What Did We Learn from the Minnesota Test Road?

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- Concrete Paving Association of Minnesota
- American Concrete Pavement Association
- North Central Cement Council
- Portland Cement Association

MnROAD Background

- Location and Environment
- History of Test Sections
  - Original PCC Paving
    - Mainline 5-year (1992)
    - Mainline 10-year (1993)
    - LVR (1993)
  - 1994-2006 Additional Cells
    - Whitetopping (1997)
    - Add 1 LVR Cells (2000)
    - Pervious Concrete Driveway (2005)

LVR Design Layout and Background

- Original LVR Concrete Cells: 36-40
- 3-yr/100,000 ESAL Design
- 110mm [4.2-in] design increased to MnDOT minimum of 150mm [6 in]

Mn/ROAD Lessons Learned:
Low-Volume Road Concrete Pavement Design and Performance

<table>
<thead>
<tr>
<th>Cell</th>
<th>Nominal Slab Thickness (mm)</th>
<th>As-Built Avg Slab Thickness (mm)</th>
<th>Joint Spacing (m)</th>
<th>Dowel Dia. (mm)</th>
<th>Subbase Type and Thickness (mm)</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>150</td>
<td>145/166</td>
<td>4.6</td>
<td>25</td>
<td>132mm +150mm/1.85 in sand</td>
<td></td>
</tr>
<tr>
<td>37</td>
<td>150</td>
<td>147/162</td>
<td>3.7</td>
<td>N/A</td>
<td>150mm +150mm/1.85 in sand</td>
<td></td>
</tr>
<tr>
<td>38</td>
<td>150</td>
<td>145/164</td>
<td>4.6</td>
<td>25</td>
<td>150mm +150mm</td>
<td></td>
</tr>
<tr>
<td>39</td>
<td>150</td>
<td>148/166</td>
<td>6.1</td>
<td>25</td>
<td>150mm +150mm</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>178/140/178</td>
<td>170/180</td>
<td>4.6</td>
<td>N/A</td>
<td>132mm +150mm Thickened Edge</td>
<td></td>
</tr>
</tbody>
</table>

Subgrade Stiffness: R-value = 12 (Mh ~ 28 MPa [4000 psi])
Subbase and Concrete Mixture Details

- **Cl5sp subbase = 25mm max size, dense-graded aggregate with 10-15% crushed particles**
- **Concrete mixture:**
  - Coarse Aggregate
    - (3/4-in-plus [19-mm-plus]): 922 lb/yd³ [548 kg/m³]
    - (3/4-in-minus [19-mm-minus]): 908 lb/yd³ [540 kg/m³]
  - Sand (SSD condition): 1211 lb/yd³ [720 kg/m³]
  - Type I Cement: 511 lb/yd³ [304 kg/m³]
  - Class C Fly Ash: 86 lb/yd³ [51 kg/m³]
  - Air-entraining admixture (target air content of 5.5 percent)
  - Resulting water-cementitious materials ratio (w/(c+p)) = 0.46

MnROAD LVR Traffic Loadings

- Est. Cumulative ESALs (through 2006):
  - Inside Lane PCC: 330,000 ESALs
  - Outside Lane PCC: 310,000 ESALs

LVR General Performance Trends

- Good ride quality (in context of loads, pavement class)
- Very little distress
- Little significant maintenance

LVR 355-kN Lane IRI History

- Typical MnDOT Highway Performance Threshold IRI = 2.16 m/km
- Linear projection: 17-62 years of service
- 500,000 - 1,600,000 ESALs
- Thinner sections (100 – 125mm) may have proven adequate, even for heavy trucks
- Cell 32 – 5-in pavement constructed in 2000

IRI Observations

- After 12 years, 300,000+ ESALs:
  - Rates of deterioration vary between sections
    - 0.024 – 0.068 m/km/yr [1.5 – 4.3 in/mi/yr]
    - Linear projection: 17-62 years of service
    - 500,000 – 1,600,000 ESALs
  - Thinner sections (100 – 125mm) may have proven adequate, even for heavy trucks
    - Cell 32 – 5-in pavement constructed in 2000
IRI Observations

