Optimizing Concrete Pavement Design

Robert Rodden, PE

CONCRETE PAVEMENT

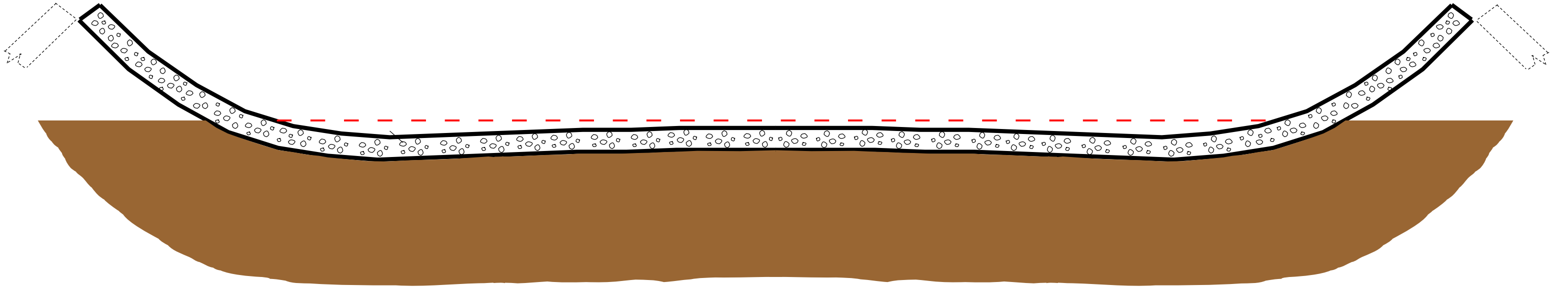
…VS…

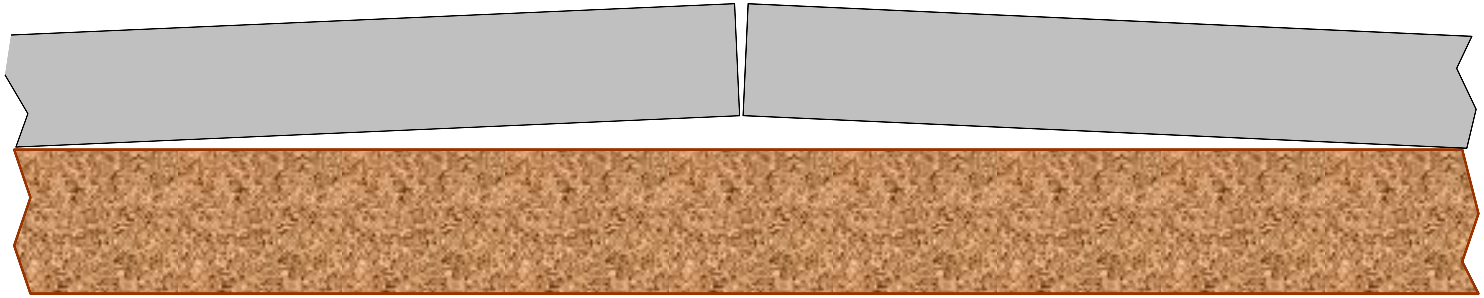
- Roads
  - Pneumatic tires
  - Channelized traffic
  - Design for fatigue
    - Cracking
      - Top-down
      - Bottom-up
      - Corner
    - Faulting
    - Roughness
  - Concrete slabs… outside

- Runways
  - Pneumatic tires
  - Relatively channelized traffic
  - Design for fatigue
    - Cracking
      - Bottom-up in FAARFIELD
        - » Low LTE assumed
        - » High k-values common
    - Faulting?
    - Roughness?
  - Concrete slabs…outside

"ALL SLABS [AND PAVEMENTS] CURL"

JERRY HOLLAND, STRUCTURAL SERVICES INC.

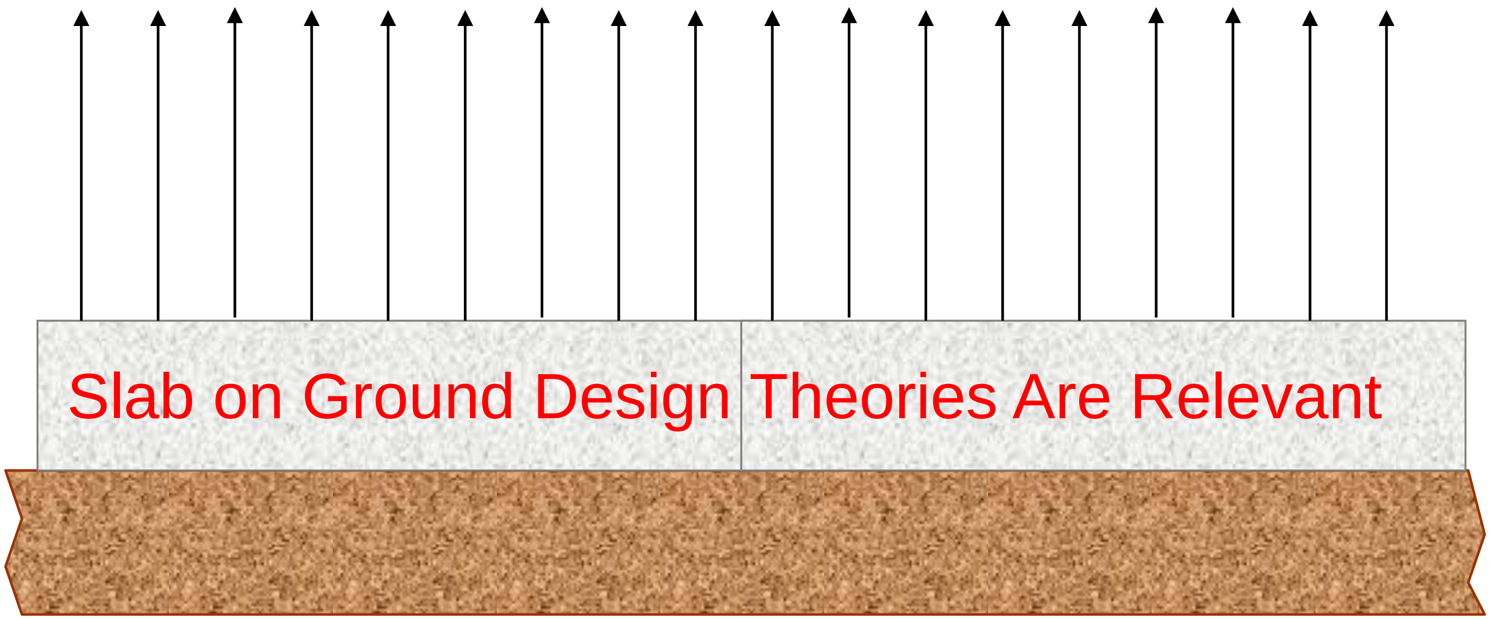




CONCRETE SLAB DESIGN (PCA, WRI, COE)

- Curling / Warping

Evaporation of Water



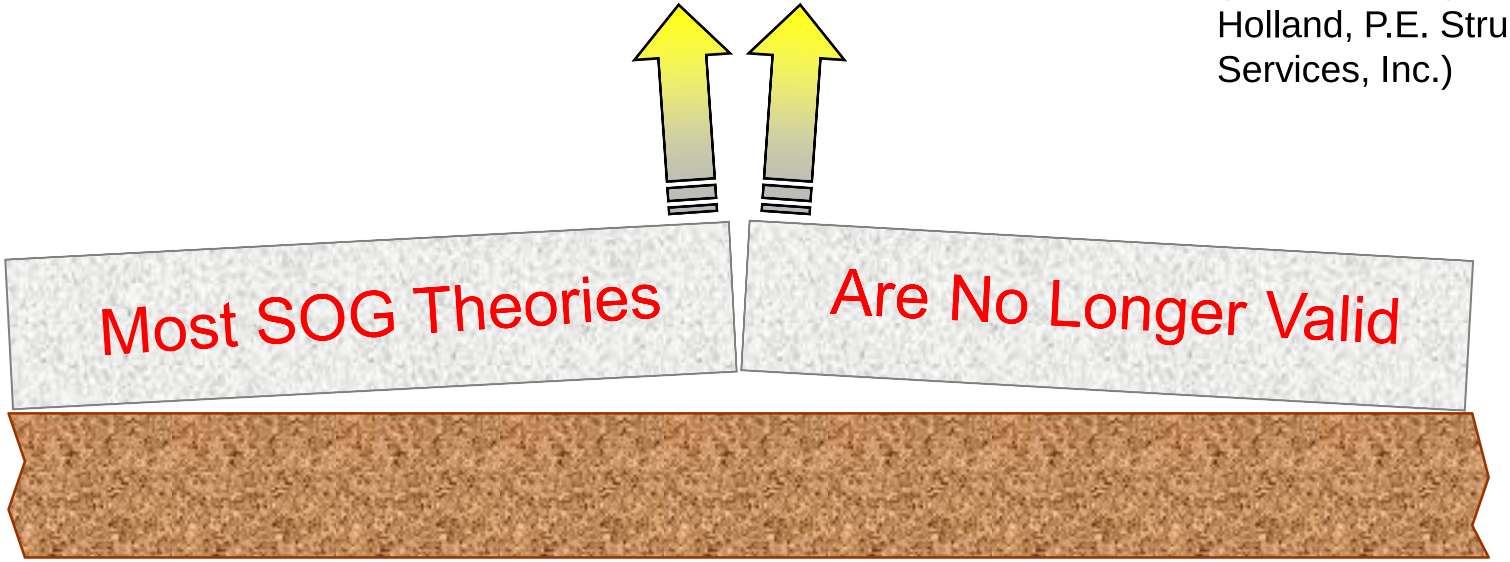
Newly Placed Concrete

(Slide courtesy of Jerry Holland, P.E. Structural Services, Inc.)

CONCRETE SLAB DESIGN (PCA, WRI, COE)

- Curling / Warping

(Slide courtesy of Jerry Holland, P.E. Structural Services, Inc.)



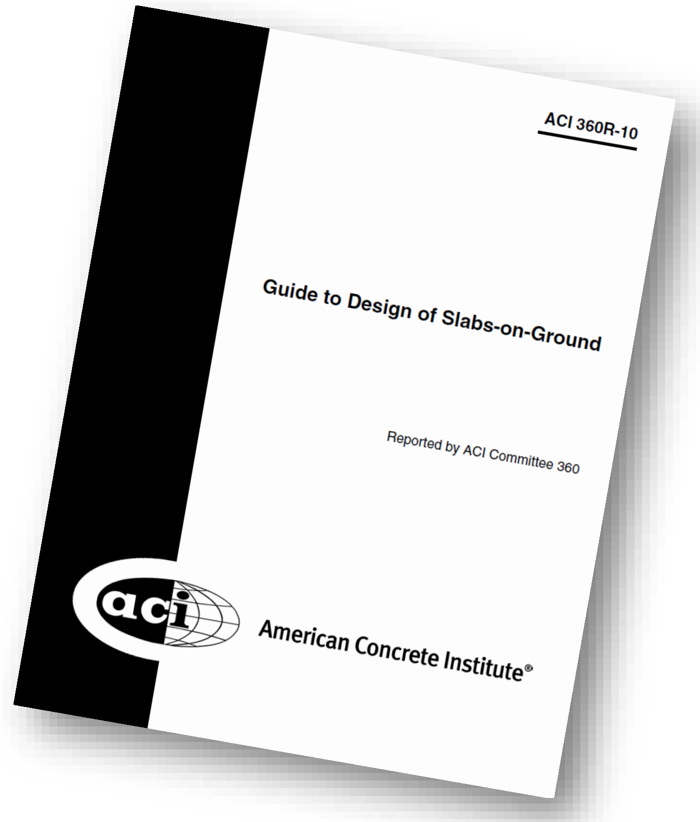
During and After Drying

ACI 360R-10: “GUIDE TO DESIGN SLABS-ON-GROUND”

“Generally accepted thickness design methods for unreinforced slabs-on-ground are:

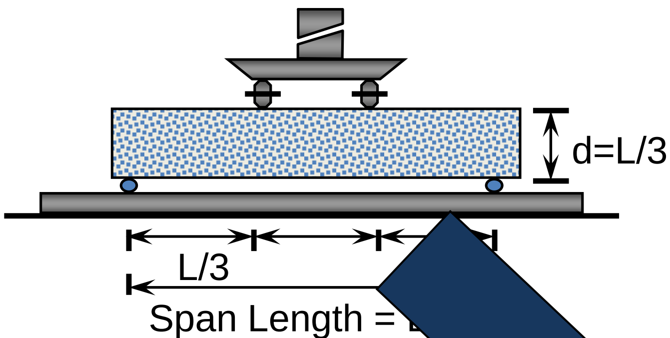
- PCA method
- WRI method
- COE method

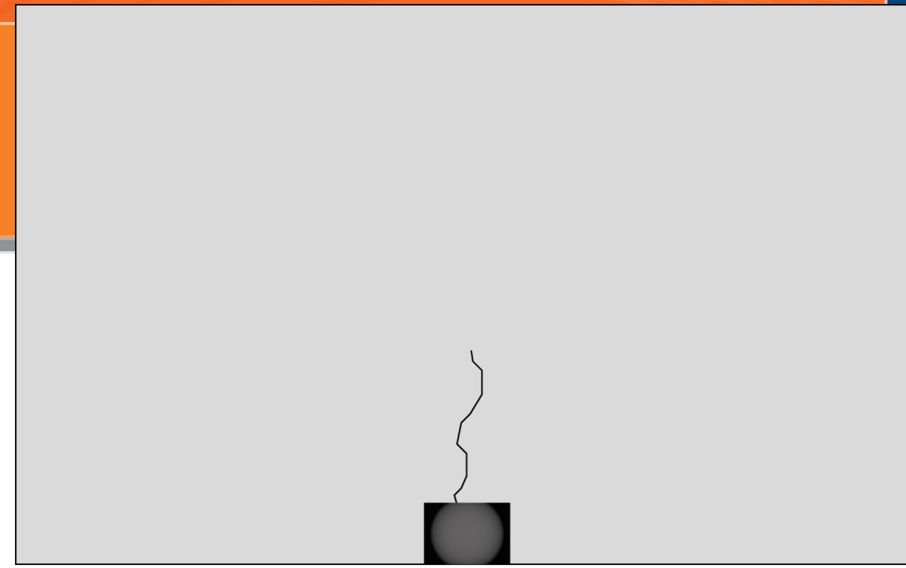
Each of these methods, described in Chapter 1, seek to avoid live load-induced cracks through the provision of adequate slab cross section by using an adequate factor of safety against rupture”.

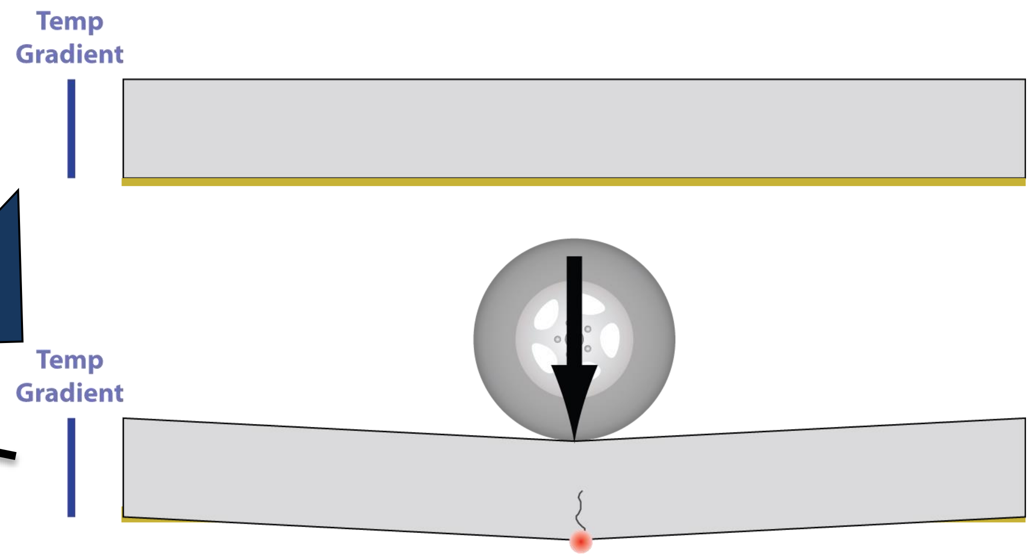


- Same document addresses curl/warp, load transfer importance, etc. for slabs-on-ground
  - Yes, curl/warp is even important on INTERIOR slab-on-ground in controlled environmental conditions

CRACKING MODES IN JPCP: BOTTOM-UP

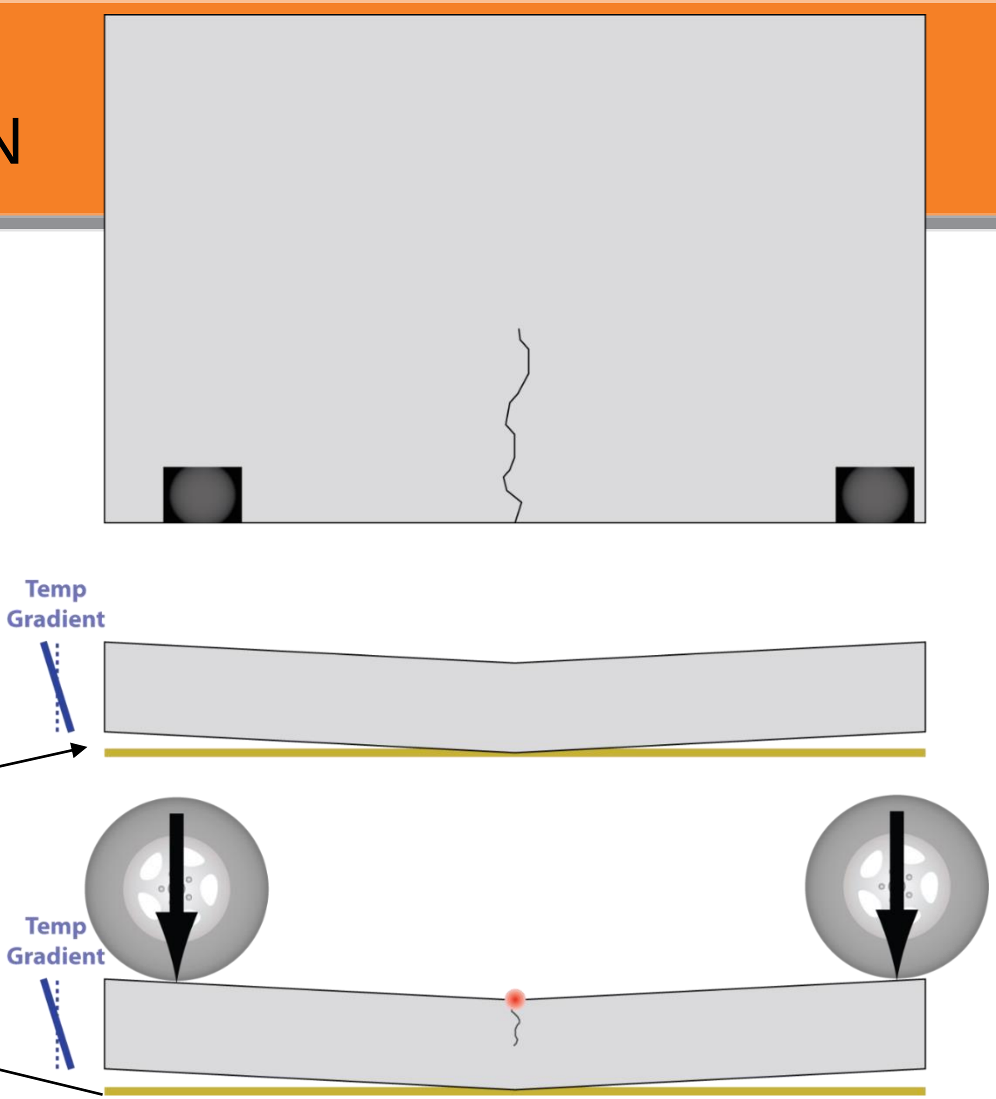






To combat, thinking is to make support stronger or slab thicker to resist deflection.

