Pavement Thickness Design Methods

Municipal Streets Seminar
November 12, 2014
Ames, Iowa

Eric Ferrebee - ACPA
U.S. JPCP Roadway Design Methods

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

AASHTO 93
/software as ACPA WinPAS/

ACPA StreetPave
325 & 330
Design Method Basis

- **Mechanistic** – Purely scientific and based on measured, defendable scientific rules and laws

\[ \epsilon = \frac{\sigma}{E} \quad \Delta L = \alpha \Delta T \cdot L_o \]

- **Empirical** – Based on observations or experimentation and requires a lot of tests to connect all the relationships

\[ Cracking = \text{loads} + \text{environment} + \text{material} \]
AASHTO 93 / ACPA WinPAS

acpa.org/winpas
AASHO Road Test (1958-1960)

- Wholly empirical
- Included 368 concrete and 468 asphalt sections | focus was highway pavement
Necessary Thickness was Gueded!

Subgrade = Clay Soil
Sections Loaded for 2 Yrs | 1.1 Mil Reps

Max Single Axle

Max Tandem Axle
Performance Estimated Subjectively

- Present Serviceability Index (PSI)
  - 4.0 – 5.0 = Very Good
  - 3.0 – 4.0 = Good
  - 2.0 – 3.0 = Fair
  - 1.0 – 2.0 = Poor
  - 0.0 – 1.0 = Very Poor

- “Failure” at the Road Test considered @ 1.5

- Typical U.S. state agency terminal serviceability in practice = 2.5
The experimental design at the AASHO Road Test included a wide range of loads as previously discussed (Section 1.4.1); however, the applied loads were limited to a maximum of 1,114,000 axle applications for those sections which survived the full trafficking period. Thus, the maximum number of 18-kip equivalent single axle loads (ESAL’s) applied to any test section was approximately one million. However, by applying the concept of equivalent loads to test sections subjected to only 30-kip single axle loads, for example, it is possible to extend the findings to $8 \times 10^6$ ESAL’s. Use of any design ESAL’s above $8 \times 10^6$ requires extrapolation beyond the equations developed from the Road Test results. Such extrapolations have, however,
Current design traffic is far beyond AASHO road test limits.

Data Limits (AASHO Road Test)

Current Designs > 100 million
“The current design guide and its predecessors were largely based on design equations empirically derived from the observations AASHTO’s predecessor made during road performance tests completed in 1959-60. Several transportation experts have criticized the empirical data thus derived as outdated and inadequate for today’s highway system. In addition, a March 1994 DOT Office of Inspector General report concluded that the design guide was outdated and that pavement design information it relied on could not be supported and validated with systematic comparisons to actual experience or research.”

...this is why Pavement ME exists!
1986-93 JPCP AASHTO 93 Equation

\[ \log(ESAL) = Z_R \cdot s_o + 7.35 \cdot \log(D+1) - 0.06 + \left( \frac{\Delta PSI}{4.5 - 1.5} \right) \frac{1 + 1.624 \times 10^7}{(D + 1)^{8.46}} \]

**WHAT DO DESIGNERS FOCUS ON?**

- Standard Normal Deviate
- Overall Standard Deviation
- **Thickness**
- Traffic
- Terminal Serviceability
- Load Transfer
- Modulus of Elasticity
- Modulus of Rupture
- Drainage Coefficient
- Modulus of Subgrade Reaction

**Change in Serviceability**

\[ S' \cdot C_d \cdot (D^{0.75} - 1.132) \]

\[ 215.63 \cdot J \cdot \left[ D^{0.75} - \frac{18.42}{(E_c / k)^{0.25}} \right] \]
Pavement ME Design

- Not "perfect" & not intended to be a "final" product
- Complex and relatively costly
- For highways and NOT street, road, parking lot, etc.

Mechanistic Calculation of Responses + Empirical Tie to Ground = Pavement Performance Prediction
JPCP Calibration – BIG INF. SPACE!

