Design and Construction Guidelines for Thermally Insulated Concrete Pavements

Lev Khazanovich
Associate Professor
Civil Engineering Department
University of Minnesota – Twin Cities
• Task 1. Literature Review
• Task 3. EICM Validation and Analysis
  – Review of last year status
  – New findings
• Task 4. Evaluation of Response Models
  – Review of last year status
  – New findings
• Task 5. Develop Design Guidelines
  – CalME models
Task 1

• First draft was submitted in April 09
  – Concentrated on AC overlays on PCC
  – Lack of information on composite pavements
  – Insufficient description of the MEPDG
• Comments were received in June 09
• New draft was submitted and approved in July-August 09
• The document has been updated. It will be used as a basis for the Synthesis
Task 3. EICM evaluation
Past Findings

• MEPDG 1.0 minimum AC thickness analysis
  – 1.9” had 14.2% cracking
  – 2.0” had 1%

• No significant differences between 4-in single layer AC system and 2 x 2” AC system

This was verified for MEPDG version 1.1
Task 3. EICM evaluation
Past Findings

• Time of traffic opening
  – Determine differences in MEPDG predictions if the date of traffic opening is changed
    • User selects month of
      – Pavement construction
      – Overlay construction
      – Traffic opening

• Conclusions
  – The month a pavement structure is opened to traffic does not affect pavement performance predictions made by the MEPDG
Task 3. EICM evaluation
Past Findings

Effect of Weather Stations

• Case 1
  – MSP – STC example: 40% difference in predicted cracking
  – 7 additional locations were selected
  – As the location becomes closer to STC, predicted cracking increases
    • STC has missing climate data
      – This was thought to cause problem – will examine further

• Case 2
  – Primary evaluation of data quality
    • Cases were run for identical locations using the interpolation option
      – Nearest station only (1 station)
      – All except nearest (5 stations)
Effect of Weather Stations

• If data quality is high, there should be little difference between the two predicted values for each station
• At some locations the predicted values are very close
• At others, there are large differences
• It’s known that some existing stations have incomplete data files
• This is thought to cause the inconsistencies
A Comprehensive Evaluation of the Effect of Climatic in MEPDG Predictions

Effect of Weather Stations

<table>
<thead>
<tr>
<th>Locations</th>
<th>Lat.</th>
<th>Long.</th>
<th>Elev.</th>
<th>% Cracking after 20 years for weather station</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Nearby station only</td>
</tr>
<tr>
<td>Columbus, OH</td>
<td>39.59</td>
<td>-82.53</td>
<td>849</td>
<td>6.4</td>
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<tr>
<td>Grand Forks, ND</td>
<td>47.57</td>
<td>-97.11</td>
<td>842</td>
<td>9.9</td>
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<tr>
<td>Fort Wayne, IN</td>
<td>41.01</td>
<td>-85.13</td>
<td>806</td>
<td>12.3</td>
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<tr>
<td>San Antonio, TX</td>
<td>29.32</td>
<td>-98.28</td>
<td>821</td>
<td>17.5</td>
</tr>
<tr>
<td>Madison, WI</td>
<td>43.08</td>
<td>-89.21</td>
<td>860</td>
<td>18.1</td>
</tr>
<tr>
<td>Oshkosh, WI</td>
<td>43.59</td>
<td>-88.34</td>
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<td>22.9</td>
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<td>-91.43</td>
<td>870</td>
<td>24.2</td>
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<td>-83.44</td>
<td>836</td>
<td>27.7</td>
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<td>Joplin, MO</td>
<td>37.09</td>
<td>-94.3</td>
<td>985</td>
<td>37.6</td>
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<tr>
<td>Lawrence, KS</td>
<td>39.01</td>
<td>-95.13</td>
<td>833</td>
<td>43.0</td>
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<tr>
<td>Oak Ridge, TN</td>
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<td>-84.14</td>
<td>916</td>
<td>51.5</td>
</tr>
<tr>
<td>Atlanta, GA</td>
<td>33.22</td>
<td>-84.34</td>
<td>837</td>
<td>58.9</td>
</tr>
</tbody>
</table>
EICM

