Continuously Reinforced Concrete Pavements - CRCP
(Pavimentos de Hormigón con Reforzamiento Continuo)

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  – Drs. Mike Darter and Lev Khazanovich

Presentation Overview

1. Introduction/Overview to CRCP
2. Illinois Experience
3. CRCP Distresses
4. Construction Process
5. CRCP Full-Scale Testing Results
6. Structural Design of CRCP

Continuous Reinforced Pavements

- No man-made “joints”
- Steel reinforcement bars
- Numerous transverse cracks

History
- First used in 1921
- Experimental sections in the 1940’s
- More than 28,000 miles in the USA

Why construct CRCP?

- Long-life pavement option
- Minimal maintenance
- Smooth ride
- High traffic volumes

What do we design for in CRCP?

1. Crack Spacing / Crack Width
   - geometry, materials, climate dependent
2. Repeated load resistance (fatigue)
   - Punchout development
**CRCP Performance Characteristics**

- 1 to 2 m crack spacing
- Tight crack widths
  - High load transfer efficiency
- Non-erodible support layers
  - No loss of support
- Low permanent deformation of support
  - Uniformity of support important
- Concrete durability
  - Many failures from non-structural deterioration

**Overview of CRCP Early Behavior**

- Basic analysis and stress diagrams

**Transverse Cracks**

- CRCP have transverse cracks to distribute movement
- Cracks are affected by
  - drying shrinkage
  - temperature changes
  - Slab-base friction
  - degree of bonding between concrete and steel
  - slab geometric and material properties
- Crack width (CW) → performance:
  - aggregate interlock → load transfer efficiency

**CRCP Failure**

- Deterioration of transverse cracks
- Punchouts

**Continuous Steel**

CRCP CRACKING PATTERN
**MECHANISTIC DESIGN CONSIDERATIONS FOR PUNCHOUT DISTRESS IN CONTINUOUSLY REINFORCED CONCRETE PAVEMENT**

**CRCP Punchout Failure**

- Longitudinal cracks propagate
- Structural failure
- Segment breaks and displace downwards

**CRCP Distress Development**

- Punchout
  - Longitudinal cracks propagate
  - Structural failure
  - Segment breaks and displace downwards

**Mechanism of Punchout Development (M-EPDG)**

- Longitudinal crack initiation
- Transverse crack
- Narrow crack spacing
- Loss of support

Selezneva (2002)

**LTE and other factors leading to CRCP failure**

- High rebar stress at crack
- Wide cracks – spalling
- LTE
- Bending stress

**Percent Longitudinal Steel**

<table>
<thead>
<tr>
<th>State</th>
<th>% steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Illinois</td>
<td>0.6 - 0.8</td>
</tr>
<tr>
<td>Texas</td>
<td>0.4 - 0.7</td>
</tr>
<tr>
<td>Oregon</td>
<td>0.6</td>
</tr>
<tr>
<td>South Dakota</td>
<td>0.7</td>
</tr>
<tr>
<td>Oklahoma</td>
<td>0.6</td>
</tr>
</tbody>
</table>

**Illinois I-55 CRCP**
History of CRCP in Illinois

- US-40 near Vandalia 1947
  - 18 & 20 cm CRCP with 0.3, 0.5, 0.7 and 1.0% steel
  - Parts replaced as part of I-70
  - Remainder performed for 50+ years
- 1960’s experimented with 15, 18, and 20 cm CRCP, base type, steel depth and percentage

- Originally adopted 18 cm and 0.6% steel as Interstate standard
  - Broken steel
  - Low cover depth steel = increased cracking
  - D-cracking problems
- Quickly adopted 20 cm CRC @ 0.7% steel as replacement for 25 cm, 100-foot jointed design
- Mid-1970’s traffic required 23 and 25 cm CRC
- Current Maximum thickness 36 cm
  - CRCP if design traffic is > 35 million ESAL’s (4,000 trucks 2-way with growth in 20 yrs)

Cluster
Y-crack
Meandering
Divided

Crack Spacing (ft)

Average: 4.2
Range: 1.8 - 10.1
Std. Deviation: 2.7


“D” CRACKED CONCRETE

I-39 CRCP Photo Review

CRCP 16 years old
“D”-Cracked Performance
Transverse Crack Spalling

- more of a problem in Texas

I-57 CRCP
Effingham, IL

Longitudinal cracking

Longitudinal Crack in Core

Longitudinal Cracking of CRCP
(I-39)

CRCP Tube Feeding

• Heavy bars (#7) sunk in concrete
• #7 bar weighs 2 times #5 bar

Bar Corrosion
Extended Life CRCP in Illinois

- 30-40 Year design life
- ~500 million ESALs
- Tighter concrete specifications

CRCP Test Sections (UIUC)

- Sec. 1 - 5: natural cracks, simulated wheel loads applied, and results reported in this study.
- Sec. 6 - 10: induced cracks, not loaded

CRCP Cross-Section

- Base must be stabilized (4 to 6 in.)
- Subbase is granular material (12 to 24 in.)

