Development and Calibration of a Mechanistic Based Design Procedure for PCC Pavements

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Fundamental Basis of 2002 Design Procedure for PCC Pavements

1. Based on **engineering mechanics principles** as much as possible
2. **Characterize structure** with FEM (stresses and deflections from traffic and climatic loads)
3. **Characterize traffic** loads as distributions of single, tandem, tridem axles

Fundamental Basis of 2002 Design Procedure for PCC Pavements

4. **Characterize materials** in terms of elastic properties (elastic modulus ”E” & Poisson's ratio) and other properties (e.g., shrinkage)
5. **Characterize climate** using hourly historical temperature, precipitation, solar radiation, wind speed, cloud cover to model effects on PCC, base and subgrade soils

Fundamental Basis of 2002 Design Procedure for PCC Pavements

6. **"Damage"** over time estimated as it occurs in nature: **incrementally**
7. **Distress prediction** with mechanistic-based models that are calibrated with field data
8. **Smoothness prediction** function of as-built smoothness, distress, and site factors

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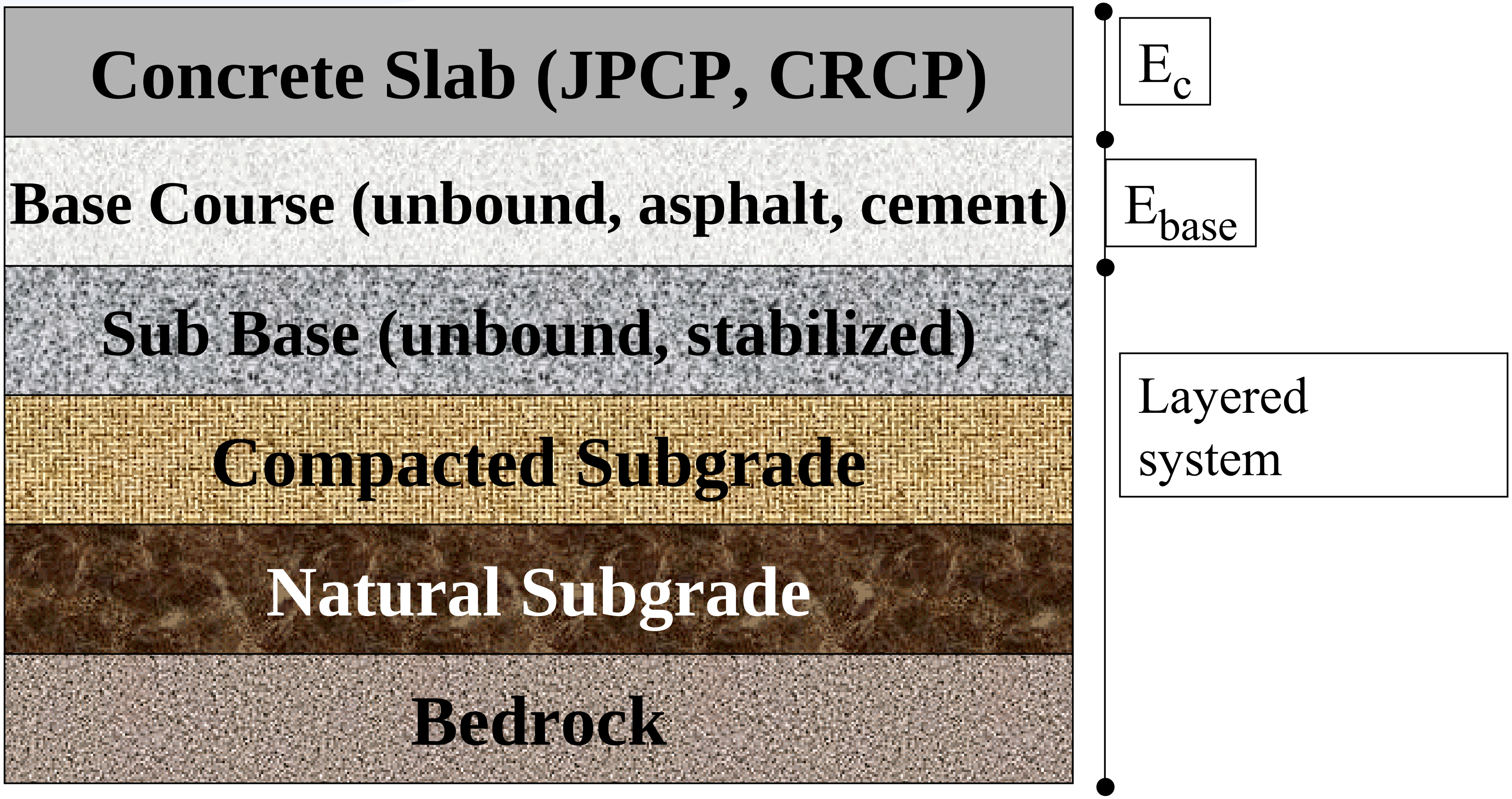
New and Rehabilitated Rigid Pavements

- Jointed plain concrete pavements (JPCP)
- Continuously Reinforced Concrete Pavements (CRCP)
- Unbonded JPCP and CRCP overlays
- Bonded PCC overlay of JPCP and CRCP
- Restoration of JPCP and CRCP w/o overlay

Rigid Pavement Layers



PCC Restoration/Overlay Analysis

Existing Flexible/Composite

Existing Rigid

Restoration

Existing Rigid

TREATMENTS

- Milling
- Patching
- Shoulder replacement
- Subdrainage

- Load Transfer Restoration
- Full-depth repair
- Partial depth repair
- Slab replacement
- Shoulder replacement
- Retrofit tied PCC shoulder
- Subdrainage

- Load Transfer Restor.
- Full depth repair
- Partial depth repair
- Slab replacement
- Shoulder replacement
- Retrofit tied PCC shoulder
- Subdrainage
- Diamond grinding

