Deterioration of Concrete Pavements Exposed to Deicing Salts and Freezing/Thawing Conditions

JAN OLEK, PhD, PE, FACI. M.ASCE
Professor of Civil Engineering
Lyles School of Civil Engineering
olek@purdue.edu
The Problem

• Some concrete pavements located in cold climates have been experiencing premature joint deterioration.
• Once initiated, the damage progresses aggressively and can result in severe damage to the pavement.
• Various contributing factors have been identified in the previous studies.
The Problem

- Most deterioration taking place at or near:
  - longitudinal joints
  - transverse joints
  - Intersection of transverse and longitudinal joints
The Problem

- In some cases, there are no visible signs of distress
  - No surface cracking
  - Sealant appears to be intact
The Problem

- In other cases there may be hints of underlying distress
  - Surface microcracking in the vicinity of the joint
  - Deterioration of the sealant
What may be causing the distress?

• **Number of potential causes suggested**
  - Poor materials selection,
  - Poor mixture proportioning
  - Poor construction practices
  - D-cracking
  - Alkali-reactive materials
  - Improper timing of sawing (either early or late)
  - Uncracked joints
What may be causing the distress?

- **Number of potential causes suggested**
  - slab warping
  - joint spacing
  - accumulation of incompressibles in joints
  - Joint sealing and sealant selection
  - Poor drainage
  - Local saturation of concrete
  - Deicing practices

[Image of exposed aggregate]
Quality of the subgrade

Water (plus deicers) can penetrate through joint and accumulate at the base of the pavement causing saturation and FT damage as well as damage due to salt crystallization.
Freeze-Thaw (FT) Resistant Concrete

Production of freeze-thaw resistant concrete requires, among others, attention to material parameters used to specify concrete

- Aggregate Quality
  - Coarse aggregate
    - D-cracking - controlled by the resistance to FT damage of the aggregate itself
    - Starts near the joints first
    - Can start at the bottom or at the top
    - Poor air can be a contributing factor
  - Fine aggregate
    - Primarily assists with the retention of entrained air in concrete
Critical Saturation

- Water entering joints, particularly longitudinal saw joint, is trapped
- Longitudinal saw cut joints not cracking or if cracking – no opening of crack – as result water can not drain out to drainable subbase under PCCP
- Silicone sealant and backer rod prevent any evaporation or air drying of trapped water
Potential Degradation Hypothesis

a) an ideal joint

b) a joint with damaged joint sealant but cracked

c) a joint with damaged joint sealant that is uncracked

d) a joint illustrating potential salt crystallization locations

(Weiss and Nantung) 2005
Critical saturation

- Concrete with degree of saturation higher than some critical value can get damaged during the FT exposure even if it is air entrained
Saturation and Freeze-Thaw Damage

There is a critical saturation that makes concrete susceptible to repeated F-T

Fundamental Premise - If it is not saturated it will not develop damage

After CEB 1957

Slide courtesy of J. Weiss
Buildup of hydraulic pressure

Empty air voids $\rightarrow$ fluid can enter and freeze without damaging the microstructure.

Missing or filled air voids $\rightarrow$ concrete cracks when hydraulic pressure exceeds tensile strength.

Courtesy of M. Glinicki
FT Damage

Cracking of the cement paste

Crystallization of ice in the air void

Courtesy of M. Glinicki
INDOT Study along I-94

- 10-yr old pavement at the time of coring
- Similar mix and materials, same contractor, one job showing different performance
- Able to compare: Sealed vs. Unsealed joints; and concrete with and without Fly Ash

WB Paved Summer 1998

EB Paved Fall 1997
I-94 Pavement Surface Appearance

Deteriorated area Non-Deteriorated

WB Paved Summer 1998

No sign of joint deterioration

EB Paved Fall 1997
I-94 near Michigan City

**WB**

1. Worst of the joint deterioration

- **Section 1:** Worst deterioration
- **Section 2:** No visible deterioration

**EB**

1. Worst of the joint deterioration

- **Section 3:** No visible deterioration
- **Section 4:** Unsealed joints
- **Section 5:** No fly ash

