TPF(5)-169: Development of an Improved Design Procedure for Unbonded Concrete Overlays

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Steven G. Sachs, PhD
Outline

• A brief summary of the previous work
• Cracking modeling
• Rudimentary software
• Remaining work
Unbonded Overlays

Concrete overlay

Interlayer

Existing concrete pavement
# Design Procedures

<table>
<thead>
<tr>
<th>Design Factors</th>
<th>AASHTO</th>
<th>Corps of Engineers</th>
<th>Rollings</th>
<th>PCA</th>
<th>Minnesota</th>
<th>MEPDG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analytical Model</td>
<td>Empirical equation: ( h = h_0 \cdot h_r )</td>
<td>Empirical equation: ( h = h_0 \cdot h_r )</td>
<td>Layered elastic theory</td>
<td>Plate theory/finite element model ISLAB</td>
<td>Corps of Engineers/PCA</td>
<td>Plate theory/finite element model ISLAB2000</td>
</tr>
<tr>
<td>Failure criteria</td>
<td>Deterioration in terms of serviceability loss</td>
<td>Cracking in 50% of slabs</td>
<td>Deterioration in terms of a structural condition index</td>
<td>Depends on failure criterion for full depth concrete design procedure</td>
<td>Not applicable</td>
<td>Transverse cracking and joint faulting</td>
</tr>
<tr>
<td>Interface condition</td>
<td>Considers overlay to be fully unbonded, ( n=2 )</td>
<td>Power in design equation is adjusted to account for level of bonding</td>
<td>Varies between full bonding and completely unbonded</td>
<td>Unbonded</td>
<td>Power in design equation is adjusted to account for level of bonding</td>
<td>Unbonded</td>
</tr>
<tr>
<td>Material properties</td>
<td>Modulus of elasticity and flexural strength for overlay concrete, ( k )-value for subgrade</td>
<td>Equivalent required thickness, ( &quot;h,&quot; ) as input to empirical equation</td>
<td>Modulus of elasticity and Poisson's ratio for all materials, and flexural strength of overlay concrete</td>
<td>Modulus of elasticity and modulus of rupture for overlay concrete, ( k )-value for subgrade</td>
<td>Modulus of elasticity and modulus of rupture for overlay concrete, ( k )-value for subgrade</td>
<td>Modulus of elasticity and Poisson's ratio for all materials, flexural strength coefficient of thermal expansion for overlay concrete</td>
</tr>
</tbody>
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</tr>
</thead>
<tbody>
<tr>
<td>Difference in strength/modulus of overlay and base pavement concrete</td>
<td>Not considered</td>
<td>Thickness of base pavement is adjusted</td>
<td>Included directly in calculation of stresses and design factors</td>
<td>Included directly in calculation of stresses and design factors</td>
<td>Not considered</td>
<td>Included directly in calculation of stresses and deflections</td>
</tr>
<tr>
<td>Cracking in base pavement before overlay</td>
<td>Effective thickness of base pavement is reduced</td>
<td>Effective thickness of base pavement is reduced</td>
<td>Modulus of elasticity of base pavement is reduced</td>
<td>Included directly in calculation of stresses using soft elements</td>
<td>Thickness of base pavement is reduced</td>
<td>PCC damage in the existing slab is considered through a reduction in its elastic modulus</td>
</tr>
<tr>
<td>Fatigue effects of traffic on uncracked base pavement</td>
<td>Effective thickness of base pavement is reduced</td>
<td>Effective thickness of base pavement is reduced</td>
<td>Included in terms of equivalent traffic</td>
<td>Not considered</td>
<td>Not considered</td>
<td>Not considered</td>
</tr>
<tr>
<td>Cracking of base after overlay</td>
<td>Not directly considered</td>
<td>Not directly considered</td>
<td>Modulus of elasticity of base pavement is reduced to compensate for cracking under traffic</td>
<td>Not considered</td>
<td>Not considered</td>
<td>Not considered</td>
</tr>
<tr>
<td>Temperature curling or moisture warping</td>
<td>Assumes AASHTO Road Test conditions</td>
<td>Not considered</td>
<td>Not considered</td>
<td>Does not affect thickness selection</td>
<td>Not considered</td>
<td>Included directly in calculation of stresses and deflections</td>
</tr>
<tr>
<td>Joint spacing</td>
<td>Maximum joint spacing 1.75*(hOL) (JPCP)</td>
<td>No recommendation provided</td>
<td>No recommendation provided</td>
<td>Maximum joint spacing in feet is 1.75*(hOL*(in)) (JPCP)</td>
<td>15 ft if 7 in &lt; hOL &lt; 10.5 in; 20 ft if hOL &gt; 10.5 in</td>
<td>Included directly in calculation of stresses and deflections</td>
</tr>
</tbody>
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</tr>
</thead>
<tbody>
<tr>
<td>Joint load transfer</td>
<td>Thickness increased if not dowelled</td>
<td>Dowels assumed</td>
<td>Not considered</td>
<td>Not specified for overlay but considered in evaluation of base pavement</td>
<td>Dowels assumed</td>
<td>Included directly in calculation of deflections</td>
</tr>
<tr>
<td>Drainage</td>
<td>Included in thickness design by empirical coefficient</td>
<td>Not considered</td>
<td>Requires retrofit of drainage system (if necessary)</td>
<td>Edge drains are recommended where pumping and erosion has occurred in the existing slab.</td>
<td>Edge drains and permeable interlayer for all pavements, interceptor drains when overlay is wider than the base pavement.</td>
<td>Requires retrofit of drainage system (if necessary)</td>
</tr>
<tr>
<td>Interlayer</td>
<td>Recommends 1-in min. thick AC interlayer or permeable open-graded interlayer</td>
<td>No recommendation provided</td>
<td>No recommendation provided</td>
<td>Thin interlayer (&lt;0.5 in) if extensive repair work performed. Thick (&gt;0.5 in) otherwise.</td>
<td>&gt;1 in &gt;2 in if base pavement is badly faulted and/or has a rough profile</td>
<td>1-2 in</td>
</tr>
</tbody>
</table>
Interlayer