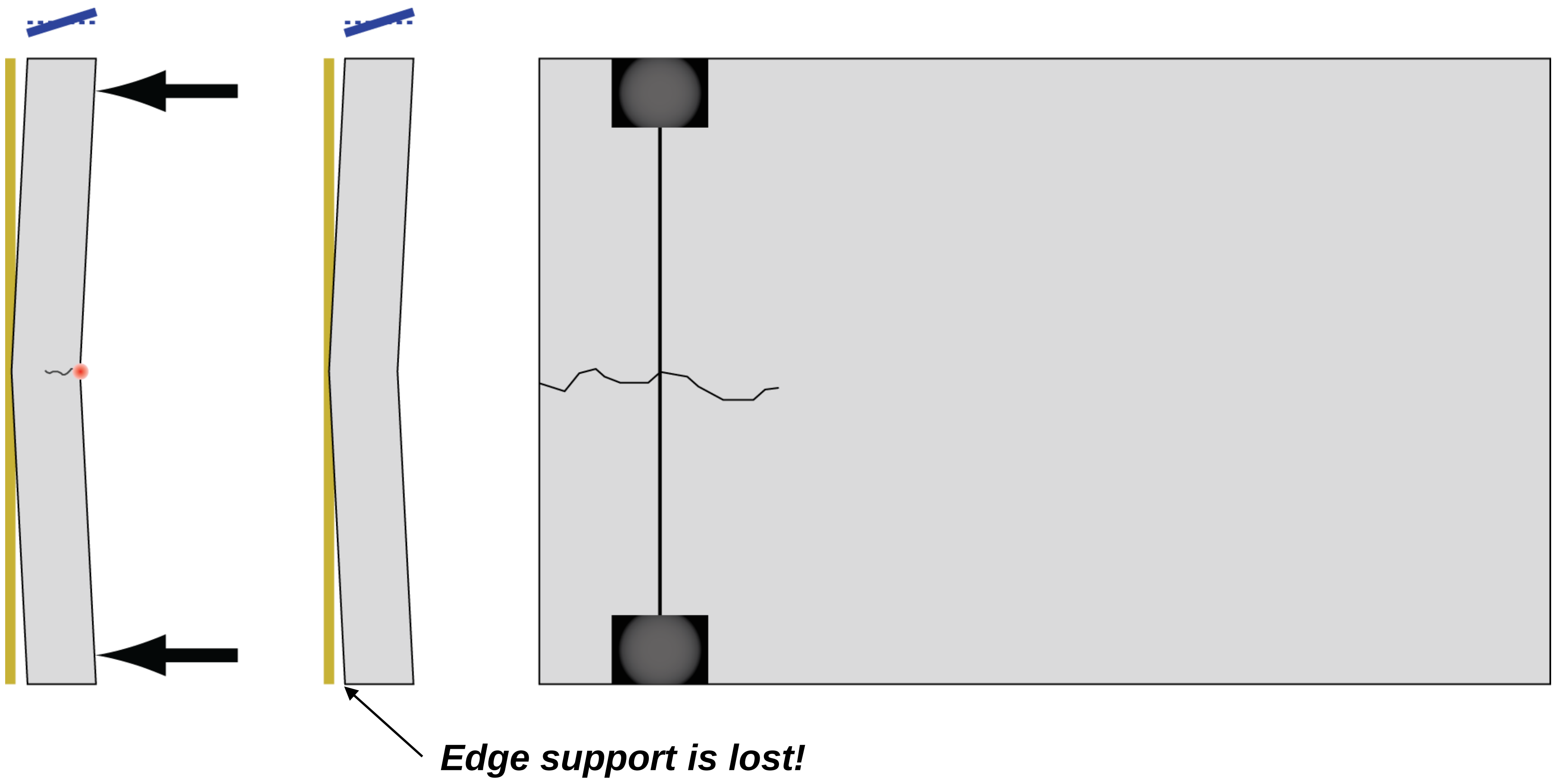
CRACKING MODES IN JPCP: TOP-DOWN



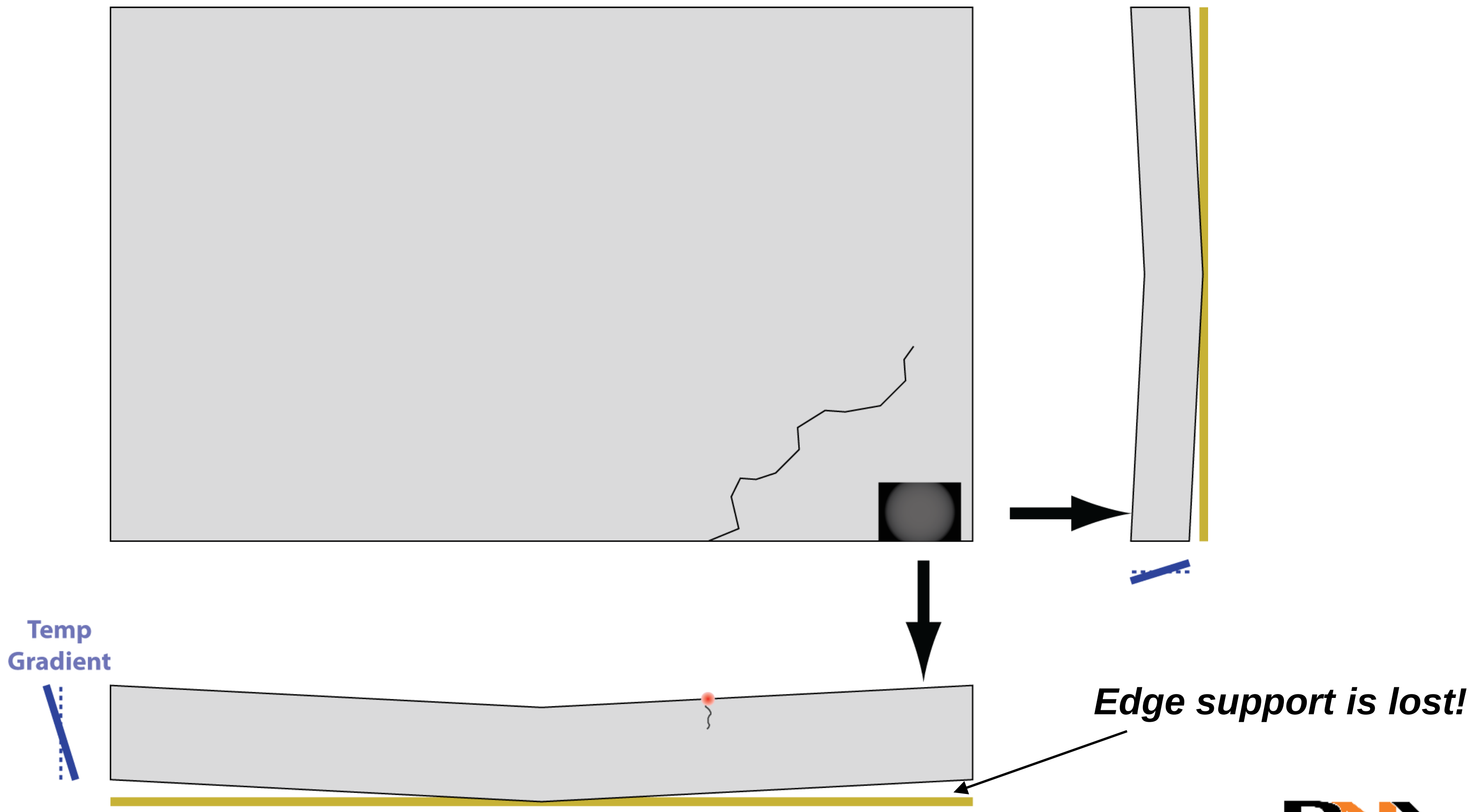
Edge support is lost!

Increasing support stiffness only worsens this!
Make slabs even thicker!

CRACKING MODES IN JPCP:
TOP-DOWN LONGITUDINAL

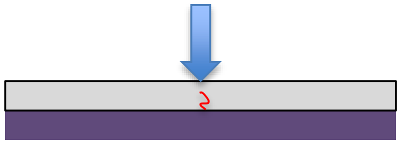


CRACKING MODES IN JPCP: CORNER



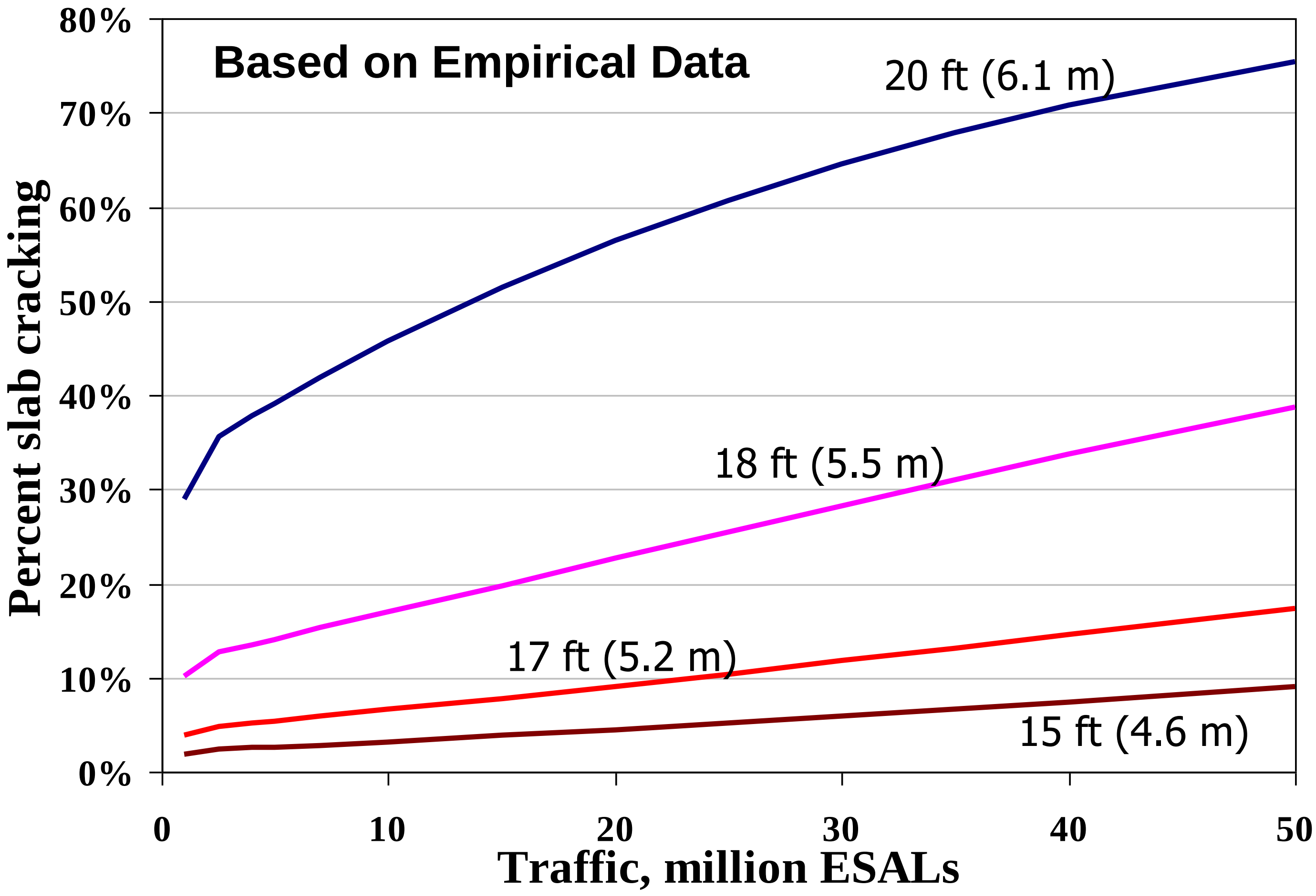
FOR ROADWAY PAVEMENTS, PRIOR TO MODERN MODELS, WE “SIMPLIFIED”…

Prevent bottom-up cracking with slab thickness:



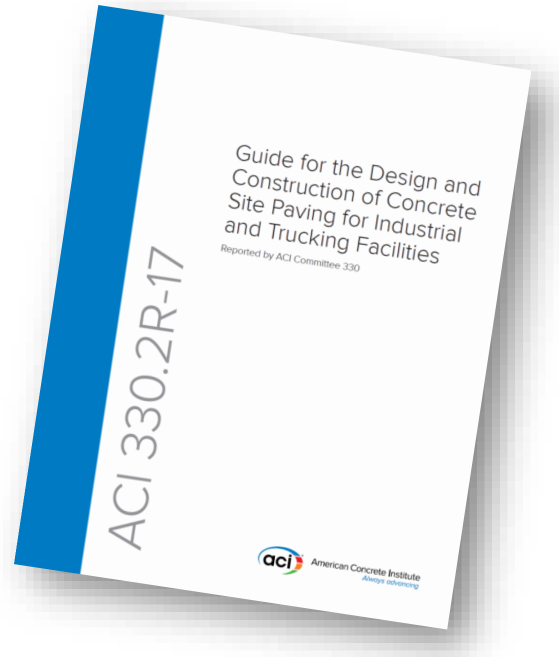
… size slabs per field performance data to reduce risk of “environmental” cracking

This is an incomplete and risky approach! Ignores top-down!



WE’VE LEARNED A LOT IN THE LAST 50 YEARS!

- “Ambient effects on pavement during construction and throughout its design life have a significant effect on the magnitude of warping and curling in the pavement panels and, therefore, the stresses in the concrete under load.”
- “After the estimation of traffic levels, the most influential factors in the design of concrete pavements are thickness; joint spacing, which also affects the magnitude of warping and curling; and joint detailing. Compared to concrete material strength and subgrade/subbase support, the pavement thickness, joint spacing, and joint detailing have a far greater impact on the load-carrying capability of the pavement.”



ACI 330.2R-17, *Guide to the Design and Construction of Concrete Site Paving for Industrial and Trucking Facilities*

DR. MICHAEL DARTER, PE

Emeritus Professor of Civil and Environmental Engineering
University of Illinois at Urbana Champaign

Principle Engineer
Applied Research Associates, Inc.

Honorary Life Member
International Society for Concrete Pavements

SPEAKING OF ONE MODERN DESIGN METHOD…

“This design can beat asphalt pavement by 20 percent first cost! No cracking or faulting has occurred on these designs.”