• Requires information about 5 weather related parameters on an hourly basis
  – Air temperature
  – Wind speed
  – Percent sunshine
  – Precipitation
  – Relative Humidity
EICM Climate Database

- 851 Stations located across the USA
- Varying amounts of climate data
- Max: 116 months
  - Requires 24 months to run
- 116 months may not be sufficient to eliminate year-to-year variations
  - Stations with less data are more sensitive to outliers (year-to-year variations)
EICM Climate Database

Wet > 25” in rainfall/yr
Freeze > 200 FI

- Dry – No Freeze region: 77 stations
- Dry – Freeze region: 136 stations
- Wet – No Freeze region: 164 stations
- Wet – Freeze region: 233 stations
MEPDG Predictions

• A identical pavement structure was analyzed at many locations
  – Composite, Rigid, & Flexible
• The only variable was the climate file
• Only stations with “complete” climate files were used
  – “No missing months”
• 610 Stations had complete data
  – Files had varying amounts of data
• MEPDG Version 1.0
Design

- Composite – 2” AC over 7” PCC
- Rigid – 9” PCC
- Flexible – 9” AC
- Granular base
  - A-1-a, 6”
- Subgrade
  - A-6, semi-infinite
- Traffic – 3200 AADTT
Design

• 1.25” Doweled transverse joints
  – 12” spacing
• 15’ joint spacing
• AC
  – 52-28PG
• Water table depth: 5’
• MEPDG default values were used unless otherwise specified
Climate had less effect on predicted Composite IRI

- IRI values for Composite and Flexible (not shown) designs were very similar
MEPDG Predictions – AC Rutting

- Histograms suggest AC/PCC pavement is less sensitive to climate than equivalent single layer AC system

- Composite values exhibit less rutting – confined to 2” AC layer
A Comprehensive Evaluation of the Effect of Climatic in MEPDG Predictions

MEPDG Predictions – Transverse Cracking in PCC Layer

- Minimum: 0.0% Bethel & Cold Bay, AK; Maximum: 79.1% Nogales, AZ (AC/PCC)
- Wide range of predicted cracking values – Rigid tended to be more extreme
- Climate has an enormous impact on predicted cracking values – investigate further
Google Earth Plot

- Transverse cracking results were plotted on Google Earth
- 4 icon colors – according to predicted percentage of cracked slabs
  - Blue: <16%
  - Green: 16-25%
  - Yellow: 26-40%
  - Red: > 40%
A Comprehensive Evaluation of the Effect of Climatic in MEPDG Predictions

Blue < 16%  Green 16-25%  Yellow 26-40%  Red > 40%

- Trends are visible, but anomalies are present

17 Dec 2009
### Cracking Percentage Organized by Environmental conditions

<table>
<thead>
<tr>
<th>Climate</th>
<th>No. of Stations</th>
<th>0-15%</th>
<th>16-25%</th>
<th>26-40%</th>
<th>40%&lt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet – Freeze</td>
<td>233</td>
<td>63</td>
<td>39</td>
<td>93</td>
<td>38</td>
</tr>
<tr>
<td>Wet - No Freeze</td>
<td>164</td>
<td>47</td>
<td>14</td>
<td>30</td>
<td>73</td>
</tr>
<tr>
<td>Dry – Freeze</td>
<td>136</td>
<td>26</td>
<td>28</td>
<td>42</td>
<td>40</td>
</tr>
<tr>
<td>Dry - No Freeze</td>
<td>77</td>
<td>14</td>
<td>13</td>
<td>15</td>
<td>35</td>
</tr>
</tbody>
</table>
Southern California Example

