Basics of Concrete Pavement Thickness Design
Concrete Pavement Design

- Geometrics
- Thickness(es)
- Joints
- Materials
Concrete Pavement Design

- Geometrics
- Thickness(es)
- Joints
- Materials

Most Often Influence Cost & Selection of Projects

Cost
Concrete Pavement Design

• Geometrics
• Thickness(es)
• Joints
• Materials

Most Often Influence Real-world Performance

Perfomance
# Concrete Pavement Design

<table>
<thead>
<tr>
<th>Design Area</th>
<th>Performance Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials Selection &amp; Proportioning</td>
<td>ASR</td>
</tr>
<tr>
<td></td>
<td>D-cracking</td>
</tr>
<tr>
<td></td>
<td>Freeze-Thaw</td>
</tr>
<tr>
<td></td>
<td>Scaling</td>
</tr>
<tr>
<td></td>
<td>Skid Resistance</td>
</tr>
<tr>
<td>Jointing &amp; Subbase</td>
<td>Blow-ups</td>
</tr>
<tr>
<td></td>
<td>Random cracking</td>
</tr>
<tr>
<td></td>
<td>Faulting</td>
</tr>
<tr>
<td></td>
<td>Pumping</td>
</tr>
<tr>
<td></td>
<td>Spalls</td>
</tr>
<tr>
<td>Thickness (Slab)</td>
<td>Fatigue Cracking</td>
</tr>
</tbody>
</table>
Principles of Design

Load stresses

Curling/Warping stresses

Volume change stresses

Thickness

Jointing or Reinforcing
Thickness Design Procedures

• Empirical Design Procedures
  • Based on observed performance
    • AASHO Road Test

• Mechanistic Design Procedures
  • Based on mathematically calculated pavement responses
    • PCA Design Procedure (PCAPAV)
Pavement design is an a priori process. The new pavement will be built in the future, on subgrades often not yet exposed or accessible; using materials not yet manufactured from sources not yet identified; by a contractor who submitted the successful "low dollar" bid, employing unidentified personnel and procedures under climatic conditions that are frequently less than ideal.
Design of Concrete Pavements

- Thickness Design Considerations:
  - Traffic Loads and Traffic Growth
  - Subgrade and Subbases
  - Drainage
  - Concrete Properties
  - Load Transfer
  - Reliability
AASHTO Design Procedures

AASHTO Guide for Design of Pavement Structures - 1993
AASHO Road Test (1958-1960)

• Third Large Scale Road Test
  • Maryland Road Test (1950-51) Rigid Pavements Only
  • WASHO Road Test (1952-54) Flexible Pavements only

• Include both Rigid and Flexible Designs

• Include a wide range of axle loads and pavement cross-sections
Figure 11. Map of AASHO Road Test.
AASHO Test Layout

TYPICAL SECTIONS

ASPHALT
- SURFACE
- BASE
- SUBBASE

CONCRETE
- CONCRETE
- SUBBASE

THICKNESS
- 5"
- 10"
- 15"
- 20"
- 25"

368 rigid test sections    468 flexible test sections
AASHO Test Traffic

Max Single Axle

Max Tandem Axle
AASHO Road Test Performance

Surviving Sections

Loop 3

Serviceability vs. Load Applications

Concrete (36 Sect)

Asphalt (4 Sect)

Loop 4

Serviceability vs. Load Applications

Concrete (38 Sect)

Asphalt (10 Sect)

Loop 5

Serviceability vs. Load Applications

Concrete (39 Sect)

Asphalt (11 Sect)

Loop 6

Serviceability vs. Load Applications

Concrete (47 Sect)

Asphalt (17 Sect)
<table>
<thead>
<tr>
<th>Year</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>1981</td>
<td>Revised Chapter III on Portland Cement Concrete Pavement Design</td>
</tr>
<tr>
<td>1986</td>
<td>Guide for the Design of Pavement Structures</td>
</tr>
<tr>
<td>1993</td>
<td>Revised Overlay Design Procedures</td>
</tr>
<tr>
<td>1998</td>
<td>Revised Portland Cement Concrete Pavement Design</td>
</tr>
</tbody>
</table>
1986-93 Rigid Pavement Design Equation

\[ \log(ESALs) = Z_R \cdot s_o + 7.35 \cdot \log(D+1) - 0.06 + \left(4.22 - 0.32p_t\right) \cdot \log \left(215.63 \cdot J \cdot \frac{S'_c \cdot C_d}{D^{0.75} - 1.132} \right) \]

- **Standard Normal Deviate**
- **Overall Standard Deviation**
- **Depth**
- **Modulus of Rupture**
- **Drainage Coefficient**
- **Load Transfer**
- **Change in Serviceability**
- **Terminal Serviceability**
- **Modulus of Elasticity**
- **Modulus of Subgrade Reaction**
- **Load Transfer**
- **Rupture**
- **Subgrade Reaction**
ESAL’s or E-18’s

The number and weight of all axle loads from the anticipated vehicles expected during the pavement design life - expressed in 18-kip (80 kN) Equivalent Single Axle Loads for each type of pavement.