- LTPP GPS-3 & RPPR JPCP Sections
- LTPP SPS-2, MnROAD, & AASHO JPCP Sections
AASHTO 93 vs. ME

AASHTO 93
- Wide range of structural and rehabilitation designs
- 50+ million load reps
- All climates over 20-50 years

AASHTO Pavement ME
- Limited structural sections
- 1.1 million load reps
- 1 climate/2 years
- 1 set of materials
- New and diverse materials
Sounds Easy Enough, Right?

\[ \text{Fault}_m = \sum_{i=1}^{m} \Delta \text{Fault}_i \]

\[ \Delta \text{Fault}_i = C_{34} \times (\text{FAULTMAX}_{i-1} - \text{Fault}_{i-1})^2 \times DE_i \]

\[ \text{FAULTMAX}_i = \text{FAULTMAX}_0 + C_7 \times \sum_{j=1}^{m} DE_j \times \log(1 + C_5 \times 5.0^{\text{EROD}})^6 \times \left( \text{Log} \left( 1 + C_5 \times 5.0^{\text{EROD}} \right) \times \text{Log} \left( \frac{P_{200} \times \text{WetDays}}{p_z} \right) \right)^6 \]

\[ \sigma_0 = \frac{E_{\text{PCC}} \Delta \varepsilon_{\text{tot}}}{2(1 - \mu_{\text{PCC}})} \]

\[ \text{IRI} = \text{IRI}_1 + C_1 \times \text{CRK} + C_2 \times \text{SPALL} + C_3 \times \text{TFault} + C_4 \times \text{SF} \]

\[ \text{SCF} = -1400 + 350 \times \text{AIR\%} \times (0.5 + \text{PREFORM}) + 3.4 \times f'c \times 0.4 - 0.2 \times (\text{FTCYC} \times \text{AGE}) + 43 \times h_{\text{PCC}} - 536 \times \text{WC\_Ratio} \]

\[ c_w = \text{Max} \left[ L \left( \varepsilon_{\text{shr}} + \alpha_{\text{PCC}} \Delta T_\zeta - \frac{c_2 f_\sigma}{E_{\text{PCC}}} \right) \right] \times 1000 \cdot \text{CC}, 0.001 \]
INPUTS, INPUTS, INPUTS!!!!
INPUTS, INPUTS, INPUTS!!!!

NOT ESALS!
OUTPUTS, OUTPUTS, OUTPUTS!!!
Some Agencies Trying to Simplify

Note the inputs that have been deemed worth varying...

...designers have a new idea of “what matters”!
Figure 7. FE model of tridem axle edge loading (lane with tied concrete shoulders).

ACPA StreetPave

acpa.org/streetpave
ACPA StreetPave

- Roots date back to the 1960s PCA Method
- Tailored for streets and roads
- Failure modes are cracking and faulting
### Traffic Spectrum + Counts

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<th>Axle Load (kip)</th>
<th>Axles/1,000 Trucks</th>
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Total trucks in design lane over the design life... calculated from trucks/day (2-way), traffic growth rate (%/yr), design life (yrs), directional distribution (%) and design lane distribution (%).
Traffic Loads Generate Stresses

Equivalent stress at the slab edge:

\[ \sigma_{eq} = \frac{6 \times M_e}{h_c^2} \times f_1 \times f_2 \times f_3 \times f_4 \]

- \( M_e \) = equivalent moment, psi; different for single, tandem, and tridem axles, with and without edge support - func on radius of relative stiffness, which depends on concrete modulus, Poisson’s ratio, and thickness and the k-value
- \( h_c \) = pavement thickness, in.
- \( f_1 \) = adjustment for the effect of axle loads and contact area
- \( f_2 \) = adjustment for a slab with no concrete shoulder
- \( f_3 \) = adjustment to account for the effect of truck (wheel) placement at the slab edge
- \( f_4 \) = adjustment to account for approximately 23.5% increase in concrete strength with age after the 28th day and reduction of one coefficient of variation (COV) to account for materials variability
Limit Stress Ratio to Allow Design Reps

- Stress Ratio (SR) = Stress / Concrete Strength
- StreetPave makes slab thicker to limit stress ratio low enough to achieve the design traffic repetitions.

Inference space normalized to SR.
A Conservative Approach!

- StreetPave fatigue calculation should be conservative relative to ME Design because:
  - **Size Effects** – Slabs have a greater fatigue capacity than beams
  - **Support** – The beam test has a k-value for support of 0 psi/in.

