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

Lev Khazanovich
Associate Professor

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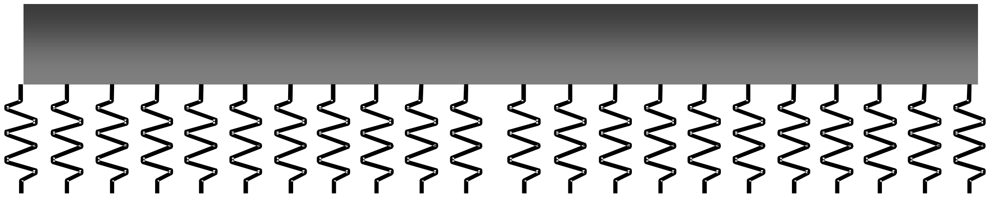
Department of Civil Engineering

Westergaard Model

- PCC layer: a plate
- Subgrade: Winkler foundation



H_{PCC}, E_{PCC}, μ_{PCC}

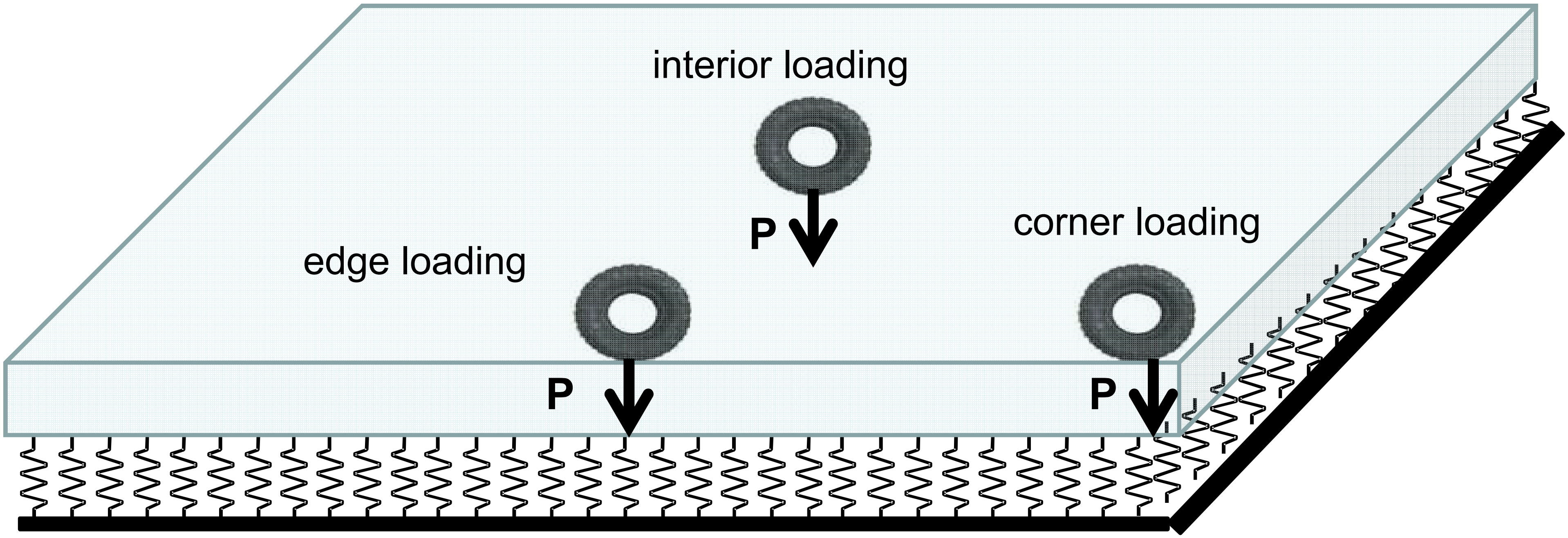
k

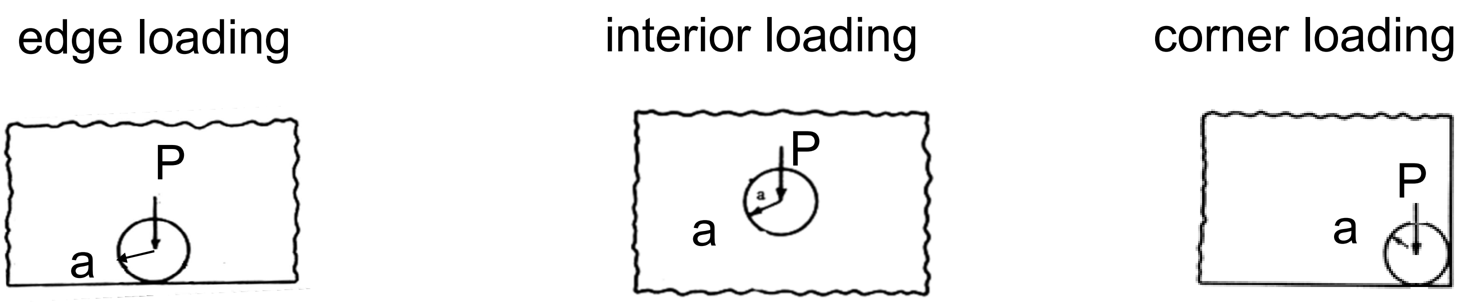
$$D\,\nabla^4 w(x,y) + k\,w(x,y) = p(x,y)$$

$$D = \frac{E_{PCC}\,h^3_{PCC}}{12(1-\mu^2_{PCC})}$$

(Westergaard 1926, 1948)

