Concrete Pavement Thickness
Design & Slab Geometry

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Agenda
- Review of Pavement Design History & Pavement Types
- Distresses Related to Pavement/Slab Geometry
- Compare AASHTO 93 vs Pavement ME Designs
- Incorporating Slab Geometry into Design Tools
- Using Slab Geometry to Control Cracking Mechanisms
  - Thickness
  - Joint Spacing
  - Widened Lanes
- Additional Design Considerations and Jointing

In The Beginning…

Early Concrete Pavement Details

- The first concrete pavements/slabs were:
  - ≈ 6” thick… no real structural design
  - 6’ to 8’ slabs
  - No crack control joints or dowels/steel
Design Challenge | Solution

- Vehicles Speeds Increased
- Loads Increased
- People Noticed Joint Roughness & Wanted to Maximize Production to Minimize Cost | Minimize Construction Joints

Less of this and more of this!

CONCRETE PAVING SOLUTIONS USING CONVENTIONAL CONCRETE

- Jointed Plain Concrete Pavement (JPCP)
  - Shorter slabs w/ dowels & aggregate interlock to transfer loads
  - 10 – 16 ft.
- Jointed Reinforced Concrete Pavement (JRCP)
  - Longer (than JPCP) jointed w/ dowels to transfer loads
  - 30 – 100 ft.
- Continuously Reinforced Concrete Pavement (CRCP)
  - Continuously reinforced to control crack width
  - 2 – 6 ft.

JOINTED PLAIN CONCRETE PAVEMENTS (JPCP) – Key Design Items

- Longitudinal joint
  (incl location & spacing)
- Transverse joint
  (incl location & spacing)
- Surface texture
- Concrete mix design
- Thickness design
- Dowel bars
- Tiebars
- Subgrade
- Subbase or base

Design requires understanding how design features impact cost and performance (and getting the right balance for the application)

Design also Requires an Understanding of How a Concrete Pavement Fails...

- Structural Distress – the ability to carry traffic
  - Cracking (dominant)
- Functional Distress – the ability to serve the user comfortably
  - Rough ride (fatigue)
  (mainly due to cracking and faulting)
- Joint Faulting (dominant)
  - Insufficient Texture/friction (address through maintenance)
Rigid Pavement Design Tools/Methods

**AASHTOWare Pavement ME**
(previously known as DARWin-ME and MEPDG)

**AASHTO 93**
(software as ACPA WinPAS)

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**Equivalent Single Axle Loads (ESALs)**

- **ESAL** = # of 18 kip (8,165 kg) equivalent single axles needed to cause same “response”
  - Because pavement responses are different for concrete and asphalt, ESALs are different for the same exact traffic loading... ESAL ≠ traffic
  - ESALs depends on thickness, among other things
  - Flexible ESALs generally about 1/3 less than rigid ESALs for highway-type traffic; NEVER COMPARE RIGID & FLEXIBLE ESALs

**TRAFFIC IS THE MAIN SOURCE OF DAMAGE FOR PAVEMENTS**
The Magnitude of Damage Depends on Vehicle Number, Type, and Load

**Equivalent Single Axle Loads (ESALs)**
- Assumes traffic is only 18,000 lbs single axles
- Conversion of trucks to ESALs is empirical
- Based on field test conducted 50 years ago
- Traffic conditions significantly changed between now and then

**Load Spectrum**
- Consider traffic composed of axles w/ different weights
- Required inputs:
  - Number of trucks
  - Axle load spectrum
  - Function of roadway type

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**Traffic Exemplary:**
- Single Tandem Tridem

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**Traffic Exemplary:**
- Single Tandem Tridem
1986-93 JPCP AASHTO 93 Equation

\[
\text{Standard Normal Deviate} \\
\text{Log(ESAL)} = Z_e \cdot s_e + 7.35 \cdot \log(D+1) - 0.06 + \frac{\text{Overall Standard Deviation}}{1 + 1.624 \times 10^4 \frac{(D+1)^{1.1}}{4.5 - 1.5}}
\]

\[
\text{Terminal Serviceability} \\
+ (4.22 - 0.32 \cdot p_r) \cdot \log \left( \frac{S_r \cdot C_r \cdot (D_0^{0.75} - 1.132)}{215.63 \cdot J \cdot D_{TS}^{0.75} \cdot 18.42 \cdot \frac{E_r}{k}} \right)
\]

WHAT DO DESIGNERS FOCUS ON?