- Large differences were observed for stations geographically close
- Los Angeles, CA – 3.8%  Elev. 326ft
- Burbank, CA – 62.7%  Elev. 734ft
- 58.9% Difference
- Distance – 18.64 miles
A Comprehensive Evaluation of the Effect of Climatic in MEPDG Predictions

Trends are visible, but anomalies are present.
East Coast Example

Blue: Less than 16% slabs cracked
Green: 16% to 25% slabs cracked
Yellow: 26% to 40% slabs cracked
Red: 40% or more slabs cracked
A Comprehensive Evaluation of the Effect of Climatic in MEPDG Predictions

Lessons from MEPDG Simulations

• 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
Lessons from MEPDG Simulations

• Data quality is non-uniform
  – MEPDG allows stations with low-quality data to be used
    • It does prevent stations with missing data to be used alone
    • Low-quality data can be used when interpolating
      – It was demonstrated that missing data can only decrease the quality of predictions

• It is recommended that all missing data is removed from the database
Lessons from MEPDG Simulations

• Improved data quality will likely improve MEPDG predictions
  – Data cleaning
  – Uniform, high-quality data
  – More data
    • Eliminate year-to-year variations
Lessons from MEPDG Simulations

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  – More data
    • Eliminate year-to-year variations
MEPDG Climate Sensitivity

- Two papers were submitted on MEPDG climate sensitivity
  - TRB (Transportation Research Board)
    - Accepted for presentation and publication
    - Award: Geology and Properties of Earth Materials Section 2010 Best Paper Award
  - JAMC (Journal of Applied Meteorology and Climatology)
    - Under review
Past Findings

• MnROAD Cell 53 data
  – Data from overlay and no-overlay sections were compared
  – Attempt was made to salvage Cell 53 data
MnROAD Cell 54

- Cell 54 was examined
- Analysis indicated that the temperature sensor began experiencing problems in 2006
- All data more recent than 2006 are considered unreliable
Closer Examination of Cell 54

Temperature of Sensor #54 Over Time


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Environmental · Geomechanical · Structures · Transportation · Water Resources
MnROAD Cells 106 & 206

- Temperature data from MnROAD cells 106 & 206 were processed to determine data quality
  - Cell 106: 48 sensors
  - Cell 206: 16 sensors
- 14 different ‘flags’
  - Each represents a different data test failure
Definition of Flags

In this section we define constants for each of the flags.

%------------------------------------------------------------------------%
% Missing data flags
FLAG_MISSING_DATA = 1;  % missing data
FLAG_NOT_YET_OPERATIONAL = 2;  % missing data at the beginning
FLAG_DEACTIVATED = 3;  % missing data at the end
FLAG_TOO_SPARSE_DAY = 4;  % not enough data in any day
% Time-series based
FLAG_OUT_OF_RANGE = 5;  % sensor outliers with annual & diurnal fit
FLAG_NEIGHBORHOOD_OUTLIERS = 6;  % sensor outliers with local neighborhood fit
FLAG_LAG_ONE_OUTLIERS = 7;  % sensor outliers in lag one
% Subset-based flags
FLAG_POINT_EXTREMES = 8;  % subset outliers, record-by-record
FLAG_DAILY_RANGE = 9;  % subset daily range outliers, day-by-day
FLAG_DAILY_EXTREMES = 10;  % subset daily extreme outliers, day-by-day
% Sensor-by-sensor consistency
FLAG_INTERMITTENT_DATA = 11;  % too many flagged data points around
FLAG_INCONSISTENT_DAY = 12;  % too small of a fraction of good data, day-by-day
FLAG_INCONSISTENT_WEEK = 13;  % too small of a fraction of good data, week-by-week
FLAG_INCONSISTENT_MONTH = 14;  % too small of a fraction of good data, month-by-month
MnROAD Cell 106, Sensor 28

- Example of erroneous sensor (#28) in cell 106
  - “Flagged”, i.e. questionable, data are green
  - “Un-flagged” data are blue