- Separates horizontal movements of the overlay and existing pavement
- Provides uniform support to the overlay
- May provide additional drainage

- Many overlay failures are attributed to poor performance of the interlayer
- Design recommendations (if any) are prescriptive
- The use of non-woven fabric interlayers has been recently proposed
TPF-5(269) Development of an Improved Design Procedure for Unbonded Concrete Overlays

Original Project

• University of Minnesota (PI: Lev Khazanovich)
• University of Pittsburgh (co-PI: Julie Vandenbossche)
• Dr. Mark Snyder (consultant)

Since November 2017

• University of Pittsburgh (Lev Khazanovich and Julie Vandenbossche)
• Dr. Mark Snyder (consultant)
TPF-5(269)

- Field studies
- Lab testing
- Analytical modeling
- Performance modeling
Field studies: lessons learned

Factors affecting interlayer performance

• Erodibility – Stripping of interlayer adjacent to joints leads to interlayer erosion.

• Strength/stiffness – There is a potential for consolidation or crushing of interlayer adjacent to transverse joint if strength or stiffness are inadequate.

• Permeability – Drainage within interlayer reduces pressure build-up.
Lab Study

Mechanisms Investigated:

1. Ability to prevent reflective cracking
2. Stiffness of interlayer
3. Friction along interlayer system
4. Vertical resistance to uplift – pull off
Specimen setup

Interlayer
- Geotextile fabric
- Open & Dense HMA

Overlay Concrete
- Conventional Paving Mix
- Target flexural strength = 650 psi

Existing Concrete
- HES Mix – simulate aged concrete
- Target flexural strength = 850 psi
- OR in-service PCC from composite pavement (asphalt IL)

