


SHRP2 SOLUTIONS
STRATEGIC HIGHWAY RESEARCH PROGRAM

# Service Life – Testing & Documentation

## Workshop W05 - International Bridge Conference

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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
- Birth Certificate Documentation
- 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

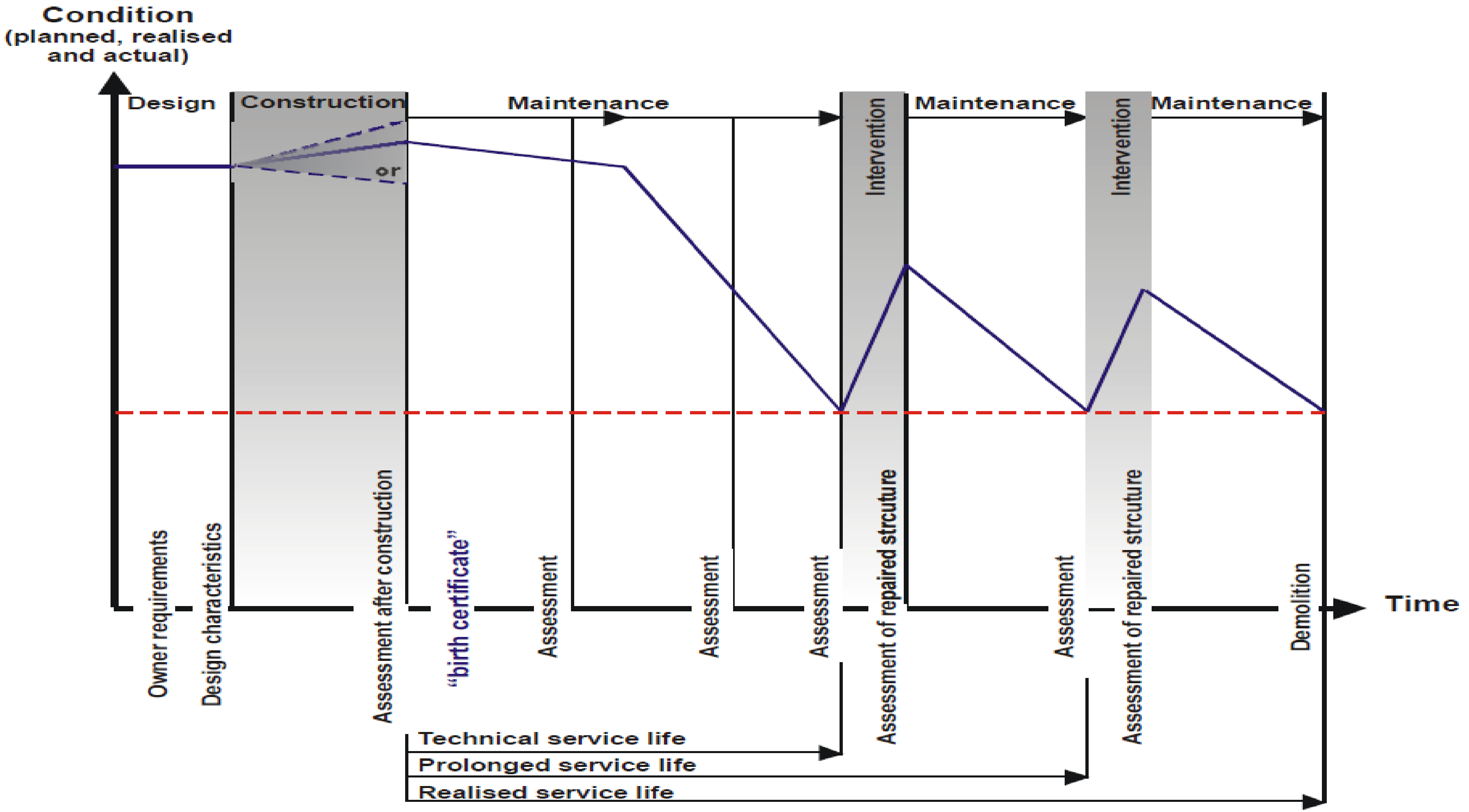



*Fig. 2-1: Complete service life from birth to death, adapted from [28]*

# Example Deterioration Model

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

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

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

$$k_e = \exp\left(b_e\left(\frac{1}{T_{ref}} + \frac{1}{\mathbf{T_{real}}}\right)\right) \qquad A(t) = \left(\frac{t_o}{t}\right)^{\boldsymbol{\alpha}}$$