- Two time periods to note
  - June ’09 onward
    • Easily observed
  - End of January ’09
    • Not as noticeable
MnROAD Cell 106, Sensor 28
MnROAD Cell 106, Sensor 28

- Not all flagged data are revealing at first glance
- A plot of Flags vs. Time accounts for this
  - Also indicated which flag was activated
MnROAD Cell 106, Sensor 28

Cell 106, Sensor 28, Subset (UNK, 2, ML, 5), Unflagged (93.20%, 93.20%)
MnROAD Cell 106, Sensor 28

- Flags present in January ’09
  - 10: Data has extreme outliers
    - Daily max & min values are too extreme
  - 12: Inconsistent from day-to-day
    - Fraction of good data is too small from day-to-day
MnROAD Cell 106, Sensor 28

• Flags present in June ’09
  – 9: Daily Range
  – 10: Daily extremes
  – 12: Inconsistent from day-to-day
  – 13: Inconsistent week-to-week
  – 14: Inconsistent month-to-month
Closer examination of January ’09 flags

Cell 106, Sensor 28, Subset (UNK, 2, ML, 5)
Closer Examination of January ’09 Flags

- The ‘expected’ minimum value was lower than what was recorded
  - This ‘expected’ value is determined by other observations in the same subset
  - Subset: sensors at the similar depth and in the same material

- Even though data looks reasonable, software indicates there is a problem
Closer examination of June ’09 flags

- Easily observed that something is wrong with the sensor
Closer examination of January ’09 flags
Similarities in Data Trends

• Sensors 4 & 12
  – Appears to be a problem near the end of the time period
  – Spike in December ’08

• Sensors 28 & 12
  – Flagged data at end of January ’09

• Sensors 20 & 28
  – Problems begin in June ’09
  – Sensor 20 returns to ‘normal’ until August ’09
  – Sensor 28 does not – erroneous data is present until end of time period
    • Also appears to be a spike in sensor 12 near mid-June, but data is unflagged
MnROAD Cell 106 & 206

• Most sensors had 98% or more data “unflagged”
  – All 16 sensors in Cell 206
  – 40 of 48 in Cell 106

• This can be slightly misleading
  – Sensor 28 (which was previously examined) reported 93.20% un-flagged data
  – Doesn’t mean there isn’t any useful data from Sensor 28
Temperature Differences in Cell 106

• Difference = Ttop – Tbot
• Results were plotted as a histogram
• 4 different sets were compared
• Sorted according to season
  – Dec, Jan, Feb
  – Mar, Apr, May
  – Jun, Jul, Aug
Differences in Temperature in Cell 106
T_top – T_bot of PCC slab

Winter

Group 1

Group 2

Group 3

Group 4

Spring

Summer

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Next Steps

• Compare with PCC temperature data from the adjacent sections
• Compare EICM and measured data
Task 4. Evaluation of Response Models

- AC characterization
  - Past findings
  - Correction of past findings
  - MEPDG E* calculation process and its limitations
- Effect of AC viscoelastic properties on responses of composted pavements
- MEPDG curling analysis modification
Past findings

- MEPDG Level 2 vs Level 3 analysis

Images of software interfaces for asphalt material properties analysis.
Past findings

- Year
- Rutting (in)

- Level 2
- Level 3

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Past findings - correction

\[ \eta = \frac{|G^*|}{10} \left( \frac{1}{\sin \delta} \right)^{4.8628} \]

- |G*| and \( \delta \) at \( \omega = 10 \) rad/sec for PG 58-28 binder

<table>
<thead>
<tr>
<th>Temp (°F)</th>
<th>G* (Pa)</th>
<th>( \delta ) (°)</th>
<th>( \eta ) (cP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>500000000</td>
<td>9.42</td>
<td>3.3228E+10</td>
</tr>
<tr>
<td>70</td>
<td>450000000</td>
<td>24.91</td>
<td>3.0158E+08</td>
</tr>
<tr>
<td>100</td>
<td>30000000</td>
<td>30.40</td>
<td>8.2300E+06</td>
</tr>
<tr>
<td>130</td>
<td>20000000</td>
<td>55.87</td>
<td>5.0148E+05</td>
</tr>
</tbody>
</table>