CRCP Structural Test Sections

- Concrete thickness (10 & 14 in.)
- Steel Content (0.6, 0.8, & 1.1%)
- Depth to steel (3.5 & 4.5 in.)
- Crack spacing
  - natural vs. induced
- Steel Bar Size (#5, #6, #7)
- 2-layer vs. 1-layer Steel

CRCP Paving Pavement Designs

- CRC
- 40 Year
- 0.8% Steel
- Epoxy Coated

Asphalt Concrete Base
Aggregate Working Platform

Section design & construction

- Concrete thickness was 10 or 14 in., on 4 in. asphalt base, and 6 in. granular subbase
- 26 longitudinal epoxy-coated steel bars, spaced 5.5” apart
- All transverse cracks developed naturally (Lane 1)
Two vs. One Layer Reinforcement

- Texas DOT used for 15 years
  - Should perform better?
- No performance information
- Cluster cracking (Zollinger 1999)
  - Result of curing and depth of steel
- Don’t coincide two layer of transverse reinforcement
- Longitudinal reinforcement on top of each other

Aggregate Subbase Compaction

Final Asphalt Concrete Base Layer
Transverse Crack Development

Crack Spacing (L) and
Width (CW) Formulas

- Concrete Placement – Lane 2
- Final CRCP Sections
- 36 cm CRCP
- Continuously Reinforced Concrete Pavement (CRCP) Sections
- Crack Spacing (L) and Width (CW) Formulas

\[
L = \frac{f'_{128} - C \sigma_0 \left(1 - \frac{2\sigma^*}{h_{PCC}}\right)}{\frac{F}{2} + \frac{U_m P_b}{c_1 d_b}}
\]

\[
cw(z) = CC \cdot L \left[ \varepsilon_{cr} \left(\varepsilon_{cr} - \frac{c_2}{E_i} \frac{U_m P_b}{c_1 d_b} + C_3 \sigma_0 \left(1 - \frac{2\sigma^*}{h}\right) \cdot \frac{L}{2} \right) \right]
\]

M-EPDG
**ATLAS CRCP Testing**

- **Loading**
  - Single aircraft tire
  - 9 to 13 km/h, a bi-directional trafficking mode
  - Fixed lateral position along the edge of the pavement
  - Load level from 45 to 245 kN (10 to 55 kips)

**Rebound Vertical Deflection**

- 0.6% steel and 10 in. thickness
- Crack 1
  - Rebound Vertical deflections with 0.8%
- Crack 2
  - Increase during times of constant loading

**Crack Spacing (Actual vs. Predicted)**

<table>
<thead>
<tr>
<th>Section</th>
<th>Number of cracks</th>
<th>Mean crack spacing (m)</th>
<th>Max</th>
<th>Min</th>
<th>STDV</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>15</td>
<td>0.62</td>
<td>1.10</td>
<td>0.86</td>
<td>0.38</td>
</tr>
<tr>
<td>S2</td>
<td>25</td>
<td>0.61</td>
<td>1.27</td>
<td>0.30</td>
<td>0.09</td>
</tr>
<tr>
<td>S3</td>
<td>13</td>
<td>0.76</td>
<td>1.71</td>
<td>0.24</td>
<td>0.37</td>
</tr>
<tr>
<td>S4</td>
<td>18</td>
<td>1.02</td>
<td>4.49</td>
<td>1.01</td>
<td></td>
</tr>
<tr>
<td>S5</td>
<td>4</td>
<td>NA*</td>
<td>1.34</td>
<td>10.49</td>
<td>NA*</td>
</tr>
</tbody>
</table>

**LTE of Cracks**

- LTE by Weight vs. Station Lane 2, Induced Cracks
- Load Transfer Efficiency
  - 9000 lbs.
  - 16000 lbs.
Load transfer efficiency (Small crack width)

Investigation in punchout one

Permanent deformation
- Estimated permanent deformation at two cracks in Section 2

Section 2 – Failure Pattern

Profile
- Longitudinal profile at the edge as loading progressed
- 20 mm peak permanent deformation
Profile Measurement for permanent deformation

Section 3

• 10 in. slab, 1.09% steel
• Testing w/ tent
• Test started on June 1st
• 33 transverse cracks

Cracking after loading

Damaging loads

• Load history, total ESALs, and ESALs at failure for each section

Summary of CRCP Section Failure

Full-Scale CRCP Testing Summary

Estimated ESALs at time of the first failure
- 230 to 548 millions for the 10 in. sections
- no damage after 764 millions in the 14 in. section