- **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, $\alpha$ is the Aging Exponent, both are functions of the concrete mix
  - a is the Concrete Cover

# 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

# 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

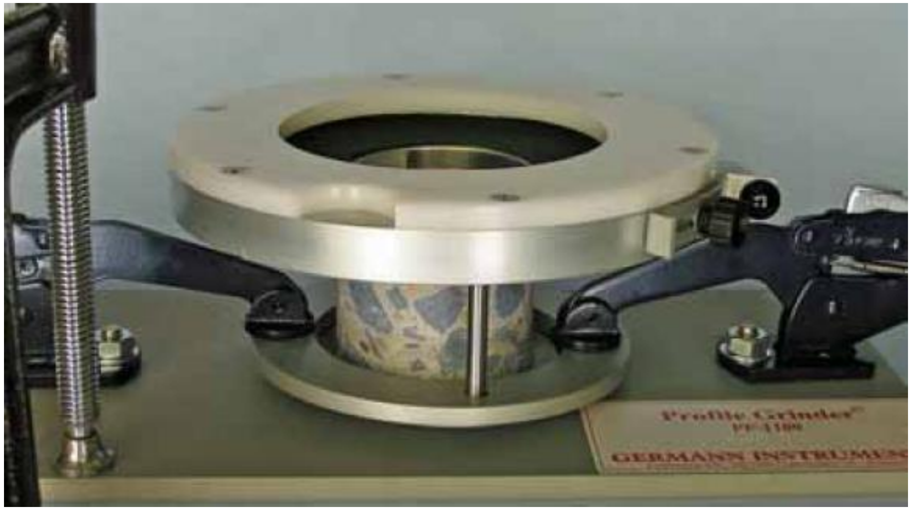
nordtest method

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

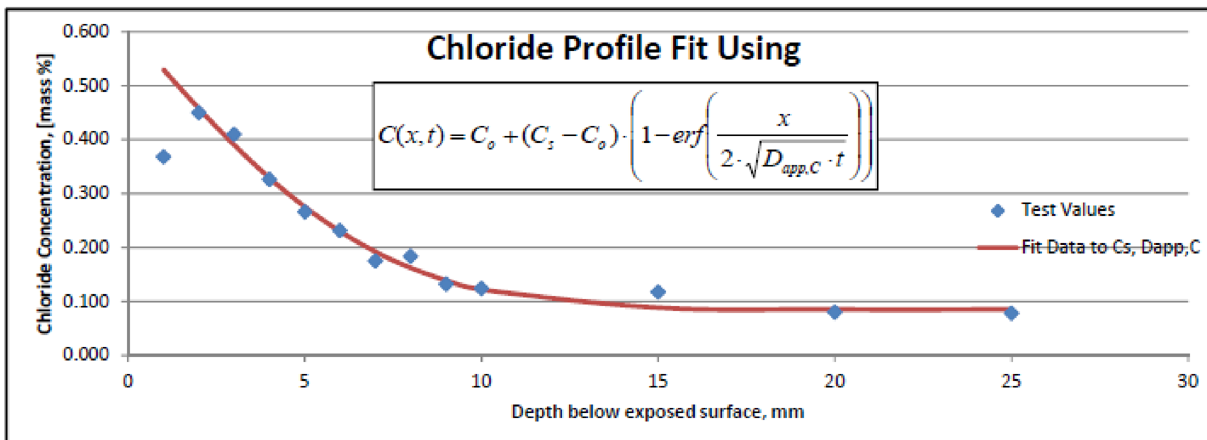
# Determining Chloride Loading

**Designation: C 1556 – 04**

**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 | [mm²/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)