Two layers of neoprene pad
- Fabcell-25
- k = 200 psi/in

Threaded Steel Rods
## Interlayers

<table>
<thead>
<tr>
<th>Roadway</th>
<th>Asphalt Description</th>
<th>Ave. Asphalt Thickness</th>
<th>Specimen Designation</th>
</tr>
</thead>
<tbody>
<tr>
<td>US-131, MI</td>
<td>Old, dense graded</td>
<td>1 in</td>
<td>MIDAU</td>
</tr>
<tr>
<td>US-131, MI</td>
<td>Old, open-graded</td>
<td>2 in</td>
<td>MIOAU</td>
</tr>
<tr>
<td>I-94, MnROAD</td>
<td>Old, dense graded, milled</td>
<td>0.875 in</td>
<td>MNDAM</td>
</tr>
<tr>
<td>I-94, MnROAD</td>
<td>Old, dense graded, unmilled</td>
<td>2.75 in</td>
<td>MNDAU</td>
</tr>
<tr>
<td>US-169, MN</td>
<td>New, open graded (PASRC)</td>
<td>1.75 in</td>
<td>MNONU</td>
</tr>
<tr>
<td>SR-50, PA</td>
<td>New, dense graded</td>
<td>1 in</td>
<td>PADNU</td>
</tr>
</tbody>
</table>

- Propex Reflectex - 15 oz/yd² fabric = F15
- Propex Geotex 1001N – 10 oz/yd² fabric = F10
Ability to prevent reflective cracking

- Load increased until reflective crack generated
- 2 LVDTs record overlay beam disp
- 2 LVDTs record existing beam disp
- Recorded 3.5 in to the left of the load

Sufficient “cushion” to prevent reflective cracking?
Conclusions

• “True” reflective cracking rarely occurs in the field, unless non-uniform support conditions exist.

• Fabric tends to increase resistance to reflective cracking when compared to HMA.
Interlayer Resilience

Reduced stiffness
- Differential movements absorbed by interlayer
- Large deflections when vehicle loads are applied

Properties Monitored
- Max deflections
- Differential deflections
- LTE

Joint sawed in overlay midspan
Elastic Deflection and Permanent Deformation

- Fabric interlayers appear different from one another
- Elastic responses of the fabric are different from all asphalt interlayers
- MN open graded asphalt appears different from other asphalts
Totski Model

- Model accounts for
  - overlay
  - existing slab
  - subgrade support
  - “cushioning” property of the interlayer using Totski springs layer

- Joints in the overlay do not necessarily match joints in the existing pavements

- Unlike AASHTO M-E, the structural model does not convert the existing pavement and overlay into a single-layer system
Totski Model

• Advantages of Totski approach:
  – Computationally efficient (big concern for finite element models)
  – Already incorporated into ISLAB2005
  – Can be adopted for more sophisticated models (e.g., 3D joint faulting) without issue
  – Modeling of gaps between the overlay and existing pavement

• Requires estimate of interlayer spring coefficient
Modeling reflective cracking beam behavior and interlayer response

- 2D finite element simulation of reflective cracking beams using ISLAB2005
- Factorial of simulations created for exact beam dimensions and support conditions
  - Interlayer coefficient varied from 10 to 50,000
Totski Interlayer k-value

- Deflection data from reflective cracking test
  - Test setup modeled in ISLAB
  - 1 kip response for different k-values

\[ y = 3015.3x^{0.988} \]

\[ R^2 = 0.99 \]
Totski Interlayer k-value

<table>
<thead>
<tr>
<th>Interlayer Type</th>
<th>Average Totski k-value (psi/in)</th>
<th>Standard Deviation (psi/in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F15</td>
<td>337</td>
<td>63</td>
</tr>
<tr>
<td>F10</td>
<td>372</td>
<td>55</td>
</tr>
<tr>
<td>MNDAU</td>
<td>3342</td>
<td>1262</td>
</tr>
<tr>
<td>MNDAM</td>
<td>3613</td>
<td>1175</td>
</tr>
<tr>
<td>MNONU</td>
<td>2555</td>
<td>901</td>
</tr>
<tr>
<td>MIDAU</td>
<td>4046</td>
<td>966</td>
</tr>
<tr>
<td>MIOAU</td>
<td>3566</td>
<td>1095</td>
</tr>
<tr>
<td>PADNU</td>
<td>3391</td>
<td>1533</td>
</tr>
</tbody>
</table>

