Internal Curing of High Performance Concrete Bridge Decks and its Effects on Performance, Service Life and Life-Cycle Cost

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Introduction

→ Presentation overview

1. High Performance Concrete Bridge Decks – Issues and Solutions
2. Effect of Internal Curing on Concrete Performance
3. Case Study – Highway Bridge Deck
4. Service Life Modelling
5. Life Cycle Cost Modelling
6. Environmental Impact
HPC bridge decks
→ Benefits and challenges

• According to the US Federal Highway Administration, most DOTs use HPC for highway bridges, to benefit from:
  ➢ high strength, low permeability, long spans, thin sections ...

• FHA reports that the main causes of deterioration in bridge decks are:
  1. Shrinkage cracking (>100,000 bridges in USA)
  2. Rebar corrosion

• Cost to upgrade all concrete bridges:
  – $80-100 billion (USA)
  – $8-10 billion (Canada)
HPC bridge decks → Reinforcement corrosion

- Corrosion cracking due to de-icing salt contamination is a common problem in concrete bridges and parking structures.

- Solutions investigated at NRC:
  - Low-permeability concrete
  - Corrosion inhibitors
  - High-performance steels

Vachon Bridge, Laval, Canada, 1996 (before rehabilitation, after 22 years of service)

Laurier-Taché Parking Garage, Hull, Canada, 2004 (before rehabilitation, after 29 years of service)
HPC bridge decks

→ Restrained shrinkage

- Shrinkage cracking due to restraint of movement is also a common problem in concrete bridges and parking structures.

- Solutions investigated at NRC:
  - Internal curing with LWA
  - Shrinkage-reducing admixtures
  - Supplementary cementing materials

Vachon bridge, Laval, Canada, 1996
(a few days after rehabilitation)

Laurier-Taché Parking Garage, Hull, Canada, 2004
(a few weeks after rehabilitation)
HPC bridge decks
→ Underlying causes

1) Chemical shrinkage
   – Volume of hydrated cement < Volume of water + cement
   – Occurs in cement-based concrete (typical value for OPC = 7% by vol.)

2) Self-desiccation
   – Internal drying due to lack of water to hydrate all cement particles
   – Occurs more often in high-strength concrete due to low w/c (< 0.42)

3) Drying shrinkage
   – External drying when ambient RH is lower than concrete RH
   – Occurs more often in normal concrete due to high permeability

4) Cooling
   – Loss of heat to the environment, accumulated due to cement hydration
   – Occurs more in high-strength concrete due to high cement content

5) Other causes
– Part 2 –

Effect of Internal Curing on Concrete Performance
Internal curing
→ Definition

- IC consists of providing curing water to concrete from inside, by using:
  - pre-soaked porous LWA, or
  - super-absorbent polymers, or
  - saturated wood fibers.

- IC can compensate for chemical shrinkage, reduce self-desiccation, and improve cement hydration, which may result in:
  - reduced early-age cracking,
  - higher concrete strength and stiffness,
  - reduced permeability and rebar corrosion.

Computer simulation by Dale Bentz, NIST
1) Chemical shrinkage
   - Can be compensated by internal curing.

Proportions before hardening:
- Mixing water
- Cement

Proportions after hardening:
- Internal curing water
- Hydrated cement paste

\{ 7\% \text{ vol.} \}
\{ 93\% \text{ vol.} \}
Effect of internal curing → Chemical shrinkage

\( \alpha_{\text{max}} = \frac{w/c}{0.36} \)

\( \alpha_{\text{max}} = 1 \)

IC water needed to reach max. hydration

\[ M_{LWA} = \frac{M_C \cdot C_S \cdot \alpha_{\text{max}}}{S_{LWA} \cdot \phi_{LWA}} \]

- \( M_{\text{lwa}} \) = dry mass of LWA
- \( C_S \) = mass of cement
- \( C_C \) = chemical
- \( S_{\text{lwa}} \) = saturation degree
- \( \phi_{\text{lwa}} \) = hydration degree

(Jensen & Hansen 2001)
Effect of internal curing
→ Desiccation & shrinkage

2) Self-desiccation

3) Drying shrinkage

Can be reduced by internal curing (higher RH),
Can also be reduced by use of SRA (lower $\gamma$).

