Construction Testing & Documentation Requirements for Service Life Design

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ASBI ANNUAL CONVENTION
NOVEMBER 2-3, 2015
DALLAS, TX

Discussion Topics

Introduction

Refresher – Service Life Design & Through-Life Management

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

Many ASBI projects use alternative project delivery

- Design-Build (DB)
- Design-Build-Operate-Maintain (DBOM)
- Public Private Partnership (P3)

Owners are specifying Service Life Design

Service Life Design is not just about design for durability

It's about management of durability issues throughout the life of the structure

Contractors need to be aware of new design, construction, and operations requirements

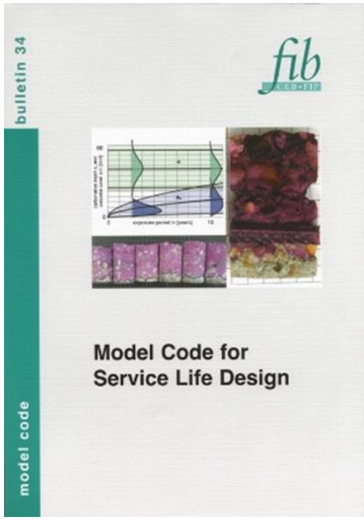
Service Life Design (SLD)

Design approach to resist Deterioration caused by Environmental Actions

- Also called Durability Design & often Design for 100-year Service Life
- Uses Scientific or Quantitative Mathematical Procedures
- Documented in *fib* Bulletin 34

Similar to design against Structural Failure caused by External Loads

- What we know as Strength Design



Deterioration

Reinforcing Steel Corrosion

Concrete Cracking, Spalling, Delamination

Environmental Exposure

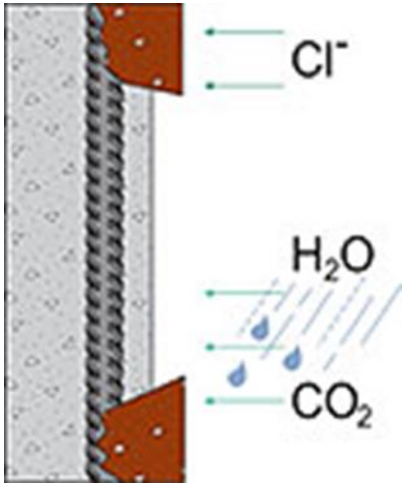
Chloride Ingress from Sea Water or De-Icing Chemicals

CO_2 Ingress from Moderate Humidity & Wet/Dry Cycles

Freeze/Thaw Cycles

Alkali-Silica Reaction (ASR)

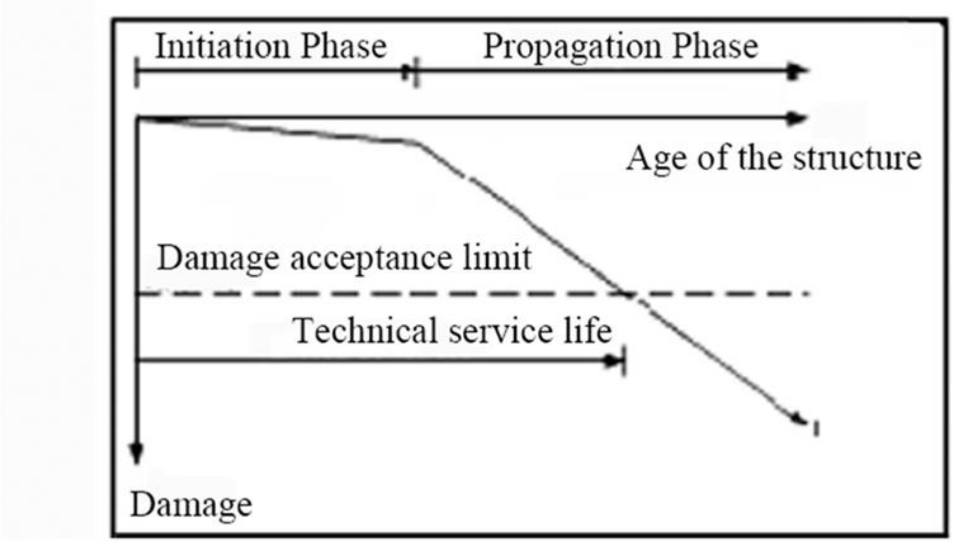
Abrasion (ice action on piers, studded tires on decks)