DESIGN

PCC Overlay
- Cracking
- Faulting
- Punchouts
- Smoothness

Existing PCC
- Cracking
- Faulting
- Punchouts
- Smoothness

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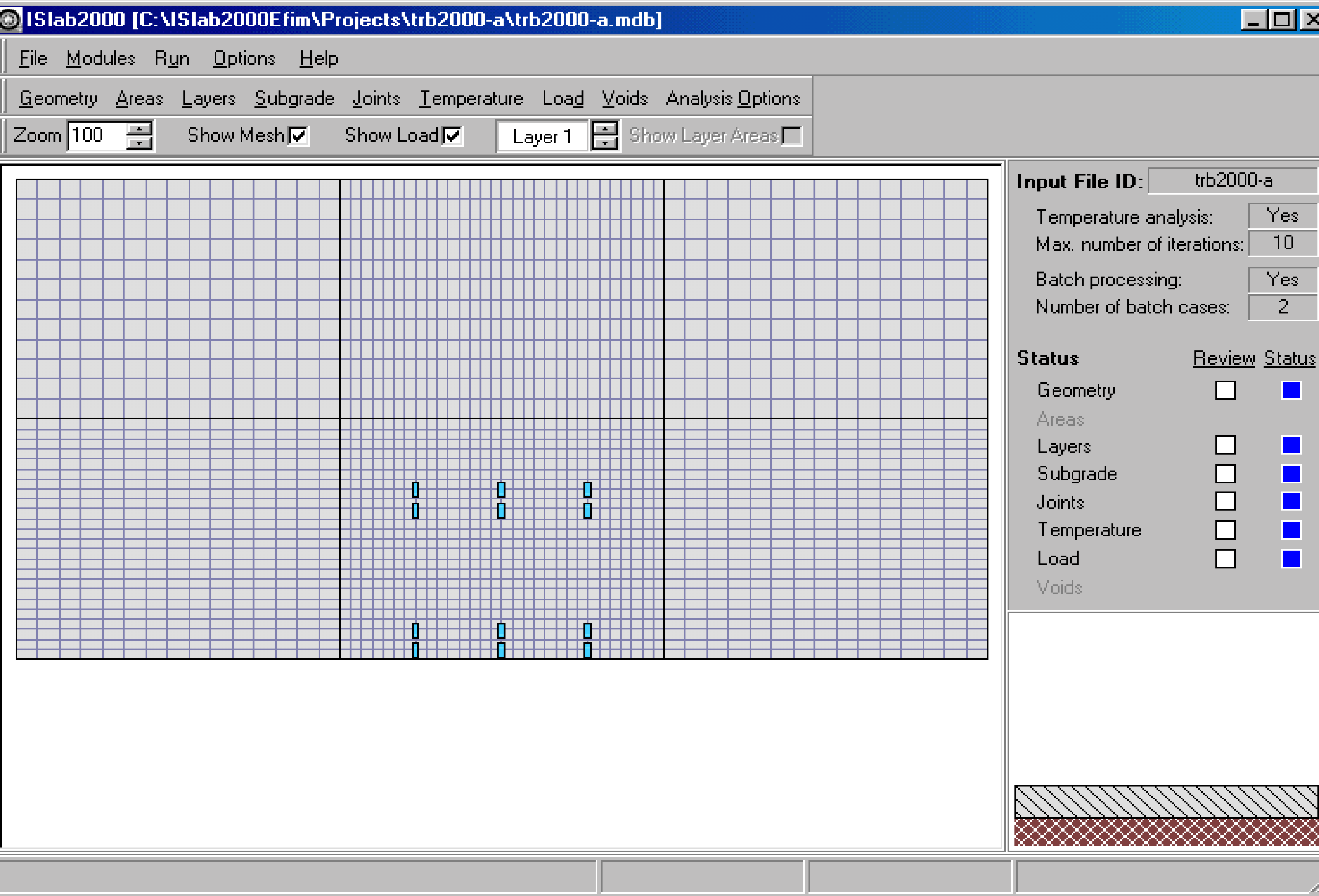
- Structural Response Model
  - ✓ISLAB2000—enhanced 2.5D FEM
  - ✓Rapid solution method required to make millions of calculations rapidly
    - Neural network with dimensional analysis and equivalent system
    - Modified MC-HARP and traditional back-propagation neural networks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Geometry Areas Layers Subgrade Joints Temperature Load Voids Analysis Options
Zoom 100
Show Mesh
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Max. number of iterations: 10
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Number of batch cases: 2
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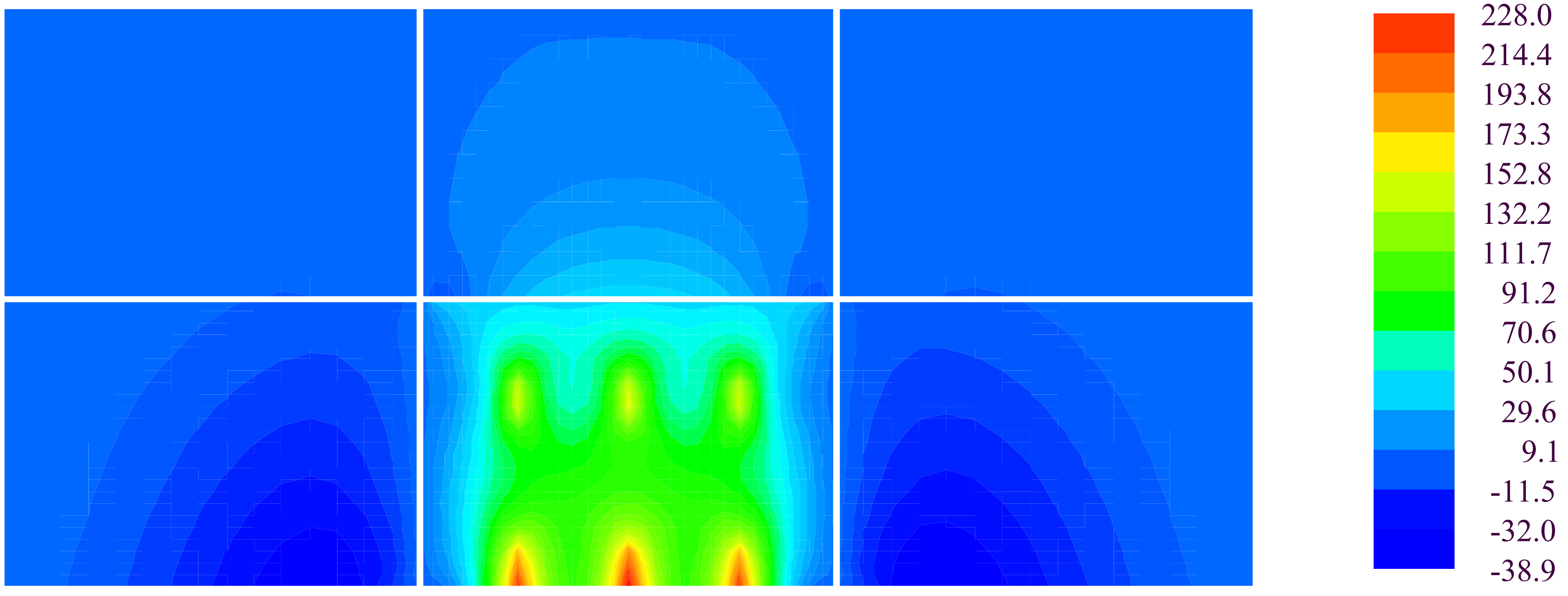
Day Time Curling, Tridem Axle Loading