- Design details correlated with IRI for LVR pavements
  - Strong influence of dowels
  - Modest influence of foundation design, panel length, etc.
- Example:
  - Cell 40 (no dowels, std subbase) had highest initial IRI, highest rate of IRI increase
  - Cell 37 (dowels, thicker subbase, sand subcut) had lowest initial IRI, lowest rate of IRI increase

LVR 355-kN Lane IRI History

LTE History for Doweled LVR Cells
(355-kN [80-kip] lanes)

LTE History for Undoweled LVR Cells
(355-kN [80-kip] lanes)

Deflection Test Data, Mar-Apr 2007

<table>
<thead>
<tr>
<th>Test Cell</th>
<th>Average Loaded Joint Deflection, mm</th>
<th>Average Transverse Joint LTE, %</th>
<th>Average Differential Deflection, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>36 (deep foundation, doweled)</td>
<td>0.17/0.17</td>
<td>69/90</td>
<td>0.016/0.023</td>
</tr>
<tr>
<td>37 (deep foundation, undoweled)</td>
<td>0.30/0.31</td>
<td>42/42</td>
<td>0.17/0.18</td>
</tr>
<tr>
<td>38 (std foundation, doweled)</td>
<td>0.36/0.37</td>
<td>95/97</td>
<td>0.034/0.048</td>
</tr>
<tr>
<td>39 (std foundation, undoweled)</td>
<td>0.32/0.34</td>
<td>92/99</td>
<td>0.026/0.038</td>
</tr>
<tr>
<td>40 (std foundation, undoweled)</td>
<td>0.42/0.25</td>
<td>83/93</td>
<td>0.20/0.049</td>
</tr>
</tbody>
</table>
**Deflection Testing Observations**

- Significant impact of dowels on deflections and LTE, even for thin pavements.
- Other design enhancements had little impact on performance of the study sections.
- For undoweled pavements, deep free-draining foundation and shorter panels (3.7m vs. 4.6m) provided higher LTE, lower deflections and less distress.

Cost-effective?

**LVR PCCP Distress Summary**

As of June 2006:

- Cells 36 – 37: No significant distress
- Cell 38: 1 panel (of 33) medium-severity; 2 panels high-severity
- Cell 39: 1 panel of 25 high-severity
- Cell 40: 1 panel (of 33) high-severity
- 1 high-severity corner break
- Up to 47% joint sealant damage

Transverse cracking is over utility trenches. Possibly accelerated by long panels (L/t > 24)

**LVR Faulting Measures (11/2006)**

<table>
<thead>
<tr>
<th>Test Cell</th>
<th>Average Joint Faulting (mm)</th>
<th>Maximum Joint Faulting (mm)</th>
<th>Std. Dev. Joint Faulting (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>36 (doweled)</td>
<td>0.43/0.46</td>
<td>1.1/1.6</td>
<td>0.58/0.32</td>
</tr>
<tr>
<td>37 (undoweled)</td>
<td>0.61/0.33</td>
<td>1.5/0.89</td>
<td>0.61/0.38</td>
</tr>
<tr>
<td>38 (doweled)</td>
<td>0.15/0.48</td>
<td>1.2/1.2</td>
<td>0.61/0.46</td>
</tr>
<tr>
<td>39 (doweled)</td>
<td>0.41/0.30</td>
<td>2.1/1.2</td>
<td>0.76/0.58</td>
</tr>
<tr>
<td>40 (undoweled)</td>
<td>2.64/1.50</td>
<td>5.0/4.3</td>
<td>1.1/1.3</td>
</tr>
</tbody>
</table>

Typical failure criterion for faulting = 6mm for short panels

**MAINTENANCE LOG**

No significant maintenance or rehabilitation has been performed on any of the original MnROAD low volume road concrete pavement test cells.

All other original cells on the low-volume road test loop have required significant maintenance or reconstruction (some more than once).

**Performance Prediction**

- One objective of MnROAD: validate pavement design procedures.
- Burnham and Pirkl (1997) used as-built parameters with several design procedures to predict service life of MnROAD test cells.
- This study updated that work using MEPDG and current IRI trends.