**Not to scale**

- **Sawn L-joint**
- **Wheel path**
- **Mid-panel**
- **Other**

**Fly ash**

**WB Paved Summer 1998**

- **Section 1:** Worst deterioration
- **Section 2:** No visible deterioration

**EB Paved Fall 1997**

- Different mix water, milder temps
- **Section 3:** No visible deterioration
- **Section 4:** Unsealed joints
- **Section 5:** No fly ash
I-94 Sealed Joints

WB Sealed Joints: Nice smooth saw cut in top ~2” then ragged concrete below 2”. What’s causing this? Saw damage during construction? The beginning of a deteriorated joint?

EB Sealed Joint: Smooth saw cut from 0”- 2.5” depth, then remaining saw cut face more ragged
I-94 EB Unsealed Joints

- Joints at surface look good.
- Smooth single saw cut. No signs of deterioration in unsealed joints.
- Occasional corner cracks in slabs with unsealed joints, more common in slabs built w/o fly ash.
### ASTM C457 Air void Analysis

<table>
<thead>
<tr>
<th>Core</th>
<th>Total Air (%)</th>
<th>Specific Surface (in²/in²)</th>
<th>Spacing Factor (inch)</th>
<th>Infilled Voids (SEM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1C1</td>
<td>2.9</td>
<td>554</td>
<td>0.011</td>
<td>Y</td>
</tr>
<tr>
<td>1D1</td>
<td>5.4</td>
<td>426</td>
<td>0.011</td>
<td>Y</td>
</tr>
<tr>
<td>1J1</td>
<td>3.6</td>
<td>477</td>
<td>0.011</td>
<td>Y</td>
</tr>
<tr>
<td>1W1</td>
<td>5.0</td>
<td>294</td>
<td>0.016</td>
<td>VL</td>
</tr>
<tr>
<td>1D2</td>
<td>7.9</td>
<td>480</td>
<td>0.007</td>
<td>---</td>
</tr>
<tr>
<td>1F2</td>
<td>3.5</td>
<td>517</td>
<td>0.011</td>
<td>Y</td>
</tr>
<tr>
<td>1S3</td>
<td>7.0</td>
<td>548</td>
<td>0.007</td>
<td>VL</td>
</tr>
<tr>
<td>2D1</td>
<td>9.1</td>
<td>489</td>
<td>0.006</td>
<td>Y</td>
</tr>
<tr>
<td>2F1</td>
<td>3.9</td>
<td>517</td>
<td>0.010</td>
<td>Y</td>
</tr>
<tr>
<td>3D4</td>
<td>5.0</td>
<td>693</td>
<td>0.007</td>
<td>VL</td>
</tr>
<tr>
<td>3F4</td>
<td>3.1</td>
<td>849</td>
<td>0.007</td>
<td>Y</td>
</tr>
<tr>
<td>3J5</td>
<td>6.3</td>
<td>619</td>
<td>0.006</td>
<td>---</td>
</tr>
<tr>
<td>3S6</td>
<td>5.6</td>
<td>702</td>
<td>0.006</td>
<td>N</td>
</tr>
<tr>
<td>4D4</td>
<td>5.6</td>
<td>702</td>
<td>0.006</td>
<td>N</td>
</tr>
<tr>
<td>4F4</td>
<td>5.0</td>
<td>665</td>
<td>0.007</td>
<td>N</td>
</tr>
<tr>
<td>5D4</td>
<td>6.3</td>
<td>605</td>
<td>0.006</td>
<td>Y</td>
</tr>
<tr>
<td>5F4</td>
<td>5.4</td>
<td>487</td>
<td>0.009</td>
<td>Y</td>
</tr>
<tr>
<td>5W4</td>
<td>5.4</td>
<td>487</td>
<td>0.009</td>
<td>N</td>
</tr>
</tbody>
</table>