Stresses in Y-direction ⟷



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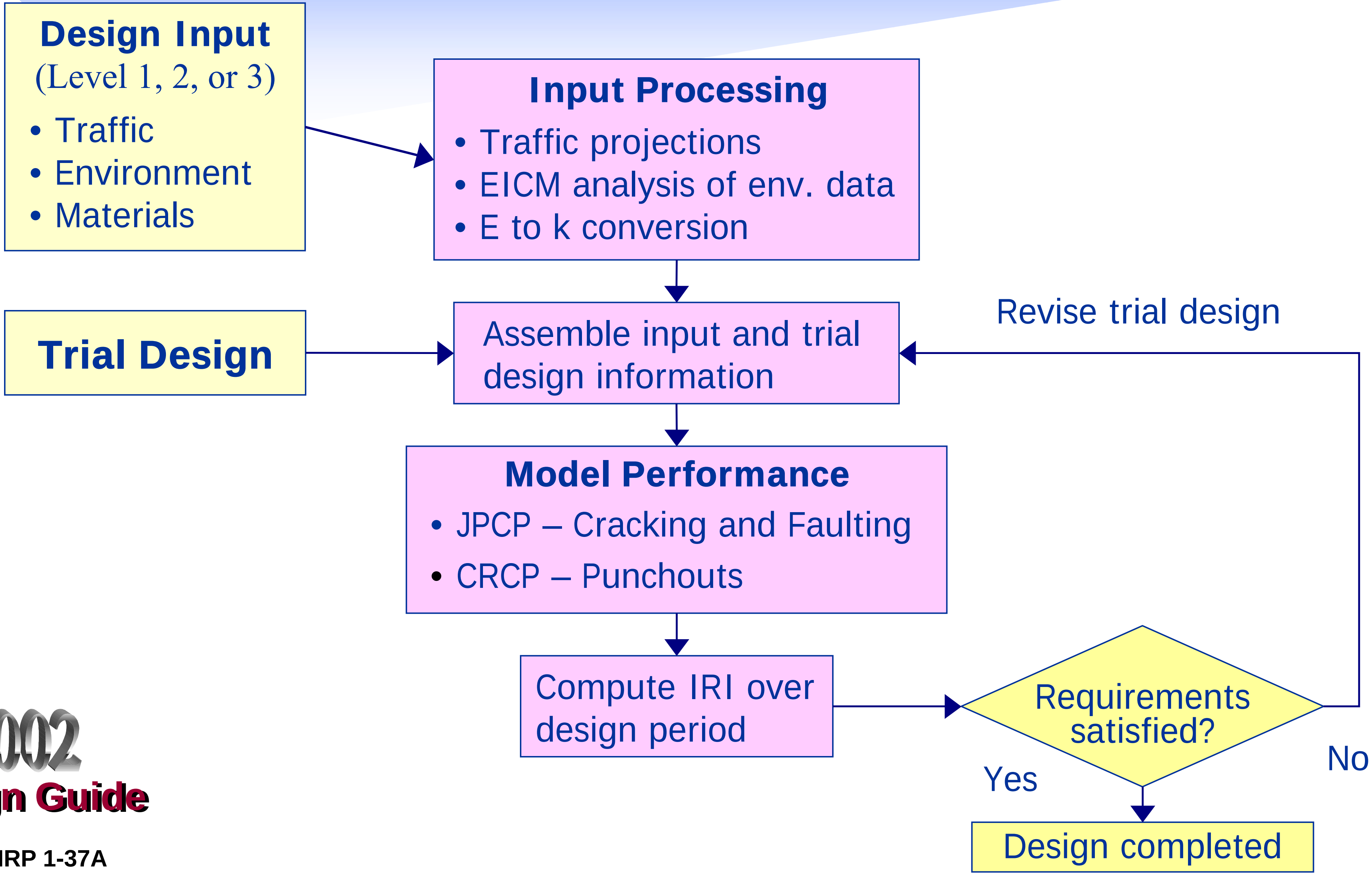
- JPCP distress types
  - ✓Joint Faulting
  - ✓Transverse cracking—bottom-up
  - ✓Transverse cracking—top-down
- CRCP distress
  - ✓Punchouts—crack LTE loss, top-down
- Smoothness (IRI)
  - ✓JPCP and CRCP

Overview of PCC Pavement Design Process



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Incremental Damage

- Divide design period into increments (year, month, day/night)
- Changes over time are addressed
  - ✓ Material strength and stiffness (all layers)
  - ✓ Seasonal moisture and temperature (hourly temperatures)
  - ✓ Traffic variation hourly, seasonally, yearly
  - ✓ Other changes (joint open/LT, erosion, ...)

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Design Inputs

1. Subgrade/foundations
2. Material characterization
3. Environmental effects
4. Traffic loading
5. Performance criteria
6. Pavement evaluation

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Subgrade/Foundation

- Characterization of the subgrade (Mr)
- Laboratory or FWD testing of subgrade
- Identification and treatment of special subsurface conditions
- Foundation improvement and strengthening

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Environmental Effects

- The Enhanced Integrated Climatic Model (EICM) is used to predict moisture and temperature states throughout pavement layers and subgrade.
- A powerful tool (temp. grad. Slab, AC Base E*, granular base Mr, subgrade Mr)

Hierarchical Input Levels

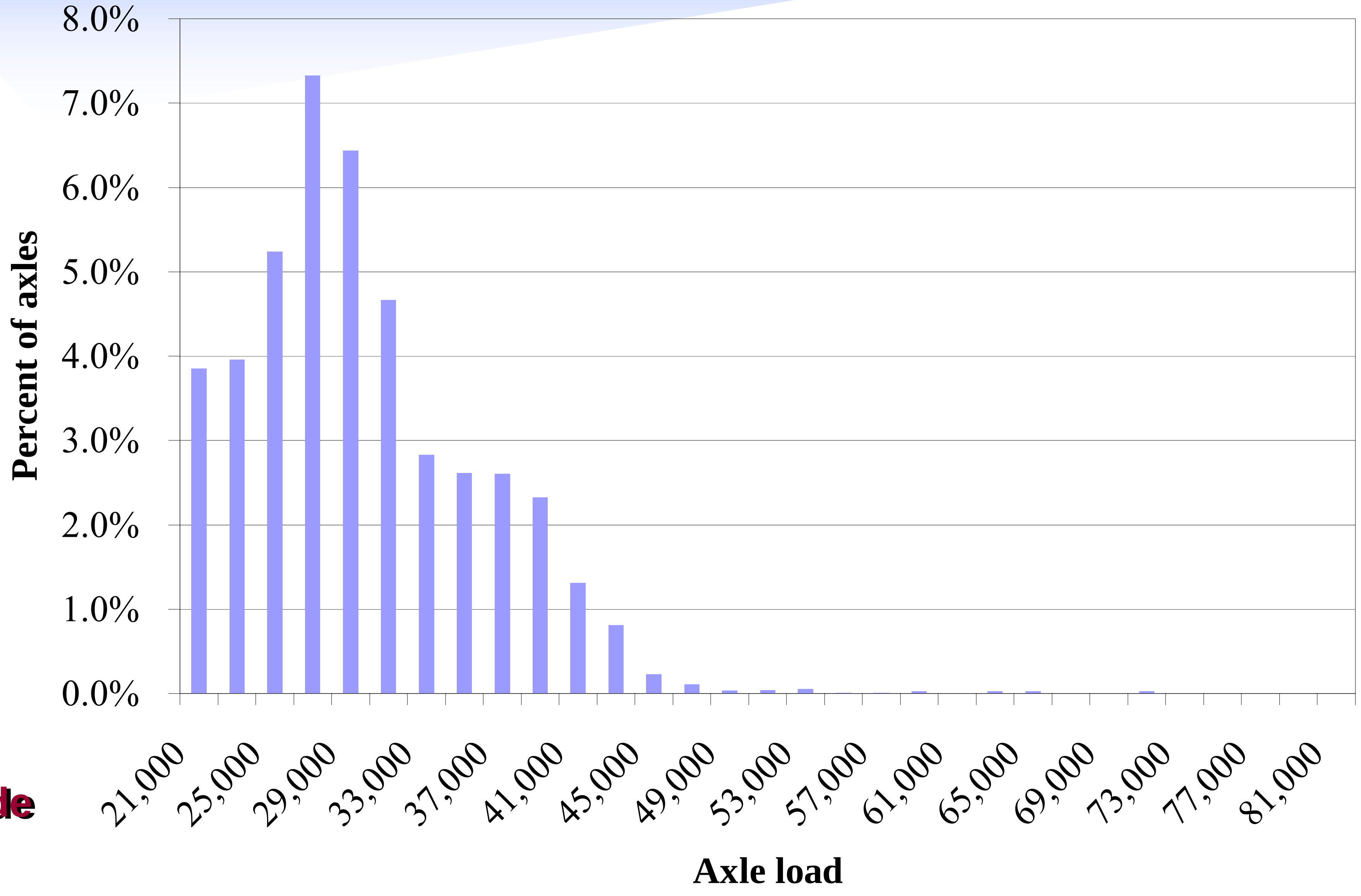
- ***Level 1 — Testing Required***
  Materials testing (Ec,MR, shrinkage, Mr)
  Deflection testing (FWD) and backcalculation
  Site traffic testing: AVC, WIM
- ***Level 2 — Correlations***
  Available test procedures with correlation equations
- ***Level 3 — Default Values***
  Default values based on research & local knowledge

Note — Calculation procedures are exactly the same regardless of design input level