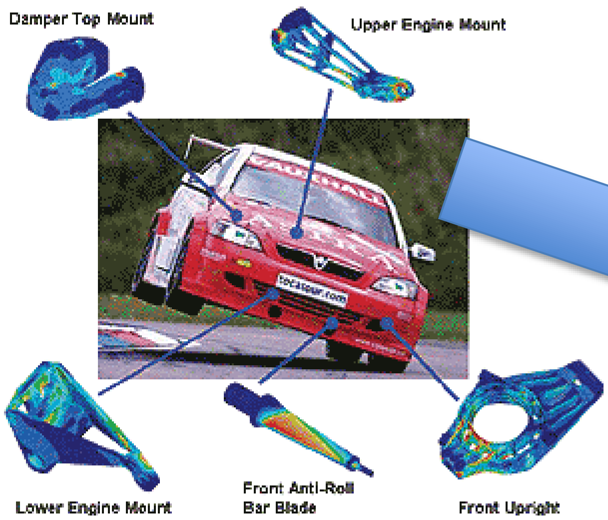
- Dr. Mike Darter PE

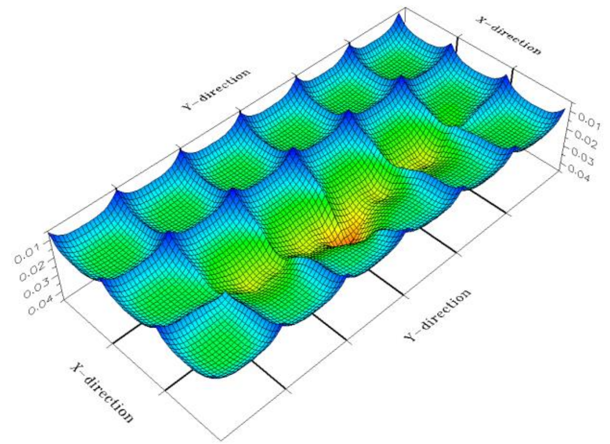
“Observations of Short Slab Concrete Pavements designed with *OptiPave*™ in Chile,” Dr. Michael Darter, April 2013

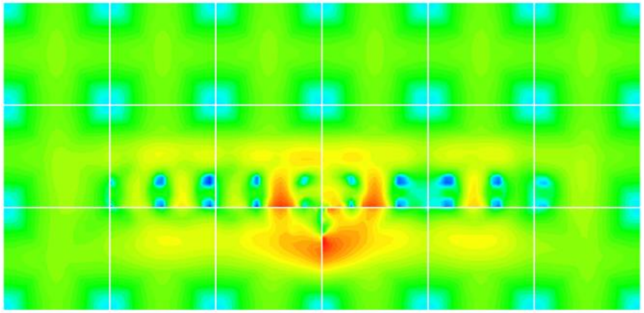
VEHICLE TECHNOLOGIES HAVE ADVANCED

PNA CONSTRUCTION TECHNOLOGIES

LIKE OTHER ENGINEERING DISCIPLINES, PAVEMENTS LEVERAGE FINITE ELEMENT ANALYSES (FEA)







MANY ENGINEERS USE ONLY AASHTO 93, WHICH PRODUCES OUTDATED AND UNOPTIMIZED DESIGNS

- The Professional Engineer’s (PE) exam by NCEES references these in its transportation design standards:
  - AASHTO *Guide for Design of Pavement Structures* (GDPS-4-M), 1993, and 1998 supplement, American Association of State Highway & Transportation Officials, Washington, DC.
    - Based on accelerated testing in one location from 1958-1960
    - Concrete design equations effectively unchanged since 1962
  - AASHTO *Mechanistic-Empirical Pavement Design Guide: A Manual of Practice,* interim edition, July 2008, American Association of State Highway & Transportation Officials, Washington, DC.
    - Based on decades of performance of >2,500 sections by DOTs across N.A.
    - Tens of millions of $’s invested in this continuously improved framework
    - Included as a PE ref in the last two years; 99.9% of PEs don’t know about it!

NCEES advancing licensure for engineers and surveyors

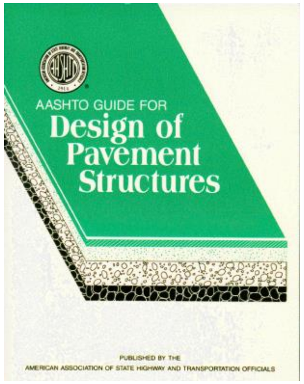
AASHTO THE VOICE OF TRANSPORTATION

PNA CONSTRUCTION TECHNOLOGIES

CONCRETE PAVEMENT DESIGN STANDARDS

Outdated

Modern Mechanistic-Empirical Designs



THE 40 YEAR DIVIDE

OptiPave 2
TCPavements

AASHTOWare Pavement

AASHTO 93
1962-1998
10 inputs
"Performance"
Field Data

StreetPave
2005-2016
12 inputs
Crack & Fault
FEA + Field Data

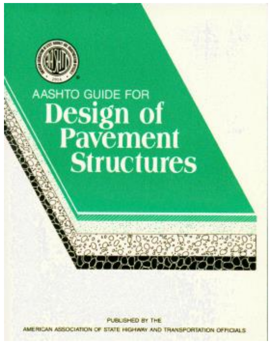
OptiPave
2009-2016
≈ 50 inputs
Crack, Fault, IRI
FEA + Field Data

Pavement ME
2009-2016
≈ 1,000 inputs
Crack, Fault, IRI
FEA + Field Data

Increasing Complexity = More Accurate Models & More *Optimization* Options

PNA CONSTRUCTION TECHNOLOGIES

MODERN DESIGNS PREDICT WHAT MATTERS…



OptiPave 2
TCPavements®

AASHTOWare Pavement

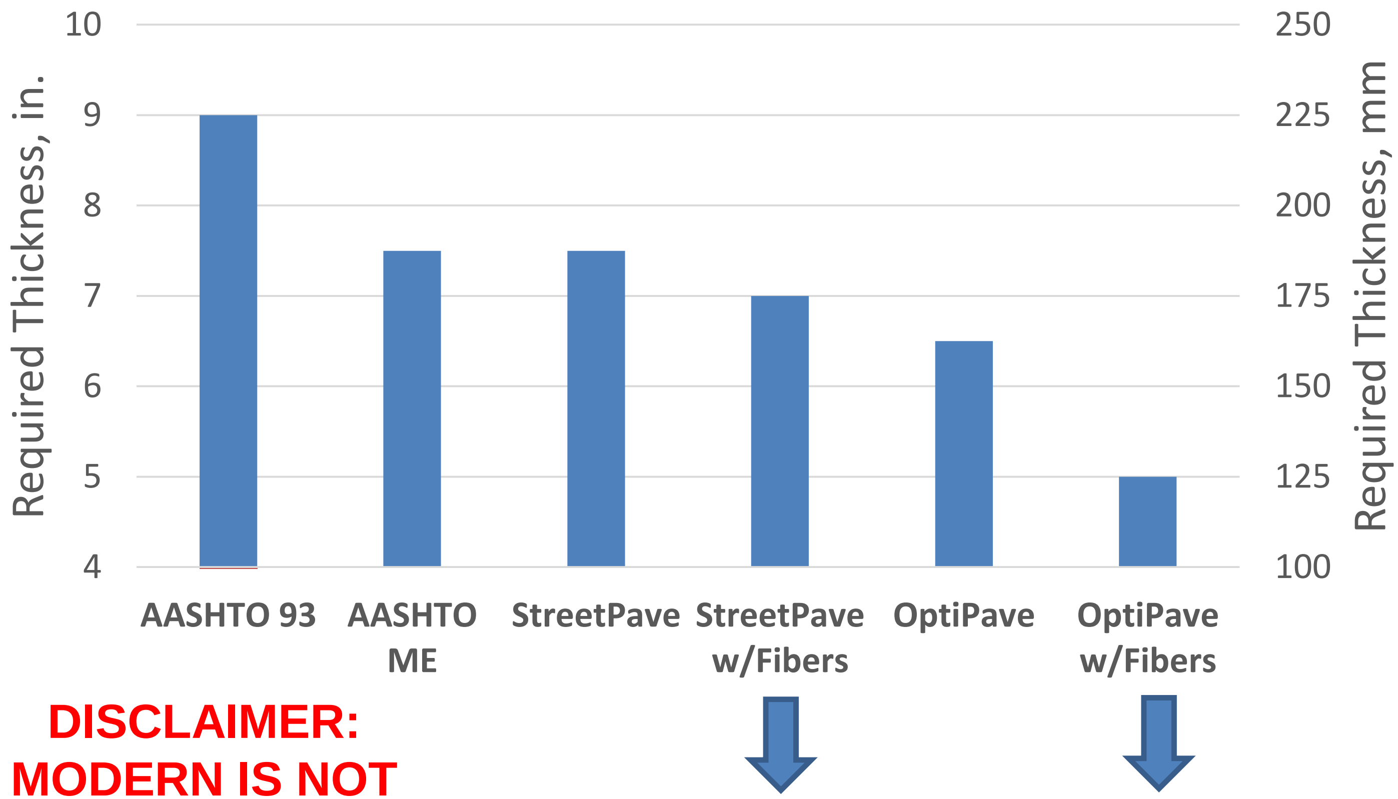
Design Method	Cracking	Faulting	IRI	Other	Curl?
AASHTO 1962-1993				X	
ACPA StreetPave	BU	X			
TCPavements OptiPave	BU, TD, C	X	X		X
AASHTOWare Pavement ME	BU, TD, C	X	X		X

Cracking Modes: BU = bottom-up | TD = top-down | C = corner

PNA CONSTRUCTION TECHNOLOGIES

MODERN DESIGNS ALLOW FOCUS ON VALUE-ADDING DESIGN OPTIMIZATION VIA VARIABLES LIKE FIBERS

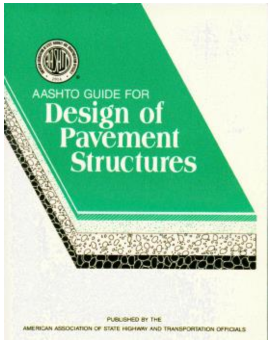
500 trucks/day, freeze-thaw climate, dowels, low support, and same inputs:



DISCLAIMER: MODERN IS NOT ALWAYS THINNER

Macrosynthetic or Steel Fibers

….AND LET YOU OPTIMIZE WHAT'S MOST IMPACTFUL

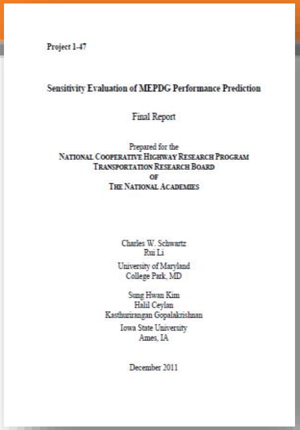


OptiPave 2 TCPavements

AASHTOWare Pavement

Design Method	Concrete Material Properties					Joint Spacing	Edge Support
	Strength & Modulus	Unit Weight	CTE	SSA	Fiber		
AASHTO 1962-1993	X						/
ACPA StreetPave	X				X		X
TCPavements OptiPave	X	X	X		X	X	X
AASHTOWare Pavement ME	X	X	X	X	/	X	X

PAVEMENT ME TOP 10 MOST-SENSITIVE INPUTS


Project 1-47

Sensitivity Evaluation of MEPDG Performance Prediction

Final Report

Prepared for the
NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
TRANSPORTATION RESEARCH BOARD
OF
THE NATIONAL ACADEMIES

Charles W. Schwartz
Rui Li
University of Maryland
College Park, MD

Sung Hwan Kim
Halil Ceylan
Kasthurirangan Gopalakrishnan
Iowa State University
Ames, IA

December 2011

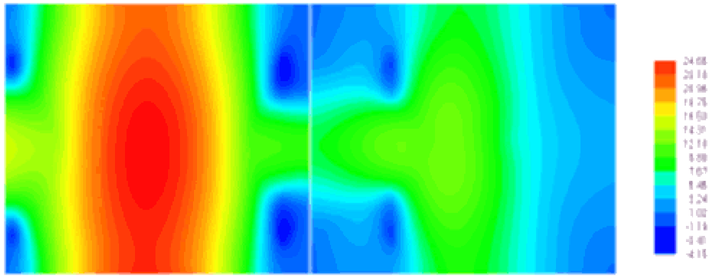
1. Concrete Flexural Strength at 28-Days
2. Concrete Thickness
3. Surface Shortwave Absorptivity (SSA)
4. **Joint Spacing – Limit is 10 ft (3 m)**
5. Concrete Modulus of Elasticity at 28-Days
6. Design Lane Width with a 14 ft (4.3 m) Widened Slab
7. Edge Support via Widened Slab
8. Concrete Thermal Conductivity
9. Concrete Coefficient of Thermal Expansion (CTE)
10. Concrete Unit Weight