- Divide G* by 1000 for input in MEPDG Level 1 or 2
  - Addresses error in MEPDG software code
\[
\log(E^*) = \delta + \frac{\alpha}{1 + e^{\beta + \gamma \log t_r}}
\]

\[
\delta = -1.249937 + 0.02932 \rho_{200} - 0.001767 (\rho_{200})^2 - 0.002841 \rho_4 - 0.058097 V_a - 0.802208
\]

\[
\alpha = 3.871977 - 0.0021 \rho_4 + 0.003958 \rho_{38} - 0.000017 \rho_{38}^2 + 0.005470 \rho_{34}
\]

\[
\beta = -0.603313 - 0.393532 \log(\eta_{T_r})
\]

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

\[
\gamma = 0.313351, \quad c = 1.255882
\]

Loading time
Loading Time

\[ t = \frac{L_{eff}}{V_s} \]
Effective Distance

\[ L_{\text{eff}} = 2 \cdot (a_c + Z_{\text{eff}}) \]

- \( L_{\text{eff}} \) = effective distance
- \( a_c \) = radius of tire contact area = 3.5 in
- \( Z_{\text{eff}} \) = effective depth
Effective Depth

\[ Z_{eff} = \sum_{i=1}^{k-1} h_i \sqrt[3]{\frac{E_{AC,i}}{E_{subgr}}} + h_k \sqrt[3]{\frac{E_{AC,k}}{2E_{subgr}}} \]

- \( Z_{eff} \) = effective depth
- \( k \) = number of the AC sublayer of interest
- \( h \) = thickness of AC sublayer
- \( E_{AC} \) = modulus of AC sublayer
- \( E_{subgr} \) = subgrade modulus
Iterative Process for E* Calculation
Limitations of the MEPDG E* procedure

- Does not account for base or PCC properties

\[ Z_{eff} = \sum_{i=1}^{k-1} h_i \sqrt[3]{\frac{E_{AC,i}}{E_{subgr}}} + \frac{h_k}{2} \sqrt[3]{\frac{E_{AC,k}}{E_{subgr}}}, \]

- The same value for temperature curling and axle loading
• Behavior of AC under constant stress
• 3D finite element model for viscoelastic analysis
  – Viscoelastic AC layer
  – Elastic PCC layer
  – Winkler foundation
  – Traffic load
  – Temperature gradient
  – Verify stresses
• Creep compliance
  – Generalized Kelvin-Voigt model

\[ J(t) = \frac{1}{E_0} + \sum_{l=1}^{L} \frac{1}{E_l} \left( 1 - e^{-\frac{t}{\tau_l}} \right) + \frac{t}{\eta_0} \]

– Bending Beam Rheometer (Zofka et al. 2008)

\[ J(t) = \frac{48I\delta(t)}{PL^3} \]
Effect of AC Viscoelastic Properties on Responses of Composted Pavements

• AC : 3 in, viscoelastic
• PCC : 6 in, elastic

ABAQUS 3D FE Model
• Video of ABAQUS moving load analysis
  – New AC only: AC over base and subgrade on a stiff Winkler foundation
  – Composite: AC over PCC on Winkler foundation

• Vertical deflections
  – Same deformation scale factors
Effect of AC Viscoelastic Properties on Responses of Composted Pavements

- System: AC – Base – Subgrade – Winkler foundation
- Vehicle speed: 5 mph, 10 mph, 30 mph, 60 mph
- Strains at the bottom of AC in the middle of slab under moving load

![Graph showing strain at bottom of AC under different speeds](image)

- **Speed_5**
- **Speed_10**
- **Speed_30**
- **Speed_60**

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- System: AC – PCC – Winkler foundation
- Vehicle speed: 5 mph, 10 mph, 30 mph, 60 mph
- Stress at the bottom of PCC in the middle of slab under moving load
### Location: O’Hare, Chicago, IL.