Traffic

- Single, tandem, tridem, quad annual axle counts in design lane over design life
- 24-Hour truck usage distribution factors
- Monthly (seasonal) distribution factors
- Axle load spectra (percent) for single, tandem, tridem, quad axles

Axle Load Spectra (Tandem Axles)



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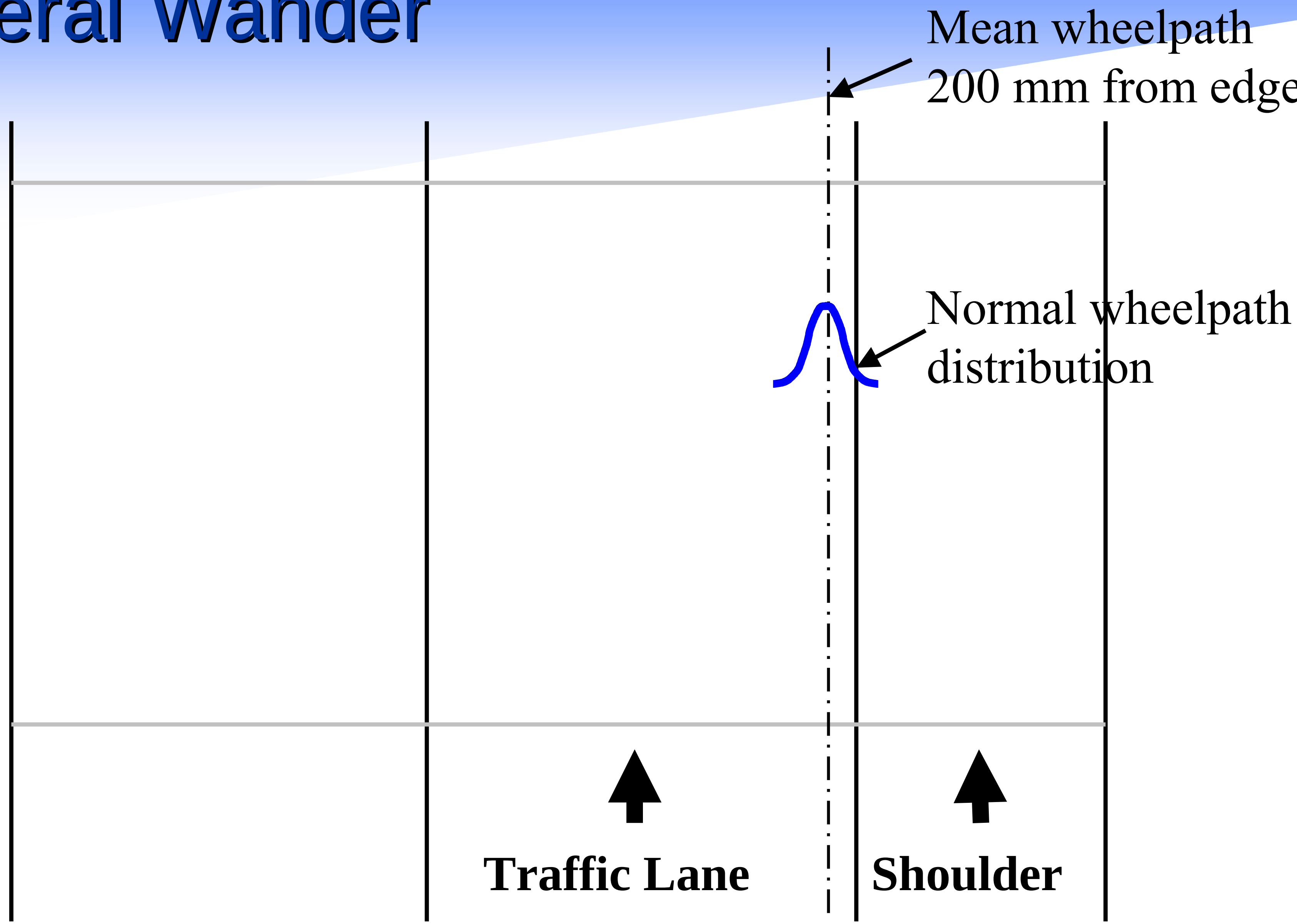
Lateral Wander



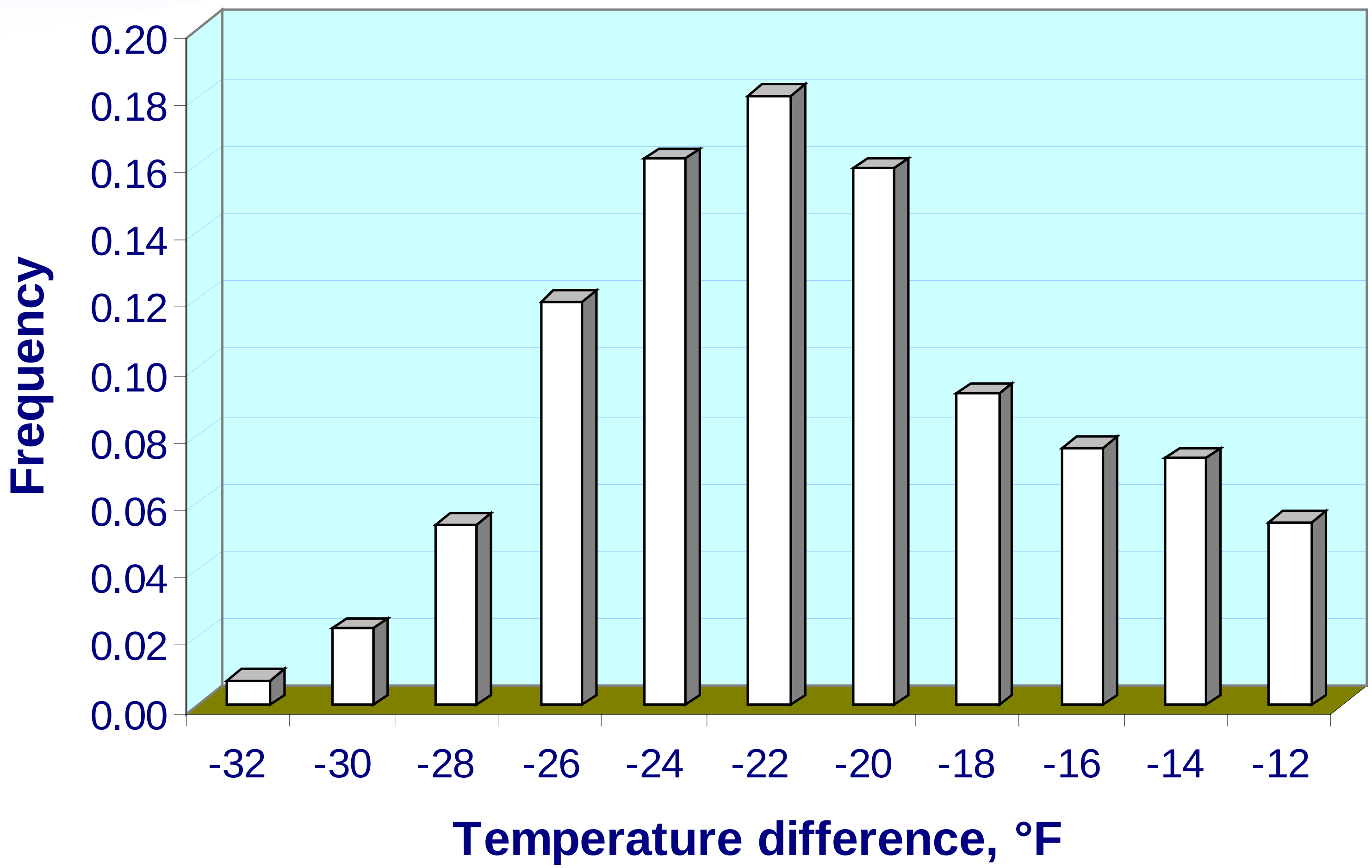
Environment

- EICM is run automatically based on weather station hourly climatic data (temp., solar radiation, precipitation, wind, relative humidity)
- EICM results include:
  - ✓ Hourly temperature profiles through PCC
  - ✓ Seasonal base and subgrade moduli values
- Nonlinear hourly temperature profiles are converted to equivalent (equal stress) linear temperature differences for computational efficiency

Environment (cont.)