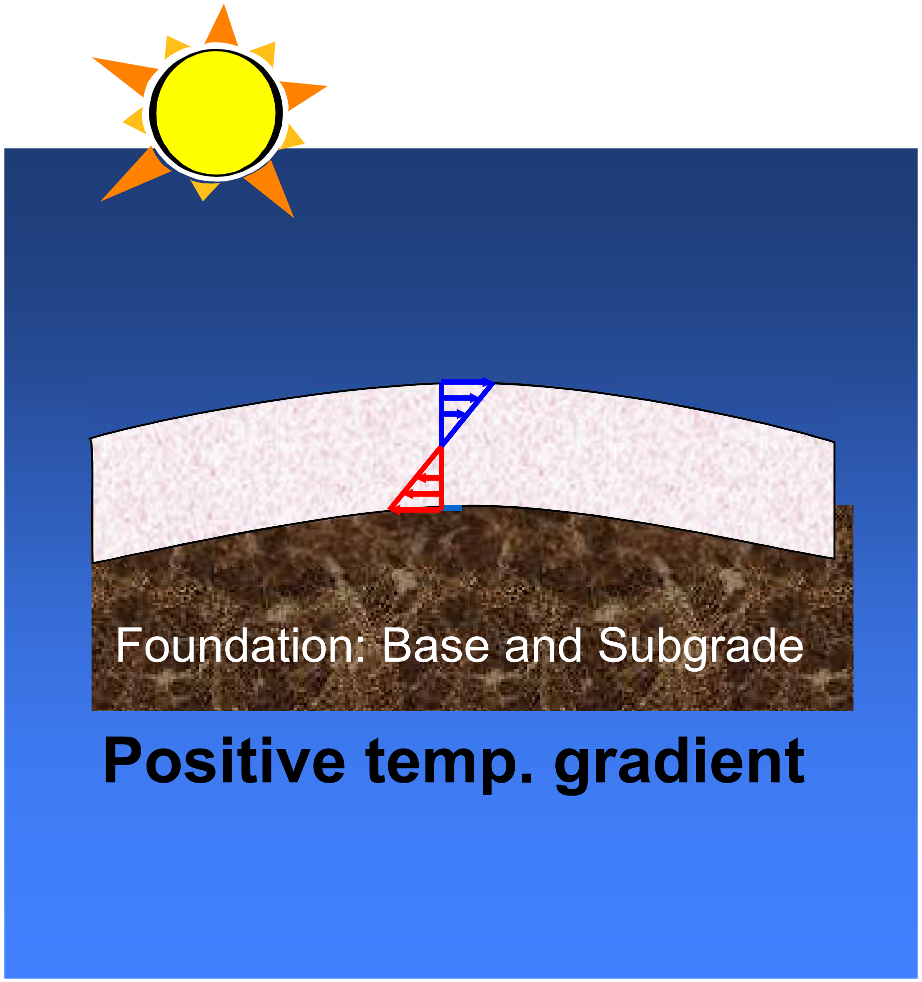
Westergaard's Solutions

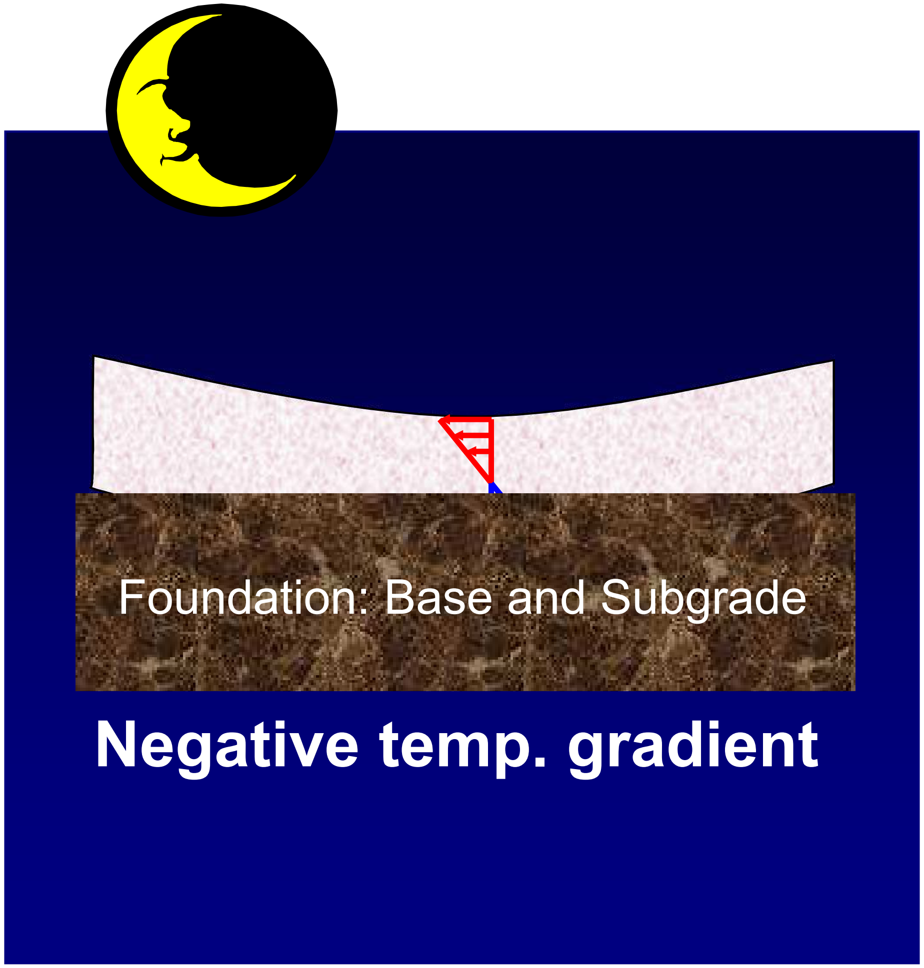




a= wheel footprint radius, P = wheel load

Curling and Warping





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

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
  - Roesler and Khazanovich (1997) – fracture mechanics-based modeling of partial depth cracks
- ISLAB2000 (Khazanovich et al. 2000)

AASHTO Empirical Design Equation

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number of axle load applications; overall standard deviation; **PCC thickness**; change in serviceability