… optimization options to reduce $$$$

… these are just the top 10 of LOTS

MATCHING STRESSES IN OPTIPAVE™ VS. PAVEMENT ME

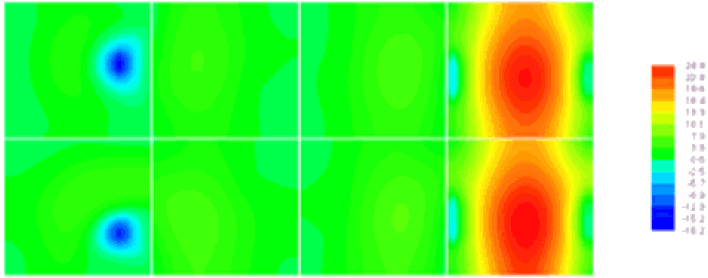
Slab Size = 12’ x 15’
(3.7 m x 4.6 m)



Pavement ME Design

Max Top Stress = 363 psi (2.5 MPa)
Thickness = 10” (250 mm)

Slab Size = 6’ x 6’
(1.8 m x 1.8 m)

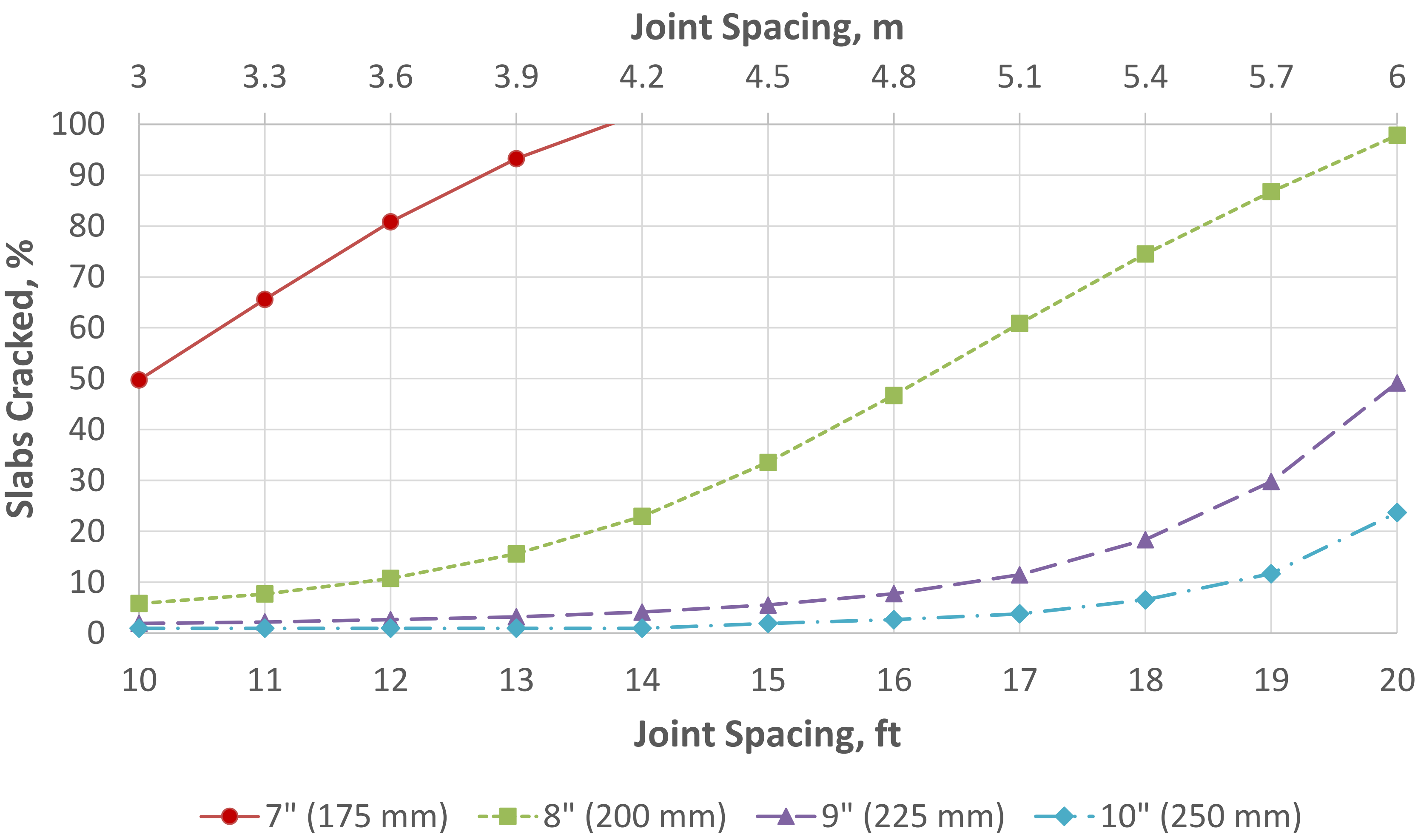


OptiPave™ Design

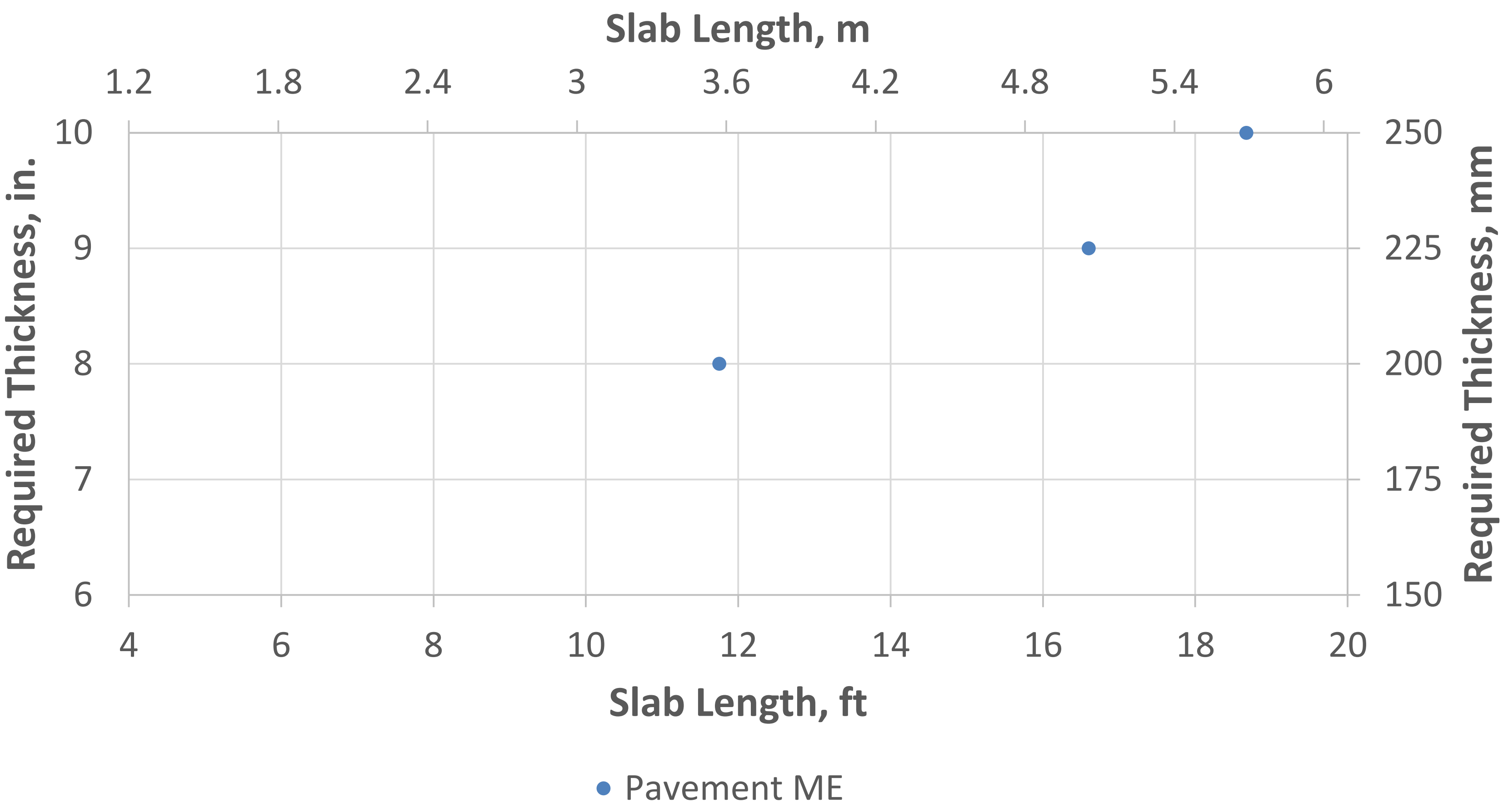
Max Top Stress = 363 psi (2.5 MPa)
Thickness = 6.3” (160 mm)

OptiPave was developed by Juan Pablo Covarrubias V. using MEPDG methods and models and in collaboration with Drs. Lev Khazanovich, Jeff Roesler, and Dan Zollinger