- Average lab and FWD for asphalt yields Totski k-value of approximately 3500 psi/in
- Average lab and FWD results is 425 psi/in for nonwoven geotextile fabric interlayer
Totski Interlayer k-value Backcalculation

- FWD data from MnROAD used to establish k-values for Cells 105 - 605

Comparison between means of established Totski k-values

<table>
<thead>
<tr>
<th>Comparison</th>
<th>P-value of t-test for difference in means</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fabric LAB vs. MnROAD Fabric FWD</td>
<td>0.126</td>
</tr>
<tr>
<td>MNONU LAB vs. MnROAD Asphalt FWD</td>
<td>0.137</td>
</tr>
<tr>
<td>MnROAD Fabric FWD vs. MnROAD Asphalt FWD</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>
Performance Modeling

• AASHTOWare Pavement ME
  • Transverse cracking model
  • Faulting model (subgrade erosion)
  Interlayer properties are ignored!

• This study
  • Cracking modeling
    • Transverse cracking model
    • Transverse joint damage model (corner/longitudinal cracking)
  • Faulting model
  Interlayer stiffness and degradation are accounted for!
Cracking Model

• PavementME (MEPDG) framework:
  – Effect of PCC age on concrete strength and stiffness
  – Axle load spectrum
  – Curling analysis
  – Effect of built-in curling
  – Incremental damage analysis

• Significant modifications
PCC Strength Gain

![Graph showing PCC strength gain over time with Modulus of Elasticity, E and Modulus of Rupture, Mr plotted against time in months. The graph includes a note that it uses MEPDG Level 3 curves.]

Uses MEPDG Level 3 curves
Traffic Analysis

• MEPDG default axle spectrum distribution
• AADTT for the first year
• Linear traffic volume growth model
Curling Analysis

- EICM is used to predict hourly temperature profile through PCC based on historical hourly climatic data
- Both daytime (positive) and nighttime (negative) thermal gradient probability distributions are obtained
Curling Analysis

- Temperature distribution that distorts PCC slabs is characterized in terms of equivalent temperature gradient affecting bending analysis.
- Nonlinear temperature component is accounted for analytically.
Curling Analysis

Actual Temperature Gradient

Built-in Curling

Frequency distribution of linearized hourly temperature gradients

\[ TG_{\text{BuiltIn}} = f(\text{Design & Site Factors}) \]

Empirical relationship based on calibration results
Incremental Damage Analysis

Fatigue Damage = \sum_{i} \sum_{j} \sum_{k} \sum_{l} \sum_{m} \sum_{n} \frac{n_{ijklmn}}{N_{ijklmn}}

\log(N) = 2.0 \times \left( \frac{M_r}{\sigma_{total}} \right)^{1.22} + 0.4371

n_{ijklmn} = \text{Applied number of load applications at condition } i,j,k,\ldots
N_{ijklmn} = \text{Allowable number of load applications at condition } i,j,k,\ldots

i = \text{Age} ; \quad k = \text{Axle combination} ; j = \text{nonlinear temperature gradient}
\quad l = \text{Load level} ; \quad m = \text{Temperature gradient} ; \quad n = \text{Traffic path}
Cracking Prediction

Damage + Cracking → Cracking

Time Damage Age
AASHTOWare Pavement ME (MEPDG)

- Adapted MEPDG performance prediction models for new pavements
- Empirical stiffness reduction factors for distresses in the existing pavement

\[ E_{BASE/DESIGN} = C_{BD} \times E_{TEST} \]
MEPDG Unbonded Overlay Cracking Model

- Modeled as newly constructed JPCP

- Joints in the overlay match joints in the existing slab
- Existing pavement is considered a base of the overlay
- Deflection basins of the overlay and the existing pavements are the same
- Interlayer deterioration is ignored
TPF(5)-169 Cracking Model