— Rigid ESAL’s or E-18’s

— Flexible ESAL’s or E-18’s
AASHTO DESIGN
Traffic - ESALs

Equivalent Number of 18k Single Axle Loads
**ESALs GENERATED BY DIFFERENT VEHICLES/DAY**

<table>
<thead>
<tr>
<th>VEHICLE</th>
<th>NUMBER</th>
<th>RIGID ESALs</th>
<th>FLEXIBLE ESALs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Units 2 Axle</td>
<td>20</td>
<td>6.38</td>
<td>6.11</td>
</tr>
<tr>
<td>Busses</td>
<td>5</td>
<td>13.55</td>
<td>8.73</td>
</tr>
<tr>
<td>Panel Trucks</td>
<td>10</td>
<td>10.89</td>
<td>11.11</td>
</tr>
<tr>
<td>Semi-tractor Trailer 3 Axles</td>
<td>10</td>
<td>20.06</td>
<td>13.41</td>
</tr>
<tr>
<td>Semi-tractor Trailer 4 Axles</td>
<td>15</td>
<td>39.43</td>
<td>29.88</td>
</tr>
<tr>
<td>Semi-tractor Trailer 5 Axles</td>
<td>15</td>
<td>57.33</td>
<td>36.87</td>
</tr>
<tr>
<td>Automobile, Pickup, Van</td>
<td>425</td>
<td>1.88</td>
<td>2.25</td>
</tr>
<tr>
<td>Total</td>
<td>500</td>
<td>149.52</td>
<td>108.36</td>
</tr>
</tbody>
</table>
Load Equivalence Factor (LEF)

The Ratio of the Effect (Damage) of a Specific Axle Load on Pavement Serviceability to the Effect Produced by an 18-kip Axle Load at the AASHO Road Test.

Change for each:
- Pavement Type
- Thickness
- Terminal Serviceability.
AASHTO DESIGN
Traffic

Load Equivalence Factor (LEF)

<table>
<thead>
<tr>
<th>Pavement Type</th>
<th>Thickness</th>
<th>Terminal Serviceability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change for each:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. of repetitions of 18-k SAL Load causing given ΔPSI</td>
<td>No. of repetitions of X-k Y-Axle Load for a same ΔPSI</td>
<td></td>
</tr>
</tbody>
</table>
LOAD EQUIVALENCY FACTORS FOR A GIVEN PAVEMENT STRUCTURE

For a Given Stress or Strain:

Stress or Strain of X-kip Load on Axle Type Y

Stress or Strain of 18-kip Load on a Single Axle
LOAD EQUIVALENCY FACTORS FOR A GIVEN PAVEMENT STRUCTURE

For a Given Serviceability Loss:

# of Repetitions of X-kip Load on Axle Type Y
# of Repetitions of 18-kip Load on a Single Axle

# of Repetitions of 18-kip Load on a Single Axle
# of Repetitions of X-kip Load on Axle Type Y
Since pavement responses are different, the equivalency factors (LEFs) are different. When multiplying the traffic by the different equivalencies, you get different ESALs.
Subgrade and Subbases

- **Subbase**
  - Layer of material directly below the concrete pavement.

- **Subgrade**
  - Natural ground, graded, and compacted on which the pavement is built.
Subgrade / Subbase Strength

Modulus of Subgrade Reaction, \( k \)

\[ k \text{ (psi/in)} = \frac{\text{unit load on plate}}{\text{plate deflection}} \]
Subgrade and Subbases

Design

• Subgrade strength is **not** a critical element in the **thickness design**.
  • Has little impact on thickness.

• Need to know if pavement is on:
  • Subgrade (k ≈ 100 psi/in.),
  • Granular subbase (k ≈ 150 psi/in.),
  • Asphalt treated subbase (k ≈ 300 psi/in.)
  • Cement treated/lean concrete subbase (k ≈ 500 psi/in.).
## AASHTO DESIGN

### Subgrade Strength

#### Typical Soil Relationships

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Strength</th>
<th>k-value (psi / in.)</th>
<th>Mr (psi)</th>
<th>CBR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silts / Clays</td>
<td>Very Low</td>
<td>50-100</td>
<td>1000-1900</td>
<td>&lt;3</td>
</tr>
<tr>
<td>Fine grained</td>
<td>Low</td>
<td>100-150</td>
<td>1900-2900</td>
<td>3-5.5</td>
</tr>
<tr>
<td>Sands</td>
<td>Medium</td>
<td>150-220</td>
<td>2900-4300</td>
<td>5.5-12</td>
</tr>
<tr>
<td>Gravely soils</td>
<td>High</td>
<td>220-250</td>
<td>4300-4850</td>
<td>&gt;12</td>
</tr>
<tr>
<td>Bitumin.Treat.</td>
<td>High</td>
<td>350-450</td>
<td>100,000+</td>
<td>&gt;12</td>
</tr>
<tr>
<td>Cement.Treat./LCB</td>
<td>High</td>
<td>400-600</td>
<td>500,000+</td>
<td>&gt;12</td>
</tr>
</tbody>
</table>
Subgrade and Subbases

Performance

• Proper design and construction are **absolutely necessary** if the pavement is to perform.
  • Must be **uniform** throughout pavement’s life.