$$\text{Log(ESALs)} = Z_R \; S_0 + 7.35 \; \text{Log}(\mathbf{H}_{\mathbf{pcc}} + 1) - 0.06 + \left[\frac{\text{Log}\left[\dfrac{\Delta \text{ PSI}}{4.5 - 1.5}\right]}{1 + \dfrac{1.624 * 10^{7}}{(\mathbf{H}_{\mathbf{pcc}} + 1)^{8.46}}} \right]$$

standard normal deviate

terminal serviceability; flexural strength; drainage coefficient

$$+ \left(4.22 - 0.32\, p_t\right) * \text{Log}\left[\frac{S'_c * C_d * \left[\mathbf{H}_{\mathbf{pcc}}^{0.75} - 1.132\right]}{215.63 * J * \left[\mathbf{H}_{\mathbf{pcc}}^{0.75} - \dfrac{18.42}{\left(E_c / k\right)^{0.25}}\right]} \right]$$

load transfer; modulus of elasticity; modulus of subgrade reaction

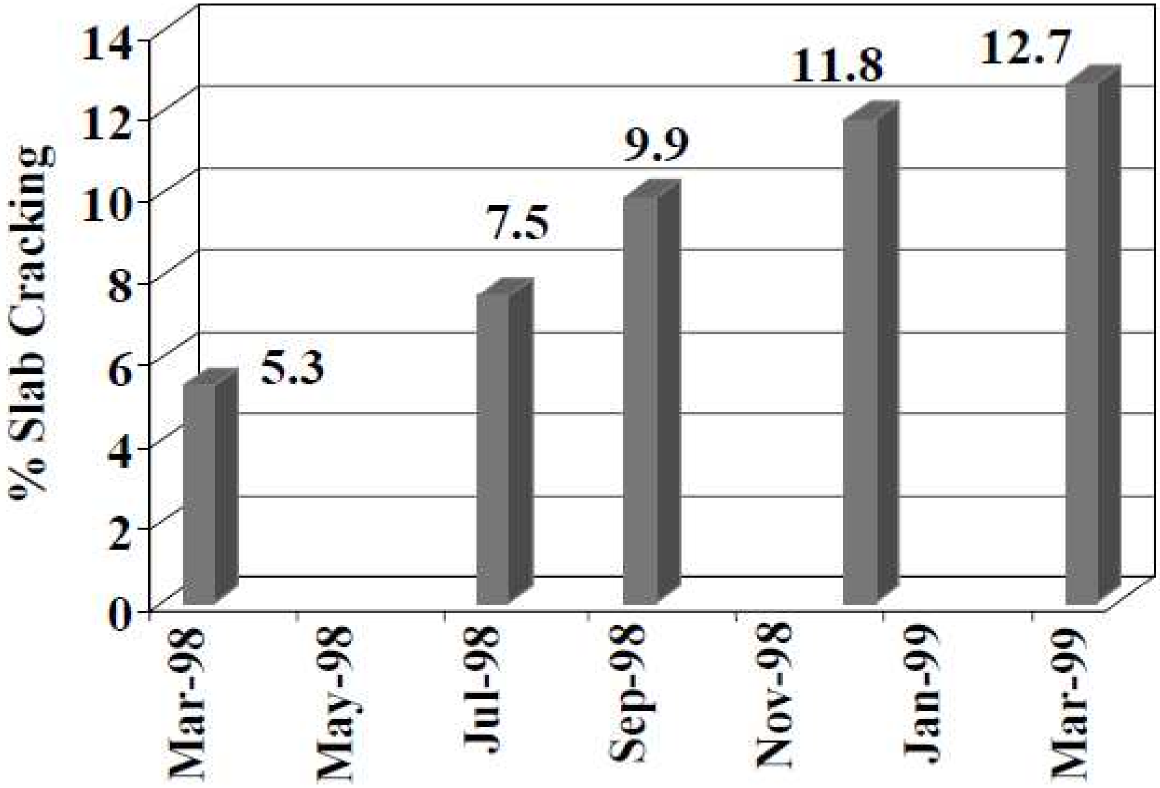
(AASHTO 1962, 1972, 1986, 1993).

