Design and Construction Guidelines for Thermally Insulated Concrete Pavements

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TPF-5(149) Acknowledgements

- MnDOT, LRRB, Caltrans, WsDOT
- FHWA
- TL: Tim Clyne
- Former and current students
- John Harvey (UC Davis), Nick Santero (MIT), Jim Signore (UC Berkeley)
• Literature Review
• LCCA
• **EICM Validation and Analysis**
• Evaluation of Response Models
• Development of Design Guidelines
• Development of Construction Guidelines
• Development of Synthesis
EICM Evaluation (1)

- A comprehensive sensitivity of the effect of climate on pavement performance predictions was conducted
  - Over 600 stations
- Environment has a significant impact on predicted pavement performance
- Many trends were reasonable
- However, differences in stations with similar climates were greater than expected
- Illustrated the need for high-quality climatic data
Blue < 16%  Green 16-25%  Yellow 26-40%  Red > 40%

- Trends are visible, but anomalies are present
• More than 10 million temperature measurements from PCC and AC/PCC
• Data was filtered using a program developed by Dr. Randal Barnes, UMN
• Subjected field data to 14 different tests to identify missing and insufficient data, sensors outliers, subset outliers
• Suspect data were flagged
MnROAD Data Screening Example

Figure 2

Cell 106, Sensor 28, Subset (UNK, 2, ML, 5)
MnROAD Data: Thermal Gradients in PCC
MnROAD Data and EICM (2)

- AC/PCC - Modeled
- PCC - Modeled

Percentage

Temperature Difference, (°C)

0% 20% 40% 60% 80% 100%

-10.0 -5.0 0.0 5.0 10.0 15.0
MnROAD Data vs. MEPDG Default

Note: MnROAD data for July

PCC Thermal Conductivity = 1.25 BTU/hr-ft-F
Model Predictions vs. Measured Data

- Good qualitative agreement, but the MEPDG underestimates frequencies of positive and negative temperature gradients
- Possible explanation is the MEPDG default thermal conductivity value is too high
- Action:
  - Adjust thermal conductivity to minimize the discrepancy for July
  - Verify the model for other months
Note: MnROAD data for July

PCC Thermal Conductivity = 0.94 BTU/ hr-ft- F
MnROAD Data and EICM, Pt. 2 (2)

Note: MnROAD data for March

PCC Thermal Conductivity = 0.94 BTU/ hr-ft- F
EICM Evaluation Conclusions

- MnROAD data confirmed thermal insulating effect of AC over PCC
- Quantitatively the EICM model accounts for this effect
- Calibration of thermal conductivity value gave better agreement between measured and modeled data
- Environmental effects should be considered with equal importance as traffic, design features and material properties
<table>
<thead>
<tr>
<th>Sieve</th>
<th>Percent Passing</th>
<th></th>
<th>Percent Passing</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>#200</td>
<td>8.7</td>
<td>A-1-a</td>
<td>5.2</td>
<td>A-3</td>
</tr>
<tr>
<td>#80</td>
<td>12.9</td>
<td>33</td>
<td>76.8</td>
<td></td>
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<tr>
<td>#40</td>
<td>20</td>
<td>94.3</td>
<td>95.3</td>
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<td>#10</td>
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<tr>
<td>3 1/2&quot;</td>
<td>97.6</td>
<td></td>
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</table>
Base Gradation: Predicted Trans Cracking

- A-1-a (MR = 40,000 psi)
- A-3 default (MR = 16,000 psi)
- A-3 modified (MR = 40,000 psi)

Percentage Cracking vs. Time (months)
Base Gradation: Modeled Res Modulus

- A-1-a (MR = 40,000psi)
- A-3 default (MR = 16,000psi)
- A-3 modified (MR = 40,000psi)
MEPDG: AC and PCC Thicknesses

• The sensitivity to PCC layer thickness was evaluated for two different AC thicknesses
  – 2” AC over 7” PCC
  – 3” AC over 6” PCC
• AADTT was adjusted to meet a target of 20% cracking
• All other inputs were identical
• PCC was adjusted ± 2” at 1” increments
MEPDG AC/PCC: Thickness and Cracking

2”AC / 7” PCC structure will support over 3000 AADTT more than 3” AC/ 6” PCC structure