- Frequency distributions of hourly thermal gradients created for each month of the year over as many years as weather station data available
- Both day-time (positive) and night-time (negative) thermal gradient probability distributions are obtained for each month

Example Frequency Distribution of Negative Temperature Gradients



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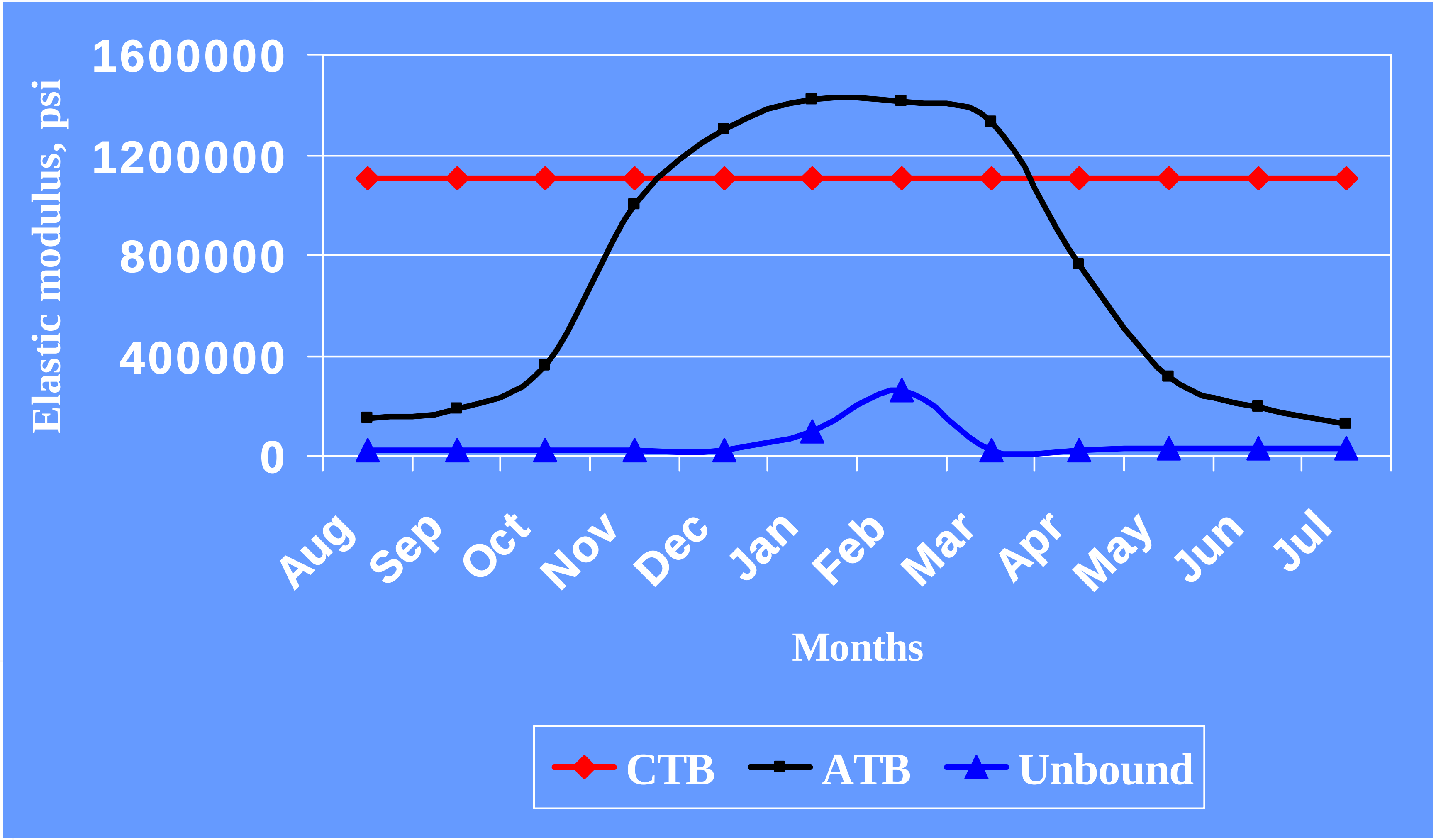
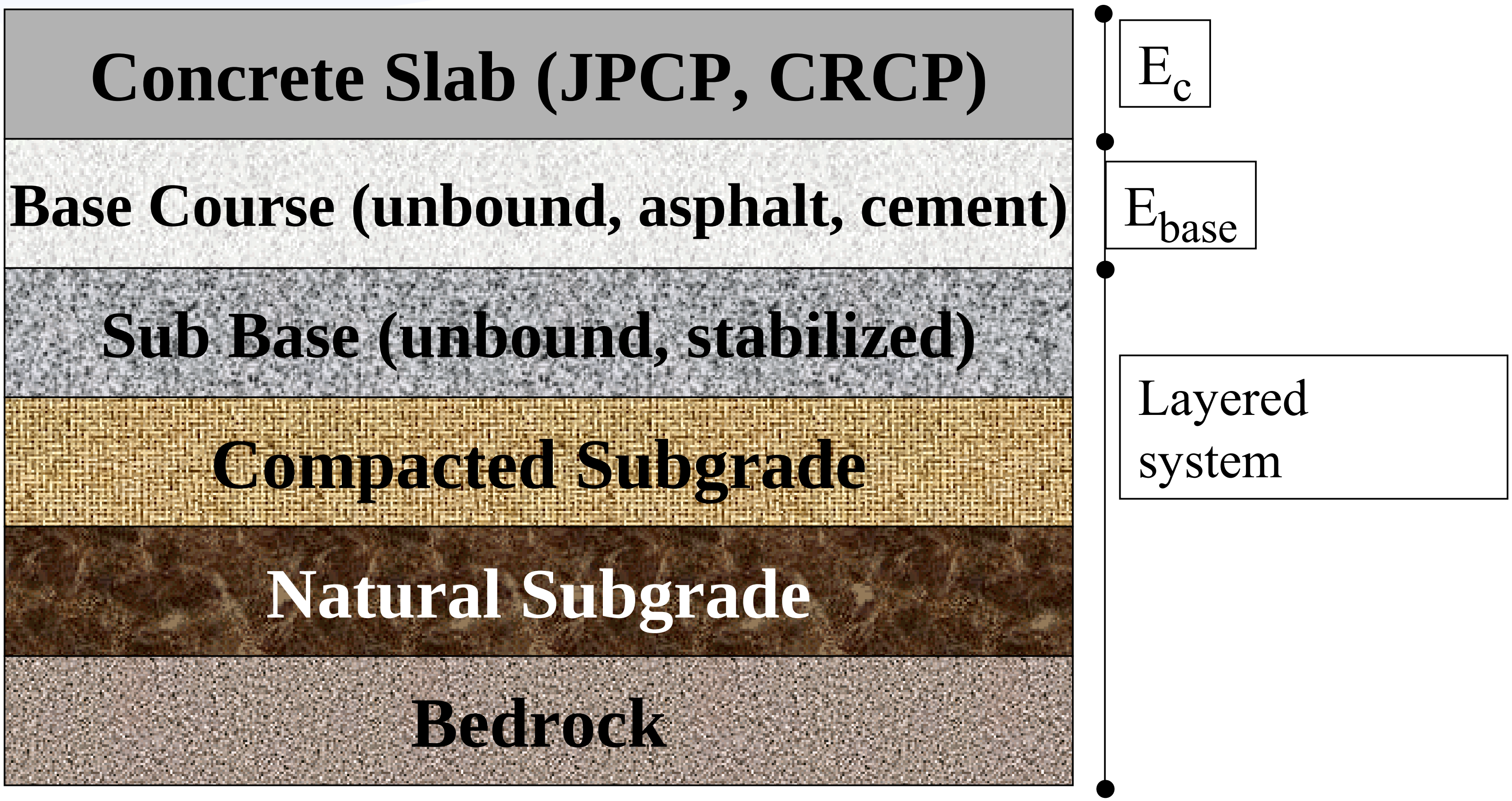
Monthly Variations of Base Modulus