# 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

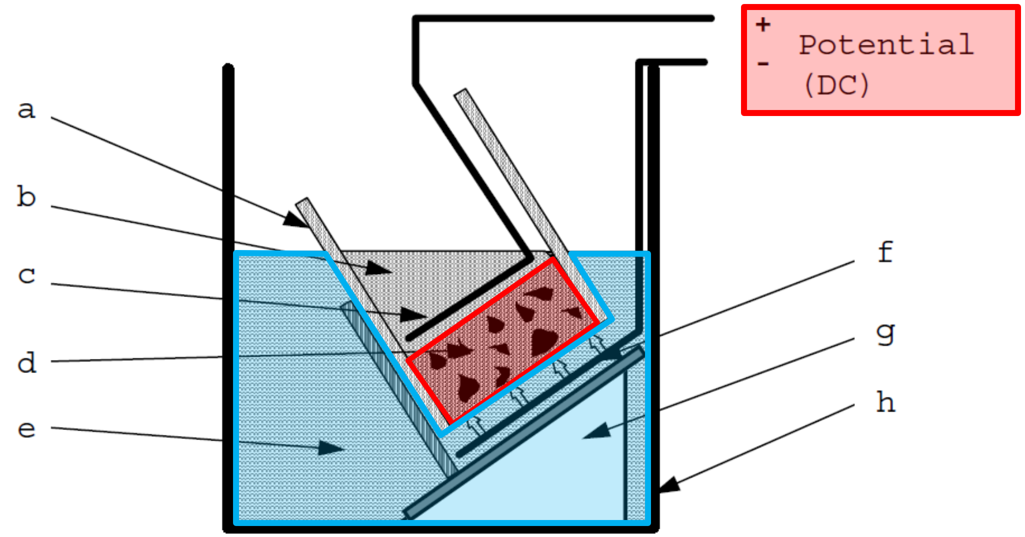
# NT Build 492

- 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

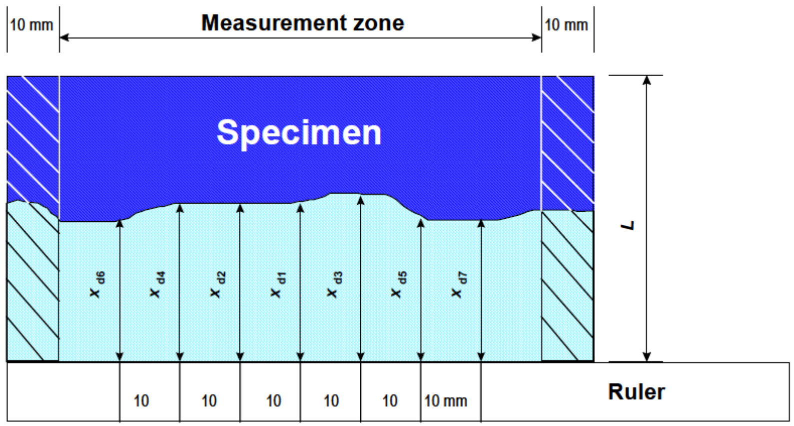



*Fig. 5. Illustration of measurement for chloride penetration depths.*

# 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

# 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

# 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

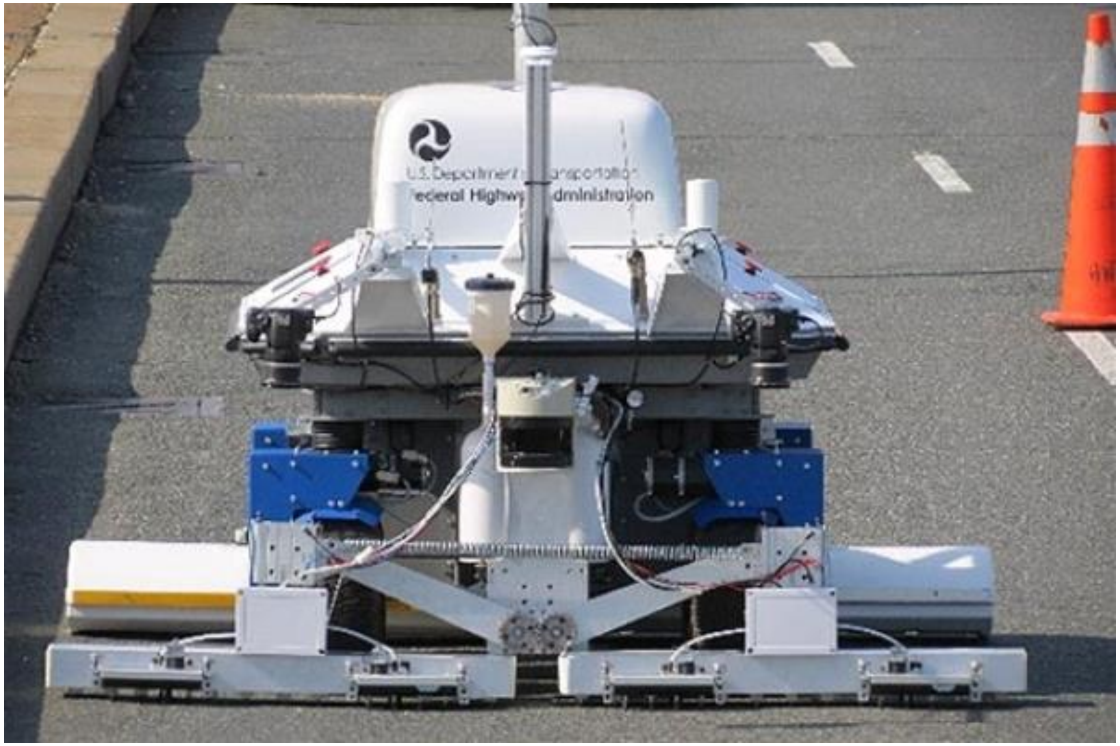
- Sources: Proceq                                        Elcometer