**From panels w/ Deteriorated Joints**

Y = Yes  
VL = Very Little  
-- = not examined  

**Good Freeze/Thaw Performance (per PCA)**

Specific Surface  
\[ > 600 \text{ in}^2/\text{in}^3 \]

Spacing Factor  
\[ < 0.008 \text{ in} \]
I-94 Study Key Observations and Recommendations

- Drainability at the joints was reduced.
- Double saw-cut sealed joints showed some degree of distress compared to the single saw-cut unsealed joints.
- The air void system in all concrete associated with deteriorated joints was inadequate even when it met total % air specification.
- **Key Recommendation**: Make sure the IN-PLACE air void system is adequate.
One item that we noticed very early on is that water is part of the story, however the fluid is not just water, it is a salt soln.

- Changes to fluid properties
- Changes saturation
- Potential reactions

*Slide courtesy of J. Weiss*
• NaCl salt one of the most common deicers used on concrete pavements
• Four phases – water, ice, concentrated solution, and NaCl·2H₂O

*Slide courtesy of J. Weiss*
Path 1: FT damage is expected.
Path 2: FT damage is expected.
Path 3: No FT damage is expected.

Slide courtesy of J. Weiss
One cycle low temp freeze-thaw tests: \( +24 \, ^\circ\text{C} \) to \( -40 \, ^\circ\text{C} \)

An unusual exothermic behavior at higher concentration

---

*Slide courtesy of J. Weiss* (Farnam et al., 2013)
One cycle low temp freeze-thaw tests: $+24 \, ^\circ\text{C}$ to $-40 \, ^\circ\text{C}$

An unusual exothermic behavior at higher concentration

\[3\text{Ca(OH)}_2 + \text{CaCl}_2 + 12\text{H}_2\text{O} \rightarrow \text{CaCl}_2 \cdot 3\text{Ca(OH)}_2 \cdot 12\text{H}_2\text{O}\]  
(Calcium oxychloride)

Slide courtesy of J. Weiss  
NaCl Concentration (%)  
(Farnam et al., 2013)
FIELD SPECIMENS
Transverse Damaged Joint from US 67
\[ C_4A\tilde{S}H_{12} + 2Cl \rightarrow C_3A \cdot CaCl_2 \cdot 10H + C\tilde{S}H_2 \]

2\(C\tilde{S}H_2 + C_4A\tilde{S}H_{12} + 16H \rightarrow C_6A\tilde{S}_3H_{32}\]
SEM Observations

\[ C_4A\bar{S}H_{12} + 2Cl \rightarrow C_3A \cdot CaCl_2 \cdot 10H + C\bar{S}H_2 \]

Friedel’s salt
SEM Observations

$2\text{C}_4\text{S}_2\text{H}_8 + \text{C}_4\text{A}_3\text{S}_3\text{H}_{32} + 16\text{H} \rightarrow \text{C}_6\text{A}_3\text{S}_3\text{H}_{32}$

Ettringite
SEM Observations

\[ 2C\tilde{S}H_2 + C_4A\tilde{S}H_{12} + 16H \rightarrow C_6A\tilde{S}_3H_{32} \]  

Ettringite
SEM Observations

- Voids frequently filled with Ettringite and/or Friedel’s salt
LABORATORY SPECIMENS
Wetting and Drying Cycles

- 8 hrs of drying at 23°C (72°F)
- 16 hrs of wetting at 4°C (40°F)
Type I specimens after W/D cycles in 25% MgCl$_2$ & 28% CaCl$_2$ solutions
Type I specimens after 168 W/D cycles in 28% $\text{CaCl}_2$ solution

Testing stopped after 168 W/D cycles due to extensive surface deterioration.
Fly Ash specimens after W/D cycles in 25% MgCl$_2$ & 28% CaCl$_2$ solution