I-80 Failure

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

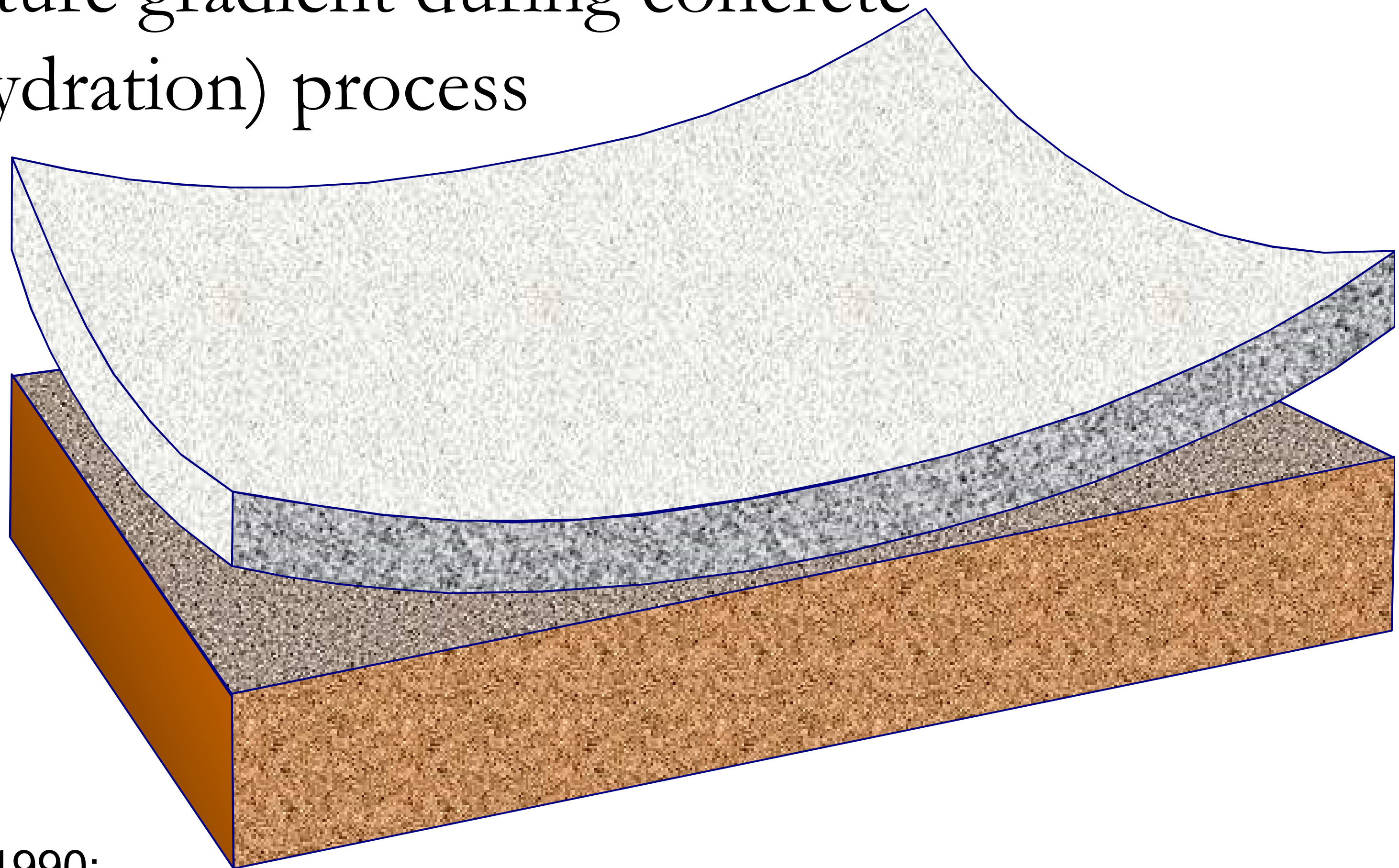
PCC thickness and strength of cores met the design requirements

I-80 Failure


% Slab Cracking
0
2
4
6
8
10
12
14
5.3
7.5
9.9
11.8
12.7
Mar-98
May-98
Jul-98
Sep-98
Nov-98
Jan-99
Mar-99