\[ \sigma_{\text{cap}} = \frac{2\gamma}{r} = -\frac{\ln(RH)RT}{V_m} \]

Kelvin–Laplace equation

Surface tension forces pulling on particles ($\gamma$)

High RH

Low RH
Effect of internal curing
→ Previous testing at NRC

- **Control concrete** (referred to as Mix-0)
  - Cement/sand/coarse aggregate ratio: 1:2:2
  - Water/cement ratio: 0.34
  - Cement content: 445 kg/m³ (ASTM type I)

- **LWA-modified concretes**
  - Same as above, plus:
  - Normal sand partly replaced by saturated LWA (15% absorption capacity)
    - 6% sand replacement (Mix-L)
    - 12% sand replacement (Mix-M)
    - 20% sand replacement (Mix-H)
Effect of internal curing
→ Restrained shrinkage testing
Effect of internal curing
→ Total strain

![Graph showing the effect of LWA on total strain](image-url)
Effect of internal curing

→ Autogenous shrinkage strain
Effect of internal curing → Net shrinkage strain
Effect of internal curing

→ Requirement to avoid shrinkage

Mix-M

- \( \text{w/c eff} = 0.30 \)
- \( \text{w/c IC} = 0.04 \)
- \( f'c_{7d} = 57 \text{ MPa} \)

Mix-H

- \( \text{w/c eff} = 0.28 \)
- \( \text{w/c IC} = 0.06 \)
- \( f'c_{7d} = 57 \text{ MPa} \)

Mix-L

- \( \text{w/c eff} = 0.32 \)
- \( \text{w/c IC} = 0.02 \)
- \( f'c_{7d} = 54 \text{ MPa} \)

Mix-0

- \( \text{w/c eff} = 0.34 \)
- \( \text{w/c IC} = 0.00 \)
- \( f'c_{7d} = 50 \text{ MPa} \)
Effect of internal curing → Basic creep strain

- Increase in tensile creep (restrained shrinkage)
- Increase in compressive creep (restrained expansion)
Effect of internal curing

→ Tensile stress

ε_{max} = \varepsilon_{\sigma=0} = 0

under sealed curing

Concrete stress

Total strain

ε_{min}

0 24 48 72 96 120 144 168

Concrete stress (MPa)

0 2 3 4 5 6
Effect of internal curing

→ Tensile stress

Exp Contraction

Concrete stress

Stress reversal

Contraction contributing to an increase in tensile stress

Contraction resulting in tensile stress

Total strain

Concre Stress reversal

Concrete Stress (MPa)

0 24 48 72 96 120 144 168

ε_{max}

ε_{σ=0}

ε_{min}

Total strain

0 2 3

-3 -2 -1 0 1 2 3

under internal curing
Effect of internal curing → Tensile stress

Mix-0 (almost a third of the stress was due to autogenous shrinkage)

Mix-H (almost none of the stress was due to autogenous shrinkage)

Thermal effects were important (but similar) in both mixes
Effect of internal curing
→ Compressive strength

![Graph showing the effect of internal curing on compressive strength at 7 days and 28 days.](image)
Effect of internal curing
→ Field demonstration

Project description:
- Large-scale paving project in Hutchins, Texas (Villarreal & Crocker 2007)
- 190 000 m³ of internally-cured concrete

Main field observations:
1. Marginal pavement cracking
2. 7-day flexural strengths > 90% of required 28-day flexural strength
3. Compressive strengths of air-cured cylinders = those of wet-cured cylinders

Main conclusions:
1. Internal curing can reduce shrinkage cracking significantly,
2. Cement hydration is more complete due to internal curing,
3. Internally-cured concrete is less sensitive to poor external curing practices or unfavorable curing conditions.
– Part 3 –