**Serviceability Life Predictions**

<table>
<thead>
<tr>
<th>Test Cell</th>
<th>Current Avg. IRI Increase per Year (157-kN lane pressure)</th>
<th>Projected Total Life</th>
<th>MnDOT Design Method (50% and 75% Reliability)</th>
<th>AASHTO 1993 Method (50% and 75% Reliability)</th>
<th>MEPDG v1.000 (50% and 75% Reliability)</th>
<th>1984 PCA Method*</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>0.045/28</td>
<td>15.5</td>
<td>33.423.7</td>
<td>27/17</td>
<td>125.8</td>
<td></td>
</tr>
<tr>
<td>37</td>
<td>0.034/21</td>
<td>37.5</td>
<td>39.821.4</td>
<td>19/12</td>
<td>41.7</td>
<td></td>
</tr>
<tr>
<td>38</td>
<td>0.027/21</td>
<td>33.5</td>
<td>40.932.2</td>
<td>25/17</td>
<td>101.8</td>
<td></td>
</tr>
<tr>
<td>39</td>
<td>0.067/20</td>
<td>24.5</td>
<td>27.834.8</td>
<td>13/8</td>
<td>97.1</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>0.064/17</td>
<td>56.0</td>
<td>54.629.8</td>
<td>11/4</td>
<td>65.7</td>
<td></td>
</tr>
</tbody>
</table>

Service life estimates based on 7,000,000 b-passes/yr, terminal PSR = 2.5, 15% slab cracking.

*Service life is for cracking criterion only, not for erosion criterion.
Effects of Design and Construction Variables on Performance

**Panel Geometry:**
- No cracking in cell with shortest panels
- Longest panels did not have the most cracking
- Transverse cracking associated with utility cuts

**Dowels**
- Highly effective in reducing deflections, increasing LTE
- Undoweled pavements had higher deflections, lower LTE, and more seasonal variability in measurements.

**Foundation Design**
- Thick foundations (and associated drainage improvements) produced modest performance improvements on the LVR.
  - This was not true for the mainline pavements, but that’s a different presentation!
- Design used on Cells 36 and 37 (total pavement thickness of 2.1m) is probably not cost-effective for LVR applications.
- Data may suggest performance differences for different in situ foundation support.

**Thickened Edge:**
- Not effective on this project (combined with no dowels and std foundation).

Implications for Design and Construction

- Concrete pavements with D < 150mm can provide good long-term performance, even in the presence of heavy loads.
- The use of contractor incentives should be evaluated as a tool to reduce initial pavement IRI.
- Steps should be taken to avoid curl/warp in concrete pavement construction – especially for thin pavements.
Implications for Design and Construction

- Designers should be aware of the apparent accuracy and precision of current design procedures for thin concrete pavements.
- In this study, the MEPDG at 50% reliability predicted observed and projected IRI trends most accurately and precisely.

5-in [125mm] Concrete Pavement Study

Cell 32 Profile: Then and Now ...

1993 Construction 1996 Reconstruction 2000 Reconstruction

MnROAD Cell 32 – 5-inch PCC

- Nominally 127mm [5-in] PCC
  - Behind paver: 121 – 140 mm (avg. 130mm)
  - Coring: 120 – 150 mm (avg. 140mm)
- 178mm [7 in] Class 1/1c subbase
- Subgrade R = 12 (M_y = 28 MPa [4000 psi])
- 3.0m x 3.7m [10 ft x 12 ft] undoweled panels
- 127mm [5-in] aggregate shoulders
- Hot-poured asphalt joint sealant
- Heavy traffic for more than six years:
  - 355-kN [80-kip] vehicles inside lane, 4 days/week
  - 453-kN [102-kip] outside lane 1 day/week

Cell 32 Foundation Aggregate

Concrete Mixture

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>% Passing Class 1</th>
<th>Class 1c (special)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19mm [¾ in]</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>9.5 mm [3/8 in]</td>
<td>60 – 90</td>
<td>65 – 90</td>
</tr>
<tr>
<td>4.75 mm [#4]</td>
<td>40 – 85</td>
<td>65 – 80</td>
</tr>
<tr>
<td>2.40 mm [#10]</td>
<td>25 – 70</td>
<td>25 – 70</td>
</tr>
<tr>
<td>0.425mm [#40]</td>
<td>10 – 45</td>
<td>10 – 45</td>
</tr>
<tr>
<td>0.075mm [#200]</td>
<td>4 – 12</td>
<td></td>
</tr>
<tr>
<td>PI</td>
<td>0 – 0.6 max</td>
<td></td>
</tr>
</tbody>
</table>

Crushing Crushed particles not allowed.