- Modulus of Rupture
- Drainage Coefficient
- Load Transfer
- Modulus of Elasticity
- Modulus of Subgrade Reaction

Concrete Pavement Design Methodologies

Outdated

- AASHTO 93
- 10 inputs
- "Performance"
- Field Data

Current Design Tools

- StreetPave
  - 2005-2017
  - 12 inputs
  - Crack & Fault
  - FEA + Field Data
- PavementDesigner
  - 2018 - Present
  - 12 inputs
  - Crack & Fault
  - FEA + Field Data
- OptiPave
  - 2009 - 2018
  - 50 inputs
  - Crack, Fault, WR
  - FEA + Field Data
- Pavement ME
  - 2009-2018
  - 1,000 inputs
  - Crack, Fault, WR
  - FEA + Field Data

Increasing Complexity = More Accurate Models & More Optimization

WinPAS Makes it Easy!

AASHTO 93 Slab Geometry involved => Thickness

Industry Developed Methods

PavementDesigner.org
**PavementDesigner.org**

**Background**

A free tool designed to simplify concrete pavement design for:
- Parking lots
- Roadways (JPCP, RCC, CRCP, Overlays Unbonded & Bonded)
- Industrial / Intermodal yards (Forklifts & Specialty Equipment)

Uses More Accurate Traffic Inputs

PD.org Slab Geometry => Thickness & Joint Spacing

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**Pavement ME Design**

- Not “perfect” & not intended to be a “final” product
- Complex and relatively costly
- Primarily for high volume roadways

 Mechanistic Calculation of Responses + Empirical Tie to Ground = Pavement Performance Prediction

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**MEPDG / DARWin-ME / AASHTOWare Pavement ME**

**Sounds Easy Enough, Right?**

\[
\text{Fault}_{\text{eff}} = \sum \text{Fault}_{i}
\]

\[
\Delta \text{Fault}_{i} = -C_{9} \times (\text{FAULTMAX}_{i} - \text{Fault}_{\text{eff}}) \times D_{E}\]

\[
\text{FAULTMAX}_{i} = C_{2} \times \left( \sum D_{E} \times \log(1 + C_{3} \times \text{ATMP}) \right)^{2}
\]

\[
\sigma_{n} = \frac{E_{PC} \Delta \text{Def}}{2(1 - M)}
\]

\[
I_{RI} = 1 \text{RI}_{o} + C_{1}^\text{RI} \text{CRK} + C_{2}^\text{RI} \text{SPALL} + C_{3}^\text{RI} \text{FAULT} + C_{4}^\text{RI} \text{SF}
\]

\[
\text{SCF} = -1400 + 350 \times ATR + (0.5 + \text{PREFORM}) + 3.4 \times f_{c} + 0.4
\]

\[
\quad - 0.2 (\text{FTCYC} \times \text{AGI}) + 45 \times h_{PC} - 356 \times W_{C} \times \text{Rratio}
\]

\[
\text{crw} = \min \left( \frac{10}{\text{EF}_{\text{eff}}} \times 1000 \times \text{CC}, 0.001 \right)
\]
Concrete Pavement Design Options

Pavement ME’s Concrete Pavement Designs
- New Pavement
  - Jointed Plain Concrete Pavement (JPCP)
  - Continuously Reinforced Concrete Pavement (CRCP)
- Overlay
  - Bonded PCC over JPCP or CRCP
  - Unbonded JPCP or CRCP over JPCP or CRCP
  - CRCP over AC
  - SJPCP over AC
- Rehabilitation

Pavement ME Inputs...