<table>
<thead>
<tr>
<th>Traffic: 7420 AADTT</th>
<th>Traffic: 4325 AADTT</th>
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<tbody>
<tr>
<td><strong>AC Thickness</strong></td>
<td><strong>PCC Thickness</strong></td>
</tr>
<tr>
<td>2</td>
<td>5</td>
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<tr>
<td>2</td>
<td>6</td>
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<tr>
<td>2</td>
<td>7</td>
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<tr>
<td>2</td>
<td>8</td>
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<tr>
<td>2</td>
<td>9</td>
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### Slab Width and Joint Spacing

<table>
<thead>
<tr>
<th>Width</th>
<th>% Cracking</th>
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<tbody>
<tr>
<td></td>
<td>AC/PCC</td>
<td>PCC</td>
<td></td>
</tr>
<tr>
<td>12'</td>
<td>20.0</td>
<td>20.0</td>
<td></td>
</tr>
<tr>
<td>12.5'</td>
<td>2.3</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>13'</td>
<td>0.1</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>13.5'</td>
<td>0.1</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>14'</td>
<td>0.1</td>
<td>0.3</td>
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### Length

<table>
<thead>
<tr>
<th>Length</th>
<th>% Cracking</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>AC/PCC</td>
<td>PCC</td>
<td></td>
</tr>
<tr>
<td>12'</td>
<td>0.0</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>15'</td>
<td>20.0</td>
<td>20.0</td>
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</tr>
<tr>
<td>17'</td>
<td>68.1</td>
<td>75.3</td>
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<tr>
<td>19'</td>
<td>91.1</td>
<td>98.4</td>
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</table>
• EICM/MEPDG very sensitive to climate data and erroneous climate files can undermine analysis entirely
• EICM/MEPDG models sensitive to thermal conductivity
• MEPDG pavement performance models very sensitive to PCC layer thickness in AC-PCC projects
Two papers submitted on MEPDG climate sensitivity

- **TRB 2010**
  - Accepted for presentation and publication
  - Award: Geology and Properties of Earth Materials Section 2010 Best Paper Award

- **TRB 2011**
  - Accepted for presentation and publication
• Literature Review
• **LCCA**
• EICM Validation and Analysis
• Evaluation of Response Models
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California LCCA Case Studies

• Case 1: Lane replacement of truck lanes in Southern California as TICP instead of JPCP.

• Case 2: Convert multi-lane highway in Northern California into divided highway by adding new direction with TICP instead of JPCP.
• Thickness of the PCC in the TICP pavement that resulted in same NPV for the TICP as for the JPCP
• The reduction in cost of the TICP PCC as a percentage of the cost of JPCP PCC that resulted in the same NPV for TICP and JPCP
• The increase of PCC life in the TICP pavement beyond the normal PCC service life
Minnesota LCCA Case Study

• New two-lane, high-volume road

• MN LCCA decision metrics
  – When is the NPV of TICP and JPCP construction comparable?
  – Cost of initial construction
  – Cost of minor and major maintenance
  – Cost of rehabilitation regimens
For ESALs > 7 million…

**JPCP Maintenance Schedule**

<table>
<thead>
<tr>
<th>Pavement Age</th>
<th>Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>initial construction</td>
</tr>
<tr>
<td>17</td>
<td>minor re-seal and minor CPR (partial depth repairs)</td>
</tr>
<tr>
<td>27</td>
<td>Minor CPR (partial depth repairs) and some full depth repairs</td>
</tr>
<tr>
<td>40</td>
<td>major CPR (Full depth repair and diamond grind)</td>
</tr>
<tr>
<td>50</td>
<td>end of analysis period (no residual value)</td>
</tr>
</tbody>
</table>

**TICP Maintenance Schedule**

<table>
<thead>
<tr>
<th>Pavement Age</th>
<th>Treatment</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>initial construction</td>
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<tr>
<td>7</td>
<td>crack fill</td>
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<tr>
<td>15</td>
<td>mill and overlay</td>
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<tr>
<td>20</td>
<td>crack fill</td>
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<tr>
<td>27</td>
<td>mill and overlay</td>
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<tr>
<td>32</td>
<td>crack fill</td>
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<tr>
<td>40</td>
<td>mill and overlay</td>
</tr>
<tr>
<td>45</td>
<td>crack fill</td>
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<tr>
<td>50</td>
<td>end of analysis period (no residual value)</td>
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</table>
Three levels of concrete and asphalt costs