Deterioration Modeling

Two-Phase Deterioration Model for Reinforcing Steel Corrosion

- Initiation – No Visible Damage is Observed
- Propagation – Corrosion Begins and Progresses



Service life of concrete structures. A two-phase modelling of deterioration.
[Tuutti model (1982)]

Through-Life Stages

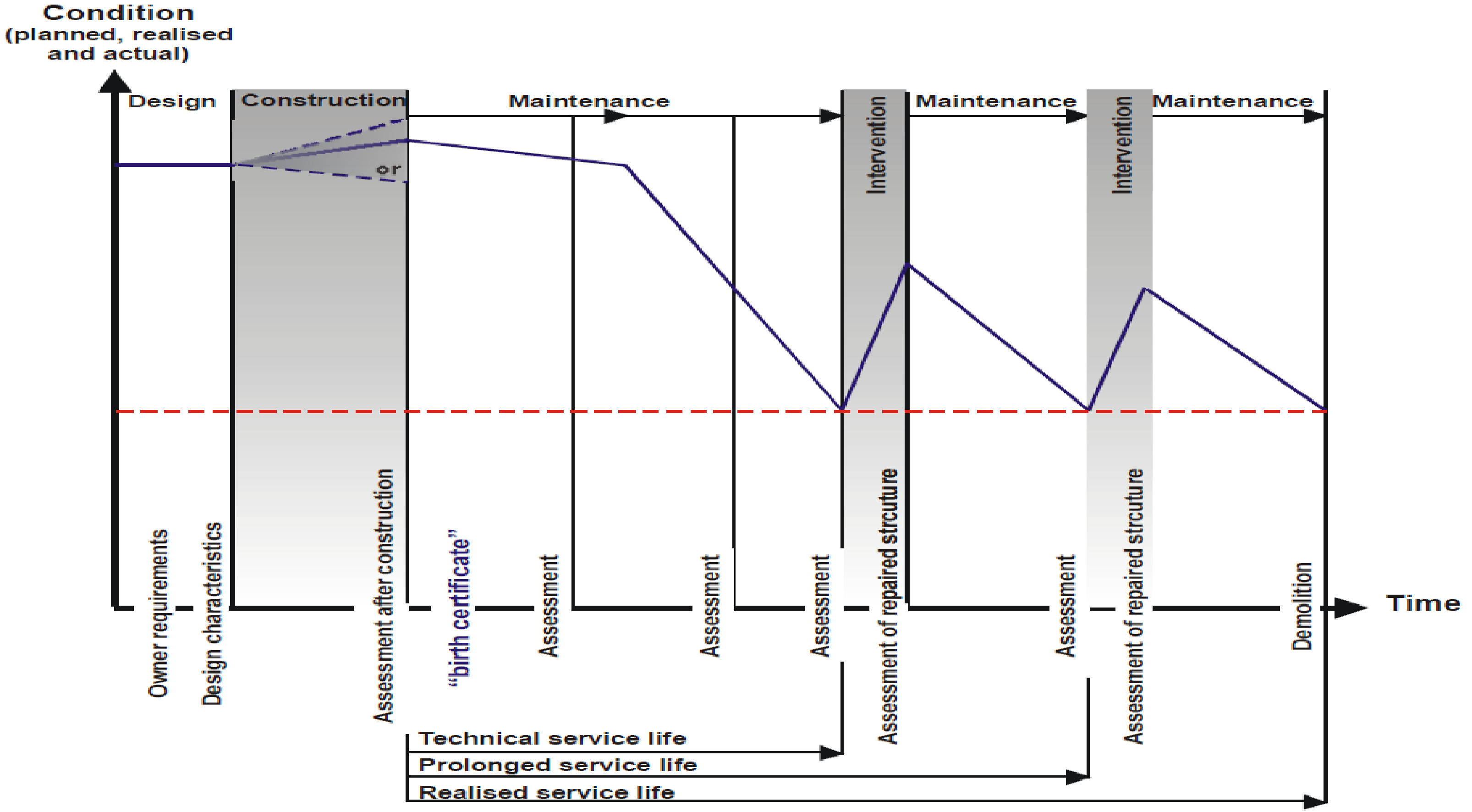


Fig. 2-1: Complete service life from birth to death, adapted from [28]

Example Deterioration Model

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

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

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

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

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