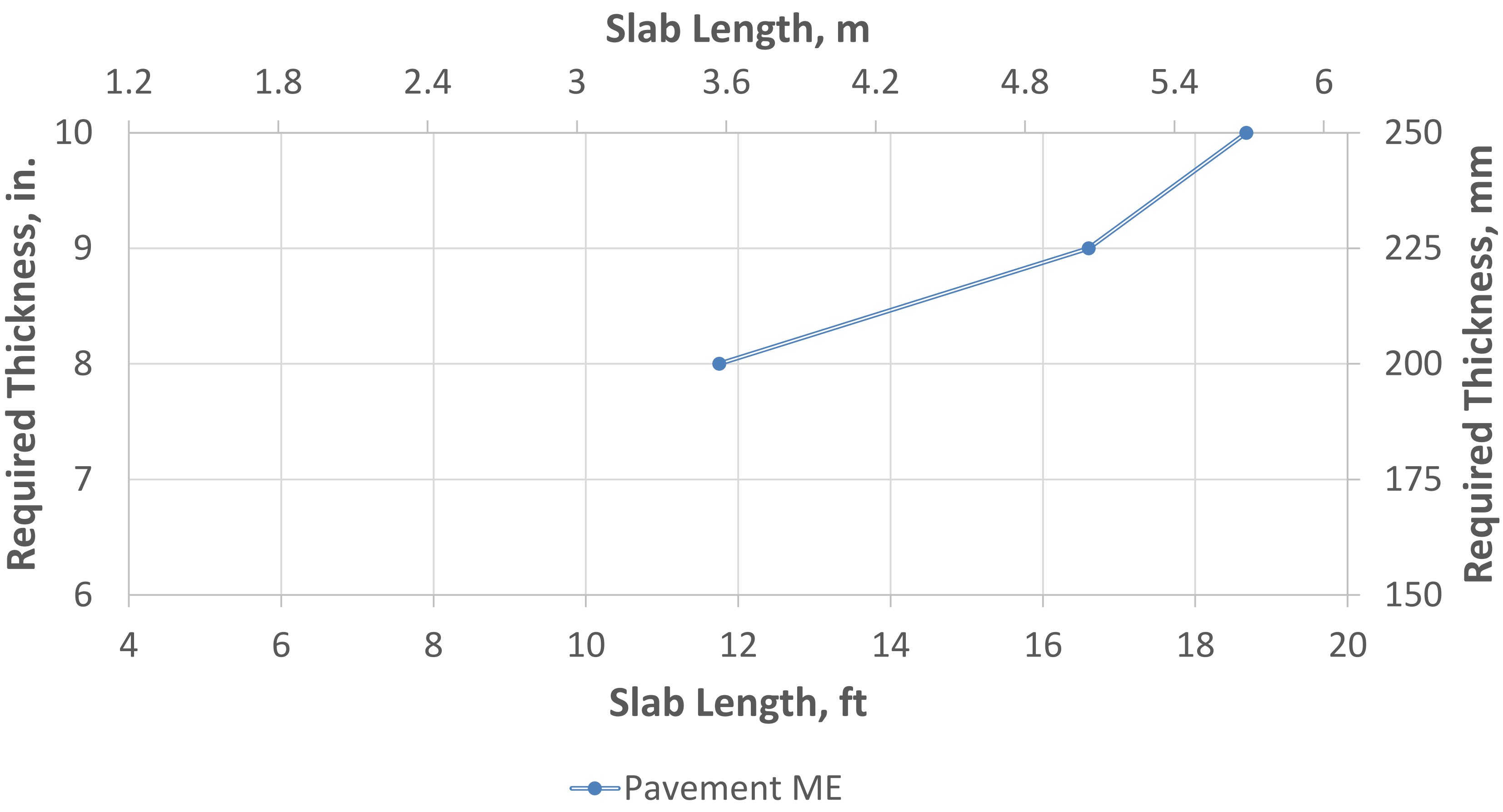
PAVEMENT ME PROVES THE INTERDEPENDENCY OF THICKNESS AND JOINT SPACING…



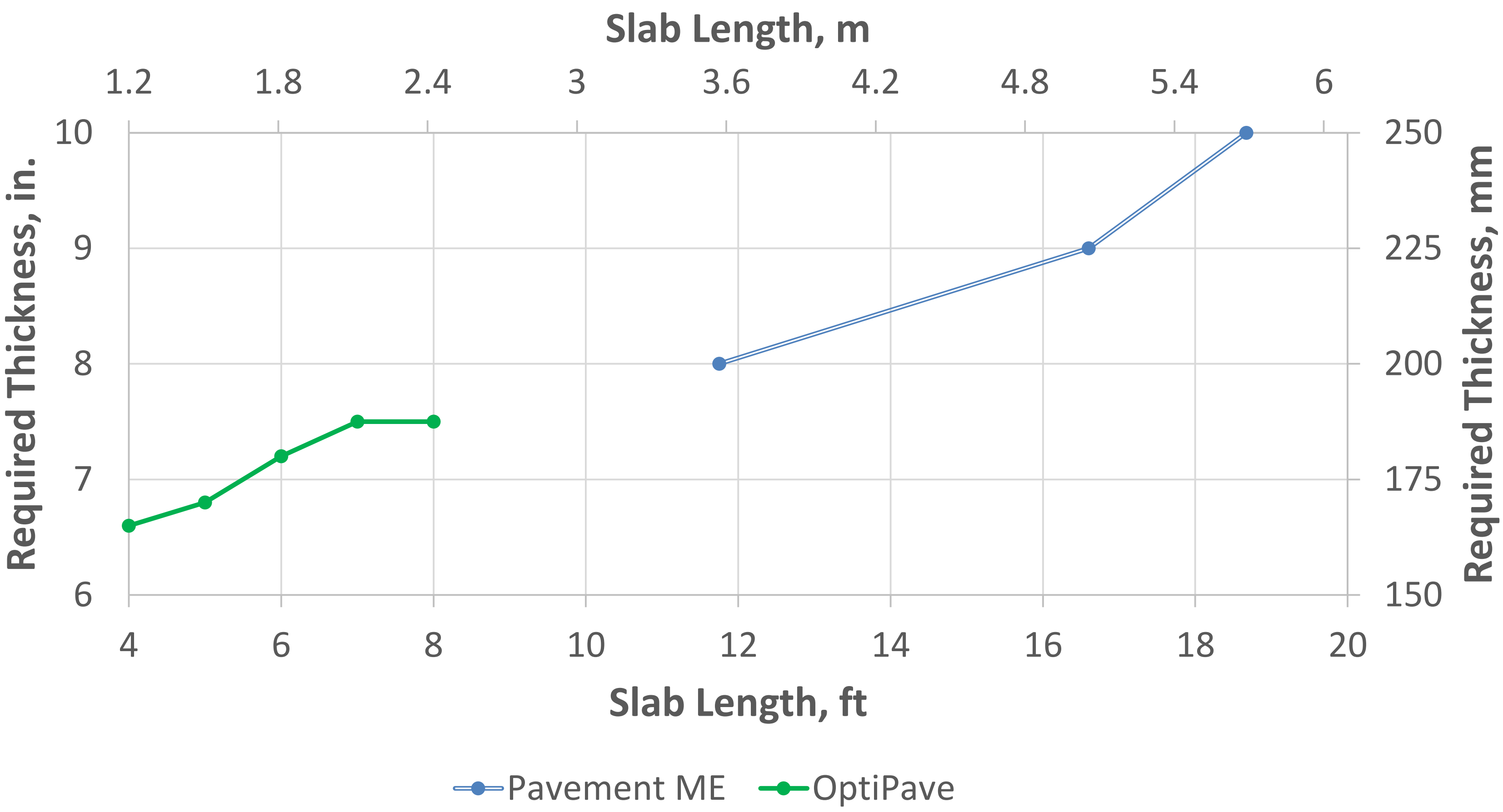
DATA @ 10% SLABS CRACKED REPLOTTED



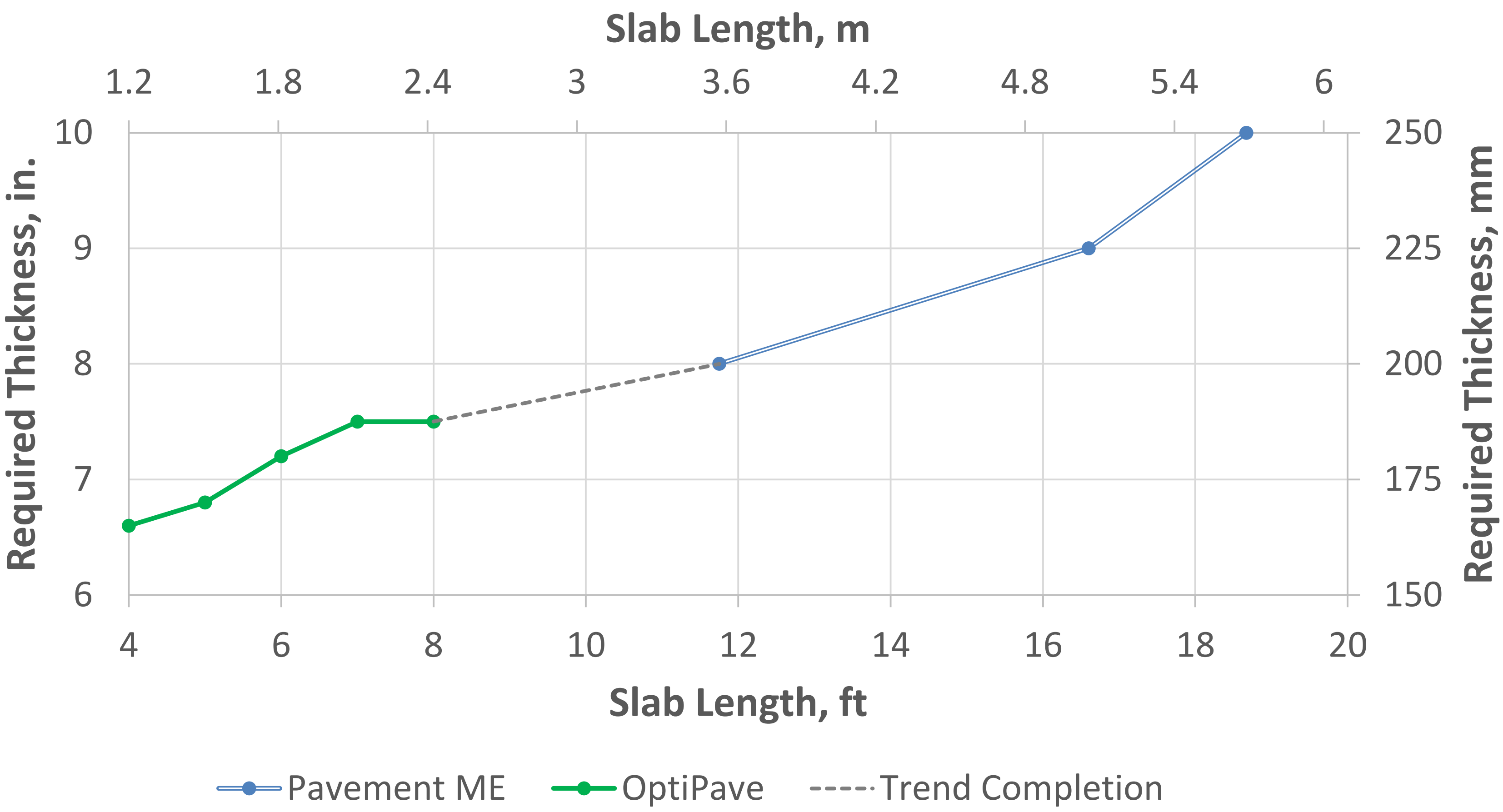
…A CLEAR TREND EXISTS…



…SAME INPUTS FOR OPTIPAVE…

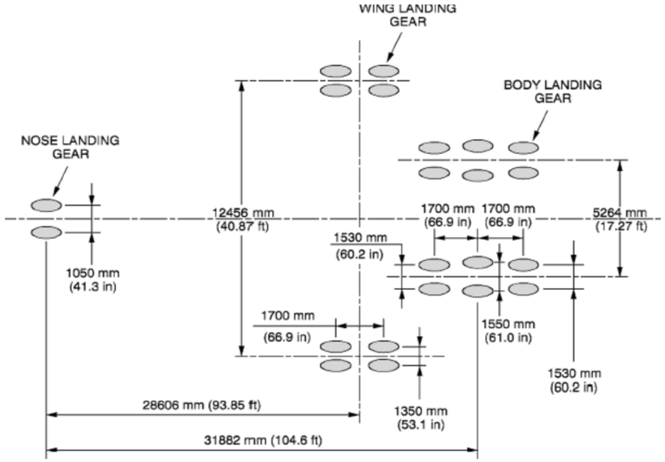


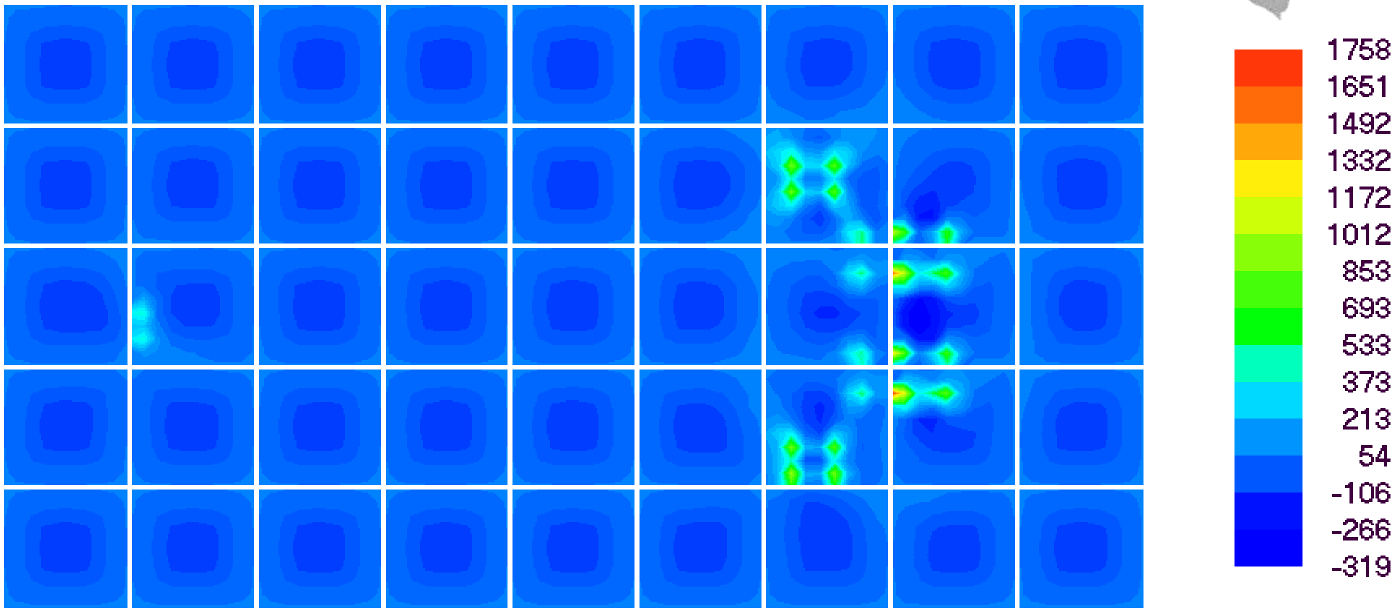
… AND WE GET A COMPLETE VIEW OF THE SENSITIVITY OF JOINT SPACING ON SLAB THICKNESS