Cost of TICP concrete could be 25%, 50%, 75%, or 100% the cost of the JPCP concrete

<table>
<thead>
<tr>
<th>Concrete or Asphalt $ per yd³ (m³)</th>
<th>Price designation</th>
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<tbody>
<tr>
<td>38 (50)</td>
<td>Low</td>
</tr>
<tr>
<td>115 (150)</td>
<td>Medium</td>
</tr>
<tr>
<td>230 (300)</td>
<td>High</td>
</tr>
</tbody>
</table>
A reduction in cost of the TICP PCC layer could be accomplished by

- Increasing the percentage of supplementary cementitious materials
- Substituting recycled concrete aggregates for conventional coarse aggregates
- Allowing a higher percentage of fine, soft, spall, or slate in the coarse aggregate.
- Decreasing the cost of concrete is not limited to these examples
MN LCCA: Primary Variable Inputs

• Cost of concrete (H, M, L)
• Cost of asphalt (H, M, L)
• Cost of concrete in TICP relative to the cost of concrete in JPCP (0%, 25%, 75%, 100%)
• Discount rate (2.5% & 5.0%)
## MN LCCA: Influence of AC Cost

<table>
<thead>
<tr>
<th>DR = 2.8</th>
<th>Asphalt Cost: Low</th>
<th>Asphalt Cost: Medium</th>
<th>Asphalt Cost: High</th>
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<td></td>
<td><img src="image1.png" alt="Graph" /></td>
<td><img src="image2.png" alt="Graph" /></td>
<td><img src="image3.png" alt="Graph" /></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>DR = 5.0</th>
<th>Asphalt Cost: Low</th>
<th>Asphalt Cost: Medium</th>
<th>Asphalt Cost: High</th>
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<tbody>
<tr>
<td></td>
<td><img src="image4.png" alt="Graph" /></td>
<td><img src="image5.png" alt="Graph" /></td>
<td><img src="image6.png" alt="Graph" /></td>
</tr>
</tbody>
</table>
MN LCCA Conclusions

• TICP becomes more cost competitive with JPCP when/as . . .
  – The cost of concrete increases
  – The cost of asphalt is low and the cost of concrete is high or medium
  – The cost of concrete for TICPs decrease relative to the cost of JPCP concrete
  – The discount rate increases
LCCA: Other Applications

- Stage Construction
- Preventive Maintenance
TICP vs. Structural Overlay

- **TICP**
- **Rehabilitation**

Diagram showing the comparison between TICP and Rehabilitation over time in terms of pavement condition.
Stage Construction/ Preventive Maintenance

Percentage of Cracked Slabs vs. Damage

- Structural Rehab
- Thin AC OL

TICP TAP, OCT 2011
• Literature Review
• LCCA
• EICM Validation and Analysis
• Evaluation of Response Models
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Structural Modeling

- Composite pavement is subjected to
  - Positive temperature gradient
  - Traffic load
- PCC layer cracks at the bottom
  - Crack propagates upwards

Critical stress region at the bottom of the slab
Curling due to day-time positive temperature gradient
Mid-slab traffic load

Transverse Joint

AC Layer
PCC Layer

Crack

TICP TAP, OCT 2011
**Bottom-up Cracking Model**

\[
CRK = \frac{100}{1 + FD^{-1.68}} \\
FD = \sum \frac{n_{t,j,k,l,m,p}}{N_{t,j,k,l,m,p}}
\]

- \(CRK\) is the percentage of bottom up PCC cracking
- \(FD\) is the fatigue damage
- \(n\) is the applied number of load applications at conditions \(t, j, k, l, m, p\)
- \(N\) is the allowable number of load applications at conditions \(t, j, k, l, m, p\)
- \(t, j, k, l, m, p\) are conditions relating to the age, month, axle type, load level, temperature difference, and traffic path, respectively

\[
\log(N_{t,j,k,l,m,p}) = C_1 \left( \frac{MR}{\sigma_{t,j,k,l,m,p}} \right)^{C_2}
\]