• Poor subgrade/subbase preparation can not be overcome with thickness.
  • Any concrete pavement, built of any thickness, will have problems on a poorly designed and constructed subgrade or subbase.
UNIFORMITY:
The Key To GOOD PAVEMENT PERFORMANCE
Design for Uniform Support

Sources of Non-Uniform Support

- Expansive soils
- Frost susceptible soils
- Pumping (loss of Support)
- Cut-fill transitions
- Poorly compacted excavations
  - Utility work
  - Culverts
The current Design does not model the contribution of bases accurately.

At the AASHO Road Test, it was found that the concrete pavements with granular bases could carry about 30% more traffic.

The current design procedures allows concrete pavements built with granular bases to carry about 5 - 8% more traffic.
Concrete Properties

Flexural Strength (S’c) Determination

Third-point Loading

Center-point Loading

Head of Testing Machine

d = L/3

Span Length = L

Span Length = L

L/3

L/2
Concrete Properties

Compressive Strength $f'_c$

$$S'_c = 8-10 \sqrt{f'_c}$$

$f'_c =$ Compressive Strength (psi)

$S'_c =$ Flexural Strength (psi)
Concrete Properties

Use average, in-field strength for design (not minimum specified)

If specify minimum flexural strength at 28-day of 550 psi & allow 10% of beams to fall below minimum:

**STEP 1**

Estimate SDEV:
- 9% for typical ready mix.
- \( SDEV = 550 \times 0.09 = 50 \text{ psi} \)

**STEP 2**

\[
S'c_{\text{design}} = S'c_{\text{minimum}} + z \times SDEV
\]
- \( S'c_{\text{design}} = 550 + 1.282 \times 50 \)
- \( S'c_{\text{design}} = 614 \text{ psi} \)
Drainage

Conditions for Pumping

• Subgrade Soil that will go into Suspension
• Free water between Slab and Subgrade
• Frequent Heavy wheels loads / Large Deflections
Drainage

NCHRP 1-34: Subsurface Drainage for Pavements

• Major Conclusions
  • For Doweled PCC Pavements, Drainage has little affect on Faulting
    • Does reduce D-cracking
  • Drainage significantly reduces fatigue cracking and rutting in AC Pavements
  • Day lighted drainage works best with permeable bases
Load Transfer

- A slabs ability to share its load with neighboring slabs
  - Dowels
  - Aggregate Interlock
  - Concrete Shoulders
    - Tied Concrete, curb & gutter, and extended lane have same effect.

\[ \Delta L = \frac{x}{2} \]
\[ \Delta U = \frac{x}{2} \]

Poor Load Transfer

\[ \Delta L = x \]
\[ \Delta U = 0 \]

Good Load Transfer
Aggregate Interlock

Shear between aggregate particles below the initial saw cut
Aggregate Interlock
Dowel bars

- Lengths from 15-18 in.
- 6.0 in. min. embedment length
- Diameter
  - 1.25 - 1.50 in. for roads
  - 1.5 - 2.0 in. for airports
- Epoxy or other coating used in harsher climates for corrosion protection
Deflections in Concrete Pavement

Load Transfer

Outside Pavement Edge (free edge)

12 ft Lanes

5 $D_i$

$\approx 3.5\ D_i$

5 $D_i$

$\approx 2.5 \ D_i$

2 $D_i$

Longitudinal Centerline (acts as tied concrete shoulder)

Undoweled transverse Joint

Doweled transverse Joint
AASHTO DESIGN

Effect of Dowels and Shoulders

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Dowels &amp; Shoulders</th>
<th>Dowels &amp; No Shoulders</th>
<th>No Dowels &amp; Shoulders</th>
<th>No Dowels &amp; No Shoulders</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.0E+00</td>
<td>1.0E+07</td>
<td>2.0E+07</td>
<td>3.0E+07</td>
</tr>
</tbody>
</table>

**Graph Details:**
- **Y-axis:** Allowable ESALs
- **X-axis:** Thickness
- **Lines:**
  - Dowels & Shoulders
  - Dowels & No Shoulders
  - No Dowels & Shoulders
  - No Dowels & No Shoulders

**Legend:**
- Dowels & Shoulders
- Dowels & No Shoulders
- No Dowels & Shoulders
- No Dowels & No Shoulders
Concrete Pavement Design

To Dowel or Not to Dowel?