Permanent (Built-in) Curling

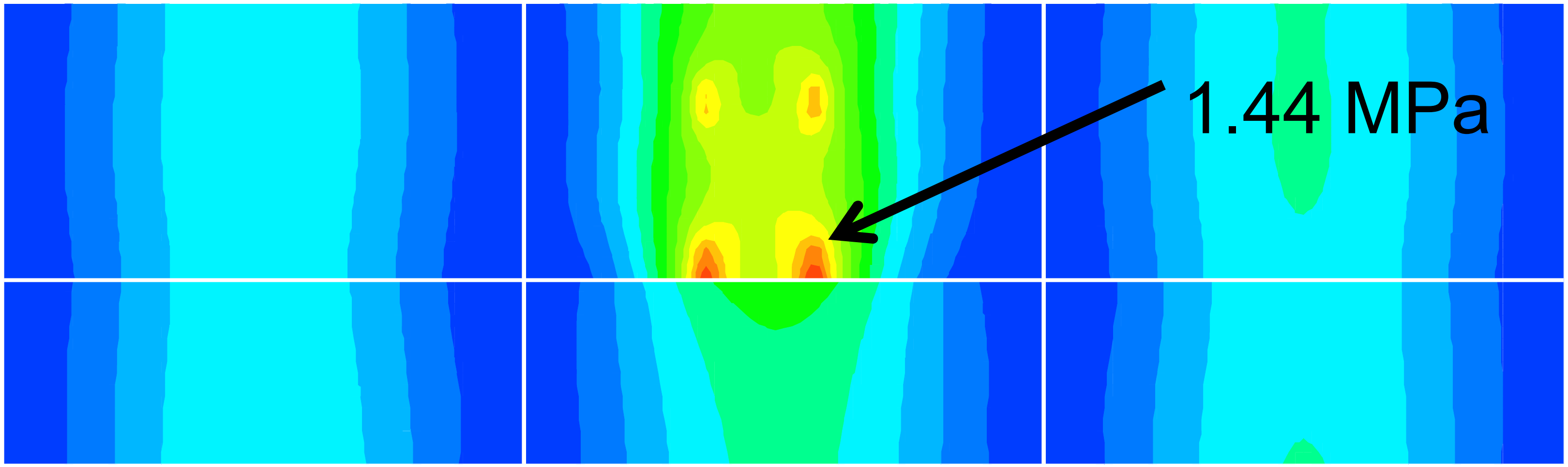
- Due to irreversible shrinkage
- Due to temperature gradient during concrete solidification (hydration) process



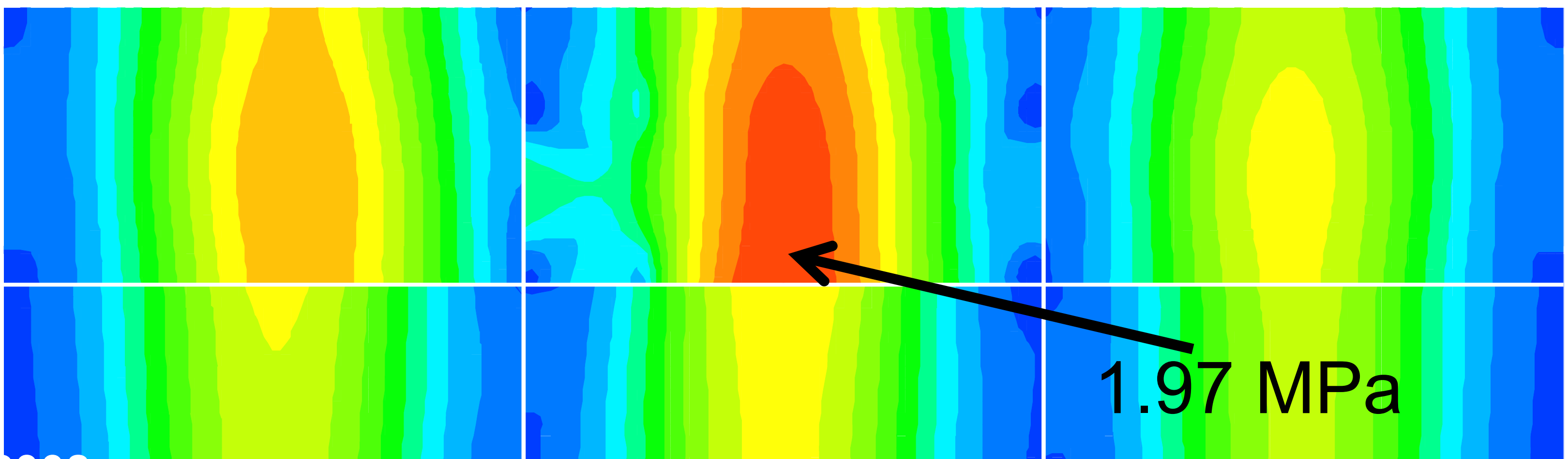
(Eisenmann and Leykauf, 1990;
Yu, Khazanovich, Darter, and Ardani 1998, Yu and Khazanovich 2001)