• Toski model for structural responses
  – Independent curling of the overlay and existing pavement
  – Composite bending behavior
  – Mismatched joints in the overlay and existing pavements
• Modified temperature frequency analysis
• Interlayer deterioration
TPF(5)-169 Cracking Model

- Modified built-in curling analysis (NCHRP 1-51 approach)
- Longitudinal edge and transverse cracking analysis
- Monte Carlo-based reliability analysis (MnPAVE Rigid-based approach)
Curling Analysis

- EICM used to predict hourly temperature profile through PCC based on historical hourly climatic data
- For each hour, the temperature distribution is approximated using quadratic distribution

\[ T(z) = A + B \cdot z + C \cdot z^2 \]
Curling Analysis

- Linear gradient and non-linear stresses at the surfaces are determined (Choubane and Tia 1992, Khazanovich 1994)

\[ T_L(z) = T_0 + B \ z \]

\[ \Delta T_L = B \ h \]

\[ \sigma_{Nxx}(z) = \sigma_{Nyy}(z) = \frac{C \ E}{1-\mu} \ \alpha \left[ \frac{h^3}{12} - z^2 \right] \]

- Frequencies of combinations of B and C are determined (Hiller and Roesler 2010)
## Frequency Table

<table>
<thead>
<tr>
<th>( \Delta T_L )</th>
<th>( C )</th>
</tr>
</thead>
<tbody>
<tr>
<td>-24.8994</td>
<td>0</td>
</tr>
<tr>
<td>-23.0144</td>
<td>0.00106</td>
</tr>
<tr>
<td>-21.1352</td>
<td>0.00376</td>
</tr>
<tr>
<td>-19.2559</td>
<td>0.00141</td>
</tr>
<tr>
<td>-17.371</td>
<td>0.00282</td>
</tr>
<tr>
<td>-15.4917</td>
<td>0.00106</td>
</tr>
<tr>
<td>-13.6124</td>
<td>0.00129</td>
</tr>
<tr>
<td>-11.7275</td>
<td>0.00117</td>
</tr>
<tr>
<td>-9.8482</td>
<td>0.00329</td>
</tr>
<tr>
<td>-7.9689</td>
<td>0.00211</td>
</tr>
<tr>
<td>-6.084</td>
<td>0.00117</td>
</tr>
<tr>
<td>-4.2047</td>
<td>0.00054</td>
</tr>
<tr>
<td>-2.3255</td>
<td>0.000305</td>
</tr>
<tr>
<td>-0.4405</td>
<td>0.00751</td>
</tr>
<tr>
<td>1.4387</td>
<td>0.000516</td>
</tr>
<tr>
<td>3.318</td>
<td>0.000246</td>
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<tr>
<td>5.2029</td>
<td>0.000017</td>
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<tr>
<td>7.0822</td>
<td>0.0000364</td>
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<tr>
<td>8.9615</td>
<td>0.000094</td>
</tr>
<tr>
<td>10.8464</td>
<td>0.000047</td>
</tr>
<tr>
<td>12.7257</td>
<td>0.000188</td>
</tr>
<tr>
<td>14.605</td>
<td>0.000023</td>
</tr>
<tr>
<td>16.4899</td>
<td>0.000059</td>
</tr>
<tr>
<td>18.3692</td>
<td>0.000059</td>
</tr>
</tbody>
</table>

*Adjusted for built-in curling*
EICM Analysis

• 70 weather stations
• Overlay thickness 4, 6, 8, and 10 in
• Frequency tables generated for each case
• Interpolation for other thicknesses
Permanent (Built-in) Curling

- Due to irreversible shrinkage
- Due to temperature gradient during concrete solidification (hydration) process

(Eisenmann and Leykauf, 1994; Yu, Khazanovich, Darter, and Ardani 1998; Yu and Khazanovich 2001; Vandenbossche 2006)
Permanent (Built-in) Curling
Permanent (Built-in) Curling

To accurately model built-in curling, first several days of concrete pavement should be simulated precisely:

- Cement hydration process
- Ambient temperature and humidity, solar radiation, and wind
- Heat transfer & moisture transport
- Concrete creep
- Concrete shrinkage
- Concrete fracture (joint formation)

Ruiz et al. 2005
Permanent (Built-in) Curling

- PavementME
  \[ \Delta T_{Built-in} = -10 \, ^\circ F \]
- NCHRP 1-51 (Khazanovich and Tompkins 2017)
  \[ \Delta T_{Built-in} = -10 \, ^\circ F \pm A \]
where A depends on the ratio between the PCC slab and base stiffnesses
Permanent (Built-in) Curling

- TPF(5)-169

\[ \Delta T_{\text{Built-in}} = -10 \, ^\circ F \pm A \]

where A depends on the interlayer stiffness and joint spacing

- \( \Delta T_{\text{Built-in}} = -10 \, ^\circ F + A \) is used for daytime curling analysis

- \( \Delta T_{\text{Built-in}} = -10 \, ^\circ F - A \) is used for nighttime curling analysis
Stress Analysis

• Several factorials of ISLAB2000 Totski model runs (more than 50,000 cases)
• Several NNs for top-down cracking and joint damage analysis
  • w/o voids in the interlayer
  • with voids in the interlayer
• NCHRP 1-37A NNs for longitudinal edge loading analysis
• Westergaard solution for daytime curling analysis
Stress Analysis

Bottom-up transverse cracking
Stress Analysis

Top-down and joint damage
NNs for Top-down and Joint Damage Analysis

- Overlay radius of relative stiffness
- Axle weight/overlay weight ratio
- Axle spacing
- Transverse joint LTE
- Korenev’s non-dimensional temperature gradient
- Overlay/shoulder LTE
- Void/no void
Two overlay structures are similar if

\[ L_1 = L_2 \]
\[ \ell_1 = \ell_2 \]
\[ \frac{AGG_{x,1}}{k_{Tot,1} \ell_1} = \frac{AGG_{x,2}}{k_{Tot,2} \ell_2} \]
\[ \frac{AGG_{y,1}}{k_{Tot,1} \ell_1} = \frac{AGG_{y,2}}{k_{Tot,2} \ell_2} \]
\[ \frac{P_1}{h_1 \gamma_1} = \frac{P_2}{h_2 \gamma_2} \]
\[ \varphi_1 = \varphi_2 \]

\[ \sigma_2 = \frac{h_1 \gamma_2 \ell_2^2}{h_2 \gamma_1 \ell_1^2} \sigma_1 + \Delta \sigma_{NLT} \]

\[ \varphi = \frac{2\alpha (1+\mu) \ell^2}{h^2} \frac{k}{\gamma} \Delta T \]

\( \gamma \) = unit weight

Korenev’s (1962) nondimensional temperature gradient
Incremental Damage Calculation

• Increment: 1 year
• Frequencies for linear and non-linear temperature gradients
• Stress and damage computations with and w/o void

\[ \text{Fatigue Damage} = \sum_i \sum_j \sum_k \sum_l \sum_m \sum_n \frac{n_{ijklmn}}{N_{ijklmn}} \]

\[ \text{Log}(N) = 2.0 \left( \frac{M_r}{\sigma_{\text{total}}} \right)^{1.22} + 0.4371 \]

• Four types of fatigue damage
  • Longitudinal edge, bottom overlay surface (transverse bottom-up cracking)
  • Longitudinal edge, top overlay surface (transverse bottom-up cracking)
  • Transverse joint, top overlay surface (longitudinal/corner cracking)
  • Transvers joint, bottom overlay surface (longitudinal cracking)
Effect of Interlay Erosion

2 cases
• No void
• 24-in long, lane-wide void
Incremental Damage Calculation

• Damage computation for the increment

\[ DAM_i = (1 - \Lambda_i) \cdot DAM_{i,w/o \ void} + \Lambda_i \cdot DAM_{i,w \ void} \]

\[ \Lambda_i \]: interlayer deterioration index for the increment \( i \).