- **Exclude dowels if:**
  - Slab thickness < 7.0 in

- **Include dowels if:**
  - Slab thickness > 8.0 in.

Trucks Control Thickness

- Slab thickness < 7.0 in
- Slab thickness > 8.0 in.
AASHTO DESIGN
Reliability

The statistical factors that influence pavement performance are:

• RELIABILITY, R
  • The statistical probability that a pavement will meet its design life.

• STANDARD DEVIATION, so
  • The amount of statistical error present in the design equations resulting from variability in materials, construction, traffic, etc.
AASHTO DESIGN
Reliability

SERVICEABILITY

Log ESALs

Design Curve

Performance Curve

$P_o$

$P_t$

$Z_R \times s_o$
PCAPAV Design Procedure

Design Basics

• Mechanistic stress analysis
• Calibrated to field tests, test roads
• Control criteria can be either:
  • Fatigue (cracking)
  • Erosion (pumping)
• Available computer program (PCAPAV)
Critical Loading Positions

Fatigue

- Midslab loading away from transverse joint produces critical edge stresses

Erosion

- Corner loading produces critical pavement deflections
Differences Between Design Procedures

- Traffic Classification:
  - AASHTO - uses 18-kip ESALs
  - PCA - uses axle load distribution

- Reliability
  - AASHTO - Reliability
  - PCA - Load Safety Factors

- Drainage
PCAPAV Design

Two design criteria:

• Fatigue
  • Keeps pavement stresses due to repeated loads within safe limits

• Erosion
  • Limits the effects of pavement deflections at edges, joints and corners.
PCAPAV Design Procedure

Design Factors

• Concrete Properties
  • Flexural strength (modulus of rupture)

• Subgrade Strength, or subgrade-subbase combination
  • modulus of subgrade reaction, k-value

• Weights, frequencies, and types of truck axle loads
• Load Transfer
• Load Safety Factor
• Design Period
PCAPAV Design
Traffic

• Numbers & weights of heavy axle loads expected during the design life
  • ADT (average daily traffic in both directions)
  • ADTT (average daily truck traffic in both directions)
    • Includes only trucks with six tires or more
    • Does not include panel and pickup trucks and other four-tire vehicles.
• Axle loads of trucks
PCAPAV Design
Traffic

- Axle loads Distribution
  - The number of single and tandem axles over the design period
  - Expressed as Axles per 1000 trucks
  - Does not include panel and pickup trucks and other four-tire vehicles.

<table>
<thead>
<tr>
<th>Axle load Kips</th>
<th>Single Axles</th>
<th>Tandem Axles</th>
<th>Axles/1000 Trucks</th>
<th>Axles in design period</th>
</tr>
</thead>
<tbody>
<tr>
<td>28-30</td>
<td>0.58</td>
<td>48-52</td>
<td>1.96</td>
<td>21,320</td>
</tr>
<tr>
<td>26-28</td>
<td>1.35</td>
<td>44-48</td>
<td>3.94</td>
<td>42,870</td>
</tr>
<tr>
<td>24-26</td>
<td>2.77</td>
<td>40-44</td>
<td>11.48</td>
<td>124,900</td>
</tr>
<tr>
<td>22-24</td>
<td>5.92</td>
<td>36-40</td>
<td>34.27</td>
<td>372,900</td>
</tr>
<tr>
<td>20-22</td>
<td>9.83</td>
<td>32-36</td>
<td>81.42</td>
<td>885,800</td>
</tr>
<tr>
<td>18-20</td>
<td>21.67</td>
<td>28-32</td>
<td>85.54</td>
<td>930,700</td>
</tr>
<tr>
<td>16-18</td>
<td>28.24</td>
<td>24-28</td>
<td>152.23</td>
<td>1,656,000</td>
</tr>
<tr>
<td>14-16</td>
<td>38.83</td>
<td>20-24</td>
<td>90.52</td>
<td>984,900</td>
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<tr>
<td>12-14</td>
<td>53.94</td>
<td>16-20</td>
<td>112.81</td>
<td>1,227,000</td>
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<tr>
<td>10-12</td>
<td>168.85</td>
<td>12-16</td>
<td>124.69</td>
<td>1,356,000</td>
</tr>
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</tbody>
</table>
## Traffic Categories

<table>
<thead>
<tr>
<th>Two-way ADTT</th>
<th>Category</th>
<th>LSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Residential</td>
<td>3</td>
<td>LR</td>
</tr>
<tr>
<td>Residential Rural &amp; secondary rds.</td>
<td>10 - 30</td>
<td>1</td>
</tr>
<tr>
<td>Collector streets Rural &amp; secondary rds.</td>
<td>50 - 500</td>
<td>2</td>
</tr>
<tr>
<td>(heavy trucks)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minor Arterial Sts. Primary roads</td>
<td>300 - 600</td>
<td>2</td>
</tr>
<tr>
<td>Major Arterial Sts.</td>
<td>700 - 1500</td>
<td>3</td>
</tr>
</tbody>
</table>
PCAPAV Design
Load Safety Factors

Recommended values

• Interstate, interprovincial, multilane projects
  • LSF = 1.2.