PCC Stresses

Day time, Ttop-Tbottom = 5 °C, **Bottom PCC Surface**



Night time, Ttop-Tbottom = -20 °C, **Top PCC Surface**

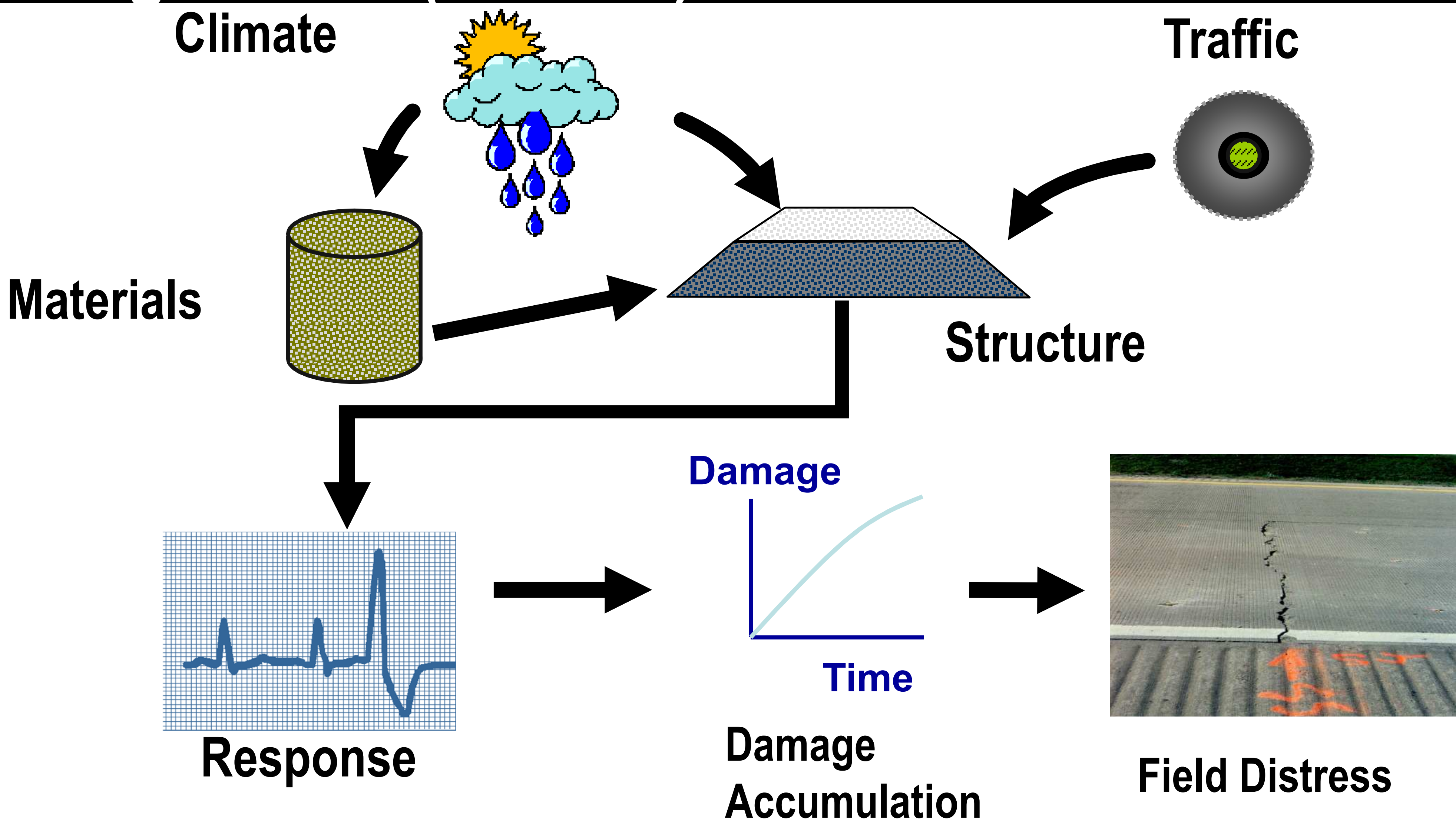


Lessons Learned from I-80 Failure

- 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)

