Specifications	Information Obtained
Develop chloride profiles from concrete cores taken from structure to verify concrete chloride durability resistance properties and chloride loading	Nordtest Method NT Build 443 (Bulk Diffusion Test)	$D_{app,C}$, Apparent Chloride Diffusion Coefficient as it changes with time, and C_S or $C_{S,\Delta x}$ and Δx to verify Chloride Surface Concentration. Used to determine α, the aging exponent in the chloride deterioration model
	ASTM C1543 (Salt Ponding Test)	
	ASTM C1556 (used with ASTM C1543)	
Measure carbonation depth	RILEM CPC-18	$x_c(t)$, Carbonation depth versus time, t, used in the carbonation deterioration model
	Accelerated Carbonation Test (ACC) / DARTS	
	Nordtest Method NT Build 357	

Monitoring & Documentation

In-Service Monitoring			Chloride Diffusion Coefficient at age t, $D_{app,C}(t)$		Surface Chloride Concentration, C_S or $C_{S,\Delta x}$		Aging Exponent, α		Service Life, t_{SL}	End of Service Date
			[in²/yr]		[wt-%/cem]		n/a		[yr]	[yyyy]
Life Cycle Stage	Age, t [yr]	Test Method	Mean, μ	Std Dev, σ	Mean, μ	Std Dev, σ	Mean, μ	Std Dev, σ		
Design/Construction										
Assumed Design	0.0767	NT Build 492	0.339	0.136	0.78	0.39	0.6	0.15	>100	2117
	100		0.005							
As-Constructed	0.0767	NT Build 492	0.335	0.134	0.78	0.39	0.45	0.2	100	2117
	100		0.013							
In Service Durability Monitoring			**Measured Properties from Chloride Profiling Tests**				**Regression Calculation**		**Monte Carlo Calculation**	
Inspection 1	2	ASTM C1556	0.095	0.038	0.78	0.39	0.386	0.171	67	2084
Inspection 2	4	ASTM C1556	0.07	0.028	0.78	0.39	0.393	0.174	70	2087
Inspection 3	8	ASTM C1556	0.05	0.02	0.78	0.39	0.403	0.179	74	2091
Inspection 4	20	ASTM C1556	0.038	0.015	0.78	0.39	0.397	0.176	72	2089
Inspection 5										
Inspection 6										
Inspection 7										
Inspection 8										
Inspection 9	100									

Monitoring & Documentation



In-Service Monitoring & Testing

Objective	Potential Testing Specifications	Information Obtained
Petrographic analysis	ASTM C856 / Standard Practice for Petrographic Examination of Hardened Concrete	Reactions occurring in the concrete, e.g., alkali aggregate, sulphate attack, leaching.
Surface half cell electrical potentials	ASTM C876 / Standard Test Method for Corrosion Potentials of Uncoated Reinforcing Steel in Concrete	Variation in surface electrical potential as generated by the reaction of the reinforcement with its local environment vs. a standard reference electrode

In-Service Monitoring & Testing

Objective	Potential Testing Specifications	Information Obtained
Insitu 4 pin Wenner probe concrete resistivity (natural and after concrete saturation, e.g., by spraying with water for an hour)	AASHTO TP 95 / Surface Resistivity Indication of Concrete’s Ability to Resist Chloride Ion Penetration	Natural gives areas of dampness where corrosion is a higher risk. Saturated gives an indication of the concrete quality and likely corrosion rate that would be supported.
Saturated core 4 pin Wenner probe concrete resistivity		Indication of concrete quality and likely corrosion rate that would be supported.
Ultrasonic pulse echo, impact echo and radar along post-tensioning line where grout specifications are suspect	Guidelines - "Improved Inspection Techniques for Steel Prestressing/Post-tensioning Strand" / Florida DOT Contract No. BDK80 977-13, June 2012	Post-tensioning grouting adequacy. Degree of duct filling to identify if further inspection and grout filling is required.

Documentation

- Design
  - Identify tests to be performed
  - Material durability & geometric design properties
- As-Built Construction
  - Achieved material durability & geometric properties
- In-Service
  - Measured performance

Questions?

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Resource: AASHTO's R19A Product Page

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