168 W/D cycles in 28% CaCl$_2$  
210 W/D cycles in 25% MgCl$_2$
Freezing and Thawing Cycles

- **Freezing**
  - 1 hr of cooling and 11 hrs of freezing at -0.4°F (-18°C)

- **Thawing**
  - 1 hr of heating and 11 hrs at 71.6°F (22°C)
F/T Exposure - Type I & Fly Ash Specimens

Type I & Fly Ash specimens after 166 F/T cycles in 15% MgCl₂ solution

Type I & Fly Ash specimens after 166 F/T cycles in 17% CaCl₂ solution
(a) PC-CaCl$_2$-W/D

(b) PC-MgCl$_2$-W/D

(c) PC-NaCl-W/D

(d) PC-DIW-W/D
Field Specimens

- Compared to laboratory specimens the field specimens exhibited larger degree of infilling of the air voids (AFt, Friedel’s salt)

- Infilling increased with depth and was more extensive in areas located near the sealed joints

- In general, specimens obtained from mid-span of the slab exhibited better air void parameters, good FT resistance and relatively lower rates of absorption compared to cores from joints
Summary - Mechanisms of Joint Deterioration

1. Freeze-thaw Damage of Saturated Concrete

- Increased saturation in the presence of the deicers
- Uncracked (or tight) joints under the saw cut
- Leaky joints, presence of backer rod that prevents (or reduces) air drying of the joints
- Paste with inadequate air void system in the to reduce saturation
- Poor drainage of the subbase
Summary - Mechanisms of Joint Deterioration

2. Chemical Deterioration of the Paste

- Formation of expansive oxychlorides (at temp. > 32°F) due to chemical reactions of chlorides with calcium hydroxide.

- Formation of expansive deposits in the paste (Friedels’ salt, ettringite)

- Formation of secondary deposits that accelerate saturation of air void system
How to Address Joints Problem?

• Design & Specification Changes
  ➢ Reduce concrete strength – better chance of getting longitudinal joint to crack under saw cut
  ➢ Use low w/cm mixtures (~0.40 to 0.42)
  ➢ Use SCM whenever possible
  ➢ Ensure adequate quality air void system behind the paver
How to Address Joints Problem?

• Design & Specification Changes
  - Reduce concrete strength – better chance of getting longitudinal joint to crack under saw cut
  - Use low w/cm mixtures (~0.40 to 0.42)
  - Use SCM whenever possible
  - Ensure adequate quality air void system behind the paver
How to Address Joints Problem?

• Design & Specification Changes

  ➢ Investigate reducing area of steel at longitudinal joint – allow joint to open and water to drain

  ➢ Consider using smooth bar at longitudinal joints

  ➢ Stabilize drainage layer – increased stiffness = increased drag/friction – better chance crack at longitudinal joint
How to Address Joints Problem?

- Design & Specification Changes
  - Eliminate sealant & backer rod at longitudinal joints to allow for air drying of joint
  - Change type of sealant
  - Spray joint faces with penetrating sealer – minimize water (and salt) migration into concrete at joint faces – current point of deterioration
How to Address Joints Problem?

- Design & Specification Changes
  - Provide adequate drainage at all locations
  - Limit usage of aggressive salts to situations where temperatures make their use necessary for safety
  - Use cementitious systems with high Si/Ca ratio (more resistant to oxychloride formation)
Acknowledgements

• INDOT/JTRP
• National Concrete Pavement Technology Center
• Jason Weiss
• Nancy Whiting
• Daria Jozwiak-Niedzwiedzka
• Jitendra Jain
• Maria del Mar Arribas,
• Mateusz Radlinski
• Adam Rudy
• Raikhan Tokpatayeva
• Parth Panchmatia
• Hyun Gu Jeong
• Mike Byers
• Dick Newell
• Tommy Nantung
Thank you