...versus...
Faulting Design in StreetPave

- If dowels used, faulting mitigated & fails by cracks
- No faulting data collected at the AASHO road test so model developed in 1980s using field performance data from WI, MN, ND, GA, and CA
- Similar to cracking models, the pavement is made thicker, as necessary, until faulting model predicts that the pavement will not fail by faulting during the design life
- StreetPave’s weak point
StreetPave Accepted in MN

MINNESOTA DEPARTMENT OF TRANSPORTATION
State Aid Division
Technical Memorandum No. 12-SA-03
October 09, 2012

To: County Engineers
   City Engineers
   MnDOT District State Aid Engineers
   MnDOT District Materials Engineers
   FHWA

From: Jure Skalim, P.E.
      State Aid Engineer

Subject: State Aid for Local Transportation (SALT)
Use of ACPA StreetPave Software for Design of Concrete Pavements for Cities and Counties

Expiration
This Technical Memorandum will remain in effect until October 09, 2017, unless superseded prior to this date, or the information provided in this Technical Memorandum is incorporated into the State Aid Manual.

Implementation
This Technical Memorandum, which allows the use of the American Concrete Pavement Association’s (ACPA) StreetPave software for jointed concrete pavement design as an alternative to the MnDOT RigidPave software, is effective immediately. In deciding which software program to use, several factors, including those mentioned in this Technical Memorandum, shall be considered by the Engineer. City, county and consultant engineers working on State Aid and Federal-aid concrete pavement projects are allowed to use the ACPA StreetPave software program as an alternative to the MnDOT RigidPave software program. However, concrete pavement projects within Trunk Highway right-of-way must continue to implement the MnDOT RigidPave design software.

StreetPave Equivalent Bituminous Design and the Life Cycle Cost Module are not approved by SALT.

Introduction
In an effort to stay abreast of new technology and design methods, State Aid for Local Transportation (SALT) has recently completed a comparison of the ACPA StreetPave concrete pavement design software and the MnDOT RigidPave concrete pavement design software (previously the only concrete pavement design software approved for State Aid and Federal-aid projects).

http://www.dot.state.mn.us/stateaid/admin/memos/12-sa-03.pdf
http://www.dot.state.mn.us/research/documents/201210.pdf
And Its Use is Growing!

- Also “approved” in VA and many other state, city, and county engineers are using it in the U.S.
- StreetPave used in design tables in:
  - ACI 325 and 330 documents
  - Dr. Norb Delatte’s textbook *Concrete Pavement Design, Construction, and Performance*
- Internationally, used in Australia, Portugal, Mexico, Uruguay, Argentina, Chile, etc.
StreetPave | Project Details

**Project Information**

- **Project Name**: StreetPave Example
- **Route**: Kane St
- **Location**: Anywhere, USA
- **Owner / Agency**: The City
- **Design Engineer**: Rodden, P.E.

**Project Description**: This is just an example to illustrate the key features of StreetPave

**Software Use**

- Design a new jointed plain concrete pavement
- Determine a comparable new asphalt pavement thickness?
- Conduct a life cycle cost analysis (LCCA)?
StreetPave | Traffic Details

Traffic Category / Load Spectrum

Typical Traffic Spectrums
- Residential
- Collector
- Minor Arterial
- Major Arterial

ACI 330 Traffic Spectrums
- Category A
- Category B
- Category C
- Category D

Custom Traffic Spectrum

Traffic Category over the Pavement Design Life

- Single Axles
- Tandem Axles
- Tridem Axles (User Defined Only)

Trucks per Day (two-way, at time of construction) 240
Traffic Growth Rate 2 % per year
Design Life 30 years
Directional Distribution 50 %
Design Lane Distribution 100 %

Average Trucks per Day in Design Lane over the Design Life 162
Total Trucks in Design Lane over the Design Life 1,778,099
General Design Inputs

Terminal Serviceability: 2  
Reliability: 85%  

Resilient Modulus of the Subgrade

- Convert CBR or R-value to MRSG: 4,118 psi
- Input a known MRSG: 4,118 psi
StreetPave | Design Details | Concrete

Percent of Slabs Cracked at End of Design Life
Slabs Cracked: 15%

Composite Modulus of Subgrade Reaction (Static k-Value)
- Use calculated composite static k-value
- Enter a known static k-value
  - Calculate: 100 psi/in.
  - Enter a known static k-value: 100 psi/in.