Performance of the CRCP:
- under small crack widths (less than 0.15 mm) ⇒ LTE remains intact despite the heavy wheel loads
- punchout failure controlled by the underlying permanent deformation
Existing CW data

- Measurement of CW
  - Crack comparators
  - Microscope
  - Dial gages, LVDTs
- CRCP CW data
  - Less than 0.2mm (IL)
  - Less than 0.5mm (TX)
  - "about" 0.1mm (Japan)
- All at the surface

Horizontal crack movement

- Vertical load
- Slab bends with load near crack
- Bottom part opens up
- Upper part of the crack closes
Crack face rotation

Load Spectra Tests

Crack Width (CW)

- Obtained from crack closing
- At the change in slope
  - Initially linear with load
  - Closing + compression at crack face

\[ CW = (\text{Closing})_L \]

Bi-linear behavior

CW with ATLAS wheel load

Factors affecting crack width

- Temperature: \( \Delta w_c = \alpha \cdot \Delta T \cdot L \) (unrestrained)
  - Daily and seasonal variations
  - Max drop in temperature (crack formation)

- Drying shrinkage
  - Non-uniform in depth
  - Specially important at early age

- Subbase friction
  - Opposes movement
  - Depends on subbase material

- Bond-slip
  - Bond-slip zone near crack's face
  - Bond stress in the bond-slip zone is complex
  - Reinforcement steel (amount and depth)

Others:

- Concrete aggregate type
- Moisture gradient
- Construction season
- Method of concrete curing

CW Variability (Section 3)
**M-EPDG Crack Width model**

- Crack Width model for CRCP

\[
CW = \frac{CL}{E_{fc}} + \frac{E_{cm} + \alpha_{cm} \Delta T - E_{cm}}{E_{cm}} \left( 1 - \frac{z}{L} \right) \frac{L}{L_f} \]

- Drying shrinkage
- Temperature drop
- Restraints

<table>
<thead>
<tr>
<th>Crack Spacing</th>
<th>Drying Shrinkage</th>
<th>Temperature Drop</th>
<th>Restraints</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</tr>
</tbody>
</table>

**Findings of ATLAS CRCP Tests**

- Achieving tight crack width \(<1\ mm\) 
  - extends performance \(<0.5\ mm\)
- Avoid support layers with high permanent deformation potential
- Infinite fatigue life at 14in. and probably at 12 in.

**Effect of Air Temperature on CRCP Failures**

<table>
<thead>
<tr>
<th>Air temperature (°F)</th>
<th>Percentage of Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>50-60</td>
<td>0%</td>
</tr>
<tr>
<td>60-70</td>
<td>5%</td>
</tr>
<tr>
<td>70-80</td>
<td>10%</td>
</tr>
<tr>
<td>80-90</td>
<td>15%</td>
</tr>
<tr>
<td>90-100</td>
<td>20%</td>
</tr>
</tbody>
</table>

**Construction Issues**

- Concrete mix design
  - Concrete shrinkage
  - Lower zero stress temperature!
    - Mix temperature (water, aggregates)
    - Mix proportions (max. size aggregate)
- Curing
  - Minimize climatic effects
  - Solar radiation, wind, evaporation
- Asphalt concrete base temperature

**Zero-stress temperature**

Estimate of \(T_{zs}\)
- M-EPDG formula
- \(95.5\%\) of peak temperature
- DG2002: "temperature at which the concrete hardens sufficiently to cause cracks to open when the concrete temperature drops below its value"

**Zero-stress temperature**

At early age:
- zero-width = zero-stress (temperature)
Later in the life of the concrete:
- zero-width should > zero-stress (temperature)
  - But it was found to be lower
  - crack width is not increasing with age
  - Total pavement length increases \(\Rightarrow\) blowups
Illinois DOT Extended-Life CRCP

- CRCP Specifications and guidelines for construction and materials

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Aggregate Screening

- ASTM 666 used since 1982.
  - Freeze in air - thaw in water.
  - Test run to 350 cycles.
  - Average expansion of 3 test beams.
- Decided to use standard test method.
  - 20 year aggregate - Limit to 0.060% expansion.
    - Field performance correlated to test.
    - No overlay during 20 years of pavement life.
  - 30 year aggregate - Limit to 0.040% expansion.
  - 40 year aggregate - Limit to 0.025% expansion.

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Cement and Fly Ash Requirements

- 30 Year pavement.
  - Same as 20 year.
  - No additional restrictions.
- 40 Year pavement.
  - Must address alkali’s - less than 0.60% in cement and less than 1.5% in fly ash.
  - Options:
    - Use a low alkali cement.
    - Test cement/fly ash/aggregate - must have expansion less than 0.10% under ASTM 1260 at 16 days.
    - Concern is in sands - source of silica.