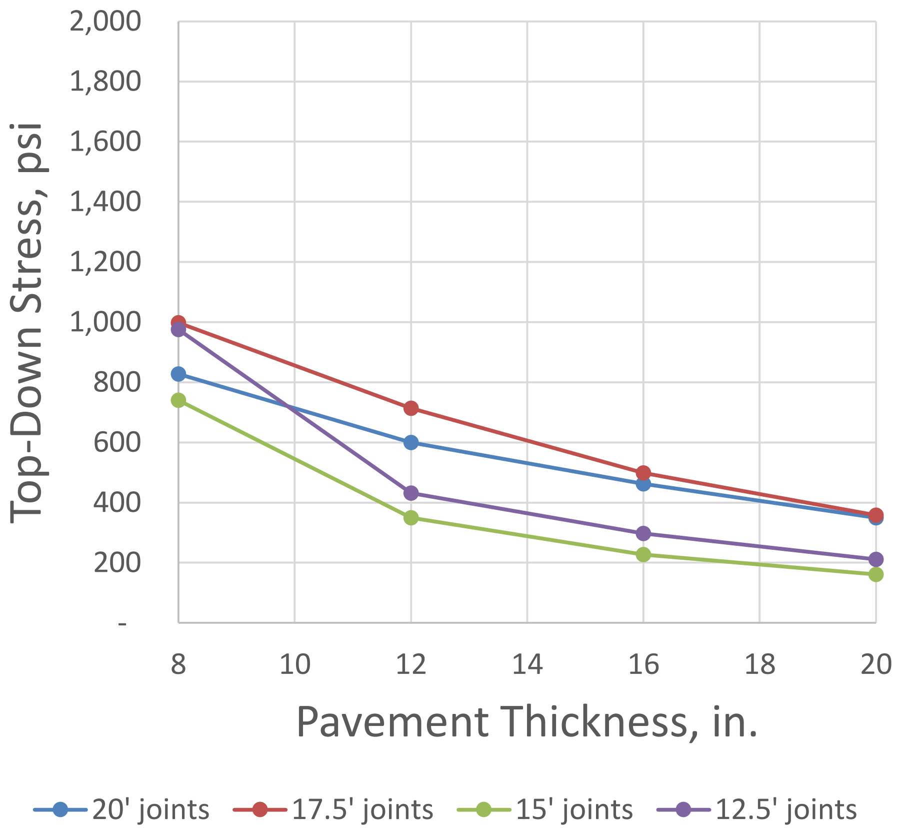
WHAT ABOUT AN AIRPLANE?

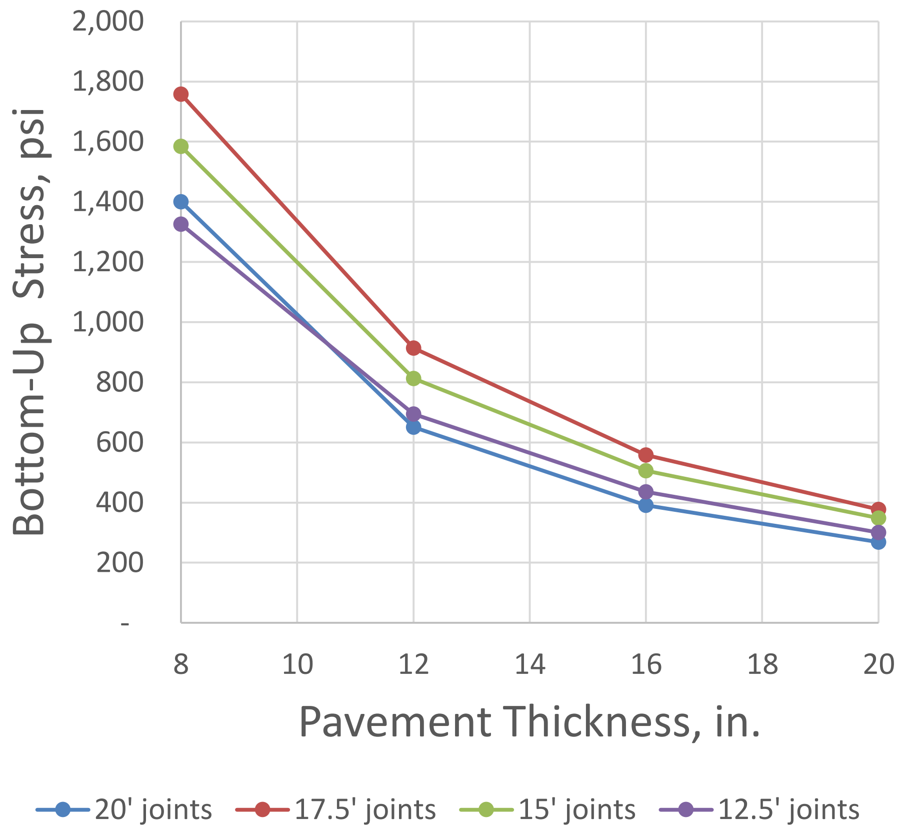
WE MODELED AN A380 IN ISLAB





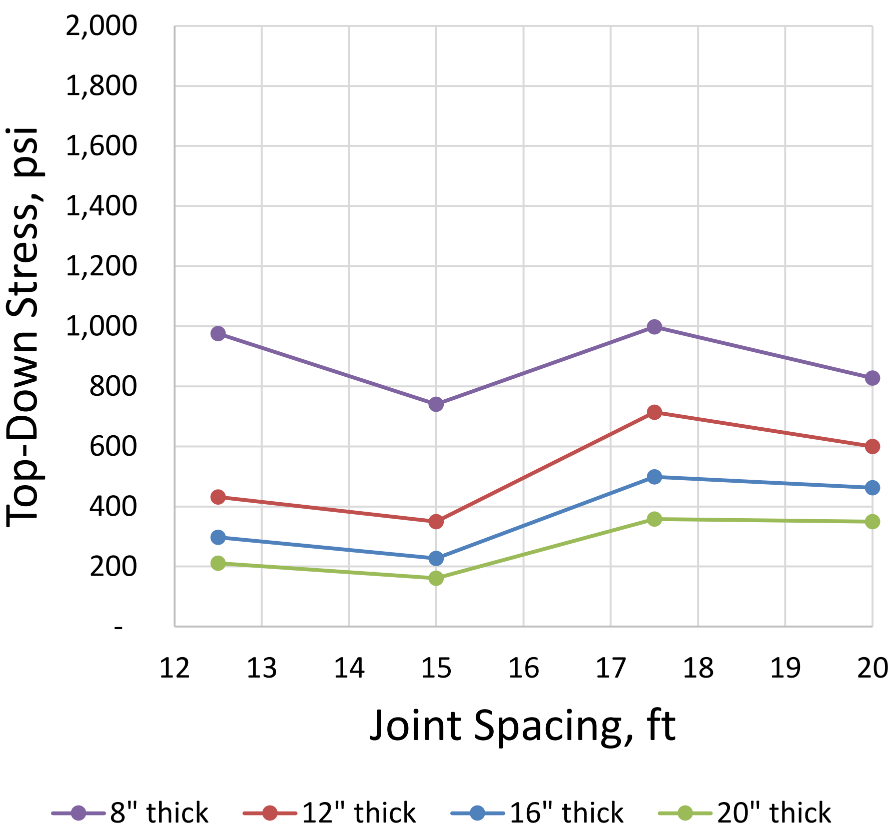
MAXIMUM STRESSES

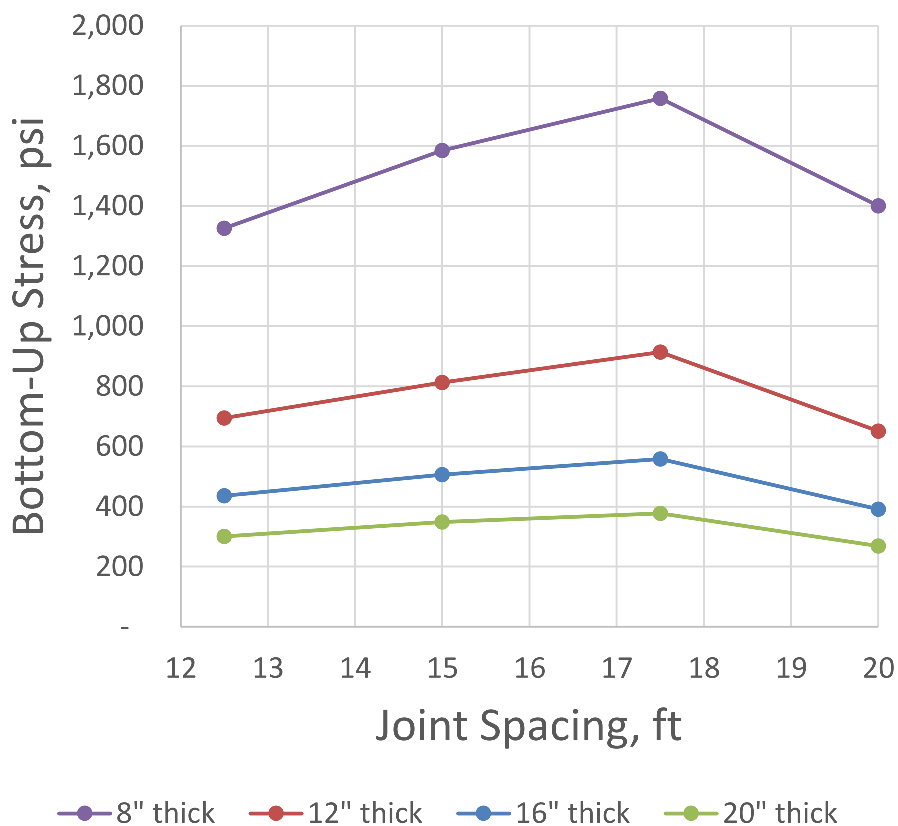




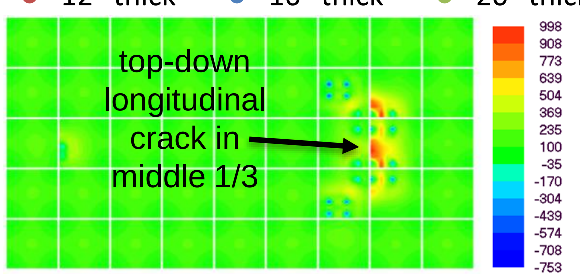
Bottom-up stresses higher, as FAARFIELD assumes.