- \(MR\) is the modulus of rupture of PCC
- \(\sigma\) is the applied stress at conditions \(t, j, k, l, m, p\)
- \(C_1, C_2\) are calibration constants (\(C_1 = 2.0, C_2 = 1.22\))
Limitations due to the adaptation

- Stiffness of the AC layer is dependent on loading time
  - Traffic loading: approx. 0.01 sec. to 0.05 sec.
  - Temperature loading: 1 hour (3600 sec)
- Fatigue cracking considers combined temperature and traffic loading
- MEPDG AC dynamic modulus does not capture VE response
AC/PCC Case for Analysis

• Composite pavement
• Location: Minneapolis, MN
• Structure: AC (4 in.) over PCC (6 in.) over A-1-a base (8 in.) over A-6 subgrade (semi-infinite)
• All other inputs: MEPDG defaults
• Dynamic modulus – mid-depth of AC layer
  – traffic load
  – temperature load

\[
\log(E^*) = \delta + \frac{\alpha}{1 + e^{\beta + \gamma (\log(t_r))}}
\]

\[
\log(t_r) = \log(t) - c \log(\eta) - \log(\eta_{T_r})
\]

Loading Time

Shift Factor
Asphalt stiffness versus pavement age

- **Traffic Load**
- **Temperature Load**

**Month**

- EAC, psi

**TICP TAP, OCT 2011**

Department of Civil Engineering
Two Alternative Approaches

- Visco-elastic analysis
  - Rigorous
  - Computationally expensive
- Two-moduli approach
  - Compatible with the MEPDG
  - Fast and inexpensive
Viscoelastic Characterization of AC


\[ J(t) = \frac{1}{E_0} + \sum_{i=1}^{N} \frac{1}{E_i} \left( 1 - e^{-\frac{E_i t}{\eta_i}} \right) \]

- Generalized Kelvin-Voigt model
• Consider that the material is stress-free for time 
  \( t < 0 \)

• Differential form

\[
\sum_{i=1}^{N} \dot{\varepsilon}_{i}^{cr}(t) = \sum_{i=1}^{N} \left( \frac{1}{\eta_i} \sigma(t) - \frac{E_i}{\eta_i} \varepsilon_{i}^{cr}(t) \right)
\]

  – Implemented in FE algorithms (Lesieutre and Govindswamy 1996, Johnson et al. 1997)

  – Creep strain approximated using time-discretization

\[
\Delta \varepsilon^{cr}(t) \approx \sum_{i=1}^{n} \left[ \varepsilon(t) - E_i \varepsilon_{i}^{cr}(t) \frac{\Delta t}{\eta_i} \right] \quad \varepsilon(t_{j+1}) = \varepsilon(t_j) + \Delta \varepsilon^{cr}(t_j)
\]
Development of VE Model (1)

- FE model incorporating viscoelastic/elastic layers
- Kirchhoff-Love plate theory for bending of isotropic and homogenous medium-thick plates
- Similar to ISLAB2000
  - four-noded rectangular plate element with three degrees of freedom at each node
Development of VE Model (2)

- Time-discretized process
  - Total time to develop creep behavior is discretized into sufficiently small time intervals

- At any time $t$, the plate is subjected to
  - Axle loads at time $t$
  - Fictitious forces due to
    - Temperature distribution at time $t$
    - Creep strains at the start of time interval $\Delta t$

\[
K \delta(t_j) = \frac{1}{3} \mathcal{R}(t_j) + \frac{1}{3} \mathcal{R}_{\text{therm}}(t_j) + \frac{1}{3} \mathcal{R}_{\text{creep}}(t_j).
\]
• Compute stress at any time $t$ (Hooke’s law)

$$\sigma(t_j) = \left( \varepsilon(t_j) - \varepsilon_{\text{herm}}(t_j) - \varepsilon_{\text{tot}}^c(t_j) \right)$$

• Update creep strain at the end of time interval $\Delta t$

$$\varepsilon(t_{j+1}) = \varepsilon(t_j) + \Delta \varepsilon^c(t_j)$$
Development of VE Model (4)