EXACT Traffic Inputs...
Pavement ME Outputs...

Pavement ME Performance Outputs

Jointed Plain Concrete Pavement (JPCP)
- JPCP Design Process
  - General Info and Performance Criteria
  - Traffic Details
  - Climate
  - Characterizing Pavement Structure
  - JPCP Design Properties

JPCP – Characterizing Pavement Structure
**JPCP – Pavement Structure – PCC Materials**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCC</td>
<td>0.2</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.2</td>
</tr>
<tr>
<td>Thickness (in)</td>
<td>11</td>
</tr>
<tr>
<td>Unit weight (pcf)</td>
<td>150</td>
</tr>
<tr>
<td>Thermal</td>
<td></td>
</tr>
<tr>
<td>PCC coefficient of thermal expansion (in/deg F x 10^-6)</td>
<td>6.5</td>
</tr>
<tr>
<td>PCC heat capacity (BTU/lb-deg F)</td>
<td>0.38</td>
</tr>
<tr>
<td>PCC thermal conductivity (BTU/lb-deg F)</td>
<td>0.25</td>
</tr>
<tr>
<td>Mix</td>
<td></td>
</tr>
<tr>
<td>Aggregate type</td>
<td>Limestone (1)</td>
</tr>
<tr>
<td>Cement type</td>
<td>Type II (2)</td>
</tr>
<tr>
<td>Water to cement ratio</td>
<td>0.42</td>
</tr>
<tr>
<td>Curing method</td>
<td></td>
</tr>
<tr>
<td>Curing Compound</td>
<td></td>
</tr>
<tr>
<td>Reversible shrinkage (%)</td>
<td>50</td>
</tr>
<tr>
<td>PCC zero-stress temperature (deg F)</td>
<td>Calculated</td>
</tr>
<tr>
<td>Time to develop 50% of ultimate shrinkage (days)</td>
<td>35</td>
</tr>
<tr>
<td>Ultimate shrinkage (microstrain)</td>
<td>500 x (calculated)</td>
</tr>
<tr>
<td>Strength</td>
<td>Level 3 (Rupture (SSR) Module) (4000000)</td>
</tr>
</tbody>
</table>

**Let’s Break it Down**

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**JPCP – Design Properties**

- SSA
- Doweled Joints
- Diameter
- Spacing

- 0.85 (Default and semi-constant)
- Typically used if thickness > 8 in
- Often depends on thickness
  - 1 inch for 8 inches or less thickness
  - 1.25 inches for 8 – 10 inches thickness
  - 1.5 inches for >10 inches
- 12 inches is most common

**Let’s Break it Down**
**JPCP – Design Properties**

<table>
<thead>
<tr>
<th>Property</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erodibility</td>
<td>Depends on soil conditions</td>
</tr>
<tr>
<td>Base Friction</td>
<td>Good defaults</td>
</tr>
<tr>
<td>Joint Spacing</td>
<td>Typical range = 12 – 20 ft</td>
</tr>
</tbody>
</table>

**Summary of Unique JPCP Critical Inputs**

- **Performance Criteria**
  - IRI, Cracking, Faulting
- **Thickness**
- **Joint Spacing**
- **Lane Width**
- **Shoulder Type**
- **Dowel Design**

**JPCP – Design Properties**

<table>
<thead>
<tr>
<th>Property</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curl/Warp Temp.</td>
<td>-10°F (Good default)</td>
</tr>
<tr>
<td>Sealant Type</td>
<td>Preformed or Other (none, liquid, silicone)</td>
</tr>
<tr>
<td>Tied Shoulder</td>
<td>Project dependent</td>
</tr>
<tr>
<td>Widened Slab</td>
<td>Project dependent</td>
</tr>
</tbody>
</table>

Pavement ME Slab Geometry Inputs include Thickness, Joint Spacing, Lane Width

**SHORT JOINT SPACING IMPROVES JPCP PERFORMANCE**

- **Reduces Shrinkage Force**
  - Curling & warping is due to differential drying and thermal shrinkage at slab surface.
  - Shorter slabs have less length, which means reduced curling.
  - ~1/4 of slab length is cantilever.
  - Reducing unsupported length reduces the bending stress.
  - Reducing length reduces uplift and improves smoothness.