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Concrete Mixture Requirements

- Same as current 20-year.
- Water/cement ratio -
- Beam Strength - 4.5 MPa (650 psi)
  - Center point loading.
  - 14 Days.
  - Unchanged from 20 year pavement design.
  - Why increased strength is not used:
    - More cement - possible additional reactivity problems.
    - More effective to add thickness to reduce stress.

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Illinois CRCP Thickness Determination

- Currently using IL-Modified AASHTO
- In use since 1970’s
- Performance indicates design is conservative
- Research underway at University of Illinois to update method
  - Will likely adopt some version of M-EPDG for CRCP
Typical Illinois CRCP Thickness Design

<table>
<thead>
<tr>
<th>Thickness</th>
<th>ESAL, Millions</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 in.</td>
<td>5</td>
</tr>
<tr>
<td>10 in.</td>
<td>20</td>
</tr>
<tr>
<td>12 in.</td>
<td>100</td>
</tr>
<tr>
<td>14 in. (max)</td>
<td>300+</td>
</tr>
</tbody>
</table>

Steel Requirements

- All epoxy coated ASTM A706.
- Percent CRC Steel
  - Grade 60
  - 0.70% (20-yr)
  - 0.80% (30-yr)
  - Maximum #7 bar
- Tie bars:
  - Grades 40 or 60
  - #6 x 24"
  - 24" centers if butt joint
  - 30" centers if sawed joint
Constructing CRCP Pavement

- **Paving Equipment:**
  - Max speed 3’ per minute unless plan in place
  - Vibrator frequency monitoring required.
- **Timing - randomly spacing (to reduce noise)**
- **Curing:**
  - Spray on curing compound.
  - Period - 7 day minimum.
  - No traffic of any kind allowed during curing.
- **Smoothness Requirement:**
  - Zero blanking band.
  - Incentive/disincentive

Constructing Support Layers

- **Embankment:**
  - AASHTO T99
    - Max. Moisture 110% of optimum.
    - Min. 96% density in all of embankment.
- **Aggregate Subbase:**
  - 12 in.
  - Crushed aggregate.
    - Stone.
    - Gravel (crushed).
    - Crushed concrete.
    - Crushed asphalt concrete
    - Well graded - Max 200 mm (8”)  

Constructing Base Layer

- **Base:**
  - Bituminous - Superpave mixture
    - 19.0 mm Binder Mix.
    - N 30.
    - Anti-strip added if needed.
- **Paving between May 15 and Oct. 15 -**
  - White-wash (lime water) bituminous base.
  - Water cool
  - reduce temperature and chance of flash setting from bottom up.

IDOT Reinforcing Bar Standards

Natural Crack shapes and patterns

- Non-uniform crack patterns are detrimental and common
- They lead to spalling and punchouts
- Out of 23 sections studied (*):
  - 20 had cluster cracks, and some had them in several locations
  - All had V-cracks (2% to 23%)
  - CRCP sections in IL, IA, OK, OR, PA, and WI

**Active Crack Control**

- Tape Insertion
- Saw-cut

**Natural vs Induced Cracks**

- Cracks vs. Time
- Number of Cracks
- Time (Days After Pour)

**Crack development**

- Crack location and time of crack surveys
- More cracks developed early in Lane 2
- Some natural cracks occurred in Lane 2

**CRCP Crack Control**

- Lane 2 – Active Crack
- Lane 1 – Passive Crack

**Continuously Reinforced Concrete Pavement DESIGN**

- DESIGN:
  - Longitudinal reinforcement
  - Random transverse cracks
  - Cracks kept tight
  - Smooth pavement, long life

- PERFORMANCE:
  - Transverse cracking
  - Punchout development

**CRCP Design Methods**

- AASHTO (1986) Nomograph
  - Thickness same as JPCP
- M-EPDG (2007)
  - Different JPCP and CRCP methods
- Proposed Method Illinois DOT (2009)
  - Modified M-EPDG
AASHTO (1986)

- Crack width criteria

AASHTO (1986)

- Crack spacing criteria

AASHTO (1986)

- Steel stress criteria

AASHTO-86/93 Guide for Design of Pavement Structures

- 3 criteria
  - Crack Spacing
  - Crack Width
  - Steel Stress

M-EPDG CRCP Design

ARA (2007)

Punchout: Structural Distress in CRCP

- Results in loss of ride quality
- Costly repairs
Mechanism of Punchout Development

1. Longitudinal crack initiation
2. Deteriorated transverse crack
3. Loss of support
4. Narrow Crack spacing
5. Tire footprint

Direction of traffic
Pavement edge

Mechanistic-Empirical Punchout Modeling Approach

Input Parameters
- Traffic, environment, material, geometry
- Fatigue Damage Prediction Model
- Loss of Edge Support Model