Concrete Material Properties
- 28-Day Flexural Strength (MR): 600 psi
- Macrofibers in Concrete: No
- Modulus of Elasticity (E): 4,050,000 psi

Edge Support
Edge support (e.g., tied concrete shoulder, curb and gutter, or widened lane) provided?
- Yes
- No
StreetPave | Design Results

**Concrete Pavement Design**

Rigid ESALs = 1,331,869

Composite Modulus of Subgrade Reaction (Static k-Value) = 100 psi/in.

**Sensitivity Analysis of Concrete Pavement Design**

- k-value
- Reliability
- Concrete Strength
- % Slabs Cracked
- Design Life

**Min. Required Thickness**

- Doweled: 7.80 in.
- Undoweled: 7.80 in.

**Design Thickness**

- Doweled: 8.00 in.
- Undoweled: 8.00 in.

**Max Joint Spacing**

- Doweled: 15 ft
- Undoweled: 15 ft

**Failure Controlled By**

- Doweled: Cracking
- Undoweled: Cracking

*Because the doweled thickness is less than 8 in. and cracking is the predicted cause of failure, dowel bars typically would not be recommended for the design details you provided.*
# StreetPave | Design Report

**Traffic Category: Major Arterial**

<table>
<thead>
<tr>
<th>Axle Load, kips</th>
<th>Axles per 1000 Trucks</th>
<th>Expected Repetitions</th>
<th>Stress Ratio</th>
<th>Allowable Repetitions</th>
<th>Fatigue Consumed</th>
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**Tandem Axles**

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**Total Fatigue Used %:** 98.53
Comparison of Results and U.S. Trends
Doweled JPCP Thickness Comparison

Remember AASHTO 93 limit?
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

Red = only ME Design input... the VALUE of the software!
Blue + Bold = common for all
Flexural Strength Sensitivity

![Graph showing the relationship between Concrete Flexural Strength (psi) and Required Thickness (in.) for different pavement design software tools.]

- **AASHTO 93 (ACPA WinPAS)**
- **AASHTOWare Pavement ME @ ORD**
- **AASHTOWare Pavement ME @ PHX**
- **ACPA StreetPave**
Modulus of Elasticity Sensitivity

... in reality, need to change strength too...
Thickness Reduction w/ Edge Support

AASHTO 93 (ACPA WinPAS)
AASHTOWare Pavement ME @ ORD
AASHTOWare Pavement ME @ PHX
ACPA StreetPave

Design Lane ESALs
Reliability Sensitivity

![Graph showing the relationship between reliability and required thickness for pavement design, with lines representing different software tools: AASHTO 93 (ACPA WinPAS), AASHTOWare Pavement ME @ ORD, AASHTOWare Pavement ME @ PHX, and ACPA StreetPave. The x-axis represents reliability (%), and the y-axis represents required thickness (in. and mm).]
k-value Sensitivity

Very few designed for < 100 psi/in. (27 MPa/m)
**U.S. Agencies Quickly Changing**

Summary of State Agency practice in 2005:

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<tr>
<th>Design Method Used</th>
<th>Percent of Responding Agencies</th>
<th>State Agency</th>
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<tr>
<td>AASHTO 72/86/93</td>
<td>85%</td>
<td>AR, AZ, DE, FL, ID, IN, IA, KS, MD, MI, NV, NC, OH, OK, SC, SD, TN, UT, VA, WA, WV, WI, WY</td>
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<td>AASHTO MEPDG</td>
<td>4%</td>
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<td>PCA Method</td>
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<td>HI, IN, IA</td>
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<td>State-Developed</td>
<td>7%</td>
<td>IL, MT</td>
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At the end of 2013, 41 state agencies had performed ME Design calibration and implementation efforts, indicating a relatively quick shift from AASHTO 93.
U.S. Roadway Length (lane miles)

- **State Agency, 19%**
- **County, 44%**
- **Town, 32%**
- **Other, 1%**
- **Federal, 3%**

AASHTO tools are being developed for these owners...

City, county, and other local engineers need to decide what to use locally because Pavement ME will not trickle down due to its cost and complexity!