# Concrete Cover Depth

- New Hampshire DOT 2010 Standard Specifications
  - Section 520.3.1.6.3.6 Concrete Cover
    - “Concrete cover over reinforcing steel will be evaluated by the Bureau of Materials and Research.
    - “Concrete cover will be determined with a GSSI SIR2 radar rebar depth measuring unit.”

# Concrete Cover Depth

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



# In Service Issues

- Monitoring actual performance vs. design
- Sampling structure for Chloride Ingress
  - Chloride Profiling to ASTM C1543 & C1556 or NT Build 443
  - NT Build 492 not used (Test only meant for testing new concrete)
- Sampling structure for carbonation
  - Can use same testing procedure as for Accelerated Carbonation Test (ACC), but eliminating the carbonation chamber exposure

# In Service Issues

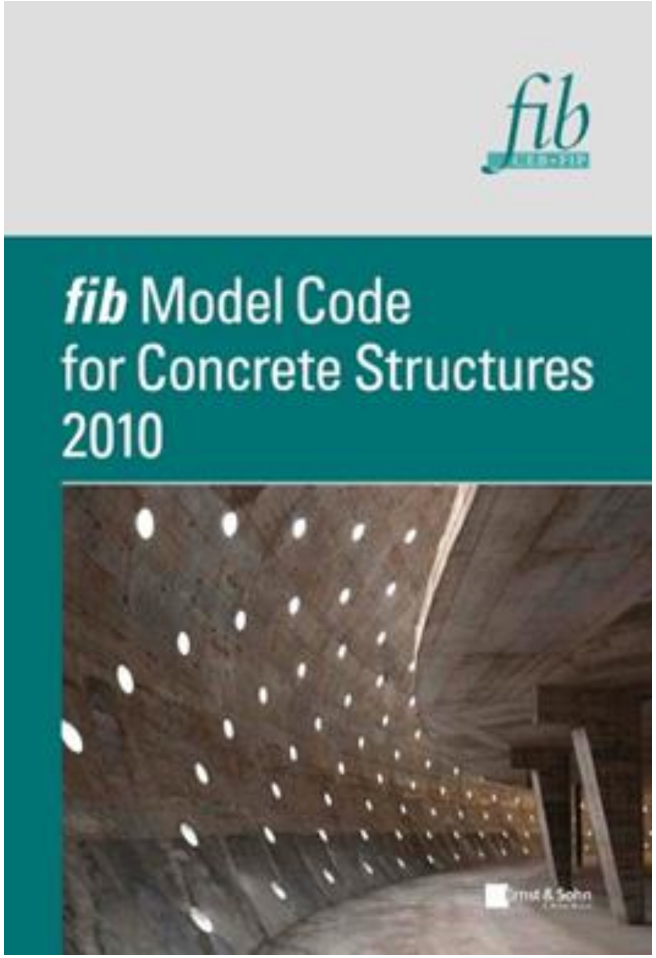
- Monitoring tests are often destructive (taking cores)
- Alternative to coring is to cast additional test specimens and store on project site in same environmental exposure
- Frequency of testing – suggest 10-20 year intervals

# Documentation

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

# Birth Certificate Definition

- A document, report or technical file (depending on the size and complexity of the structure concerned) containing engineering information formally defining the form and the condition of the structure after construction.