Red – Environmental Loading

Green – Material Resistance

$\mathbf{C_o}$ **&** $\mathbf{C_s}$ are the Chloride Background and Surface Concentrations

$\mathbf{D_{RCM,0}}$ is the Chloride Migration Coefficient, $\boldsymbol{\alpha}$ is the Aging Exponent

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

ASTM INTERNATIONAL

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

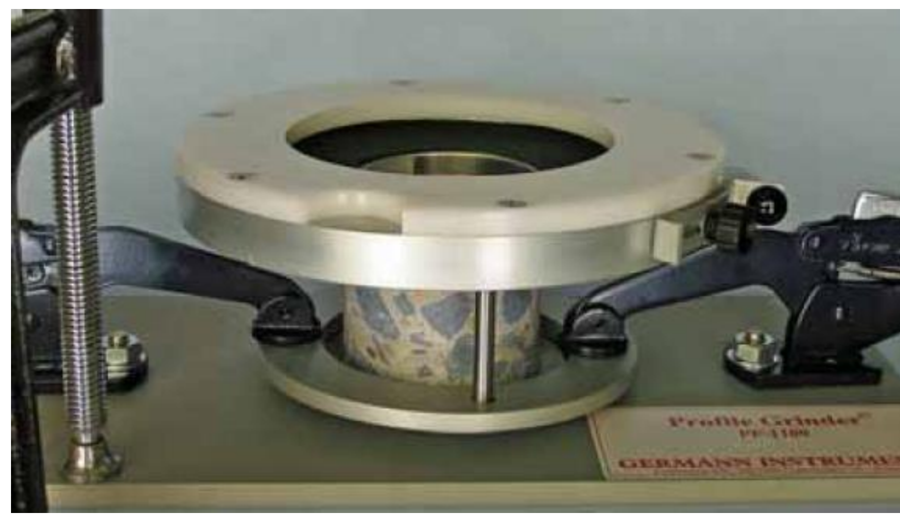
nordtest method

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

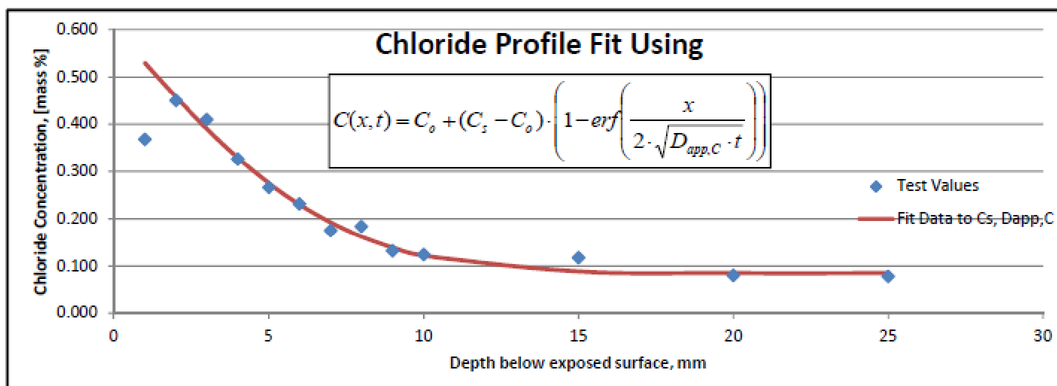
Determining Chloride Loading

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	[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
  - Gas Furnace Blast Slag
  - Microsilica