Transverse Crack Modeling
- Crack Load Transfer Deterioration Model
- CRCP Structural Response Model
- Effective Slab Thickness Model

CRCP Structural Response Model

- Unloaded plate element
- Loaded plate element
- Subgrade spring element
- Traffic load

Transverse Crack LTE Deterioration Model

\[ FD = \sum_{n=1}^{N} \frac{w_n}{N_n} \]

CRCP Structural Response Model (continue)

Detail A

Axle Loading Used in CRCP Response Model

<table>
<thead>
<tr>
<th>Axle Name</th>
<th>Total Wheels</th>
<th>Wheel Spacing, inch</th>
<th>Axle Spacing, inch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single</td>
<td>4</td>
<td>12</td>
<td>84</td>
</tr>
<tr>
<td>Tandem</td>
<td>8</td>
<td>12</td>
<td>84</td>
</tr>
<tr>
<td>Tridem</td>
<td>12</td>
<td>12</td>
<td>84</td>
</tr>
</tbody>
</table>

Models Used to Characterize Properties of Finite Elements

- PCC Strength Gain Model
- Effective Slab Thickness Model
- Transverse Crack Width Model
- Crack Load Transfer Deterioration Model
- Loss of Slab Support Model
- Equivalent Temperature Differential Model
- Enhanced Integrated Climatic Model
CRCP Stress Distribution for Different Transverse Crack LTE

<table>
<thead>
<tr>
<th>LTE = 95%</th>
<th>LTE = 20%</th>
</tr>
</thead>
<tbody>
<tr>
<td>150 psi</td>
<td>342 psi</td>
</tr>
</tbody>
</table>

Direction of traffic

Design Parameters Over CRC Pavement Life

Each load application

PCC Modulus
Traffic
Transverse Crack LTE
Transverse Crack Width
Granular Base Modulus
Subgrade Modulus

CRCP Structural Design Algorithm

<table>
<thead>
<tr>
<th>Inputs (Structure, Traffic, Climate)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selection of Trial Design</td>
</tr>
<tr>
<td>Structural Responses (σ, τ, LTE)</td>
</tr>
<tr>
<td>Damage Accumulation with Time</td>
</tr>
<tr>
<td>Calibrated Punchout Model</td>
</tr>
<tr>
<td>Performance Verification (Failure criteria = punchouts per mile)</td>
</tr>
<tr>
<td>Design Reliability</td>
</tr>
<tr>
<td>Design Requirements Satisfied?</td>
</tr>
</tbody>
</table>

2002 Design Guide

2002 Design Guide

Loss of Edge Support Model

\[ EE = AGE^* (7.4 + 0.342P200 + 1.557BEROD + 0.234PRECIP)/12 \]

- **EE** = Erosion extent from pavement edge, inch
- **AGE** = Pavement age, month
- **P200** = Percent subgrade passing the No. 200 sieve, %.
- **PRECIP** = Mean annual precipitation, inch.
- **BEROD** = Base erodibility index:
  1 for LCB;
  2 for CTB with 5% cement;
  3 for ATB and CTB with cement <5%;
  4 for GB with 2.5 % cement;
  5 for untreated GB.

Crack LTE Deterioration Model (based on Zollinger et al.)

\[ \text{LTE}_{	ext{old}} = 100^* \left\{ 1 - \left( 1 - \frac{1}{1 + \log \left( \frac{0.214 - 0.18 \text{LTE}_{	ext{old}} - \log(\text{LTE}_{	ext{old}}) - (500 - 3)}{1.18} \right)} \right) \right\} \]

\[ \text{Log}(\text{LTE}) = \text{ac} + \text{de} + \text{ge}^* \left( \frac{\sigma_i}{\text{MR}_{	ext{PCC}}} \right) + \text{e} \cdot \text{e}^* \left( \frac{\tau_j}{\text{MR}_{	ext{PCC}}} \right) \]

\[ \sigma_i = \sum \left( 0.055 \left( \frac{\sigma_i}{\text{MR}_{	ext{PCC}}} \right) \right) \]

\[ \tau_j = \sum \left( 0.068 \left( \frac{\tau_j}{\text{MR}_{	ext{PCC}}} \right) \right) \]

Fatigue Damage Prediction Model

- **Miner's hypothesis:**

\[ \text{Damage} = \sum \frac{\text{Applied loads} (n_j)}{\text{Allowable loads} (N_j)} = f (\sigma_j, \text{MR}_{	ext{PCC}}) \]

- **Number of Allowable Loads:**

\[ \text{Log} N_j = 2.0 (\text{MR}/\sigma_j)^{1.22} - 1 \]