- Elastic / VE Plate
- Elastic / VE Winkler foundation
- Winkler foundation
  - Proportionality of applied pressure and plate deflection at any point
  - Spring formulation
Any temperature distribution can be split into the following 3 components:

1. Constant-strain-causing temperature component
   - Does not cause stress
2. Linear-strain-causing temperature component
   - Bending stresses computed using FE analysis
3. Nonlinear-strain-causing temperature component
   - Self equilibrating stress calculated using analytical solutions (Khazanovich 1994)
Total stress

- Bending stress in the equivalent single layer slab
- Stress due to nonlinear-strain-causing temperature component
  \[ \sigma_{NL}(z) = -\frac{E(z)\alpha(z)}{(1-\mu)} \zeta_{NL}(z) - T_o(z) \]
- Stress due to nonlinear-strain-causing creep component
  \[ \alpha_{NL}^{cr}(z) \leftarrow \text{[D]} \left( \alpha_{NL}^{cr}(z) \right) \alpha_0^{cr}(z) \]

\[ \sigma(x, y, z, t) = \beta(z) \star \sigma_{eq}(x, y, t) + \sigma_{NL}(z) + \sigma_{NL}^{cr}(x, y, z, t) \]

\[ \beta(z) = \frac{2z}{h_{eq}} \frac{E(z)}{E_{eq}} \]
1. Viscoelastic plate on viscoelastic Winkler foundation

2. Viscoelastic plate with simply supported corners

3. Sensitivity to internal parameters
VE Plate on VE Foundation

Deflection w(t), in

Time, sec

- FE Solution
- Semi-Analytic Solution

TICP TAP, OCT 2011
Two-Moduli Approach

• Why?
  – Compatibility with the existing MEPDG framework
• EACL & EACT
• Combined stress procedure
• Verification examples
• Comparison with the existing MEPDG stress computation procedure
1. EACL
   Traffic-duration-dependent AC dynamic modulus to characterize the pavement response under typical traffic loads, and

2. EACT
   Temperature-duration-dependent AC dynamic modulus to characterize the pavement response for the duration of temperature loads, $t_T$. 
Non-linear Slab-Foundation Interaction

Critical stress region at the bottom of the slab

Curling due to day-time positive temperature gradient

Mid-slab traffic load

AC Layer

PCC Layer

Critical stress region at the bottom of the slab
Three Systems to Model

• System 1
  – Temperature curling only
  – AC layer characterized by long-term modulus

• System 2
  – AC layer characterized by short-term modulus
  – Determine fictitious loading that produces the same deflection profile as in System 1

• System 3
  – AC layer characterized by short-term modulus
  – Subjected to traffic and fictitious loading
Boundary Value Problem # 1

- System 1: AC layer characterized with EACT
- Subjected to temperature distribution $T(z)$ only
• System 2: AC layer characterized with EACL
• Deflection profile of system 2 = deflection profile of system 1

\[ R_f = \frac{1}{2} K_2 \delta_1 \]

\[ \delta_2 e = \frac{1}{2} L \delta_1 e \]
• System 3: AC layer characterized with EACL
• Subjected to traffic load $F$ and fictitious load $F_{fict}$
Two-Moduli Stress Calculation

- Total stress due to combined loading

\[ \sigma_{2M} = \sigma_1 + (\sigma_3 - \sigma_2) \]

- Advantages
  - Accounts for the duration of loading
  - 2-moduli approach permits using existing MEPDG procedure for AC dynamic modulus
  - Accounts for non-linearity of slab-foundation interaction
  - Substitutes viscoelastic analysis
### Comparison with Simple Addition of the Stresses

<table>
<thead>
<tr>
<th>Location, in X</th>
<th>Deflection, in Y</th>
<th>Rotation θy</th>
<th>Rotation θx</th>
<th>Longitudinal Stress, psi</th>
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</thead>
<tbody>
<tr>
<td><strong>Three elastic solution</strong></td>
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<td></td>
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<td>-0.0077</td>
<td>0.00</td>
</tr>
<tr>
<td># 2</td>
<td>90</td>
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<td>-0.0077</td>
<td>0.00</td>
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<tr>
<td># 3</td>
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<td><strong>Combined stress</strong></td>
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<tr>
<td><strong>Viscoelastic FE solution</strong></td>
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<td>0.0038</td>
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<tr>
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<td><strong>EACL, traffic load only</strong></td>
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<tr>
<td><strong>% Difference</strong></td>
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<tr>
<td>Location, in</td>
<td>Deflection, in</td>
<td>Rotation</td>
<td>Longitudinal Stress, psi</td>
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<td>Y</td>
<td>θy</td>
<td>θx</td>
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<td>72</td>
<td>-0.0054</td>
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<td># 3</td>
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<td>2123.06</td>
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</table>