Case Study – Highway Bridge Deck
Case Study → Highway Bridge Deck

Width = 13 m

Length = 35 m

Cross-section of bridge

Cross-section of bridge slab

75 mm

30 mm
## Case Study
→ Concrete mix formulations

<table>
<thead>
<tr>
<th>Bridge deck</th>
<th>Initial cracking</th>
<th>Water (kg/m³)</th>
<th>Cement (kg/m³)</th>
<th>SCM (%)</th>
<th>w/cm</th>
<th>LWA (kg/m³)</th>
<th>Cost ($/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC</td>
<td>No</td>
<td>140</td>
<td>350</td>
<td>0</td>
<td>0.40</td>
<td>0</td>
<td>$450</td>
</tr>
<tr>
<td>HPC</td>
<td>Yes</td>
<td>160</td>
<td>450</td>
<td>25</td>
<td>0.35</td>
<td>0</td>
<td>$600</td>
</tr>
<tr>
<td>HPC-IC</td>
<td>No</td>
<td>160</td>
<td>450</td>
<td>25</td>
<td>0.35</td>
<td>200</td>
<td>$625</td>
</tr>
<tr>
<td>VHPC-IC</td>
<td>No</td>
<td>160</td>
<td>525</td>
<td>25</td>
<td>0.30</td>
<td>200</td>
<td>$750</td>
</tr>
</tbody>
</table>

- Lightweight Aggregate (LWA) costs 75$/ton (vs. $15/ton for normal sand).
- A cost of 200 kg/m³ of LWA and long-distance transportation (e.g. 600 km) only increase the in-place cost of concrete by approximately $50 per m³.
Exposure conditions (all deck options):

Surface chlorides: 9 kg/m³ (typical of severe conditions in Canada)

Corrosion threshold: 0.7 kg/m³ (typical for normal steel reinforcement)

Corrosion rate: 0.5 μA/cm² (typical moderate value in concrete)
Part 4 - Service Life Modelling of Bridge Deck

SLAB-D
Service Life Analysis of Bridge Decks
Version 1.0 2006
written by:
Lyne Daigle and Zoubir Lounis
Service life modelling → Two-phase damage model
(modified from Tuutti 1982)

- Corrosion initiation period (several decades)
- Propagation period (few years)
- Delamination or spalling
- Surface cracking
- Internal cracking
- Initial cracking
- Chloride contamination
- Rebar corrosion
- Time (years)
- Failure
Service life modelling
→ Chloride diffusion in concrete

Fick’s 2nd law of diffusion:
Frank 1975)

\[ \frac{\partial C}{\partial t} = D c \left( \frac{x}{2 \sqrt{D_c t}} \right) \]

Chloride diffusion coefficient:
Hulfiga et al. 2003)

\[ D_c = -3.9 \left( \frac{w}{c} \right)^2 + 7.2 \left( \frac{w}{c} \right) - 14.0 \quad \text{(no SCMs)} \]

\[ D_c = -3.0 \left( \frac{w}{c} \right)^2 + 5.4 \left( \frac{w}{c} \right) - 12.7 \quad \text{(with SF / Slag)} \]

C = chloride concentration
C_s = surface chloride content
D_c = chloride diffusion coefficient
x = depth in concrete
t = time of exposure
Service life modelling

→ Cl diffusion in cracked concrete

Effect of cracking on chloride penetration (seared approach):

\[ D_{\text{cr}} = D_c + \frac{w_{cr}}{s_{cr}} D_{cr} \]

<table>
<thead>
<tr>
<th>Bridge deck</th>
<th>w/cm (actual)</th>
<th>( D_c ) (m²/s)</th>
<th>( D_{\text{app}} ) (m²/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC</td>
<td>0.40</td>
<td>18 x 10^{-13}</td>
<td>18 x 10^{-13}</td>
</tr>
<tr>
<td>HPC (cracks)</td>
<td>0.35</td>
<td>6.6 x 10^{-13}</td>
<td>8.1 x 10^{-13}</td>
</tr>
<tr>
<td>HPC-IC</td>
<td>0.35</td>
<td>6.6 x 10^{-13}</td>
<td>*6.6 x 10^{-13}</td>
</tr>
<tr>
<td>VHPC-IC</td>
<td>0.30</td>
<td>4.4 x 10^{-13}</td>
<td>*4.4 x 10^{-13}</td>
</tr>
</tbody>
</table>

Conservative estimate

Diffusion in cracks: 5 x 10^{-10}
Service life modelling
→ Chloride profile after 20 years
Service life modelling
→ Chloride ingress at rebar level