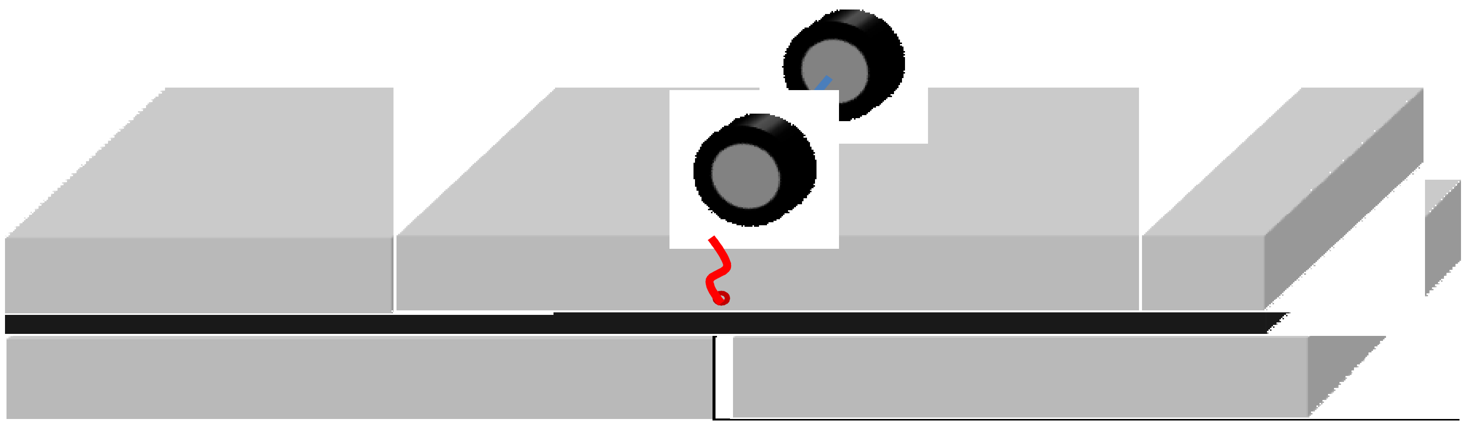


FUTURE

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

Pavement Rehabilitation

- Unbonded concrete overlays
- Conventional concern: reflective cracking



Rehabilitation

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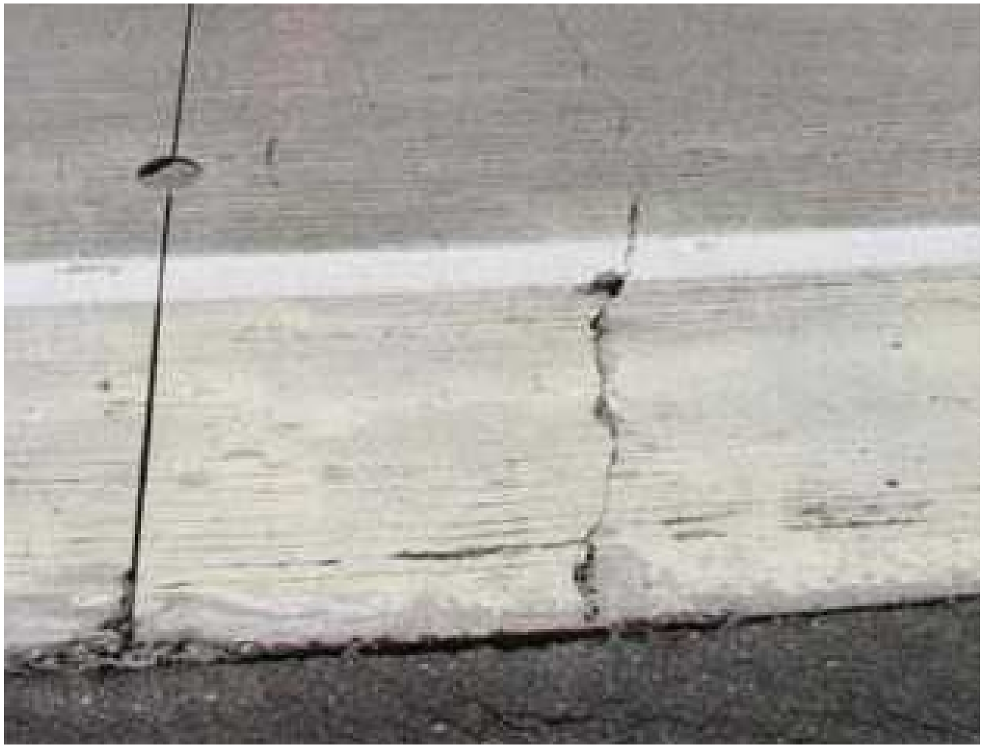
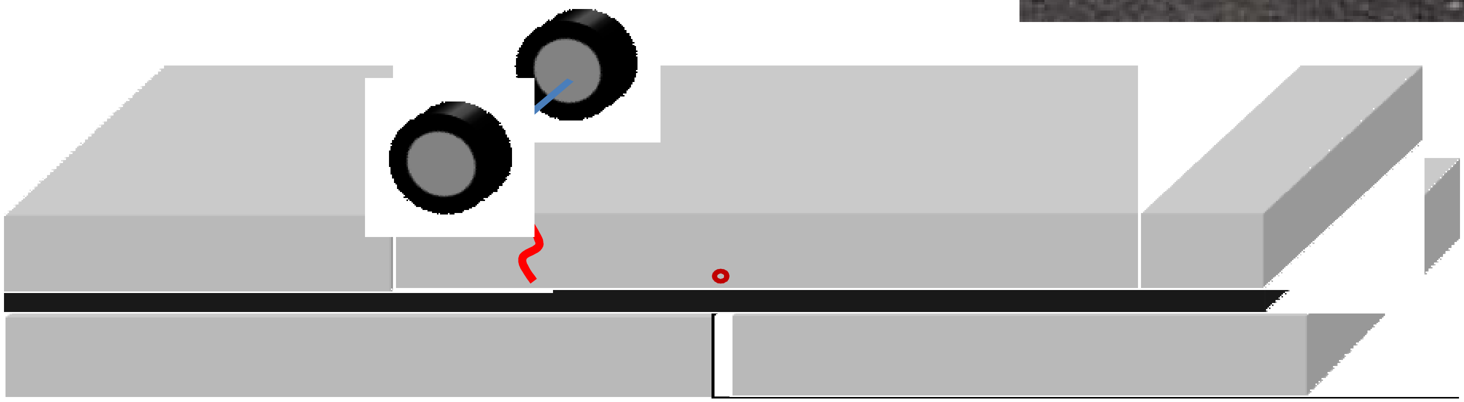
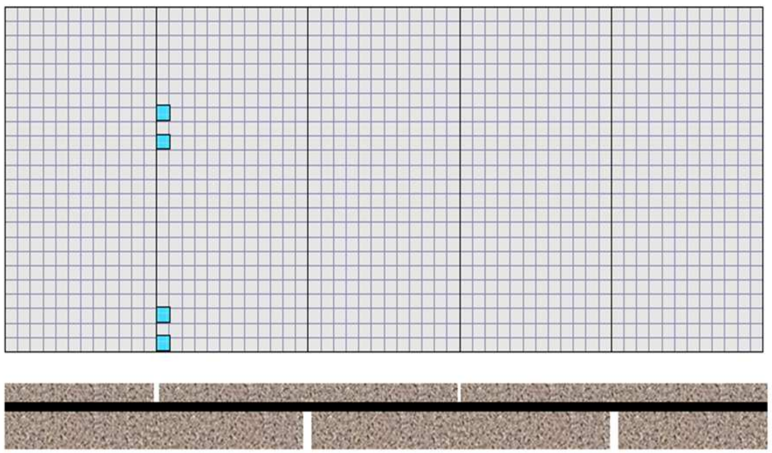
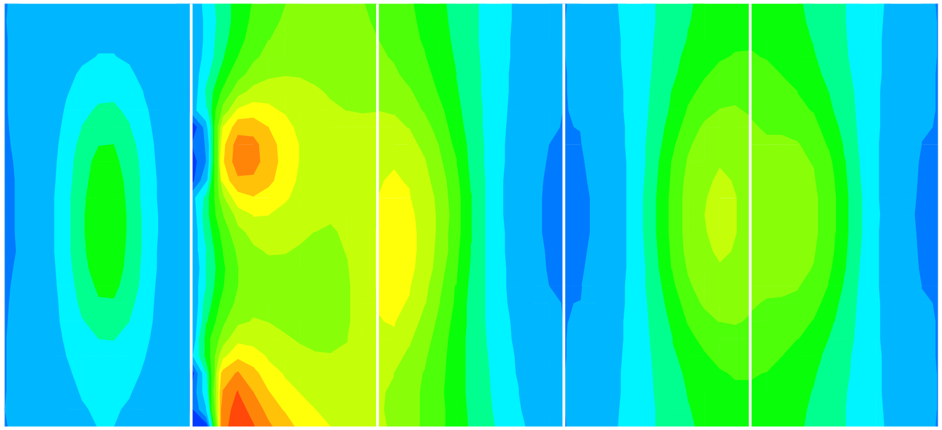
- Overlay failed in 2 years
- No reflective cracking was observed
- Forensics indicated that cracking was top-down