- Coarse Aggregate: 1026 kg/m³ [1735 lb/yd³]
  - 3/4-in-plus [19-mm-plus]: 615 lb/yd³ [366 kg/m³]
  - 3/8-in-memory [19-mm-memory]: 760 lb/yd³ [452 kg/m³]
  - #4: 360 lb/yd³ [208 kg/m³]
- Sand: 817 kg/m³ [1390 lb/yd³]
  - #67: 196 lb/yd³ [115 kg/m³]
  - 42 /"safety grit": 446 lb/yd³ [264 kg/m³]
- Type I Cement: 364 lb/yd³ [228 kg/m³]
- GGBF Slag: 206 lb/yd³ [122 kg/m³]
- Water: 218 lb/yd³ [130 kg/m³]
  - w/c = 0.57
  - W/C = 0.57
- Water reducer
  - 5 oz/100 lb cement (325 ml/100g cement)
Concrete Mixture Strength

- **Compressive Strength (f’c):**
  - 3-day: 14.2 MPa [2057 psi];
  - 7-day: 18.8 MPa [2729 psi];
  - 28-day: 27.5 MPa [3988 psi];

- **Flexural Strength (f’r):**
  - 3-day: 3.0 MPa [441 psi]
  - 7-day: 3.9 MPa [564 psi]
  - 28-day: 4.9 MPa [714 psi]

Cell 32 Performance to Date

IRI History – Cell 32

MnROAD Cell 32 Distresses

**No significant distress until 2005...**

MnROAD Cell 32 Distresses (as of October-November 2006)

- **Inside (80-k) Lane:**
  - 3m [8 ft] of medium-severity longitudinal cracking in 1 panels
  - No transverse cracking (46 panels)
  - 2.5 mm [0.1 in] average faulting (Nov 2006)
  - 1 small low-severity joint spall

- **Outside (102-k) Lane:**
  - 10m [30 ft] of low- and medium-severity longitudinal cracking in 3 panels
  - 2 low-severity transverse cracks in 46 panels (not yet full-width)
  - 0.8 mm [0.1 in] average faulting (Nov 2006)
  - 1 small low-severity joint spall

*...and no rutting or potholes!*
**Cell 32 Faulting History**

![Faulting History Graph]

**Cell 32 Maintenance**

None (through 2006).

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**Relating Cell 32 to “The Real World”**

<table>
<thead>
<tr>
<th>School Bus</th>
<th>Transit Bus</th>
<th>Garbage Truck</th>
<th>Tractor Semi-Truck</th>
<th>Other Heavy Trucks</th>
<th>Life in 10,000(\text{ESALs}),\text{years}</th>
<th>Typ. Load</th>
<th>Typ. Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>1 per day, 2 days per wk</td>
<td>2 per week</td>
<td>1 per week</td>
<td></td>
<td>5.0</td>
<td>12.0</td>
<td></td>
</tr>
<tr>
<td>Collector</td>
<td>9 per day, 6 days per wk</td>
<td>4 per week</td>
<td>2 per week</td>
<td>20 per day</td>
<td>10</td>
<td>6.7</td>
<td></td>
</tr>
<tr>
<td>Arterial</td>
<td>50 per day, 3 days per week</td>
<td>3 per day</td>
<td>15 per day</td>
<td>100 per day</td>
<td>0.8</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>County Road</td>
<td>1 per day, 3 days per wk</td>
<td>0</td>
<td>100 per day</td>
<td>300 per day</td>
<td>0.6</td>
<td>1.0</td>
<td></td>
</tr>
</tbody>
</table>