**Viscoelastic FE solution**

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>Y</td>
<td>θy</td>
<td>θx</td>
</tr>
<tr>
<td># 1</td>
<td>90</td>
<td>0</td>
<td>0.1220</td>
</tr>
<tr>
<td># 2</td>
<td>90</td>
<td>0</td>
<td>0.1220</td>
</tr>
<tr>
<td>% Error</td>
<td>-0.00015%</td>
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</table>
### Comparison with VE FE Solution (2)

<table>
<thead>
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<tbody>
<tr>
<td>X</td>
<td>Y</td>
<td>θ(_y)</td>
<td>θ(_x)</td>
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</tbody>
</table>

**Three elastic solution**

<table>
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</thead>
<tbody>
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<td>0</td>
<td>0.0188</td>
<td>-0.0007</td>
</tr>
<tr>
<td># 2</td>
<td>90</td>
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<td>-0.0007</td>
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<td># 3</td>
<td>90</td>
<td>0</td>
<td>0.0466</td>
<td>-0.0011</td>
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**Combined stress**

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<td>0</td>
<td>0.0466</td>
<td>-0.0011</td>
</tr>
<tr>
<td># 2</td>
<td>72</td>
<td>54</td>
<td>0.0106</td>
<td>-0.00026</td>
</tr>
<tr>
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<td>54</td>
<td>0.0106</td>
<td>-0.00026</td>
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</table>

**% Error**

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<td>72</td>
<td>54</td>
<td>0.0106</td>
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</table>

**Edge node**

**Interior node**
• Why is there a significant difference?
  – Self-equilibrating stresses are based on EACT instead of EACL as in the MEPDG
  – Reference temperature follows existing MEPDG guidelines
Simplification of the Structural System in the MEPDG

(a) original multi-layered system

(b) single slab system A

(c) two-slab system B
Simplification of the Structural System in the MEPDG (2)

• System A
  – Case I: temperature loading only, $\sigma^A_1(0,T)$
  – Case II: combined traffic and temperature loading, $\sigma^A_2(0,T^*)$
  – Case III: traffic loading only, $\sigma^A(P,0)$

• System B
  – Case I: no load transfer between the slabs, $\sigma^B(0)$
  – Case II: load transfer efficiency between two slabs is equal to shoulder LTE, $\sigma^B(LTE)$

$$\sigma_{Tot} = \sigma^A_1(0,T) + LTE \ * \ \frac{1}{3} (P,T^*) - \sigma^A_2(0,T^*) \ \sigma^A(P,0) + \sigma^B(0)$$
- Factorial of 98 cases
- Wheel offset
  - 0, 2, 4, 6, 12, 18, and 24
- PCC thickness
  - 2-15” in 1” incr

\[ y = 1.0236x \]
\[ R^2 = 0.9991 \]
Equivalency Techniques

• Simplify multi-layered pavement in terms of single layer slab

• If the following are valid (AASHTO 2008)…
  – Equality of slab stiffness,
    \[ D = \frac{E h^3}{12(1 - \mu^2)} \]
  – Equality of Korenev’s non-dimensional temperature gradient,
    \[ \phi = \frac{2\alpha(1 + \mu)l^2 k}{h^2} \gamma \Delta T \]
  – Equivalency of radius of relative stiffness,
    \[ l = \frac{4D}{k} \]
  – Equivalency of normalized load ratio,
    \[ q^* = \frac{P}{LW\gamma h} \]
If (above) valid, then...