Depends on the interlayer age and properties.
Cracking Analysis

\[
\% \text{ of Cracked Slabs} = \frac{100\%}{1 + C_3 DAM^{C_4}}
\]

• Step 1
  • Top-down transverse cracking
  • Bottom-up transverse cracking
  • Top-down longitudinal cracking
  • Bottom-up longitudinal cracking
Cracking Analysis

• Step 2
  • Transverse cracking

\[ TRCRACK = (TCRK_{\text{Bottom\_up}} + TCRK_{\text{top\_down}} - TCRK_{\text{Bottom\_up}} \times TCRK_{\text{top\_down}}) \times 100\% \]

  • Longitudinal cracking

\[ LCRACK = (LCRK_{\text{Bottom\_up}} + LCRK_{\text{top\_down}} - LCRK_{\text{Bottom\_up}} \times LCRK_{\text{top\_down}}) \times 100\% \]

• Step 3: Total cracking

\[ CRACK = (TRCRACK + LCRACK - TRCRACK \times LCRACK) \times 100\% \]
Reliability Analysis

• Inputs:
  • Reliability Level
  • Coefficient of variation of Overlay thickness
  • Coefficient of variation PCC strength
  • Allowable cracking level at the end of the design life

• Procedure
  • Perform simulation for a factorial of PCC overlay thicknesses and strengths
  • Determine the overlay thickness resulting in the percentage of thickness/strength combinations with cracking less than the specified allowable level
Rudimentary Software

- **Climate Station**: MOBILE AL
- **Reliability, percent**: 90
- **Design Life, years**: 20
- **AADTT year 1**: 1000
- **Number of Lanes (two-way)**: 2
- **Joint Spacing, ft**: 13.5
- **Flexural Strength, psi**: 650
- **Shoulder Type**: Asphalt/Non-Tied PCC/Aggregate
- **Dowel Diameter, in**: 0
- **Interlayer Type**: Asphalt
- **Existing PCC thickness, in**: 10
- **Existing PCC Modulus, psi**: 4000000

[Run]
Remaining Work

• Add 6 ft x 6 ft slabs
• Check analysis for thin overlays (< 6 in)
• Increase the number of weather stations
• Incorporate the faulting model into the software
• Upgrade the interlayer deterioration model
• Provide default inputs
Pavement ME limitations

• Modeled as newly constructed JPCP
  • Interlayer is the base layer
Pavement ME limitations

• Erodibility index

Assigned integer value based upon base type

1 – extremely erosion resistant
to

5 – very erodible

UBOL EROD = 1
Faulting model framework

1. Lab Investigation
2. Structural Model $\sigma, \varepsilon, \delta$
3. Neural Network to predict critical response
4. Damage Model: Relate response to damage
5. Faulting Model: Relate damage to faulting
6. Field Data Analysis
7. Calibration of Faulting Model
Differential Energy

\[ DE_m = n_i k \left( \frac{\Sigma \delta_{L,i}^2}{2} - \frac{\Sigma \delta_{U,i}^2}{2} \right) \]

- \( DE_m \) = diff energy density deformation accumulated in month m
- \( \Sigma \delta_{L,i} \) = sum deflections for loaded slab caused by axle loading
- \( \Sigma \delta_{U,i} \) = sum deflections for unloaded slab caused by axle loading
- \( k \) = interlayer Totsky k value
- \( n_i \) = # of ESAL applications for month m
Predictive Model Response
Predictive Model Response
Predictive Model Response

- **Deflection Basin Approach Slab:**
  - $\sum (\delta_{UL}^2 \times Area)$
  - 2 ft x 6 ft rectangle

- **Deflection Basin Leave Slab:**
  - $\sum (\delta_{UL}^2 \times Area)$
  - 2 ft x 6 ft rectangle
Faulting model

\[
F_0 = \left( C_1 + C_2 \times FR^{0.25} \right) \times \delta_{\text{curl}} \times [C_5 \times E]^{C_6} \times \log(WETDAYS \times P_{200})
\]

\[
F_i = F_{i-1} + C_7 \times C_8 \times DE_i \times [C_5 \times E]^{C_6}
\]

\[
\Delta Fault_i = \left( C_3 + C_4 \times FR^{0.25} \right) \times (F_{i-1} - Fault_{i-1}) \times C_8 \times DE_i
\]

\[
Fault_i = Fault_{i-1} + \Delta Fault_i
\]