- **Reduces Environmental Stress**
  - 1/4 of slab length is cantilever.
  - Reducing unsupported length.

- **Improves Load Transfer**
  - Shorter slabs have smaller joint/crack opening.
  - Agg. Interlock stronger for tighter cracks.
  - High load transfer results in less stress in concrete.

**BOLD => Inputs Related to Slab Geometry**
SHORT JOINT SPACING REDuces SLAB CRACKING

Joint Spacing vs. Slabs Cracked

Maximum Joint spacing = 18 to 24 times thickness (15 ft max)

Engineering Solutions – Widened Slab Example

Widening the slab reduces longitudinal edge midpanel stresses but this could increase stresses in other locations not considered in Pavement ME

With 14 ft wide slab there is a much higher risk of longitudinal cracking due to increased stresses at interior transverse joint edge locations
Highway Design Problem

- 7,860 trucks (~20M ESALs)
- 90% Reliability
- 5% Slabs Cracked
- 6 lane facility
- R-Value = 20
- MOR = 630 psi
- EPCC = 3,500,000 psi

- Edge Support
- HMA Subbase = 1"
- Cement Stb Subgrade = 6"

- Design:
  - AASHTO 93 = 11"
  - PavementDesigner = 8.5"
  - Pavement ME = 9"

Additional Design Considerations Related to Slab Geometry

- Dowels
- Dowel Spacing
- Dowel Bar Diameter
- Edge Support
- Tie Shoulders
- Jointing Layouts

...CRCP Design Properties

Top 10 ME Design Most Sensitive

1. Concrete Flexural Strength at 28-Days
2. Concrete Thickness
3. Surface Shortwave Absorptivity (SSA)
4. Joint Spacing
5. Concrete Modulus of Elasticity at 28-Days
6. Design Lane Width with a 14 ft (4.3 m) Widened Slab
7. Edge Support via Widened Slab
8. Concrete Thermal Conductivity
9. Concrete Coefficient of Thermal Expansion (CTE)
10. Concrete Unit Weight

Engineer Solutions - Faulting

- Improve Mechanical LT
- Increase Dowel Size
- Decrease Dowel Spacing
- Decrease Joint Spacing
- Increase Width of Lanes
- Reduce Underlying Layer Erosion
- Increase Erodibility Index
- Decrease Joint Spacing
- Reduce Thickness
- Only if Cracking is Passing
Sensitivity of JPCP Faulting to Dowel Diameter

- 1" dowel
- 1.25" dowel
- 1.375" dowel
- 1.5" dowel

Faulting for 10 inch slab, ins

0 0.05 0.1 0.15 0.2 0.25 0.3 0.35

Age, months

Sensitivity of JPCP IRI Sensitivity to Dowels

- 1.25-in dowel
- 1.375-in dowel

1.25 million trucks (TTA2) (30 million ESALs)
6.8-in slab; 15-ft joint spacing
6-in aggregate base
28-day MRpcc = 690 psi; Epcc = 4.4 Mpsi

0 50 100 150 200 250

Pavement age, years

IRI, in/mi

Sounds Easy Enough, Right?

\[
Fault_u = \sum_\varepsilon \Delta Fault_{i,t}
\]

\[
\Delta Fault_{i,t} = C_{\Delta} \times \left(Fault_{i,t} - \bar{Fault}_{i} \right)^3 \times DE,
\]

\[
\bar{Fault}_{i} = \frac{\sum \left(\Delta Fault_{i,t} \times DE\right)}{\sum DE}
\]

\[
F_{\text{fault}} = \frac{\dot{f}}{2(1-\mu icc)}
\]