- Deflections are related as:

\[ w_1 = \frac{\gamma_1 h_1 k_2}{\gamma_2 h_2 k_1} w_2 \]

- Stresses are related as:

\[ \sigma_1 = \frac{h_2 \gamma_1}{h_1 \gamma_2} \sigma_2 \]
### Equivalency Techniques (3)

<table>
<thead>
<tr>
<th>Location, in</th>
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</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>Y</td>
<td>$\sigma_{SL}$</td>
</tr>
<tr>
<td># 1</td>
<td>90</td>
<td>0</td>
</tr>
<tr>
<td># 2</td>
<td>90</td>
<td>0</td>
</tr>
<tr>
<td># 3</td>
<td>90</td>
<td>0</td>
</tr>
<tr>
<td>Combined stress</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Three elastic solution – Three-layered composite pavement

#### Three elastic solution – Equivalent single layer slabs SL1 and SL2

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<tbody>
<tr>
<td>X</td>
<td>Y</td>
<td>$\sigma_{SL}$</td>
</tr>
<tr>
<td>SL1: # 1</td>
<td>90</td>
<td>0</td>
</tr>
<tr>
<td>SL2: # 2</td>
<td>90</td>
<td>0</td>
</tr>
<tr>
<td>SL2: # 3</td>
<td>90</td>
<td>0</td>
</tr>
<tr>
<td>Combined stress</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### % Difference

| % Difference | 0.000% |
Conclusions on Two-Moduli Approach and MEPDG Stress Comparison

- A novel stress computation procedure was developed
  - Uses different moduli for curling and axle load analysis
  - Verified with viscoelastic finite element solutions
- A framework for the implementation of the proposed stress procedure into the MEPDG was developed
  - Minimum modifications to the existing MEPDG framework are required to be implemented into the MEPDG for predicting fatigue cracking
Reflection Cracking Modeling

• Lattice 3D model
  – Developed at UC-Davis by Prof. John Bolander
  – Modified under R21 project to account for mixed mode failure

• Coupling with ISLAB (FEM) completed, currently being validated for additional beam and slab problems
Reflection Cracking Modeling

Mode I

\[ \tau \text{ (MPa)} \]

\[ \sigma \text{ (MPa)} \]

\( I_1 = 490 \)

\( I_i = 490 \)
Reflection Cracking Modeling

Mode II

\[
\tau \text{ (MPa)} = -\sigma \text{ (MPa)} + \tau_0
\]

\(\tau_0 = 25\)

\(I_i = 25\)

\(I_0 = 25\)
• Weakened interface moves away from mid-span
• Effect near support is an “unzipping,” with shear initiating fracture then tensile events increasing in number
• Literature Review
• LCCA
• EICM Validation and Analysis
• Evaluation of Response Models
• Development of Design Guidelines
• Development of Construction Guidelines
• Development of Synthesis
Synthesis

- TICP focuses on new construction
  - Life-cycle cost analysis
  - EICM/MEPDG revisions/enhancements
  - CalME/MEPDG merging
  - Construction guidelines

- Scope of synthesis should include conventional AC overlays (rehabilitation)
1. Introduction
   - AC-over-PCC (AC-PCC) as pavement preservation
   - Benefits of AC-PCC
2. Evaluation of existing PCC
   - Structural and Functional Evaluations
3. Repair and preparation of existing PCC
   - Slab support, Full- and partial-depth repair, edge drains, restoring LTE, cleaning
4. AC overlay mix design
   - Overlay mix guidelines TBD
5. Geotextile interlayer

6. AC overlay structural design
   - MEPDG & CALME

7. AC-PCC performance evaluation
   - Includes extensive LTPP experience

8. AC overlay construction
   - Saw & seal technique and effectiveness
   - Construction guidelines TBD with UCD experience
AC-PCC Benefits

- AC overlay on PCC plays to both materials’ strengths:
  - Long-term performance of PCC
  - Renewability and low noise performance of AC
- With some planning, best possible long-term performance can be achieved affordably
Evaluate existing PCC (1)

- Evaluation procedure
  - From office (historical records) to field (surveys and tests)
- Structural evaluation
  - Survey extent of damage and drainage
  - NDT for slab strength, subgrade reaction, etc.
- Functional evaluation
  - Assess friction, roughness, noise
- Decide on rehabilitation or maintenance
Evaluate existing PCC (2)