---

**Validation of LVR Design Procedures**

### 1993 AASHTO LVR Design for 50k-300k ESALs:
- Dowelled joints, 150mm [6-in] subbase, \(f'r = 4.1\text{MPa} [600 \text{psi}]\), plus ...
  - 50% Reliability: 130mm [5 in] PCC
  - 75% Reliability: 130 – 150 mm [5 – 6 in] PCC

### Cell 32:
- Undowelled, 180mm [7-in] subbase, \(f'r = 4.9\text{MPa} [720 psi]\), 170k ESALs to date, little distress, acceptable IRI for LVR

---

**Validation of LVR Design Procedures**

- **Cell 32 may show 1993 AASHTO LVR Design to be conservative**

- **Important, however, to remember “accelerated loading” nature of MnROAD LVR ...**
  - Reduced opportunity for environmental effects and interaction

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**Validation of LVR Design Procedures**

- **PCA Simplified Design Procedure:**
  - Developed for local roads where axle load data unavailable
  - Fatigue consumption and erosion criteria
  - Assumes \(f'r = 4.5\text{MPa} [650 \text{psi}]\), medium subbase support, no dowels, no shoulder or curb, 20 years
    - 125 – 140 mm [5.0 – 5.5 in] PCC for residential applications and 3k – 55k heavy trucks
    - 150 mm [6 in] PCC for collector/rural road applications and up 15k heavy trucks
Validation of LVR Design Procedures

Cell 32:
- 355-kN [80-kip] lane has carried more than 46k heavy trucks without significant distress or sign of failure.
  - Exceeds PCA expectations for 125-mm [5-in] residential pavement [5840 trucks over 20 years]
  - Exceeds PCA expectations for 150-mm [6-in] collector/rural pavement [<30000 trucks over 20 years]

Cell 32 appears to show PCA Simplified Design to be conservative
- Must consider accelerated nature of MnROAD LVR test and “built-in” reliability of PCA Simplified Design

MnROAD (125mm [5-in]) PCC - What have we learned?

- Thin (125-mm [5-in]) PCC pavements can be built successfully on lower volume roads, even when some heavy loads are expected.
- Quality of materials and construction must be good.
- Short panels may be key to good performance.
- Generally accepted concrete pavement design procedures may significantly underestimate performance life (or overestimate required thickness) for thinner concrete pavements.

MnROAD (125mm [5-in]) PCC - What have we learned?

- Many thin concrete pavements (e.g., 125 – 150mm) were built on residential streets and other lower-volume roads throughout the U.S. in the 1940s, 50s and 60s and are still in service today.
- Minor design enhancements (e.g., small dowels, edge support) may further improve performance of thinner concrete pavements.

MnROAD (125mm [5-in]) PCC: What have we learned?

Whitetopping Design, Construction, Performance and Rehabilitation
### 1997 Whitetopping Traffic Loadings

- **Full stream of diverted I-94 westbound traffic**
- **1994:** 38,000 AADT (two-way), 12% heavy trucks
- **2006:** 66,000 AADT (two-way), 12.5% heavy trucks

### Oct 2004 Reconstruction of Cells 93-95

- **New Cells 60-63:**
  - h = 4 or 5 in, 5 ft x 6 ft, no fibers (cost, effectiveness issues)
  - Sealed and unsealed joints

- **Goals:**
  - Determine optimum slab thickness
  - Evaluate value of AC-PCC bond for these designs
  - Investigate effects of layer thickness on reflective cracking
  - Evaluate need and cost-effectiveness of joint sealing
  - Provide added data for development/validation of design procedures

### Summary of 2004 Whitetopping Design Features

<table>
<thead>
<tr>
<th>Cell</th>
<th>Nominal Slab Thickness (in)</th>
<th>Nominal Asphalt Thickness (in)</th>
<th>Panel Size (ft x ft)</th>
<th>Dowels</th>
<th>Sealed Joints</th>
<th>Fiber Reinforcement Type</th>
<th>Service Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>5</td>
<td>7</td>
<td>5 x 8</td>
<td>None</td>
<td>Yes</td>
<td>None</td>
<td>2004 – present</td>
</tr>
<tr>
<td>61</td>
<td>5</td>
<td>7</td>
<td>5 x 8</td>
<td>None</td>
<td>No</td>
<td>None</td>
<td>2004 – present</td>
</tr>
<tr>
<td>62</td>
<td>4</td>
<td>8</td>
<td>5 x 8</td>
<td>None</td>
<td>Yes</td>
<td>None</td>
<td>2004 – present</td>
</tr>
<tr>
<td>63</td>
<td>4</td>
<td>8</td>
<td>5 x 8</td>
<td>None</td>
<td>No</td>
<td>None</td>
<td>2004 – present</td>
</tr>
</tbody>
</table>