- **N_j** = Allowable number of load applications of j-th magnitude
- **MR** = Concrete modulus of rupture (psi).
- **σ_j** = Bending stress due to loads of j-th magnitude, psi.
Calibrated Punchout Prediction Model

\[ PO_i = \sum_{i=1}^{Life} \frac{a}{1 + b \cdot D_i^c} \]

- \( PO_i \): Number of punchouts per mile at the end of the \( i \)-th monthly increment
- \( D_i \): Accumulated damage at the end of the \( i \)-th increment
- \( a = 216.842 \) (Calibration constant)
- \( b = 33.1579 \) (Calibration constant)
- \( c = -0.58947 \) (Calibration constant)

Pennsylvania LTPP Section 42-5020

- Cumulative Truck Volume per Lane
- Average Crack Width
- Average Crack LTE
- Pavement age, years
- Punchout per mile

PCC CTE Sensitivity for Mississippi LTPP Section 28-5006

- LTPP Section 28-5006
- Slab thickness: 9.3 inch
- % Steel: 0.6
- Base Type: GB
- Avg. crack spacing: 55 inch
- Climatic zone: WF
- AADTT (base year): 1,100
- Avg. ESAL/truck: 1.0
- Truck Growth: 6.5%
- CTE = 7 \( \times 10^{-6} \) \(^{\circ}F^{-1}\) (LTPP)

Initial MEPDG v1.0 CRCP Analysis

- Concrete Materials
  - MOR = 585 psi at 28 days (3rd point bending)
  - Cement content: 550 lbs/cy (w/c=0.42)
  - CTE = 5.5 \( \times 10^{-6} \) \(^{\circ}F^{-1}\) (absorbivity=0.85)

- Reinforcement
  - 20-year: 0.7% steel, #6 bars
  - 30-year: 0.8% steel, #7 bars
  - steel depth:
    - 3.5" for 10, 60 million ESALs
    - 4.5" for 230 million ESALs
  - -10\(^{\circ}F\) Built-in Curl

Traffic Inputs

- Bolingbrook Data
  - vehicle class distribution
- M-EPDG Default Values
  - hourly adjustment
  - axle load distribution
  - # of axle types/truck class
- Tire pressure = 80 psi

CRCP Traffic Assumptions

- AADTT values for MEPDG v1.0
  - 20-year design
    - 10 million ESALs = 1,657 AADTT
    - 60 million ESALs = 9,918 AADTT
    - 230 million ESALs = 38,021 AADTT
  - 30-year design
    - 10 million ESALs = 1,105 AADTT
    - 60 million ESALs = 6,612 AADTT
    - 230 million ESALs = 25,347 AADTT

AADTT = Average Annual Daily Truck Traffic
Design Features

- PCC thickness is design variable
- BAM = 4 inch
- A-7-6 soil (E = 7,500 psi)
- Crack spacing = calculate
- Construction month = August

Failure Criteria

- Punchout = 10/mile @ 95% reliability
- IRI = ignore this failure criteria

Proposed CRCP Design Method
Illinois DOT (2009)

- Implement simplified version of M-EPDG method into spreadsheet
- Similar mechanistic principles
- Use ESALs
**Proposed CRCP Inputs**

- Pavement thickness
- Design life
  - percent steel, bar size, depth to steel
- Climatic data (seasonal)
  - temperature gradients through pavement, temperature at steel depth, ambient temperature
- Shoulder type
  - tied PCC, asphalt, gravel
- Design ESALs

**CRCP Inputs, con’t**

- Concrete properties
  - modulus, COTE, strength, ultimate shrinkage, cementitious content
- Base/subgrade properties
  - modulus, thickness, type, k-value → unbonded case
- Construction season
  - spring, summer, fall, winter
- Fatigue equation
  - MEPDG, IDOT, ACPA

**CRCP Design Process**

1. Environmental Effects
   - Four cyclic seasons
     - Frequency of temperature gradients through pavement
     - curling stress calculation
     - Average pavement temperature at steel depth
     - crack spacing, crack width calculations
     - Average ambient temperature
     - Tset calculation