STH 38, Racine County, Wisconsin
from Wen et al 2005
Repair and prepare existing PCC (1)

- Restore PCC slab support
  - Alleviate pumping or loss of support
  - Use slab stabilization or slab jacking

- Partial-depth slab repair
  - Repair functional damage (i.e. not structural) such as shallow spalled joints or cracks
  - Define repair area, remove questionable material, use fill material (AC, PCC, or other alternatives)

STH 38, Racine County, Wisconsin
from Wen et al 2005
Repair and prepare existing PCC (2)

- Full-depth slab repair
  - Repair major structural damage, can include corner breaks, severe cracking, d-cracking, etc.
  - Ensure that repair area includes all deterioration through slab, use repair material based on lane closure time
Repair and prepare existing PCC (3)

• Install edge drains or reseal joints
  – Assess need for improved drainage, if required, retrofit edge drains or repair existing damage/blocked drains

• Improve LTE across joints
  – Restore LTE by replacing damaged dowels or retrofitting dowels to undoweled pavement

• Clean and prepare slab for overlay
  – Grinding and grooving to restore surface
Repair and prepare existing PCC (4)

STH 38, Racine County, Wisconsin

from Wen et al 2005
AC overlay mix design

- AC overlay mix design to be determined
  - Prof. Marasteanu at UMN will be consulted for overlay mix design
- AC mix design will consider paving concerns (site conditions, etc.) for TPF(5)-149 member states
Geotextile interlayer

- Interlayer to arrest crack propagation from existing PCC into AC overlay
  - While it has been shown to be effective in reducing reflective cracking in thin overlays…
  - The cost of implementation may outweigh the benefits
- Guidelines will briefly detail interlayers in hope of informing user on both sides of existing research (still in process)
AC-PCC long-term performance (1)

• LTPP AC-PCC sections included:
  – GPS-7. AC Overlay of PCC Pavements
  – SPS-6. Rehab Using AC Overlays of PCC Pavements
  – These include 8-inch OL over crack-and-seat, 4-inch OL over crack-and-seat or intact pavement, and full-depth repair with/without grinding

• U. Mich. found that for Arizona SPS-6 pavements:
  – Reflective cracking was the greatest contributor to post-overlay roughness
  – A layered Asphalt Rubber AC (ARAC) and AC over reduced the development of post-overlay roughness better than a conventional AC overlay

• NCHRP 20-50 found… (cont.)
NCHRP 20-50 found that for 4-inch asphalt overlays of intact slabs no significant mean differences in long-term roughness or cracking performance were detected between (cont.):
- minimal versus intensive preoverlay preparation
- sections without versus with sawing and sealing of transverse joints
- overlays with sawed and sealed joints versus overlays of cracked/broken and seated slab

NCHRP 20-50 ranked effectiveness of rehab as
- 8-inch over crack and seat
- 4-inch over crack and seat or intact
- Non-overlay full-depth repair with diamond grind
- Non-overlay full-depth repair without grind

TICP TAP, OCT 2011
AC-PCC construction

• AC overlay construction to be determined
  – UCD will be consulted for its AC overlay construction expertise
  – Earlier sections on existing PCC slab preparation will be revised to reflect UCD input

• Construction will include details on sawing and sealing, which was investigated for the SHRP2 R21 project and implemented at MnROAD
AC-PCC saw and sealing (1)

- Guidelines cite saw & seal spec developed for Illinois Tollway by SHRP2 R21
  - Saw cutting no longer than 48 hours after overlay paving, sawed joints to be ½ inch wide by 5/8 inch deep for 3-inch AC OL
  - Locating underlying JPCP joint is critical (*misidentified joint below*)
  - Joint cleanliness and site conditions emphasized

Elseifi et al 2011
• Saw and seal found to be effective in Louisiana DOT and SHRP2 R21 experience
  – SHRP2 R21 tour of EU countries that implemented saw and seal in AC-PCC (Austria, Germany, Netherlands)
Conclusions: TICP and AC Overlays

• Guidelines for AC overlays of existing PCC pavements in development
  – AC OL mix design and AC OL construction await expert input

• Inclusion of AC over existing PCC alongside new construction of TICP…
  – further expands definition of TICP and
  – expands possible user base for TICP products