• Highways and arterial streets
  • LSF = 1.1

• Roads, residential streets, and other streets that carry small volumes of truck traffic
  • LSF = 1.0
PCAPAV Design
Simplified Procedure

• Designs presented in Tabular Form
  • Traffic
    • Type of road
    • Axle-load category (for the road type)
    • Avg. daily truck traffic
    • Probable maximum truck weights
  • Subgrade and Subbase
  • Dowels & slab edge support
  • Concrete strength
# PCAPAV Design
## Simplified Procedure

### No Dowels - No edge support

<table>
<thead>
<tr>
<th></th>
<th>40</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Foundation Support, k, MPa/m</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexural Strength, MPa</td>
<td>3.8</td>
<td>4.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>150 mm</th>
<th>140</th>
<th>140</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Resident. 2-way ADTT = 3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residential</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rural &amp; Sec. Rd.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADTT = 10</td>
<td>165</td>
<td>150</td>
<td>140</td>
</tr>
<tr>
<td>20</td>
<td>165</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>50</td>
<td>175</td>
<td>165</td>
<td>150</td>
</tr>
<tr>
<td>Collector</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rural &amp; sec. Rd.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADTT = 50</td>
<td>190</td>
<td>190</td>
<td>175</td>
</tr>
<tr>
<td>100</td>
<td>200</td>
<td>190</td>
<td>175</td>
</tr>
<tr>
<td>500</td>
<td>215</td>
<td>215</td>
<td>190</td>
</tr>
<tr>
<td>Minor Arterial</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADTT = 300</td>
<td>215</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>600</td>
<td>225</td>
<td>215</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ADTT = 50

Residential: 150 mm

140 125 125

ADTT = 10

20

165 150 150

Rural & Sec. Rd.

50

175 165 150

Collector

100

190 190 175

Rural & sec. Rd.

500

200 190 175

Minor Arterial

600

215 200 200

200 190 175

200 190 190
<table>
<thead>
<tr>
<th>No Dowels - With Edge Support</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Foundation Support, k, MPa/m</strong></td>
<td>40</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>Flexural Strength, MPa</td>
<td>3.8</td>
<td>4.1</td>
<td>4.5</td>
</tr>
<tr>
<td>Light Resident. 2-way ADTT = 3</td>
<td>125 mm</td>
<td>125</td>
<td>125</td>
</tr>
<tr>
<td>Residential</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADTT = 10</td>
<td>140</td>
<td>125</td>
<td>125</td>
</tr>
<tr>
<td>20</td>
<td>140</td>
<td>140</td>
<td>125</td>
</tr>
<tr>
<td>50</td>
<td>150</td>
<td>140</td>
<td>125</td>
</tr>
<tr>
<td>Rural &amp; Sec. Rd.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Collector</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADTT = 50</td>
<td>165</td>
<td>150</td>
<td>160</td>
</tr>
<tr>
<td>100</td>
<td>175</td>
<td>165</td>
<td>160</td>
</tr>
<tr>
<td>500</td>
<td>175</td>
<td>175</td>
<td>160</td>
</tr>
<tr>
<td>Rural &amp; sec. Rd.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minor Arterial</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADTT = 300</td>
<td>190</td>
<td>175</td>
<td>165</td>
</tr>
<tr>
<td>600</td>
<td>190</td>
<td>190</td>
<td>175</td>
</tr>
</tbody>
</table>
Typical Concrete Pavement Thickness

• Depends on traffic load, subgrade, and climate.
  • City streets, secondary roads, and small airports
    • 100 to 175 mm (4 to 7 in.)
  • Primary roads and interstate highways
    • 175 to 280 mm (7 to 12 in.)
  • Large airports
    • 200 to 460 mm (8 to 18 in.)
1986-93 RIGID PAVEMENT DESIGN

Factors Affecting Rigid Pavements

Thicknes
Serviceability ($p_o$, $p_t$)
Traffic (ESALs, E-18s)
Load Transfer ($J$)
Concrete Properties ($S'_c$, $E_c$)
Subgrade Strength ($k$, LS)
Drainage ($C_d$)
Reliability ($R$, $S_o$)
Serviceability - the pavement’s ability to serve the type of traffic (automobiles and trucks) that use the facility.