Chloride Migration Test
NT Build 492

nordtest method

NT BUILD 492

Approved 1999–11

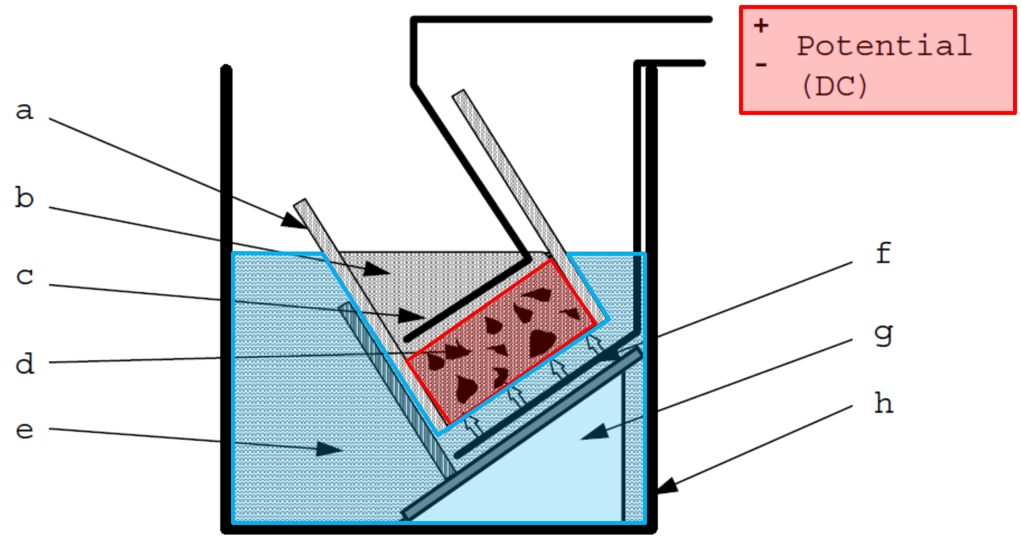
Chloride Migration Coefficient from Non-Steady State Migration Experiments

- 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

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



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 – 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, $D_{RCM,0}$

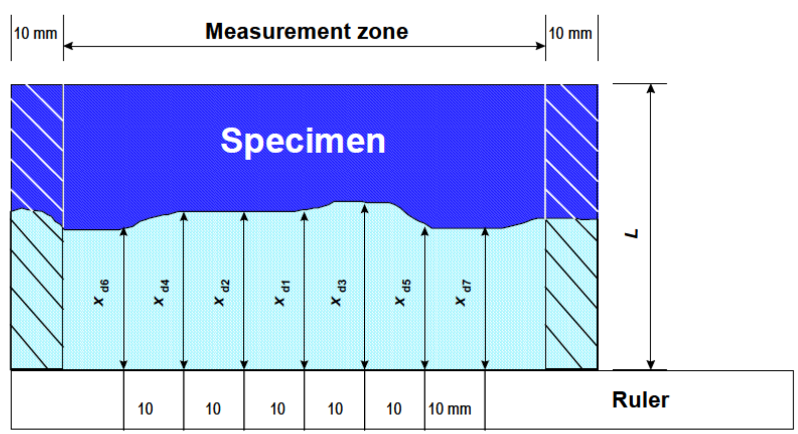


Fig. 5. Illustration of measurement for chloride penetration depths.