![Graph showing chloride ingress at different levels of concrete and rebar.](image-url)
Propagating time for each damage level:
(from onset of corrosion to initial cracking, surface cracking and spalling)

\[
t_p = \frac{\pi d (\Delta d)}{2 S j_r \left[ \frac{1}{\rho_r} - \frac{\alpha}{\rho_s} \right]}
\]

where:
d = rebar diameter
S = rebar spacing
\( j_r \) = rust production rate
\( \rho_r \) = rust density
\( \rho_s \) = steel density
Service life modelling
→ Average SL prediction

- Onset of spalling
- Onset of surface cracking
- Onset of internal cracking
- Onset of corrosion

- Onset of spalling: 71 years
- Onset of surface cracking: 49 years
- Onset of internal cracking: 41 years
- Onset of corrosion: 21 years
Service life modelling → Reliability analysis

Reliability analysis takes into account variability and uncertainty in input parameters (properties, dimensions, environmental conditions, etc.).

<table>
<thead>
<tr>
<th>Model parameter</th>
<th>Average</th>
<th>COV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface chlorides</td>
<td>9 kg/m³</td>
<td>30%</td>
</tr>
<tr>
<td>Diffusion coefficient</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- NC</td>
<td>18 x 10^{-13} m²/s</td>
<td>30%</td>
</tr>
<tr>
<td>- HPC</td>
<td>8.1 x 10^{-13} m²/s</td>
<td></td>
</tr>
<tr>
<td>- HPC-IC</td>
<td>6.6 x 10^{-13} m²/s</td>
<td></td>
</tr>
<tr>
<td>- VHPC-IC</td>
<td>4.4 x 10^{-13} m²/s</td>
<td></td>
</tr>
<tr>
<td>Cover depth</td>
<td>75 mm</td>
<td>30%</td>
</tr>
<tr>
<td>Chloride threshold</td>
<td>0.7 kg/m³</td>
<td>30%</td>
</tr>
<tr>
<td>Corrosion rates</td>
<td>0.5 μA/cm²</td>
<td>30%</td>
</tr>
</tbody>
</table>
Service life modelling
→ Probability of spalling
## Service life modelling

→ Assessment of deck condition

<table>
<thead>
<tr>
<th>Condition State</th>
<th>Description (from AASHTO guidelines)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The surface of the deck has no patched area and no spalls in the deck surface.</td>
</tr>
<tr>
<td>2</td>
<td>The combined distress area (existing patches, delam. and spalling) of the deck is less than 10%.</td>
</tr>
<tr>
<td>3</td>
<td>The combined distress area of the deck is between 10% and 25%.</td>
</tr>
<tr>
<td>4</td>
<td>The combined distress area of the deck is between 25% and 50%.</td>
</tr>
<tr>
<td>5</td>
<td>The combined distress area of the deck is more than 50%.</td>
</tr>
</tbody>
</table>

- In this case study:
  - 10% distress area: minor repair
  - 25% distress area: major repair
  - > 50% distress area: deck replacement
– Part 5 –
Life Cycle Cost Modelling of Bridge Deck

SLAB-D
Service Life Analysis of Bridge Decks
Version 1.0 2006
written by:
Lyne Daigle and Zoubir Lounis
Life cycle cost modelling
→ Present value approach

(Grant et al. 1990; Hawk 2003)

\[
PVLCC = C_0 + \sum_{t_i=1}^{T} \frac{C_i}{(1 + r)^{t_i}} - \frac{R_v}{(1 + r)^T}
\]

\[\text{(r=3\%)}\]
\[\text{(T=70 yrs)}\]
Life cycle cost modelling → Maintenance of NC deck
Life cycle cost modelling → Maintenance of HPC deck

- Replacement
- Patch repair
- Protection
- Non-destructive evaluation
- Routine inspection

Initial service life vs. 2nd service life diagram.
Life cycle cost modelling → Maintenance of HPC-IC deck

- Initial service life
- 2nd service life

- Replacement
- Patch repair
- Protection
- Non-destructive evaluation
- Routine inspection
Life cycle cost modelling
→ Maintenance of VHPC-IC deck
Life cycle cost modelling
→ Maintenance costs to agency