Present Serviceability Index (PSI):

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

Accumulated Traffic

Rehabilitation Required

$\Delta PSI$

$P_o$

$P_t$
There are two concrete properties that influence pavement performance

- **Flexural Strength (Modulus of Rupture),** $S'_c$
  - Average 28-day strength
  - 3rd-Point Loading
- **Modulus of Elasticity,** $E_c$
Flexural Strength ($S'_c$) Determination

**Third-point Loading**
- Span Length = $L$
- $d = L/3$

**Center-point Loading**
- Span Length = $L$
- $L/2$
Use average, in-field strength for design (not minimum specified)

If specify minimum flexural strength at 28-day of 550 psi & allow 10% of beams to fall below minimum:

**STEP 1**
Estimate SDEV:
- 9% for typical ready mix.
- \( SDEV = 550 \times 0.09 = 50 \) psi

**STEP 2**
\[
S'c_{design} = S'c_{minimum} + z \times SDEV
\]
\[
S'c_{design} = 550 + 1.282 \times 50
\]
\[
S'c_{design} = 614 \text{ psi}
\]
AASHTO DESIGN
Concrete Properties

Modulus of Elasticity

\[ E_c = 6750 \ S'_c \]
\[ E_c = 57,000 \ (f'_c)^{0.5} \]

<table>
<thead>
<tr>
<th>Flexural Strength</th>
<th>Modulus of Elasticity</th>
</tr>
</thead>
<tbody>
<tr>
<td>600 psi</td>
<td>3,900,000 psi</td>
</tr>
<tr>
<td>650 psi</td>
<td>4,200,000 psi</td>
</tr>
<tr>
<td>700 psi</td>
<td>4,600,000 psi</td>
</tr>
</tbody>
</table>
Avenues for water entry

1. From Edge
2. Capillary Suction from Water-Table
3. Natural Drainage from High-Ground
4. Vapor Movement
5. Water-Table Rise

Surface Entry

WATER-TABLE

AASHTO DESIGN
Drainage, $C_d$
The statistical factors that influence pavement performance are:

- **RELIABILITY, R** - The statistical probability that a pavement will meet its design life.

- **STANDARD DEVIATION, \( s_o \)** - The amount of statistical error present in the design equations resulting from variability in materials, construction, traffic, etc.
PCAPAV Design Procedure

Design Basics
• Mechanistic stress analysis
• Calibrated to field tests, test roads
• Control criteria can be either:
  • Fatigue (cracking)
  • Erosion (pumping)
• Available computer program (PCAPAV)
Differences Between Design Procedures

• Traffic Classification:
  • AASHTO - uses 18-kip ESALs
  • PCA - uses axle load distribution

• Reliability
  • AASHTO - Reliability
  • PCA - Load Safety Factors

• Drainage
  • PCA does not include
PCAPAV Design

Two design criteria:

• Fatigue
  • Keeps pavement stresses due to repeated loads within safe limits

• Erosion
  • Limits the effects of pavement deflections at edges, joints and corners.
Fatigue Analysis

- Performed for edge stresses (critical stresses)
- Based on stress ratio
  \[ SR = \frac{\text{Equivalent Flexural Stress}}{\text{28-Day Modulus of Rupture}} \]
- Fatigue not consumed by repetitions of one load is available for repetitions of other loads.
Fatigue Analysis

- Allowable number of load repetitions for each axle group is determined from nomographs
- % Fatigue is calculated for each axle group

\[
\% \text{ Fatigue} = \frac{\text{Expected repetitions}}{\text{Allowable repetitions}}
\]

- Total fatigue consumed should not exceed 100%.
Erosion Analysis

• Repetitions of heavy axle loads cause:
  • pumping; erosion of subgrade, subbase and shoulder materials; voids under and adjacent to the slab; and faulting of pavement joints.

• Erosion is a function of Power, or rate of work.
  \[
  \text{Power} = \text{corner deflection (w)} \times \text{pressure (p)} \times \text{area duration of deflection}.
  \]

• A thin pavement with its shorter deflection basin receives a faster load punch than a thicker slab.
Erosion Analysis

- Performed for corner deflections (critical deflections)
- Erosion factor is determined from tables
- Allowable number of load repetitions for each axle group is determined from nomographs
- Erosion Damage is calculated for each axle group
  \[
  \% \text{ Erosion Damage} = \frac{\text{Expected repetitions}}{\text{Allowable repetitions}}
  \]
- Total erosion damage from all axle groups should be less than 100%
PCAPAV Design

Design controlled by:

- Fatigue usually controls design of light-traffic pavements
  - Single-axles usually cause more fatigue damage
- Erosion usually controls design of undoweled medium- and heavy-traffic pavements
  - Tandem-axles usually cause more erosion damage
PCAPAV Design Procedure

