Mechanistic-Empirical Design of Concrete Pavements: Past, Present, and Future

Lev Khazanovich
Associate Professor

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Department of Civil Engineering
Westergaard Model

- PCC layer: a plate
- Subgrade: Winkler foundation

\[ D \nabla^4 w(x, y) + k w(x, y) = p(x, y) \]

\[ D = \frac{E_{PCC} h_{PCC}^3}{12(1 - \mu_{PCC}^2)} \]

(Westergaard 1926, 1948)
Westergaard’s Solutions

- edge loading
- interior loading
- corner loading

- $a$ = wheel footprint radius, $P$ = wheel load

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Limitations of Westergaard’s Solutions

• Single slab
  – no joints
• Infinite/semi-infinite in horizontal direction
  – no slab size effect
• Single layer slab
• Full contact of the plate with the foundation
  – no separation
• Single wheel
  – no axle loads

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Finite Element Programs

- KenSlab (Huang 1973), JSLAB (Tayabji 1977), EverFE (1999)
- ILLISLAB
  - Tabatabai and Barenberg (1978) – multiple slabs, base layer, doweled joints
  - Ioannides (1985) – Pasternak and elastic half-space foundations
  - Korovesis (1989) – slab curling, separation from subgrade
  - Khazanovich (1994) – nonlinear temperature distribution, separation between slab and base
- ISLAB2000 (Khazanovich et al. 2000)
AASHTO Empirical Design Equation

\[
\log(ESALs) = Z_R S_0 + 7.35 \log(H_{pcc} + 1) - 0.06 + \left( 4.22 - 0.32 p_t \right) \ast \log
\]

number of axle load applications

overall standard deviation

PCC thickness

standard normal deviate

terminal serviceability

\( H_{pcc} \)

change in serviceability

load transfer

flexural strength

drainage coefficient

terminal serviceability

load transfer


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I-80 Failure

- Re-constructed in 1993
- 325-mm thick PCC pavement
- Design life: 40 years
- Transverse cracks developed within a few years

*PCC thickness and strength of cores met the design requirements*
Permanent (Built-in) Curling

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

PCC Stresses

Day time, $T_{\text{top}} - T_{\text{bottom}} = 5 \, ^{\circ}\text{C}$, **Bottom PCC Surface**

Night time, $T_{\text{top}} - T_{\text{bottom}} = -20 \, ^{\circ}\text{C}$, **Top PCC Surface**
Lessons Learned from I-80 Failure

• Cracking initiation from the top surface can be explained mechanistically by accounting of built-in curling
• Magnitude of built-in curling can have a profound effect and can significantly affect failure mode
• Entire truck loading must be considered in night time curling analysis

• Thick PCC pavement and high strength of concrete do not guarantee good pavement performance
Mechanistic-Empirical Pavement Design Guide (MEPDG)

- Climate
- Traffic
- Materials
- Structure

Damage Accumulation

Response

Time

Field Distress

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• Longitudinal cracking model
• Rehabilitation
• Reliability analysis
• Built-in curling modeling
• Fracture prediction
Pavement Rehabilitation

• Unbonded concrete overlays
• Conventional concern: reflective cracking
• Overlay failed in 2 years
• No reflective cracking was observed
• Forensics indicated that cracking was top-down
• Plausible explanation of failure: excessive overlay built-in curl caused voids under overlay joints

• Built-in curling changes mode of failure

• Built-in curling characterization is as important as concrete fracture property characterization
To accurately model permanent distortion of concrete slabs, we should accurately simulate concrete pavement responses after placement:
- Ambient temperature and humidity, solar radiation, wind
- Cement hydration process
- Heat transfer & moisture transport
- Concrete creep
- Concrete shrinkage
- Concrete fracture
  (joint formation)

There is a need for a reliable early age concrete creep model.

Ruiz et al. 2005
• Significant progress has been made in development robust, mechanistic-based design procedure
• More work needs to be done, especially for design of overlays
• Future design procedures
  – Require better characterization of concrete properties
  – Tied to construction control