Material Properties

- PCC placement & opening to traffic dates
- PCC strength gain over time
- PCC elastic modulus gain over time
- PCC coefficient of thermal expansion
- PCC Poisson’s ratio and unit weight
- PCC drying shrinkage (ultimate and change over time)
- Seasonal base and other sublayers modulus values
- Time when PCC slab and treated base debonds
- Base erosion index (material, climate, subgrade)

Rigid Pavement Layers



PCC Strength Gain

- Strength parameters
  - ✓ Flexural strength, MR
  - ✓ Compressive strength, fc
  - ✓ Elastic modulus, Ec
  - ✓ Tensile strength (indirect), ft

PCC Strength Gain Model

$$STRATIO = 1 + 0.1249\log_{10}(AGE/0.0767) - 0.01566[\log_{10}(AGE/0.0767)]^2$$

where

STRATIO = ratio of PCC strength at a given age to 28-day strength

AGE = PCC age, yr

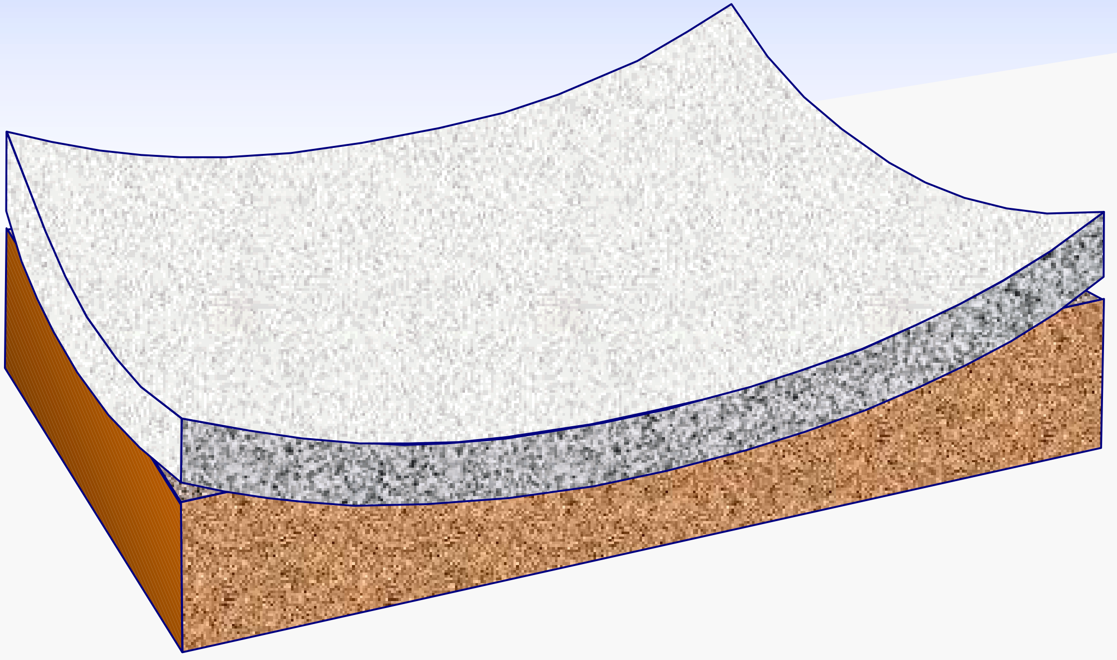
N = 679 (3 days to 20 years)

R^2 = 79% SEE = 0.12 (of *STRATIO*)

Mean Strength Ratio’s (from model)

Age	Strength Ratio
28-day	1.00
1-yr	1.12
20-yr	1.21

Curling and Warping



$$\Delta T = \Delta T_{Actual} + \Delta T_{Built-in} + \Delta T_{Shrinkage}$$

Curling and Warping

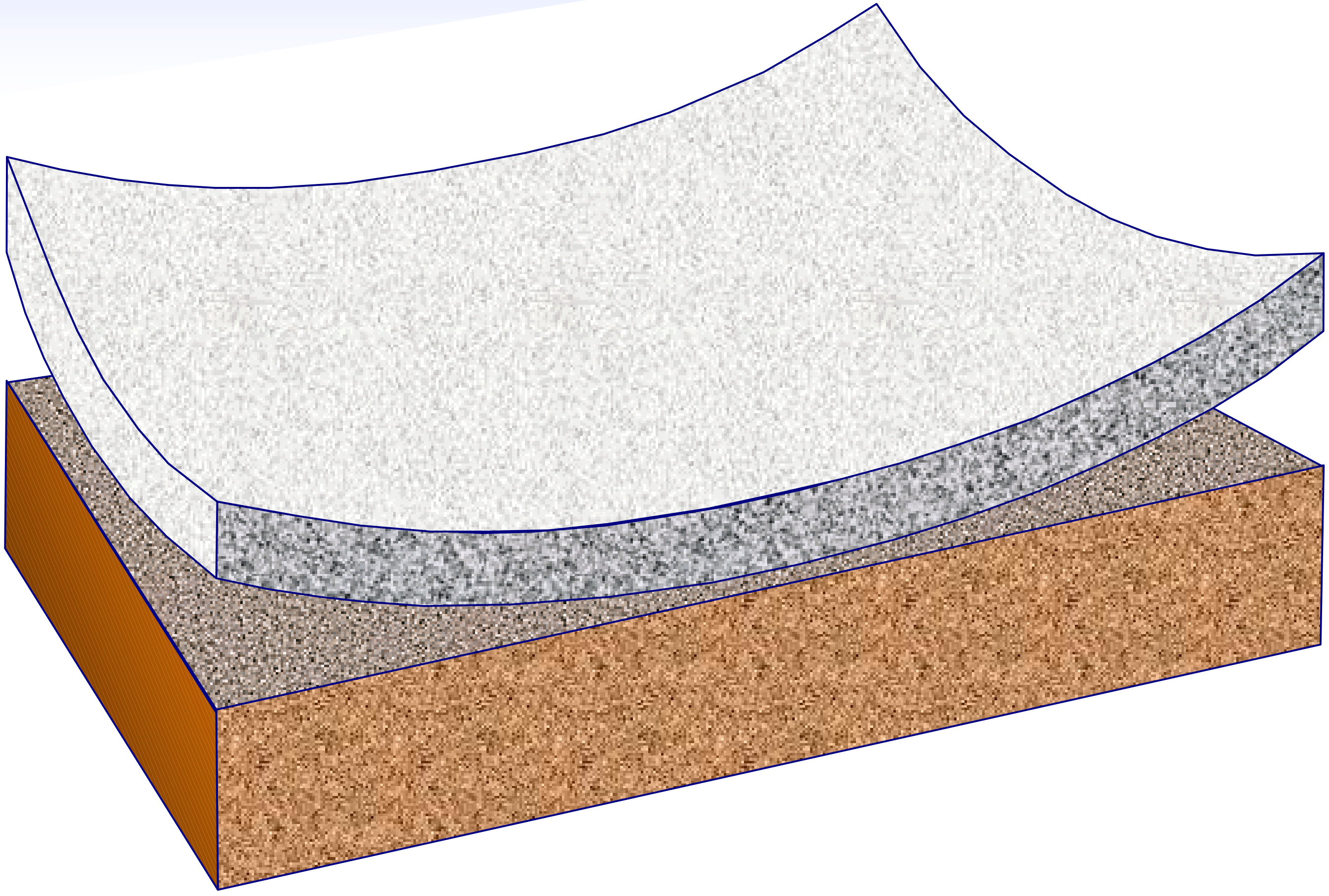
- Refers to the distortions of PCC slabs caused by
  - ✓ Temperature gradient (curling)
  - ✓ Moisture gradient (warping)
- Consists of two parts
  - ✓ **Permanent**, built-in component
  - ✓ **Transitory**, varies continuously in response to climatic conditions