<table>
<thead>
<tr>
<th>S. No.</th>
<th>File Name</th>
<th>General Information</th>
<th>Traffic</th>
<th>Structure - Thickness (in)</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Type</td>
<td>Des. Life (years)</td>
<td>AADTT</td>
<td>Speed (mph)</td>
</tr>
<tr>
<td>1</td>
<td>AC_5</td>
<td>New AC</td>
<td>10</td>
<td>10000</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>AC_10</td>
<td>New AC</td>
<td>10</td>
<td>10000</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>AC_30</td>
<td>New AC</td>
<td>10</td>
<td>10000</td>
<td>30</td>
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<tr>
<td>4</td>
<td>AC_60</td>
<td>New AC</td>
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<td>10000</td>
<td>60</td>
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<tr>
<td>5</td>
<td>AC_PCC_5</td>
<td>Overlay</td>
<td>10</td>
<td>10000</td>
<td>5</td>
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<tr>
<td>6</td>
<td>AC_PCC_10</td>
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<td>10</td>
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<td>10</td>
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<tr>
<td>7</td>
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<td>10</td>
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<td>30</td>
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<td>8</td>
<td>AC_PCC_60</td>
<td>Overlay</td>
<td>10</td>
<td>10000</td>
<td>60</td>
</tr>
</tbody>
</table>
• Composite pavement is subjected to
  – Positive temperature gradient
  – Traffic load
• PCC layer cracks at the bottom
  – Crack propagates upwards
• MEPDG PCC cracking model for composite pavement
  – Adoption from new rigid pavement
  – Based on equivalency concept
  – Over-simplification
CRK is the percentage of bottom up PCC cracking

\[ CRK = \frac{100}{1 + FD^{-1.68}} \]

FD is the fatigue damage

\[ FD = \sum \frac{n_{t,j,k,l,m,p}}{N_{t,j,k,l,m,p}} \]

- 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

\[
\log(N_{t,j,k,l,m,p}) = C_1 \left( \frac{MR}{\sigma_{t,j,k,l,m,p}} \right)^{C_2} + 0.4371
\]

- \( MR \) 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 \( (C_1 = 2.0, C_2 = 1.22) \)
• Does not account for
  – AC layer temperature gradient
  – Viscoelastic behavior of AC
  – Temperature sensitivity of AC
Proposed Approach

1. Two-moduli approach
2. Stress combination
3. Verification of stress prediction
4. Modification of existing MEPDG model
5. Comparison with existing MEPDG model
6. Verification of proposed cracking model
Two-Moduli Approach

- $E_L$ for traffic load analysis
- $E_T$ for temperature gradient analysis

$E_L = \frac{\sigma_L}{\varepsilon_L}$

$E_T = \frac{\sigma_T}{\varepsilon_T}$

- Verification
  - ABAQUS viscoelastic model for traffic only
  - ABAQUS viscoelastic model for temperature gradient only

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Two-Moduli Approach

Stress Computation

• “Equivalent elastic” analysis

• AC and PCC layers assumed linear elastic

• Slab-foundation interaction is non-linear
  – Separation from base due to curling
Stress Computation

• Consider system 1

\[ \sigma_1 = f T_1 \quad \bar{P} = 0, E_{AC} = E_T \]
Two-Moduli Approach

Stress Computation

• Consider system 2
  – Find $T_2$ for similar deflection profile

$$\sigma_2 = f T_2 , P = 0, E_{AC} = E_L .$$
Two-Moduli Approach

Stress Computation
• Consider system 2 + Traffic

\[ \sigma_3 = f \cdot T_2 \cdot \bar{P}, E_{AC} = E_L \]
Two-Moduli Approach

Stress Computation

• Total stress

\[ \sigma_{Tot.} = \sigma_1 + (\sigma_3 - \sigma_2) \]
• Implement in MEPDG
  – Edit source code
  – Apply the new stress solution
  – Tedious process which requires
    • Implementation for each hour of analysis
    • Adaption of rapid solutions
    • Multiple rapid solutions for a single load application
    • Repeat for combination of axle loads and types
  – Compute cracking in PCC layer over the entire design life
• Compare existing model with modified model
  – Assess difference