<table>
<thead>
<tr>
<th>Activity</th>
<th>Agency Cost</th>
<th>Duration</th>
<th>Road length affected</th>
<th>Reduced traffic speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Routine inspection</td>
<td>2 $/m²</td>
<td>0.25 d</td>
<td>0.25 km</td>
<td>70 km/h</td>
</tr>
<tr>
<td>Non-destructive evaluation</td>
<td>20 $/m²</td>
<td>1 d</td>
<td>0.5 km</td>
<td>50 km/h</td>
</tr>
<tr>
<td>Protection</td>
<td>20 $/m²</td>
<td>1 d</td>
<td>0.5 km</td>
<td>50 km/h</td>
</tr>
<tr>
<td>Patch repair</td>
<td>200 $/m²</td>
<td>2 d</td>
<td>1 km</td>
<td>50 km/h</td>
</tr>
<tr>
<td>Replacement (disposal &amp; reconstruction)</td>
<td>C.C. + 350 $/m²</td>
<td>15 d</td>
<td>1 km</td>
<td>50 km/h</td>
</tr>
</tbody>
</table>
Life cycle cost modelling
→ Maintenance costs to users

Costs to users:

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value of car driver’s time</td>
<td>$12/h</td>
</tr>
<tr>
<td>Value of truck driver’s time</td>
<td>$20/h</td>
</tr>
<tr>
<td>Vehicle operating cost</td>
<td>$9/h</td>
</tr>
<tr>
<td>Accident rate during activity</td>
<td>6 accidents per million vehicle-km</td>
</tr>
<tr>
<td>Cost per accident</td>
<td>$40,000</td>
</tr>
</tbody>
</table>

Traffic information:

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual average daily traffic (AADT)</td>
<td>4000</td>
</tr>
<tr>
<td>Percent of truck in AADT</td>
<td>25%</td>
</tr>
<tr>
<td>Normal traffic speed</td>
<td>100 km/h</td>
</tr>
<tr>
<td></td>
<td>2 accidents per million vehicle-km</td>
</tr>
</tbody>
</table>
Life cycle cost modelling
→ Initial construction cost
Life cycle cost modelling

→ Present value of life cycle cost

<table>
<thead>
<tr>
<th>Agency cost</th>
<th>User cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>870</td>
<td>89</td>
</tr>
<tr>
<td>471</td>
<td>38</td>
</tr>
<tr>
<td>380</td>
<td>29</td>
</tr>
<tr>
<td>324</td>
<td>15</td>
</tr>
</tbody>
</table>

46% reduction
56% reduction
63% reduction
Life cycle cost modelling
→ PV cumulative expenditure

Initial service life of NC deck

5 years to breakeven

Initial service life of HPC-IC deck

Normal concrete deck

HPC deck with internal curing
– Part 6 –

Environmental Impact
Environmental impact

→ CO₂ emissions

Long service life and low maintenance of concrete structures can minimize impact on environment by reducing CO₂ emissions.

Emission of carbon dioxide can be reduced by:

- Using SCM to reduce cement content in concrete; 25% SCM (1 ton of cement produced = 1 ton of CO₂),
- Reducing transportation of non-locally available LWA and SCM (1 ton of material transported over 1000 km = 0.022 ton of CO₂),
- Reducing car delays due to deck maintenance activities (1 hour car delay = 4 kg of CO₂).
Environmental impact → CO₂ emissions over life cycle

- Production of cement
- Transportation of LWA and SCM
- Car delay during deck maintenance
Conclusions

HPC structures can be designed to include new shrinkage prevention technologies without significantly increasing initial construction cost.

Service performance of bridge decks can be improved due to reduced shrinkage cracking and reduced reinforcement corrosion.

Service life of bridge decks can be extended by at least 10 years due to external curing alone, and by up to 50 years due to use of VHPC and IC.

Life cycle costs of bridge decks can be substantially reduced due to:
- Fewer maintenance activities (inspection, protection and repair),
- Lower user costs (delays and accidents),
- Longer service life (over 70 years).
- Higher initial construction cost of HPC-IC deck vs. NC deck can be offset in only 5 years.

Environmental impact can be reduced due to fewer maintenance activities and longer service life.