Curling and Warping in Cracking, Faulting, & Punchout Models

Assumptions:

- All factors (temperature, moisture) that distort PCC slabs can be represented in terms of **equivalent temperature gradient**
- Not all distortions measurable on pavement surface affect stresses in PCC slabs

Contact Condition Assuming the Foundation is Flat



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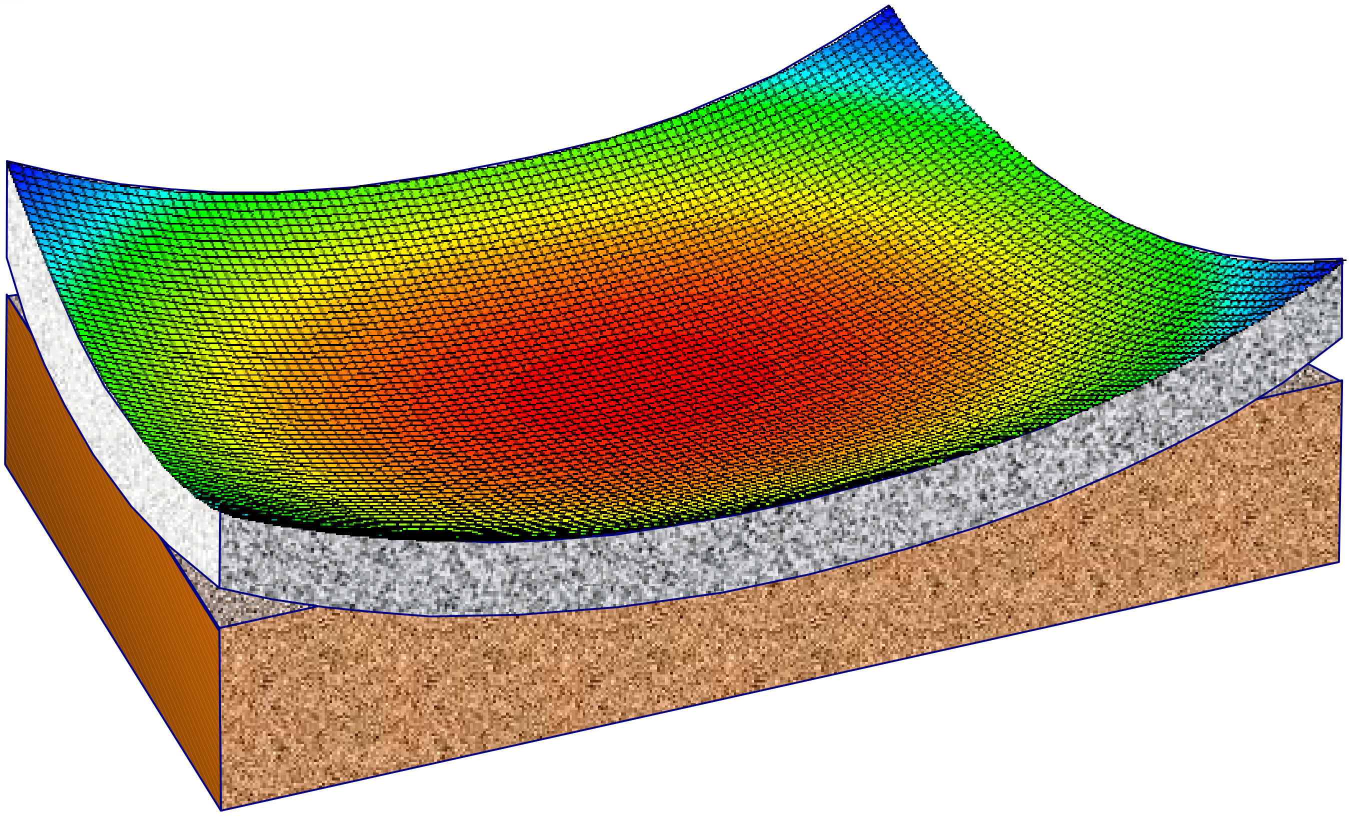
Actual Contact Condition



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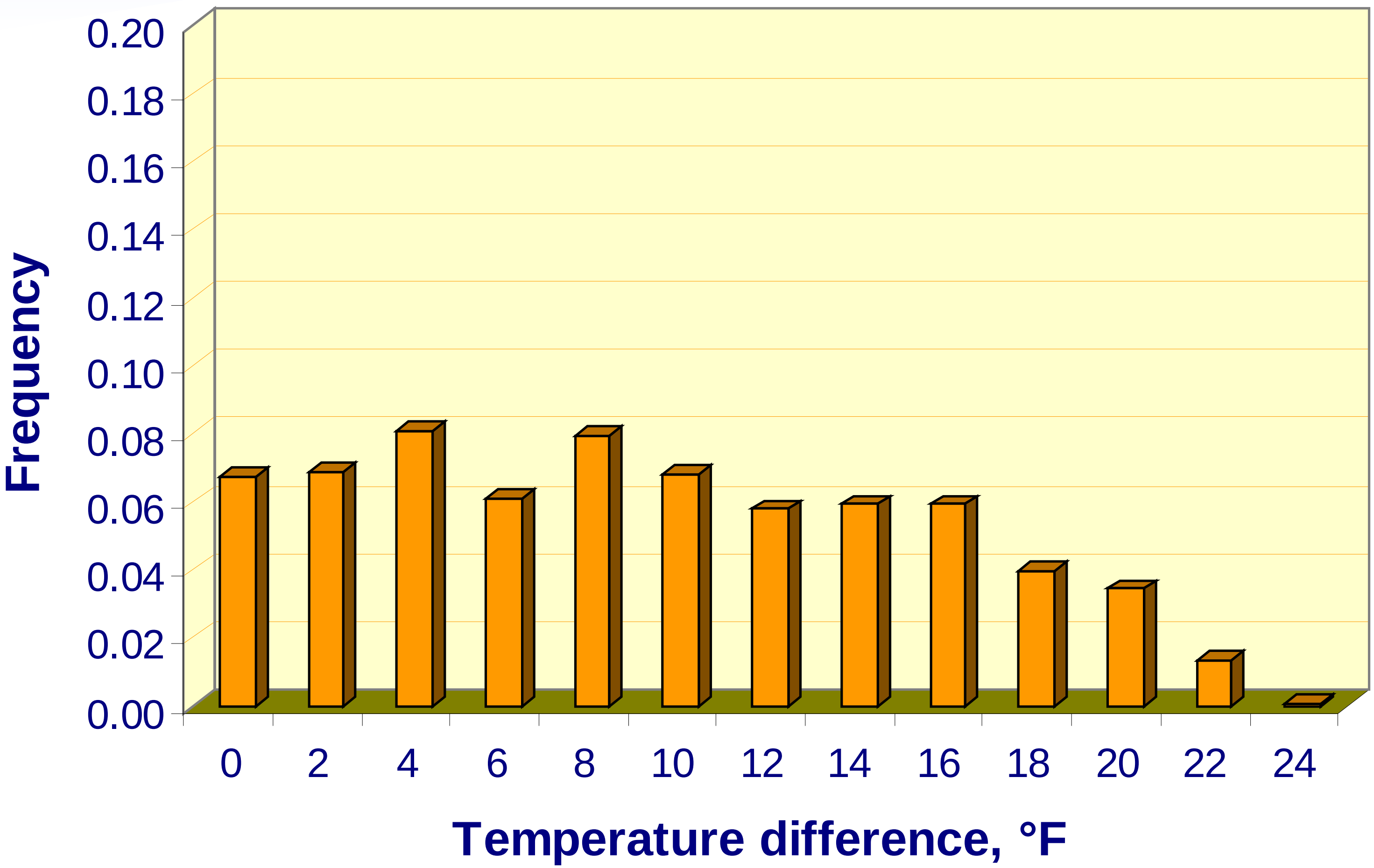
Permanent Curl/Warp