# Birth Certificate Purpose

- Documents parameters important to the durability & service life of the structure
- Provides means of comparing actual behavior/performance vs. design
- Facilitates ongoing (through-life) evaluation of the service life

# Birth Certificate Purpose

- Outlines an operational schedule for:
  - Routine maintenance
  - Regular inspections
  - Durability performance monitoring
  - Replacement activities
- Similar to an automobile Owner’s Manual
- Identifies potential demolition schemes

# Birth Certificate Process

- Initially developed during design phase
  - Records the intended design
- Updated at completion of construction
  - As-Built material properties and test results
    - Concrete Classes/Mix Designs
    - Steel Reinforcement/Prestressing Grades
    - Chloride Migration Coefficient
    - Cover Dimensions
- Updated after maintenance, inspection & long term performance monitoring

# Birth Certificate Table of Contents

- Asset identification & description
- Design & construction parameters
- Environmental exposure conditions
- Deterioration mechanisms & models
- Testing requirements
- Structure & replaceable element data
- In-service conservation plan
- Dismantling plan

# BC Asset Identification

## Identification of Asset

| | |
|---|---|
| Owner | Public Works and Government Services Canada |
| Structure Classification | Bridge |
| Structure Name | Confederation Bridge (or Fixed Link) |
| Inventory ID # | XXX |
| Structure Description | 11.6 m wide by 12.9 km long precast, post-tensioned segmental concrete structure with West and East Approaches and a Main Bridge Unit. Typical spans are 93 m for the Approaches and 250 m for the Main Bridge Unit. |
| Geographic Location | Carries NB 16/PEI 1 (Trans-Canada Highway) over Northumberland Straits between Borden–Carleton, PEI and Cape Jourimain, NB |
| Date Placed in Service | 31-May-1997 |