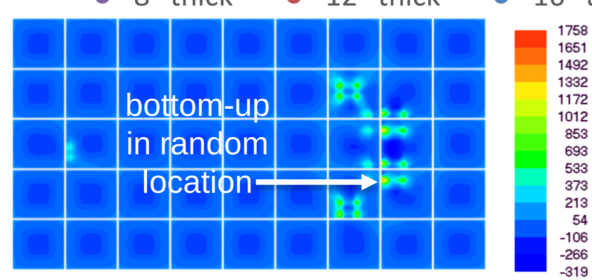
DATA PIVOTED TO FOCUS ON JOINT SPACING





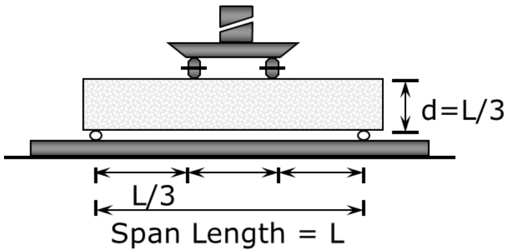
8 in. x
17.5 ft





CAPACITY
BEAM VS. SLAB TOP-DOWN VS. SLAB BOTTOM-UP

BEAM Capacity



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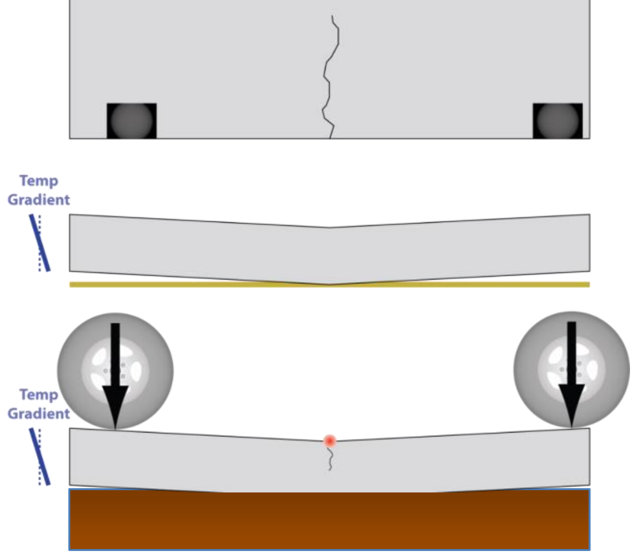
SLAB Top-Down Capacity

- beam-to-slab ratio to address size effects
- strength dev w/time



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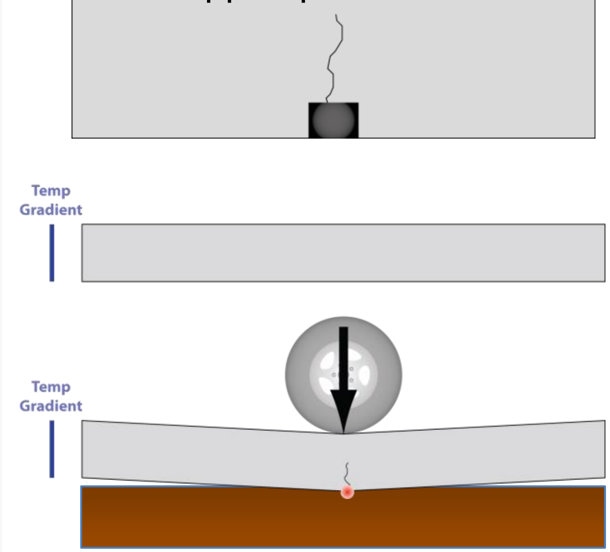
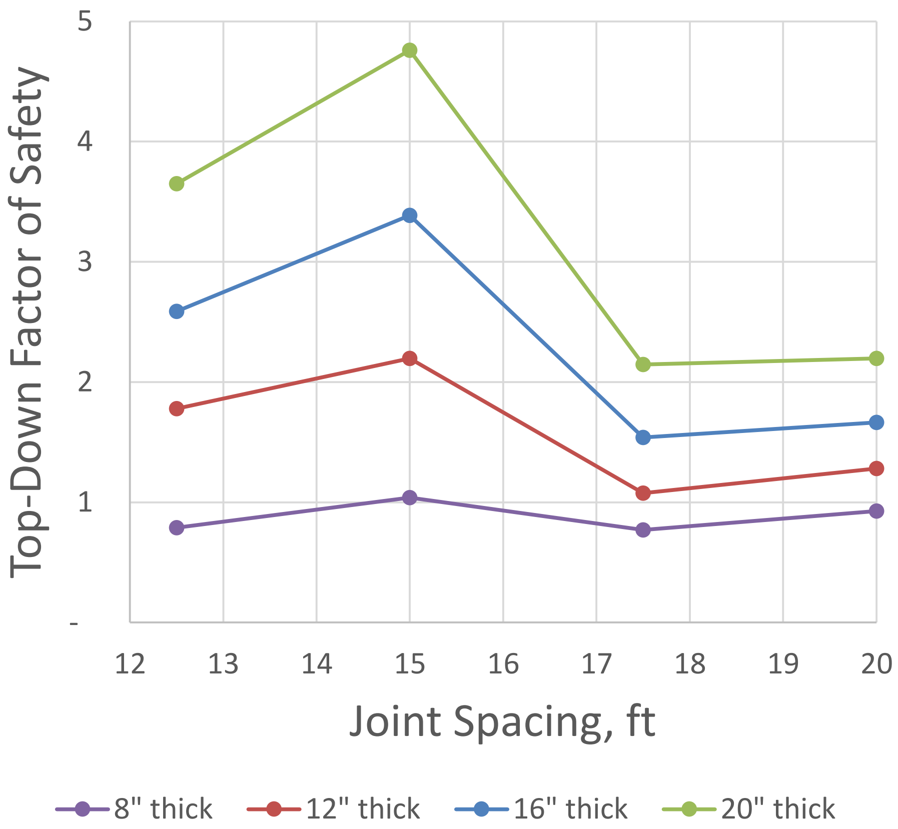
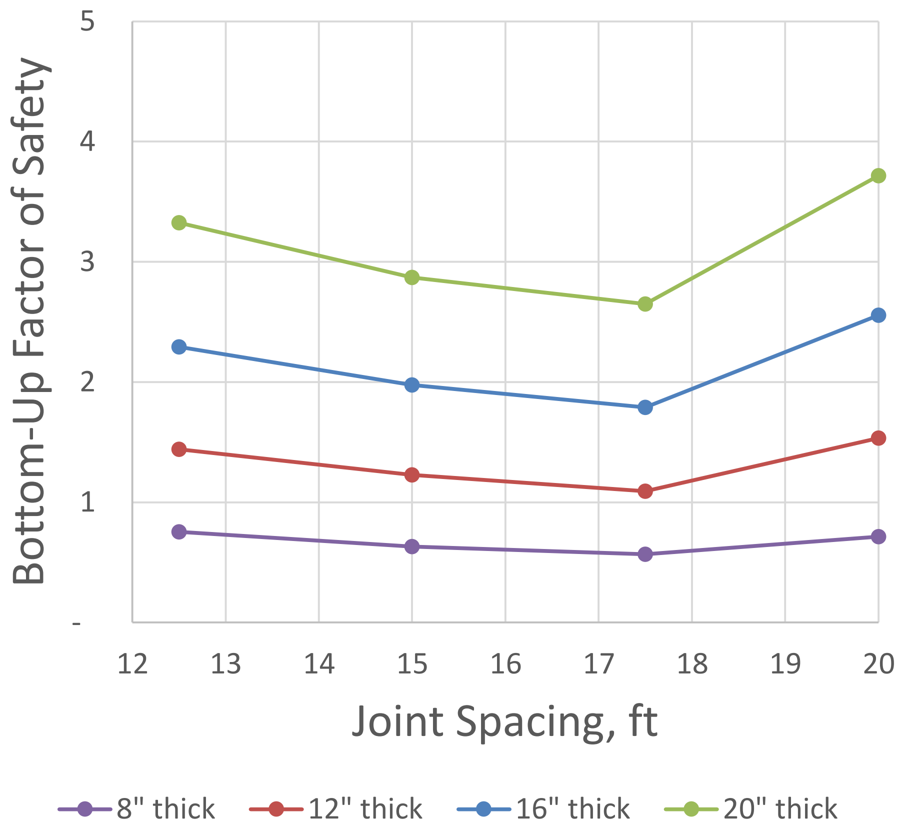
SLAB Bottom-Up Capacity

- lower deflection
  = lower strain
  = lower stress
- support pushes back



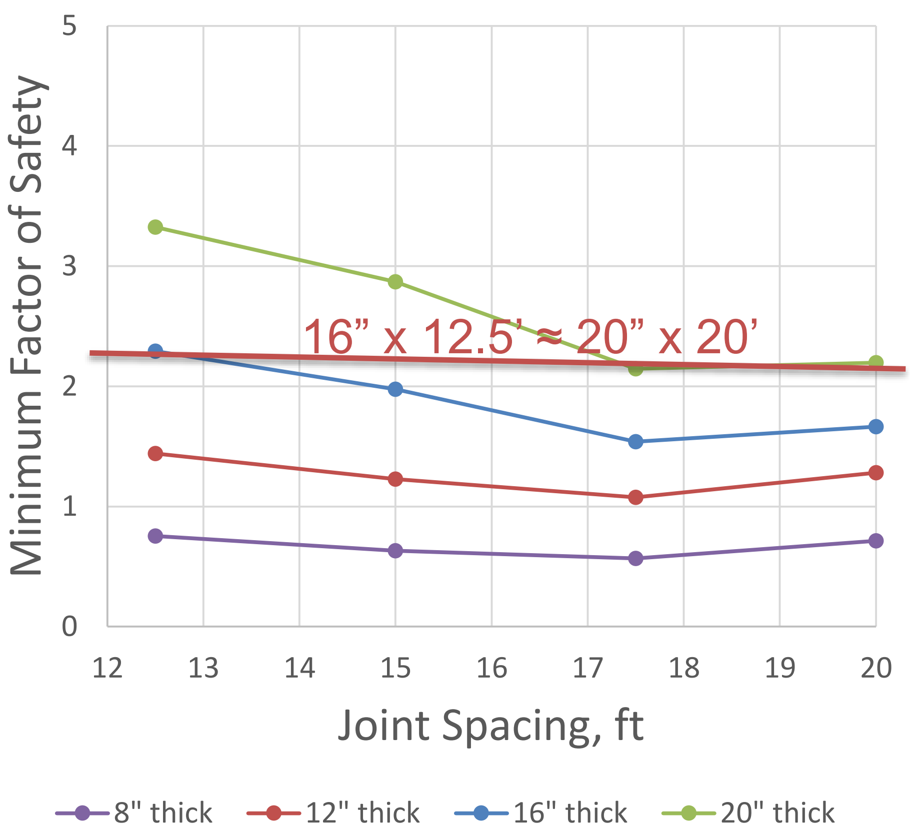
FACTOR OF SAFETY AGAINST CRACKING





$$Stress\ Ratio\ (SR) = \frac{1}{Factor\ of\ Safety}$$

MINIMUM FACTOR OF SAFETY
…AT LONGER JOINT SPACING, RISK OF TOP-DOWN



Thickness, in.	Joint Spacing, ft	Which Controls?
8	20	Bottom-Up Controls
8	17.5	Bottom-Up Controls
8	15	Bottom-Up Controls
8	12.5	Bottom-Up Controls
12	20	Top-Down Controls
12	17.5	Top-Down Controls
12	15	Bottom-Up Controls
12	12.5	Bottom-Up Controls
16	20	Top-Down Controls
16	17.5	Top-Down Controls
16	15	Bottom-Up Controls
16	12.5	Bottom-Up Controls
20	20	Top-Down Controls
20	17.5	Top-Down Controls
20	15	Bottom-Up Controls
20	12.5	Bottom-Up Controls

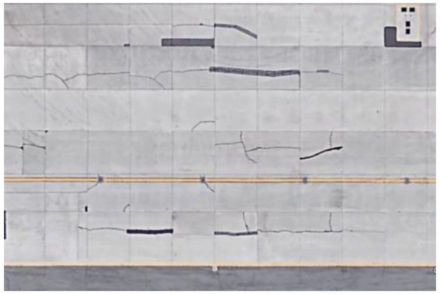
- **FAARFIELD assumes bottom-up only**
- **AC 150/5320-6F recommendations for joint spacing per thickness on stabilized subbase are indicated in green cells to the right**

INCOMPLETE MODELS EXPOSE US TO RISK

- This isn't to say that FAARFIELD is incorrect; it is fair in its simplification of bottom-up cracking to a single flat panel

- However, if bottom-up always controlled, critical load/fatigue would cause cracking of successive panels simultaneously and with no preferential location
  - Field evidence suggests other
  - Structural cracking tends to be corner cracking or in the middle 1/3 of the panel in practice

- Future models of all exterior concrete pavements should consider curl/warp and load configuration w.r.t. joints



Google Maps @ YYZ

Thank you for your time.

Robert Rodden | robert@pna-inc.com

PNA CONSTRUCTION TECHNOLOGIES