• Sensitivity analysis
  – Layer thickness
  – Layer stiffness
  – Coefficient of thermal expansion
  – Other parameters
CalME Models

• Reflective cracking model
  – Based on critical strains in AC overlays over joints and cracks of existing PCC pavement
  – Recursive-incremental damage approach with a time increment of 30 days
  – Calibrated using accelerated loading test data from the Caltrans heavy vehicle simulator

• Rutting model
  – Based on shear deformation approach developed by Deacon et al. (2002)
  – Postulates that the rutting will occur at the top 100 mm of AC layers
  – Recursive incremental damage approach
Cracking:

\[ Cr \, m/m^2 = \frac{10}{1 + \left( \frac{\omega}{\omega_0} \right)^\alpha} \]

Fatigue Damage:

\[ \omega = \left( \frac{MN}{MN_p} \right)^\alpha \]

where:

\[ MN_p = A \times \left( \frac{\mu \varepsilon}{\mu \varepsilon_{ref}} \right)^\beta \times \left( \frac{E}{E_{ref}} \right)^\gamma \times \left( \frac{E_i}{E_{ref}} \right)^\delta \]

\( E \) is the modulus of damaged material,
\( E_i \) is the modulus of intact material,
\( MN \) is the number of load repetitions in millions \((N/10^6)\),
\( \mu \varepsilon \) is the strain at the bottom of the asphalt layer in \( \mu \) strain, and
\( \alpha, \beta, \gamma, \) and \( \delta \) are constants.
Comparison of fatigue damage versus no. of load repetitions for different materials at a reference temperature of 20°C and a constant strain of 500 μstrain.
• Comparison of cracking in (m/m²) versus damage for different materials with crack initiation corresponding to 0.5 m/m² of cracking and $\alpha = -8$
Permanent Deformation:

\[ dp_i = K \times h_i \times \gamma^i \]

where: \( h_i \) is the thickness of layer \( i \) (above a depth of 100 mm), and \( K \) is a calibration constant. \( K = 1.4 \)

Inelastic Shear Strain:

\[ \gamma^i = \exp\left( A + \alpha \times \left[ 1 - \exp\left( -\ln\left( \frac{N}{\gamma} \right) \times \left( 1 + \frac{\ln\left( N / \gamma \right)}{\gamma} \right) \right] \right) \times \exp\left( \beta \times \frac{\tau}{\tau_{\text{ref}}} \right) \times \gamma^e \]

where: \( \gamma_e \) is the elastic shear strain,
\( \tau \) is the shear stress,
\( N \) is the number of load repetitions,
\( \tau_{\text{ref}} \) is a reference shear stress (0.1 MPa ≈ atmospheric pressure), and \( A, \alpha, \beta, \) and \( \gamma \) are constants determined from the RSST-CH.
• Comparison of the down rut (in mm) for different asphalt materials, assuming a shear stress of 0.1 MPa, a temperature of 50 C, and a loading time of 0.015 seconds.
MnRoad Composite Cells 106 and 206

- 2” PG 64-34
- 5” PCC, 15’x12’
  - Cell 106: 1” dowels
  - Cell 206: no dowels
- 6” Class 5 aggregate base
MnROAD Distress Data

- Cell 106 (doweled)
  - 2 transverse cracks
  - Numerous reflective cracks
  - More cracks in truck lane
- Cell 206 (undoweled)
  - 1 transverse crack
  - Reflective cracks
  - Longitudinal cracks