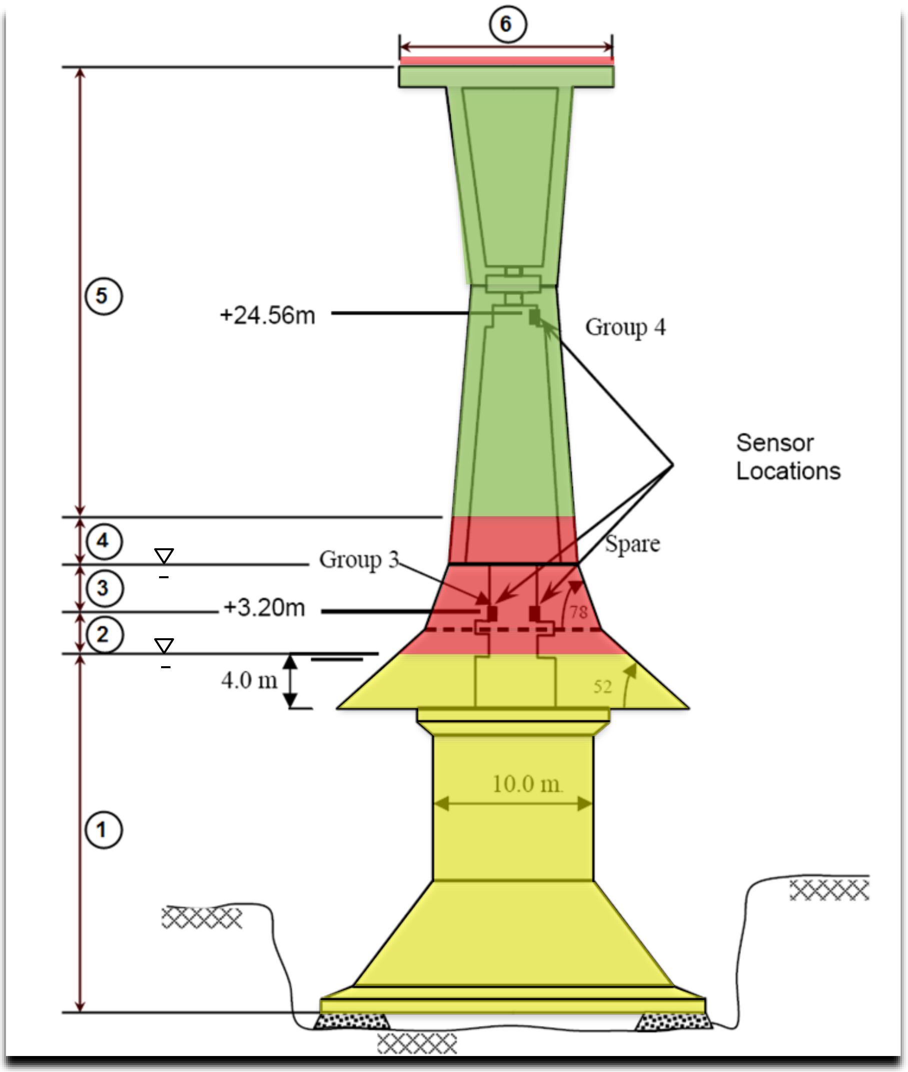
# BC Design/Construction Parameters

| Design Parameters | | |
|---|---|---|
| Consequence Class (CC) of Failure or Malfunction | CC3 - High consequence for loss of human life, or economic, social or environmental consequences very great | (Table A2-1 of MC-SLD) |
| Design Supervision Level (DSL) | DSL3 - Extended Supervision (Third party checking: Checking performed by an organisation different to that which has performed the design) | (Table A4-1 of MC-SLD) |
| Service Life Design Strategy / | Strategy B - Providing resistance to the deterioration mechanisms active in the service environment | |
| Methodology | Method B4. A reliability-based methodology (Full probabilistic design) | |
| Primary Protection Strategies | Material's own resistance | |
| | Basic resistance using a single protection strategy | |
| | | |
| Durability Limit State (DLS) | DLS1 - Depassivation of reinforcing | |
| Target Service Life | 100 years | |

# BC Environmental Parameters

| Environmental Parameters | | |
|---|---|---|
| Macro-Environment | Coastal Marine | |
| Macro-Climate | Cold | |
| Mean High Temperature | 28 °C | CHBDC CAN/CSA S6-88 |
| Mean Low Temperature | -28 °C | " |
| Mean Relative Humidity | 80% | " |
| Deterioration Mechanisms | Chloride Ingress | |
| | Freeze-Thaw | |
| | Ice Abrasion | |
| Exposure Classes | XS: Corrosion of reinforcement induced by chlorides from sea water | (EN 206-1) |
| | XD: Corrosion of reinforcement induced by chlorides other than from sea water | |
| | XF: Freeze - thaw attack upon concrete | |

# BC Environmental Parameters




| Component | Figure ID | Exposure Class (EN206) |
|---|---|---|
| | | |
| Substructure | | |
| Submerged Zone | 1 | XS2 |
| Tidal Zone | 2 | XS3 |
| Splash Zone | 3 | XS3 |
| Spray Zone | 4 | XS3 |
| Atmospheric Zone | 5 | XS1 |
| Superstructure | | |
| Atmospheric Zone | 5 | XS1 |
| Roadway & Traffic Barrier | 6 | XD3 |

# BC Deterioration Models

## BIRTH CERTIFICATE DOCUMENT
## Deterioration Mechanisms & Models

| | |
|---|---|
| Inventory ID | X10625 |
| Structure Name | Hwy. 5 Overcrossing Hwy. 12 |
| Deterioration Mechanism | Chloride ingress |
| Deterioration Model | Fick's 2nd Law |
| Source | fib Bulletin 34 - Model Code for Service Life Design |