Source: HM-10, 2012 FHWA Highway Statistics
Overlay Design – Bonded Concrete on Asphalt

University of Pittsburgh

ACPA

Bonded Concrete Overlay on Asphalt (BCOA) Thickness Designer
Bonded over Asphalt/Composite

- AASHTO 93: not applicable
- AASHTO ME: limited to a joint spacing > 10 ft (3 m) and not applicable to thinner (2-6 in. [50-150 mm]) concrete overlays; refers people to ACPA
- ACPA BCOA and StreetPave: account for bond to asphalt and short slab size, fibers, etc.
Bonded over Asphalt/Composite

- Not an extension of an existing design method; a completely custom-built design method
- For ACPA BCOA and StreetPave based primarily on FHWA-ICT-08-016
- Other methods include CDOT 6x6x6 and recently released FHWA pooled fund TPF-5(165)
BONDED CONCRETE OVERLAY OF ASPHALT PAVEMENTS MECHANISTIC-EMPIRICAL DESIGN GUIDE (BCOA-ME)

VALIDATION STUDIES

University of Pittsburgh
Department of Civil and Environmental Engineering
Pittsburgh, Pennsylvania 15261

Prepared by:
Nicole Dufalla
Julie M. Vandenbosch, Ph.D., P.E.

Prepared for:
FHWA Pooled Fund Project: TPF-5-165
Pitt BCOA ME

- FHWA Pooled Fund Study TPF 5-165
BCOA ME failure modes

≤ 4.5 ft
Corner Break

5 to 7 ft
Long. & Diag Crack

10 x 12 ft
12 x 12 ft
12 x 15 ft
Trans. Crack

Negative ΔT

Positive ΔT

Positive ΔT
Inputs

Stress for corner cracks
- Jt. Spacing < 4.5 ft

Stress for long. & diag. cracks
- Jt. Spacings 5 to 6 ft

Fatigue model

Pitt Model

Stress for trans. cracks
- Jt. Spacings 10 x 12 ft, 12 x 12 ft, 15 x 12 ft

ACPA Model

CDOT Model

h_{pcc}
Wheel wander considered

(a) Real Situation in the Road

(b) Critical condition
Variation in HMA stiffness

Seasonal variation
- Soft HMA
- Stiff HMA

Daily variation
- Soft HMA
- Stiff HMA
Effective temp. gradient

Design input required:
Effective temp. gradient (ETG)
Regional variation in temp. grad.

Vandenbossche and Mu (2010)
Calibration - Stress Adj. Factors

Stress adjustment factor (Joint spacing > 4ft x 4ft)

Linear (Series2)

$R^2 = 0.9294$
Pitt BCOA-ME Web App
Pitt BCOA-ME Web App

Annual Mean Daily Average Temp

ACPA k-value web app
Results of the BCOA-ME

- BCOA ME is <1/3 ACPA BCOA app, <1/3 CDOT procedure and the remainder was developed at Pitt
- Comparison to ACPA BCOA app:
  - JS ≤ 4.5 ft, the model is similar but thicknesses possibly greater because BCOA ME was calibrated to field performance, accounting for loading directly in the wheel path
  - JS > 4.5 ft, it will not compare because failure mode changes (e.g., no longer corner cracking); BCOA ME will almost always be thinner than ACPA BCOA for a 6’ x 6’ JS
- Comparison to CDOT design procedure:
  - Depends on failure mode
Bonded over Asphalt/Composite
### Design considerations

**Overlay thickness**

- **PCC = 4 in or less**
  - **HMA**

- **PCC = 5 in or more**
  - **PCC**

**Load carrying layer**

- **PCC = 4 in or less**
  - **HMA**

- **PCC = 5 in or more**
  - **PCC**

*Bond is essential*

*Bond enhances performance*
Design considerations

10 in HMA

4 in PCC
6 in HMA

6 in PCC
4 in HMA
### Design Considerations

#### Critical Stress for 6ft x 6ft slab, psi

<table>
<thead>
<tr>
<th>PCC Thickness</th>
<th>3 in</th>
<th>4 in</th>
<th>6 in</th>
</tr>
</thead>
<tbody>
<tr>
<td>HMA Thickness</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 in</td>
<td>352</td>
<td>339</td>
<td>274</td>
</tr>
<tr>
<td>6 in</td>
<td>246</td>
<td>234</td>
<td>211</td>
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<td>8 in</td>
<td>198</td>
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</tbody>
</table>
Thank you.

Questions? FEEDBACK!

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Eric Ferrebee
Technical Services Engineer
American Concrete Pavement Association
eferrebee@acpa.org  |   847.423.8709

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