• Selection of an adequate thickness is dependent upon the choice of other design features:
  • Jointing system
  • Shoulder type
  • Subbase type
PCAPAV Design Procedure
Concrete Properties

- Flexural Strength (Modulus of Rupture),
  - Avg. 28-day strength in 3rd-point loading
- Other Factors
  - Fatigue Properties
  - Concrete Strength Gain with Age

Third-point Loading

\[ d = \frac{L}{3} \]

Span Length = \( L \)
PCAPAV Design
Concrete Properties

Comparison of $f'_c$, MR, and Required Thickness

<table>
<thead>
<tr>
<th>Compressive Strength</th>
<th>Third Point Flexural Strength</th>
<th>Effect on Slab Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>3000 psi</td>
<td>450 - 550 psi</td>
<td>7.0 in</td>
</tr>
<tr>
<td>4000 psi</td>
<td>510 - 630 psi</td>
<td>6.5 in.</td>
</tr>
<tr>
<td>5000 psi</td>
<td>570 - 710 psi</td>
<td>6.0 in.</td>
</tr>
</tbody>
</table>
PCAPAV Design
Subgrade Properties

Modulus of Subgrade Reaction, k-value

\[ k = \frac{\text{Plate load on subgrade}}{\text{Plate deflection on subgrade}} \]

\[ k = \frac{5.0 \text{ psi}}{0.5 \text{ in}} = 100 \text{ psi / in.} \]
PCAPAV Design
Subgrade Properties

- Plate-load test is rarely performed
  - time consuming & expensive
- Estimate k-value by correlation to other tests
  - e.g. California Bearing Ratio (CBR) or R-value tests.
- Lean concrete subbases increases k-value.
Comparison of Soil Types and k-value

<table>
<thead>
<tr>
<th>k-value</th>
<th>Type of Soil</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 psi/in.</td>
<td>Silts and clays</td>
<td>Satisfactory</td>
</tr>
<tr>
<td>200 psi/in.</td>
<td>Sandy soils</td>
<td>Good</td>
</tr>
<tr>
<td>300 psi/in.</td>
<td>Sand-gravels</td>
<td>Excellent</td>
</tr>
</tbody>
</table>
Effect of Untreated Subbase on k-value

<table>
<thead>
<tr>
<th>Subgrade k-value (psi/in)</th>
<th>Subbase k-value</th>
<th>4 in.</th>
<th>6 in.</th>
<th>9 in.</th>
<th>12 in.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>85</td>
<td>96</td>
<td>117</td>
<td>140</td>
</tr>
<tr>
<td>75</td>
<td></td>
<td>165</td>
<td>180</td>
<td>210</td>
<td>243</td>
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<tr>
<td>150</td>
<td></td>
<td>235</td>
<td>242</td>
<td>280</td>
<td>330</td>
</tr>
<tr>
<td>225</td>
<td></td>
<td>320</td>
<td>330</td>
<td>367</td>
<td>430</td>
</tr>
<tr>
<td>300</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Effect of Cement-treated Subbase on k-value

<table>
<thead>
<tr>
<th>Subgrade k-value (psi/in)</th>
<th>Subbase k-value</th>
<th>4 in.</th>
<th>6 in.</th>
<th>9 in.</th>
<th>12 in.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>220</td>
<td>294</td>
<td>386</td>
<td>496</td>
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<td>75</td>
<td></td>
<td>367</td>
<td>477</td>
<td>680</td>
<td>845</td>
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<tr>
<td>150</td>
<td></td>
<td>514</td>
<td>698</td>
<td>900</td>
<td>--</td>
</tr>
<tr>
<td>225</td>
<td></td>
<td></td>
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</table>
### PCAPAV Design
Subgrade Properties

**Effect of Untreated Subbase on k-value**

<table>
<thead>
<tr>
<th>Subgrade k-value (psi/in)</th>
<th>Subbase k-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4 in.</td>
</tr>
<tr>
<td>75</td>
<td>85</td>
</tr>
<tr>
<td>150</td>
<td>165</td>
</tr>
<tr>
<td>225</td>
<td>235</td>
</tr>
<tr>
<td>300</td>
<td>320</td>
</tr>
</tbody>
</table>
**PCAPAV Design**  
**Subgrade Properties**

**Effect of Cement-treated Subbase on k-value**

<table>
<thead>
<tr>
<th>Subgrade k-value (psi/in)</th>
<th>Subbase k-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4 in.</td>
</tr>
<tr>
<td>75</td>
<td>220</td>
</tr>
<tr>
<td>150</td>
<td>367</td>
</tr>
<tr>
<td>225</td>
<td>514</td>
</tr>
</tbody>
</table>
PCAPAV Design
Design Period

• 20 to 35 years is commonly used
• Shorter or longer design period may be economically justified in some cases
  • A special haul road to be used for only a few years.
PCAPAV Design
Traffic

• Numbers & weights of heavy axle loads expected during the design life
  • ADT (average daily traffic in both directions)
  • ADTT (average daily truck traffic in both directions)
    • Includes only trucks with six tires or more
    • Does not include panel and pickup trucks and other four-tire vehicles.
  • Axle loads of trucks
PCAPAV Design
Traffic

- Axle loads Distribution
  - The number of single and tandem axles over the design period
  - Expressed as Axles per 1000 trucks
- Does not include panel and pickup trucks and other four-tire vehicles.