- Plausible explanation of failure: excessive overlay built-in curl caused voids under overlay joints



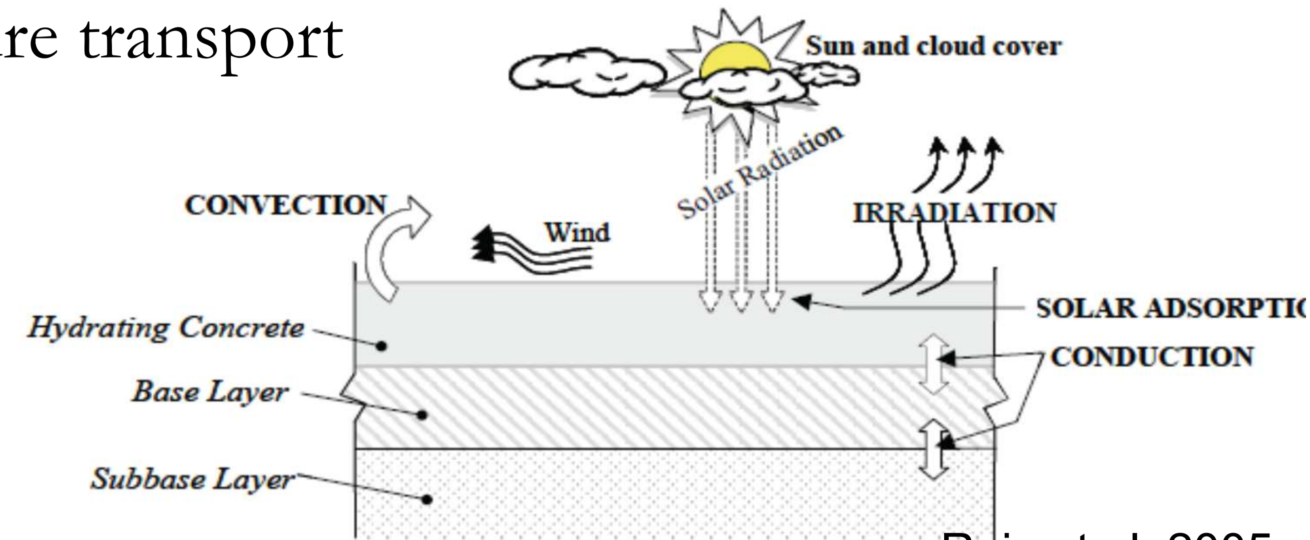


- Built-in curling changes mode of failure
- Built-in curling characterization is as important as concrete fracture property characterization

Early Age Deformations

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)



Ruiz et al. 2005

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

Final Remark

- 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