### Summary of 1997 Whitetopping Design Features

<table>
<thead>
<tr>
<th>Cell</th>
<th>Nominal Slab Thickness (in)</th>
<th>Nominal Asphalt Thickness (in)</th>
<th>Panel Size (ft x ft)</th>
<th>Dowels</th>
<th>Sealed Joints</th>
<th>Fiber Reinforcement Type</th>
<th>Service Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>92</td>
<td>6</td>
<td>7</td>
<td>10 x 12</td>
<td>Yes</td>
<td>Polyprop.</td>
<td>1997 – present</td>
<td></td>
</tr>
<tr>
<td>93</td>
<td>4</td>
<td>9</td>
<td>4 x 4</td>
<td>None</td>
<td>Yes</td>
<td>Polyprop.</td>
<td>1997–2004</td>
</tr>
<tr>
<td>94</td>
<td>3</td>
<td>10</td>
<td>4 x 4</td>
<td>None</td>
<td>Polyprop.</td>
<td>1997–2004</td>
<td></td>
</tr>
<tr>
<td>95</td>
<td>3</td>
<td>10</td>
<td>5 x 6</td>
<td>None</td>
<td>Polyolefin</td>
<td>1997–2004</td>
<td></td>
</tr>
<tr>
<td>96</td>
<td>6</td>
<td>7</td>
<td>5 x 6</td>
<td>None</td>
<td>Yes</td>
<td>Polyprop.</td>
<td>1997–present</td>
</tr>
<tr>
<td>97</td>
<td>6</td>
<td>7</td>
<td>10 x 12</td>
<td>None</td>
<td>Polyprop.</td>
<td>1997–present</td>
<td></td>
</tr>
</tbody>
</table>
Concrete Mixture Details

<table>
<thead>
<tr>
<th>Saturated/Solids Contents Ratio</th>
<th>Cells 92-94, 96-97</th>
<th>Cell 95</th>
<th>Cells 60-63</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water/Cementitious Ratio</td>
<td>0.38</td>
<td>0.41</td>
<td>0.40</td>
</tr>
<tr>
<td>Cement, lb/yd (kg/m³)</td>
<td>850 (684)</td>
<td>855 (684)</td>
<td>400 (321)</td>
</tr>
<tr>
<td>Class C Fly Ash, lb/yd (kg/m³)</td>
<td>0</td>
<td>0</td>
<td>170 (136)</td>
</tr>
<tr>
<td>Fine Aggregate, lb/yd (kg/m³)</td>
<td>1817 (1464)</td>
<td>1297 (1064)</td>
<td>540 (386)</td>
</tr>
<tr>
<td>CA (L.5-in minus), lb/yd (kg/m³)</td>
<td>0</td>
<td>0</td>
<td>1059 (629)</td>
</tr>
<tr>
<td>CA (3/4-in minus), lb/yd (kg/m³)</td>
<td>1600 (949)</td>
<td>1500 (890)</td>
<td>866 (514)</td>
</tr>
<tr>
<td>CA (3/8-in minus), lb/yd (kg/m³)</td>
<td>277 (164)</td>
<td>277 (164)</td>
<td>0</td>
</tr>
<tr>
<td>Fiber Content, lb/yd (kg/m³), %</td>
<td>3 (2), 0.45%</td>
<td>25 (18), 8.5%</td>
<td>0, 0%</td>
</tr>
<tr>
<td>Admixtures, oz/100 lb CM (ml/100 kg CM)</td>
<td>1000, 34.0 (22.1)</td>
<td>11.5 (7.5)</td>
<td>KB-1000, 34.4</td>
</tr>
<tr>
<td>Measured Air, percent</td>
<td>5.75</td>
<td>7.2</td>
<td>7.6</td>
</tr>
<tr>
<td>Measured Slump, in (mm)</td>
<td>2.5 (65)</td>
<td>2.75</td>
<td>1.5 (38)</td>
</tr>
<tr>
<td>28-day Compressive Strength, psi (MPa)</td>
<td>6100 (42.1)</td>
<td>5300 (36.5)</td>
<td>4085 (28.1)</td>
</tr>
</tbody>
</table>