### Axle load Distribution

<table>
<thead>
<tr>
<th>Axle load</th>
<th>Axles/1000 Trucks</th>
<th>Axles in design period</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Single Axles</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>125-133</td>
<td>0.58</td>
<td>6,310</td>
</tr>
<tr>
<td>115-125</td>
<td>1.35</td>
<td>14,690</td>
</tr>
<tr>
<td>107-115</td>
<td>2.77</td>
<td>30,140</td>
</tr>
<tr>
<td>97.8-107</td>
<td>5.92</td>
<td>64,410</td>
</tr>
<tr>
<td>88.8-97.8</td>
<td>9.83</td>
<td>106,900</td>
</tr>
<tr>
<td>80.0-88.8</td>
<td>21.67</td>
<td>235,800</td>
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<tr>
<td>71.1-80.0</td>
<td>28.24</td>
<td>307,200</td>
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<tr>
<td>62.2-71.1</td>
<td>38.83</td>
<td>422,500</td>
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<tr>
<td>53.3-72.2</td>
<td>53.94</td>
<td>586,900</td>
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<tr>
<td>44.4-53.3</td>
<td>168.85</td>
<td>1,837,000</td>
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<tr>
<td><strong>Tandem Axles</strong></td>
<td></td>
<td></td>
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<tr>
<td>213-231</td>
<td>1.96</td>
<td>21,320</td>
</tr>
<tr>
<td>195-213</td>
<td>3.94</td>
<td>42,870</td>
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<tr>
<td>178-195</td>
<td>11.48</td>
<td>124,900</td>
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<tr>
<td>160-178</td>
<td>34.27</td>
<td>372,900</td>
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<tr>
<td>142-160</td>
<td>81.42</td>
<td>885,800</td>
</tr>
<tr>
<td>125-142</td>
<td>85.54</td>
<td>930,700</td>
</tr>
<tr>
<td>107-125</td>
<td>152.23</td>
<td>1,656,000</td>
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<td>88.8-107</td>
<td>90.52</td>
<td>984,900</td>
</tr>
<tr>
<td>71.1-88.8</td>
<td>112.81</td>
<td>1,227,000</td>
</tr>
<tr>
<td>53.3-71.1</td>
<td>124.69</td>
<td>1,356,000</td>
</tr>
</tbody>
</table>
### Traffic Categories

<table>
<thead>
<tr>
<th>Two-way ADTT</th>
<th>Category</th>
<th>LSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Residential</td>
<td>3</td>
<td>LR</td>
</tr>
<tr>
<td>Residential</td>
<td>10 - 30</td>
<td>1</td>
</tr>
<tr>
<td>Rural &amp; secondary rds.</td>
<td>50 - 500</td>
<td>2</td>
</tr>
<tr>
<td>Collector streets</td>
<td>300 - 600</td>
<td>2</td>
</tr>
<tr>
<td>Minor Arterial Sts.</td>
<td>700 - 1500</td>
<td>3</td>
</tr>
<tr>
<td>Primary roads</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Major Arterial Sts.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
PCAPAV Design
Load Safety Factors

Recommended values

- Interstate, interprovincial, multilane projects
  - LSF = 1.2.
- Highways and arterial streets
  - LSF = 1.1
- Roads, residential streets, and other streets that carry small volumes of truck traffic
  - LSF = 1.0
Warping and Curling of Concrete

- **Warping** - moisture variations.
  - Creates compressive restraint stresses in the slab bottom.

- **Curling** - temperature variations.
  - During the day, the top surface is warmer than the bottom and stresses develop at the slab bottom.
  - During the night, the top is colder and stresses develop at the slab surface.

- Assumed to cancel each other out.
PCAPAV Design
Design Procedures

• Rigorous
  • Detailed axle-load-distribution data is available
• Simplified
  • Axle-Load Data Not Available
  • Designer does not directly use the axle-load data
  • Tabular form
PCAPAV Design
Rigorous Procedure

• Requires the following design factors:
  • Type of joint and shoulder
  • Concrete flexural strength (MR) at 28 days
  • k-value of subgrade or subgrade-subbase combination
  • Load safety factor (LSF)
  • Axle-load distribution
  • Expected number of axle-load repetitions

• Use PCAPAV Computer Program
Design Tip

Don’t Drink and Design