**CRCP Design Procedure**

**Frequency Analysis - Champaign 12” PCC (fall)**

<table>
<thead>
<tr>
<th>ΔT (°F)</th>
<th>% Time at ΔT</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 30</td>
<td>≤ 0.0%</td>
</tr>
<tr>
<td>27.5 to 30</td>
<td>2.0%</td>
</tr>
<tr>
<td>25 to 27.5</td>
<td>4.0%</td>
</tr>
<tr>
<td>22.5 to 25</td>
<td>6.0%</td>
</tr>
<tr>
<td>20 to 22.5</td>
<td>8.0%</td>
</tr>
<tr>
<td>17.5 to 20</td>
<td>10.0%</td>
</tr>
<tr>
<td>15 to 17.5</td>
<td>12.0%</td>
</tr>
<tr>
<td>12.5 to 15</td>
<td>14.0%</td>
</tr>
<tr>
<td>10 to 12.5</td>
<td>16.0%</td>
</tr>
<tr>
<td>7.5 to 10</td>
<td>18.0%</td>
</tr>
<tr>
<td>5 to 7.5</td>
<td>20.0%</td>
</tr>
<tr>
<td>2.5 to 5</td>
<td>22.0%</td>
</tr>
<tr>
<td>0 to 2.5</td>
<td>24.0%</td>
</tr>
<tr>
<td>-2.5 to 0</td>
<td>26.0%</td>
</tr>
<tr>
<td>-5 to -2.5</td>
<td>28.0%</td>
</tr>
<tr>
<td>-7.5 to -5</td>
<td>30.0%</td>
</tr>
<tr>
<td>-10 to -7.5</td>
<td>32.0%</td>
</tr>
<tr>
<td>-15 to -10</td>
<td>34.0%</td>
</tr>
<tr>
<td>-20 to -15</td>
<td>36.0%</td>
</tr>
<tr>
<td>-22.5 to -20</td>
<td>38.0%</td>
</tr>
<tr>
<td>-25 to -22.5</td>
<td>40.0%</td>
</tr>
<tr>
<td>-27.5 to -25</td>
<td>42.0%</td>
</tr>
<tr>
<td>-30 to -27.5</td>
<td>44.0%</td>
</tr>
</tbody>
</table>

**Mean Crack Spacing**

\[
s_{\text{CURL}} = C \frac{E \epsilon \Delta T}{2}
\]

\[
s_{\text{TOT}} = \sum (s_{\text{CURL}} \times R_{\text{LOAD}})
\]

\[
R=1.0 \text{ for new}
\]

\[
\sigma_{\text{TOT}} = \sum (s_{\text{CURL}} \times R_{\text{LOAD}})
\]

**CRCP Design Procedure**

2. Mean Crack Spacing

\[
 f_{\text{CR}} = C \sigma_{\text{f}} \left( 1 - \frac{2d}{h_{\text{pc}}} \right)
\]

\[
 L = \frac{f_{\text{CR}} \sum c_{i} d_{i}}{2}
\]

MEPDG (2007)
3. Crack Width

\[ CW = T \left( \varepsilon_{cr} + \alpha_{PCC} \Delta T_{cool} - \frac{c_{f,T}}{E_{PCC}} \right) \times 1000 \]

MEPDG (2007)

4. LTE across cracks
   - Dimensionless shear capacity
   - Crack stiffness
     - Assume no shear capacity loss

\[ LTE = 100 \left( 1 - \left[ 1 - \log \left( \frac{0.214 - 0.18(\sigma_f)}{100} \right) - 1 \right] / 100 \right) \]

MEPDG (2007)

5. Traffic Stresses
   - STT, STB, SLB functions of LTE, LTEc CS/RRS
   - Cataloged ILLISLAB results
   - Calculate stress due to traffic loading, \( \sigma_{LOAD} \)

6. Damage
   - Fatigue equations
     - MEPDG: \( \log N = 2.0(M_{b}/\sigma_{TOT})^{1.22} - 1 \)
     - IDOT: \( \log N = 17.61 - 17.61(\sigma_{TOT}/M_{b}) \)

   - Damage equation
     \[ D_i = \sum f_i \frac{M_i}{N_i} + D_{ex} \]
### Equivalent Damage Ratio (EDR)

\[
EDR_{STR, i} = \begin{cases} 
IF \quad L/T_e \leq 60, \quad -0.1424 \left( \frac{L_e}{\ell_i} \right) + 0.2806 \\
IF \quad 60 < L/T_e \leq 85, \quad -0.1138 \left( \frac{L_e}{\ell_i} \right) + 0.2688 \\
IF \quad 85 < L/T_e \leq 98, \quad -0.0965 \left( \frac{L_e}{\ell_i} \right) + 0.3064 \\
IF \quad L/T_e > 98, \quad -0.0933 \left( \frac{L_e}{\ell_i} \right) + 0.3414 
\end{cases}
\]

\[
EDR_{STR, i} = -0.2264 \left( \frac{L_e}{\ell_i} \right) + 0.5533
\]

### CRCP Design Procedure

7. Punchouts / mile

\[
PO_j = \sum_{i=1}^{m} \frac{1}{a + b \cdot c^{-\log T_{ret, i}}}
\]

- \(a, b, c = \) calibration constants of 0.02, 1.000 \( \times 10^{-32} \), 13975
- 50 Punchout/mile saturation limit

### MEPDG CRCP Calibration

- 22 States w/ 4 climatic regions
- 58 CRCP sections
  - 10 sections from Illinois
  - Vandalia (US40), I-80, I-94 Edens – Heavy traffic