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 US 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

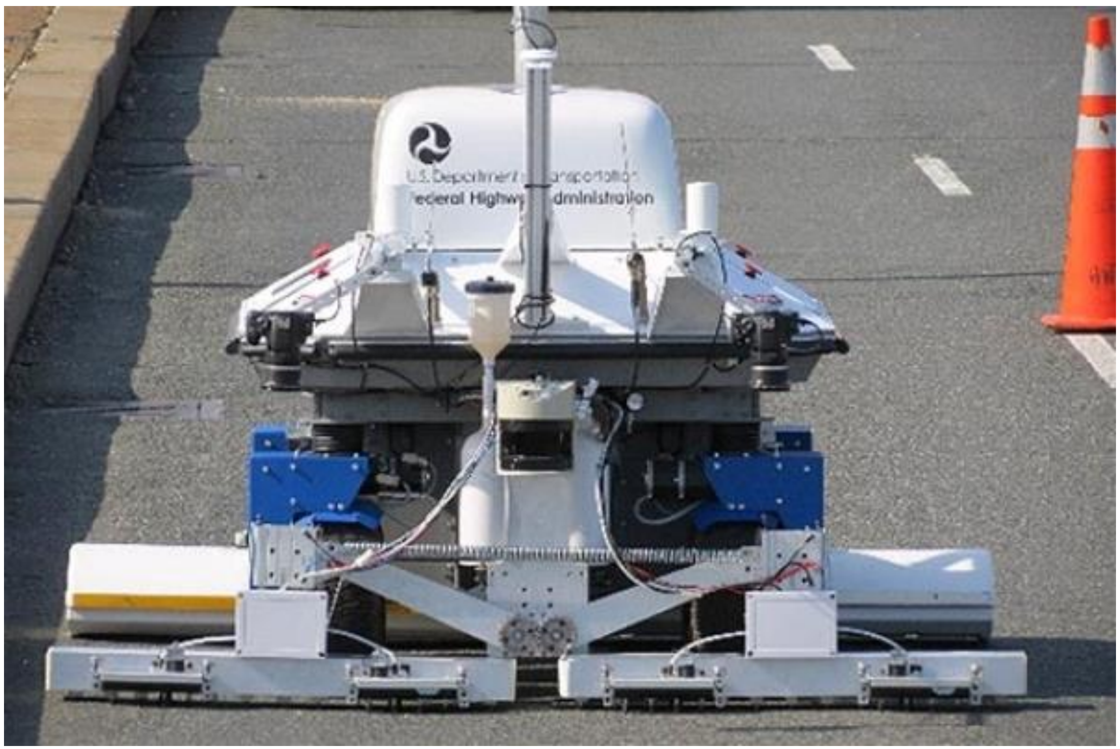
Concrete Cover Depth

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

Summary – What's Expected in SLD?

Owner Establishes a Performance Specification

- Design Methodology likely Full-Probabilistic
- Expected Structure Life Duration
  - End of Service Life – 75, 100, 125, or more years
- Limit State – Deterioration Defining End of Service Life
  - Initiation of Corrosion – Does Not Mean Structure Is Not Fit for Service
- Reliability
  - % Probability of Achieving No Corrosion at End of Service Life
  - 90% or Reliability Index, $\beta = 1.3$

Summary – Common Specification Oversights

Asking the Contractor to

- State what Service Life Duration they are providing, or
- State the level of Reliability achieved

Requiring Full-Probabilistic approach with no defined Limit State or level of Reliability

Requiring the use of Proprietary Software that may not be based on universal deterioration models or methodologies

Summary – New Contract Requirements

Goal is to insure that Service Life Design intent is achieved during construction

Incorporate tests on concrete durability properties during construction

- Chloride Migration Coefficient ($D_{RCM,0}$)

  or

- Inverse Carbonation Resistance ($R_{ACC,0}^{-1}$)

Collect measurements on concrete cover dimension

Summary – New Contract Requirements

Identify means to deal with variations from design intent

- Incentives/Penalties for not achieving durability properties
- Similar to current practice on concrete strength tests

For DBOM and PPP contracts, identify in-service monitoring tests to be performed

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Thank you for your time!

QUESTIONS?

This concludes the educational content of this activity

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Purpose and Learning Objectives

Purpose

The Convention provides an educational forum to learn new techniques used in successful projects, lessons learned from development projects, and showcases a case study allowing for discussion of the project.

Learning Objectives

At the end of this presentation you will:

- Be Knowledgeable About the Advantages of Segmental Construction
- Learn About Segmental Substructures
- Hear About Lessons Learned