IRI = IRI0 + C1*CRK + C2*SPALL + C3*TAULT + C4*SF

\[
SCF = -1400 + 350 \times AIR + (0.5 + \text{PREFORM}) + 3.4 f_c + 0.4 - 0.2 \times (f_{\text{CTC}} + \text{AGE}) + 43 \times \text{MRPCC} - 7.3 \times \text{WC Ratio}
\]

\[
CW = \min \left( L_{\text{crit}} - \frac{E_{\text{mod}}}{E_{\text{pcc}}} \Delta T + \frac{C_{\text{cri}} - E_{\text{pcc}}}{E_{\text{pcc}}} \cdot 1000 \times CC, 0.001 \right)
\]

Continuously Reinforced Concrete Pavement (CRCP)

- Resources: Check out crcpavement.org for more!


9.8-in slab; 15-ft joint spacing
6-in aggregate base
28-day MRpcc = 690 psi; Epcc = 4.4 Mpsi

19 million trucks (TTA2) (30 million ESALs)
CRCP Design Properties Related to Slab Geometry

- Lane Width
- Crack Spacing (Dependent on Steel Design & Base Friction)
- Steel Design
  - % Steel
  - Bar Diameter
  - Bar Depth
- Base Friction Coefficient
- Shoulder Type

Local Calibration Examples

- Indiana DOT:
  - Changed JPCP IRI J3 from 1.4929 to 1.05 because it was too sensitive to it
- Ohio DOT:
  - Changed JPCP IRI calibrations

<table>
<thead>
<tr>
<th>Calibration Coefficient</th>
<th>Default (national)</th>
<th>Ohio</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCC IRI J1</td>
<td>0.6203</td>
<td>0.82</td>
</tr>
<tr>
<td>PCC IRI J2</td>
<td>0.4417</td>
<td>3.7</td>
</tr>
<tr>
<td>PCC IRI J3</td>
<td>1.4929</td>
<td>1.711</td>
</tr>
<tr>
<td>PCC IRI J4</td>
<td>25.24</td>
<td>5.703</td>
</tr>
<tr>
<td>PCC IRI JPCP Standard Deviation</td>
<td>5.4</td>
<td>5.4</td>
</tr>
</tbody>
</table>

- Many states at this point are working on or have completed local calibrations.

Pavement ME Allows Agencies To Develop And Use Local Calibration Coefficients

You can save your local calibration coefficients as default or restore the national as default at one click.

Local Calibration Result In ½-In Or Less Difference In Required Thickness Vs. National Calibration

Low Volume Application

- Pavement ME
- Pavement ME_NC
- AASHTO 1993

High Volume Application

- Pavement ME
- Pavement ME_NC
- AASHTO 1993

However, using Pavement ME result in ~2-3 in thinner JPCPs when compared to the AASHTO 93 guide.

(Mu, 2017)
Simpler ME Option: Design Tables

<table>
<thead>
<tr>
<th>Slab Geometry</th>
<th>Thickness</th>
<th>Joint Spacing</th>
<th>Lanes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slab A</td>
<td>10 in.</td>
<td>4 ft.</td>
<td>3</td>
</tr>
<tr>
<td>Slab B</td>
<td>12 in.</td>
<td>3 ft.</td>
<td>4</td>
</tr>
<tr>
<td>Slab C</td>
<td>14 in.</td>
<td>2 ft.</td>
<td>5</td>
</tr>
</tbody>
</table>

Conclusions:

- Slab Geometry is KEY to Optimizing Pavement Designs
- Thickness is not the ONLY Slab Geometry that Improves Performance
- Shorter Joint Spacings & Widened Lanes Improve Pavement Performance
- Improvements in Design Tools, such as Pavement ME, have allowed Designers to Utilize all aspects of Slab Geometry to Yield more Economical and Better Performing Concrete Pavements

125 Yrs of Success and Performance

It's all about the thickness... right?

Acknowledgements & References

Resources

- Application Library: http://apps.acpa.org/

Some States with Pavement ME User Guides

- Utah: https://www.utahdot.utah.gov/main/udotowner.gp?n=2039215312778663

Q&A / Discussion

Thank you!