\( F_0 \) = initial maximum mean transverse joint faulting (in)
\( FR \) = base freezing index (% time that the top of the base is below freezing (<32°F))
\( \delta_{\text{curl}} \) = max mean monthly PCC upward slab deflection due to curling
\( E \) = erosion potential of interlayer: \( f(\% \text{ binder content}, \% \text{ air voids}, P_{200}) \)
\( P_{200} \) = Percent of interlayer aggregate passing No. 200 sieve
\( WETDAYS \) = Average number of annual wet days (> 0.1 in of rainfall)
\( F_i \) = maximum mean transverse joint faulting for month i (in)
\( F_{i-1} \) = maximum mean transverse joint faulting for month i-1 (in)
\( DE_i \) = Differential energy density of accumulated during month i
\( \Delta Fault_i \) = incremental monthly change in mean transverse joint faulting during month i (in)
\( C_1 \ldots C_8 \) = Calibration coefficients
\( Fault_{i-1} \) = mean joint faulting at the beginning of month i (0 if i = 1)
\( Fault_i \) = mean joint faulting at the end of month i (in)
Calibration

• Adjust calibration coeff. to minimize ERROR function
  • Shape of erosion function also fit based upon interlayer characteristics
• Macro driven excel spreadsheet was developed to calibrate the model
• Several calibration coeff. fixed
  • remaining coefficients varied to minimize error
  • switch coefficients being modified
• Bias of model must be considered in calibration coeff.

\[
\text{ERROR}(C_1, C_2, C_3, C_4, C_5, C_6, C_7, C_8) = \sum_{i=1}^{N} (\text{FaultPredicted}_i - \text{FaultMeasured}_i)^2
\]
Faulting model

\[ F_0 = (C_1 + C_2 \cdot FR^{0.25}) \cdot \delta_{curl} \cdot [C_5 \cdot E]^{C_6} \cdot \log(WETDAYS \cdot P_{200}) \]

\[ F_i = F_{i-1} + C_7 \cdot C_8 \cdot DE_i \cdot [C_5 \cdot E]^{C_6} \]

\[ \Delta \text{Fault}_i = (C_3 + C_4 \cdot FR^{0.25}) \cdot (F_{i-1} - \text{Fault}_{i-1}) \cdot C_8 \cdot DE_i \]

\[ \text{Fault}_i = \text{Fault}_{i-1} + \Delta \text{Fault}_i \]

\[ C_1 = 3.0 \quad C_5 = 0.015 \]
\[ C_2 = 2.5 \quad C_6 = 2.202 \]
\[ C_3 = 35 \quad C_7 = 80 \]
\[ C_4 = 0.001 \quad C_8 = 0.0000002 \]
Erosion

\[ \alpha = \log(1 + a \times \%Binder + b \times \%AV + c \times P_{200}) \]

\( \alpha \) = Erodibility index

\( \%Binder \) = Percent binder in asphalt interlayer

\( \%AV \) = Percent air voids in asphalt interlayer

\( P_{200} \) = Percent passing No. 200 sieve in interlayer

\( a, b, c \) = Calibration coefficients (0.226, 0.247, 0.066)

\[ E = \begin{cases} 
(3.5628 \times \alpha^2 - 3.7689 \times \alpha + 1.0928) & \text{Undoweled pavements} \\
(3.0284 \times \alpha^2 - 3.2036 \times \alpha + 0.9283) & \text{Doweled pavements} \\
(3.5628 \times \alpha^2 - 3.7689 \times \alpha + 0.09) & \text{NWGF sections}
\end{cases} \]
Erosion Calibration

Undoweled - Erosion Model

\[ y = 3.5628\alpha^2 - 3.7689\alpha + 1.0921 \]
\[ R^2 = 0.99 \]