### CRCP Calibration Sections
**Design Charts**

30 year, $K_d=50$ psi/in, Reliability=95%

<table>
<thead>
<tr>
<th>Design ESALs (millions)</th>
<th>Slab Thickness (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 40 70 200</td>
<td>8.0 8.5 9.0 9.5 10.0 10.5 11.0 11.5 12.0</td>
</tr>
</tbody>
</table>

**Design Charts**

30 year, $K_d=100$ psi/in, Reliability=95%

<table>
<thead>
<tr>
<th>Design ESALs (millions)</th>
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<tbody>
<tr>
<td>10 40 70 200</td>
<td>8.0 8.5 9.0 9.5 10.0 10.5 11.0 11.5 12.0</td>
</tr>
</tbody>
</table>

**Design Charts**

30 year, $K_d=200$ psi/in, Reliability=95%

<table>
<thead>
<tr>
<th>Design ESALs (millions)</th>
<th>Slab Thickness (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 40 70 200</td>
<td>8.0 8.5 9.0 9.5 10.0 10.5 11.0 11.5 12.0</td>
</tr>
</tbody>
</table>

**Design Comparisons**

<table>
<thead>
<tr>
<th>k-value (psi/in.)</th>
<th>Design ESALs (millions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>IDOT M-E IDOT M-E IDOT M-E IDOT M-E</td>
</tr>
<tr>
<td>10</td>
<td>9.5 10.5 11.0 11.0 12.0 11.5 13.5 12.5</td>
</tr>
<tr>
<td>40</td>
<td>9.0 10.0 11.0 10.5 12.0 11.0 13.5 12.0</td>
</tr>
<tr>
<td>70</td>
<td>9.0 9.5 11.0 11.0 12.0 10.5 13.5 11.5</td>
</tr>
</tbody>
</table>

*Both design procedures assume 20 year designs and tied concrete shoulders
*M-E design procedure assumes 95 percent reliability

**Summary of New Features**

- Proposed CRCP Design Process
  - Crack spacing prediction
  - Fatigue-based thickness design
- New Equivalent damage ratios
- Top of slab strength reduction factor

**CRCP Program Limitations**

- Erosion analysis
- Reliability is a Traffic Multiplier of 4
- Load and temperature stress superposition
  \[ \sigma_{TOT} = \sum (\sigma_{CUR} + R\sigma_{LOAD}) \]
  - $R=1.0$
- Widen Lane stresses - none
- Tied shoulder*
Limitations, con’t

- Verification for high ESAL count
  - >100 million
- Calculated stresses are extremely low
  - Is this the right approach or are we using the wrong thickness?
- CRCP = 0.8*JRCP
  - No guarantee that CRCP will be thinner

Acknowledgements

The Illinois Center for Transportation (ICT) is an innovative partnership between the Illinois Department of Transportation (IDOT) and the University of Illinois at Urbana-Champaign (UIUC).

Questions?

jroesler@uiuc.edu or 217-265-0218

Projects Publications


CRCP Projects Reports


Projects Publications


http://www.crcpavement.com/
Crack Shear Capacity

\[ s_{0i} = 0.05 \cdot h_{PCC} \cdot e^{-0.032 \cdot c_{w,j}} \]

Transverse Crack Shear Stiffness (Aggregate Interlock)

\[ \log(J_z) = a e^{-\left| \frac{c_{w,i}}{c_{w,i}} \right|} + d e^{-\left| \frac{c_{w,i}}{c_{w,i}} \right|} + g e^{-\left| \frac{c_{w,i}}{c_{w,i}} \right|} \cdot e^{-\left| \frac{c_{w,i}}{c_{w,i}} \right|} \]

Transverse Crack LTE

\[ \text{LTE}_{c,i} = \frac{100}{1 + \log \left[ \frac{0.214 - 0.183 \frac{c_{w,i}}{c_{w,i}} - \log(J_z)}{1.18} \right]} \]

Shear Transfer Deterioration of Cracks

\[
\begin{array}{c|c}
\text{LTE}_{c,i} & \Delta \alpha_i \\
\hline
\text{If } \text{< 3.8} & \Delta \alpha_i = \sum \frac{0.005}{1 + \left( \frac{c_{w,i}}{c_{w,i}} \right)} \left( \frac{c_{w,i}}{c_{w,i}} \right) \cdot \text{ESR} \quad (55a) \\
\text{otherwise} & \Delta \alpha_i = \sum \frac{0.004}{1 + \left( \frac{c_{w,i}}{c_{w,i}} \right)} \left( \frac{c_{w,i}}{c_{w,i}} \right) \cdot \text{ESR} \quad (55b)
\end{array}
\]