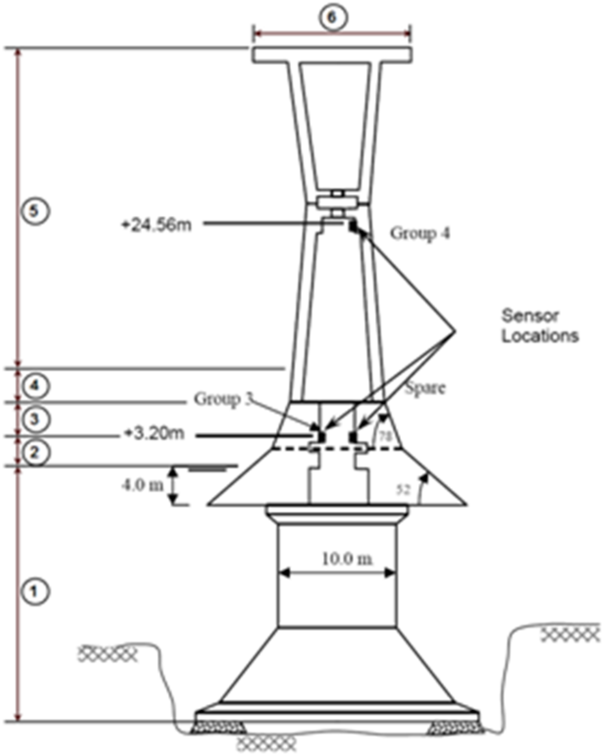
$$C_{crit} = C(x = cov, t) = C_o + \left(C_{s,\Delta x} - C_o\right) \cdot \left(1 - erf\left(\frac{cov - \Delta x}{2 \cdot \sqrt{D_{app,C} \cdot t}}\right)\right)$$

| Function Variables | Description | Units |
|---|---|---|
| $t$ | Time | [yr] |
| $x$ | Depth with corresponding content of chlorides C(x,t) | [mm] |
| $C_{crit}$ | Critical chloride content | [wt.-%/c] |
| $C_o$ | Initial chloride content of the concrete | [wt.-%/c] |
| $C_{s,\Delta x}$ | Chloride concentration at surface or a depth Δx | [wt.-%/c] |
| $\Delta x$ | Depth of the convection zone (concrete layer, up to which the process of chloride penetration differs from Fick's 2nd law of diffusion) | [mm] |
| cov | Concrete cover | [mm] |
| $D_{app,C}$ | Apparent coefficient of chloride diffusion through concrete | [mm$^2$/yr] |

# BC Structure Component Data

## Structure Component Monitoring

Inventory ID XXX
Structure Name Confederation Bridge (or Fixed Lin
Component Name Pier
Location # 20
Deterioration Model Fick's 2nd Law




| Sub-Component | Figure ID | Status | Exposure | | Concrete | | | Reinforcing Steel | | C[illegible] [kg/m³] | Remaining Service Life [yrs] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Class | C[illegible] [kg/m³] | Class/ Grade [MPa] | C[illegible] [kg/m³] | D[illegible] [mm²/yr] | Type/ Grade [MPa] | cov [mm] | | |
| | | | | | | | | | | | |
| Ice Shield, splash zone | 3 | Design | XS3 | 17.7 | HPC/55 | 0 | 15.1 | Plain/400 | 100 | 1.59 | 115 |
| | | As-Built | XS3 | 17.7 | HPC/55 | 0.085 | 15.324 | Plain/400 | 95 | 1.59 | 100 |
| | | In-Service | | | | | | | | | |
| | | #1 (10 yr) | XS3 | 17.04 | HPC/55 | 0.05 | 15.7 | Plain/400 | 95 | 1.59 | 99 |

# Inspection & Monitoring Plan

- Initial (End of Construction)
  - Birth Certificate documentation
- Routine inspections (current ~ 2 yrs)
- Special inspections (Scour, FCM)
- Damage (EQ, Flood, Fire, Collision)
- In-depth monitoring (~ 10-20 yr)
  - Chloride penetration tests
  - Depth of Carbonation tests

# BC Maintenance Schedule

| | | | | | |
|---|---|---|---|---|---|
| **Structure Name** | Confederation Bridge (or Fixed Link) | | **Initials** | | |
| **Inventory ID #** | XXX | | **Actual Date** | | |
| **Geographic Location** | Carries NB 16/PEI 1 (Trans-Canada Highway) over Northumberland Straits between Borden–Carleton, PEI and Cape Jourimain, NB | | **Sched. Date** | 31-Aug-97 | 3-Mar-98 |
| **Date Placed in Service** | 31-May-97 | | **Yr** | 1 | |
| | | | | | |
| **Routine Maintenance Action** | **Location/Component** | **Frequency** | | | |
| | | | | | |
| Clean / Clear | | | | | |
| Sweep roadway deck surface | | 6 months | | | |
| Clear bridge deck drains | | 6 months | | | |
| Flush drainage piping | | 6 months | | | |
| Pressure wash | | 1 year | | | |
| Clean abutment seats | | 1 year | | | |

# Questions?

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**Additional Resources:**

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

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