MnROAD Whitetopping Traffic Loadings

<table>
<thead>
<tr>
<th>Time to 2.8M ESALs, yrs</th>
<th>Time to 6.4M ESALs, yrs</th>
<th>Time to 11.7M ESALs, yrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential Street</td>
<td>&gt;50</td>
<td>&gt;50</td>
</tr>
<tr>
<td>Collector</td>
<td>&gt;50</td>
<td>&gt;50</td>
</tr>
<tr>
<td>County Road</td>
<td>7</td>
<td>19</td>
</tr>
</tbody>
</table>

Development and Measurement of Pavement Distress

- Initial IRI is good
- Increases generally proportional to PCC thickness and traffic
- Exceptions for Cells 95 and 93 due to joint placement
- Cells 92 and 96 still good
- Use of dowels (92) and smaller panels (96) to reduce curl/warp
- IRI irregularities due to repairs

1997 Whitetopping IRI Histories

- First cracks observed in June 1998 (cells 93-95) – mostly corner breaks
- Some transverse cracking in Jan 1999 (~40°F)
- Greatest amount in cell 94 (3-in PCC, 4-ft panels)
- >70% of early cracking was reflective of AC cracks
- No cracking in 6-in slabs until 2001 (4 years, 3M ESALs)
Cell 93 Crack Development History

Source: Vandenbossche and Fagerness, 2002

Cell 94 Crack Development History

Source: Vandenbossche and Fagerness, 2002

Cell 95 Crack Development History

Source: Vandenbossche and Fagerness, 2002

Whitetopping Distress

Source: Vandenbossche and Fagerness, 2002

Cell 93 Reflection Crack, April 2001

Source: Burnham, 2005

Cell 95, November 2003

Source: Burnham, 2005
**2004 Cracking Summary**

<table>
<thead>
<tr>
<th>Test Cell Number</th>
<th>Corner cracks</th>
<th>Transverse cracks</th>
<th>Panels cracked (%)*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Driving Lane</td>
<td>Posting Lane</td>
<td>Driving Lane</td>
</tr>
<tr>
<td>02</td>
<td>45</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>04</td>
<td>391</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>06</td>
<td>20</td>
<td>16</td>
<td>5</td>
</tr>
</tbody>
</table>

* Panels required in 7001 not included.

**Oct 2006 Distress Summary for Surviving 1997 Cells**

<table>
<thead>
<tr>
<th>Cell</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3-in concrete 7 in HMA</td>
<td>6-in concrete 7 in HMA</td>
<td>6-in concrete 7 in HMA</td>
</tr>
<tr>
<td>Grade</td>
<td>2%</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>Longitudinal crack</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Transverse crack</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Dowel</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Joint seal</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

Oct 2006 Distress Summary for Surviving 2004 Cells

<table>
<thead>
<tr>
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<td>No</td>
</tr>
<tr>
<td>Joint seal</td>
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<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

**Distress Observations/Lessons**

- Joint location influences cracking
- Longitudinal placement w.r.t. wheel paths
- Transverse placement w.r.t. asphalt cracks
- 3-in 5x6 panels outperformed 4-in 4x4 panels
- Panel size influences cracking
- 3-in 10x12 panels have much more cracking than 3-in 5x6 panels
- Too early to comment on effect of joint sealing
Interlayer Bonding Studies: 3 Modes of Debonding

Each mode reduces slab support and increases PCC stresses.

Source: Vandenbossche, 2005

Evidence of bonding/debonding

Source: Burnham, 2005

Results of Forensic Work

- Debonding always occurred at slab edges or cracks (available water)
- Causes of debonding:
  - Stripping
  - Freeze-thaw
  - Debonding led to cracking

Source: Burnham, 2005

Concrete Strain Measurements

(9000-lb FWD, Cell 95)

Illustrates importance of considering seasonal effects in predicting performance life.

Concrete Strain Measurements

(9000-lb FWD, Cell 95)

Reflection Cracking

- Development = f(relative stiffnesses of AC and PCC layers, accumulated traffic loads)
  \[ D = \frac{E h^3}{12(1-\mu)^2} \]
- Reflection cracking is most likely when \( D_{AC} > D_{PCC} \)
  - Example 1:
    - \( E_{AC} = 4.0 \times 10^6 \text{ psi}, E_{PCC} = 4.0 \times 10^6 \text{ psi}, \mu_{AC} = 0.15, \mu_{PCC} = 0.35 \)
    - Reflection cracking likely when \( h_{AC} > 2h_{PCC} \)
  - Example 2:
    - \( E_{AC} = 4.0 \times 10^6 \text{ psi}, E_{PCC} = 1.5 \times 10^6 \text{ psi}, \mu_{AC} = 0.15, \mu_{PCC} = 0.35 \)
    - Reflection cracking likely when \( h_{AC} > 1.15h_{PCC} \)

Source: Vandenbossche, 2005

Pre-overlay Preparation to Minimize Reflective Cracking

- When feasible, place whitetopping joints directly over asphalt cracks.
- Alternative: prevent AC/PCC bond in vicinity of crack (reduce concentration of stress)
  - Asphalt-impregnated roofing paper, duct tape, fabric, silica sand, etc.
Use of fabric or “tar paper” to prevent reflection cracking

Saw cut of longitudinal joint to prevent bond and corner cracking due to mismatched transverse joints.

Use of Fiber Reinforcing

- Purposes:
  - Strengthen concrete
  - Reduce shrinkage cracks
  - Reinforce across cracks
  - No apparent effect on development of cracking
  - Polyolefin fibers bridged cracks
  - No significant benefit from polypropylene fibers

Source: Burnham, 2005

Rehabilitation of Whitetopping – Best Practices

- Best practices (Vandenbossche, 2005)
- Core to assess asphalt deterioration
- AC removal to 1” below lift interface using milling machines (opt. saw cuts) plus light jackhammers
- Bondbreaker material over AC cracks
- Prevent moisture loss at AC, surface
- Saw joints to T/2 ASAP; saw longitudinal joint between mismatched transverse joints

What have we learned?

- Project Selection

  - Good performance of thin (3 – 6 in) PCC under years of heavy traffic is due in part to good support
    - All MnROAD whitetopping cells constructed over at least 7 in of good AC
  - Recommendations:
    - Minimum 3 inches sound AC after milling
    - Core to insure AC quality

- Design and Construction

  - Avoid placing longitudinal joints near wheel paths
  - Avoid reflection cracking
    - Consider relative stiffnesses of AC and PCC layers
    - Provide local debonding at AC/PCC interface near cracks
  - Largest temperature gradients in thinnest PCC
    - Use small panels to minimize curl/warp, debonding
    - Polyolefin fibers provided benefit, polypropylene didn’t
  - Long-term benefits of joint sealing not yet determined

What have we learned?

- Behavior

  - Load-related strains are strongly affected by seasonal variations AC modulus
    - Consequences of predicting life in various climates and environments
### What have we learned?

#### Performance

- Performance of any thickness = \( f(\text{traffic volume, wheel placement, layer bonding}) \)
- Rate of reflective cracking = \( f(\text{traffic volume}) \)
- Bonding is essential for PCC \( \leq 4 \) in thick
  - After debonding, top-down cracking starts at approach corner
- Reflective cracking common for PCC \( < 5 \) in thick when bonded to AC \( \geq 6 \) in thick
- All test cells performed well for at least 7 years under heavy traffic (corresponding to > 50 years of typical traffic on lower volume roads)

### What have we learned?

#### Maintenance and Rehab

- Whitetopping panel replacement is relatively simple.
- Recommended best practices focus on:
  - achieving good bond,
  - avoiding reflective cracking,
  - providing good curing

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**Thank you for your time and attention!**