- Three components
  - ✓ Built-in temperature gradient at time of set
  - ✓ Permanent portion of drying shrinkage
  - ✓ Creep of slab and settlement into base
- Single equivalent temperature value determined through calibration
  - ✓ Value that gives the best correlation between the calculated damage and slab cracking

Transitory Component

- Temperature—hourly variation is considered
  - ✓ EICM used to predict hourly temperature profile through PCC from hourly climatic data
  - ✓ Nonlinear temperature gradient is utilized
- Moisture gradient—monthly variation in relative humidity utilized

Example Frequency Distribution of Positive Temperature Gradients



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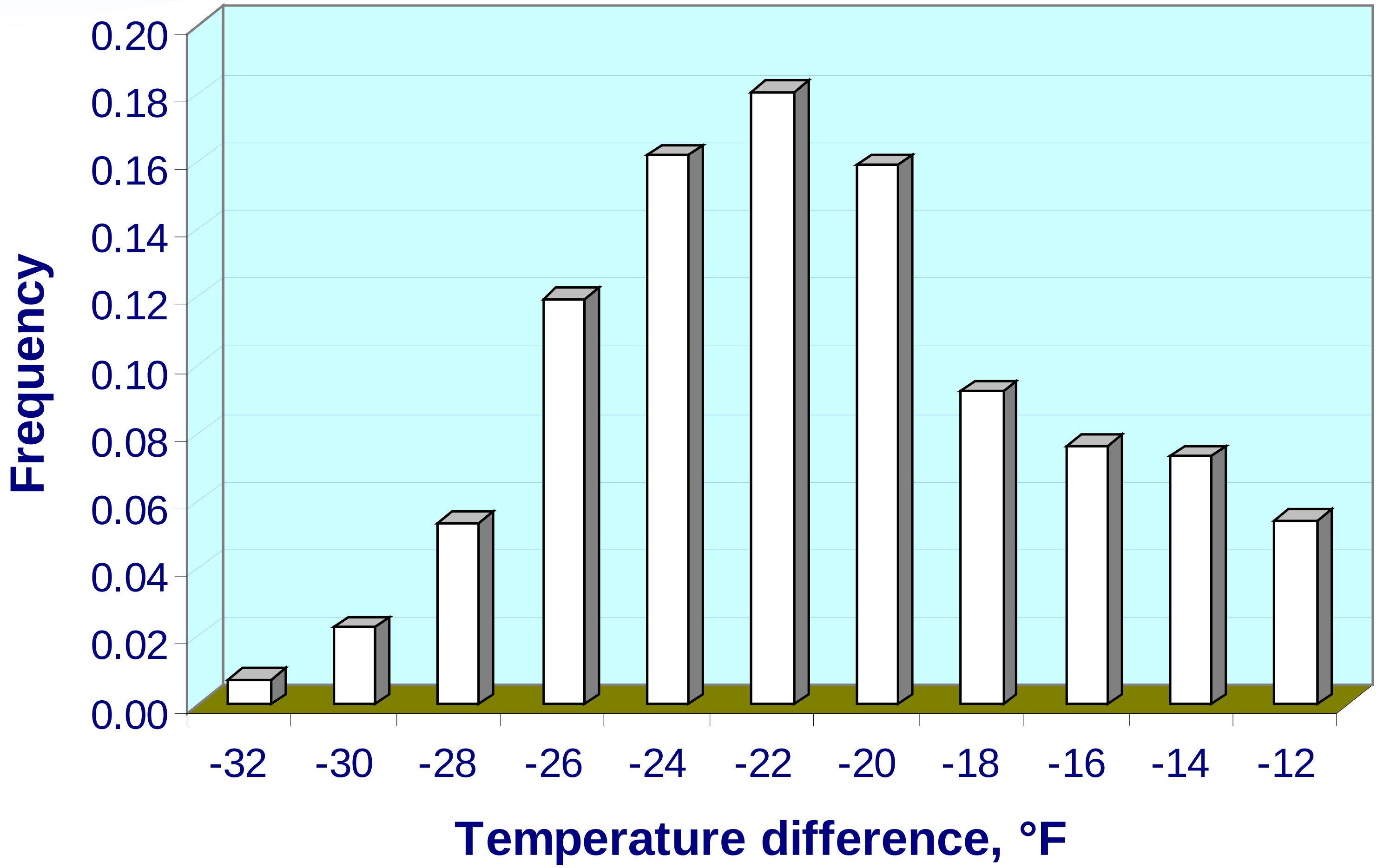
Example Frequency Distribution of Negative Temperature Gradients



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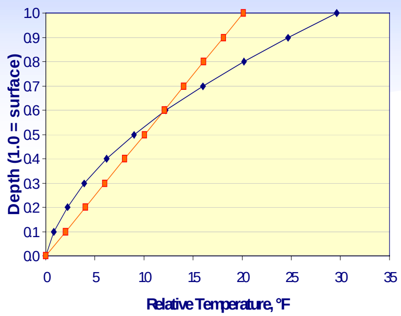
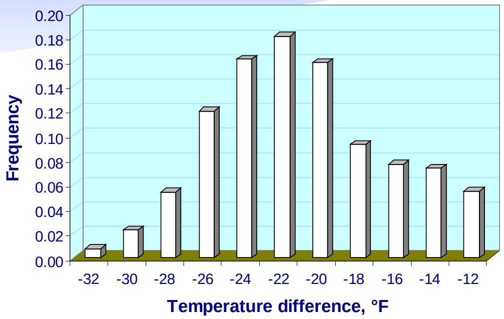
Components of Curl/Warp Stress

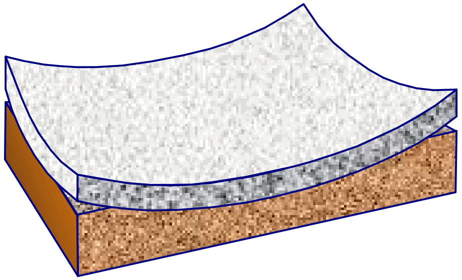
Actual Temperature Gradient





Frequency distribution of linearized hourly temperature gradients

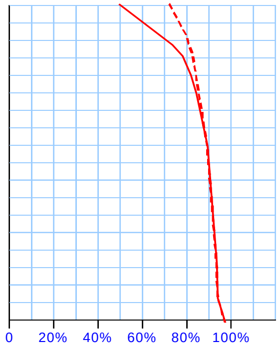
Built-in Curling

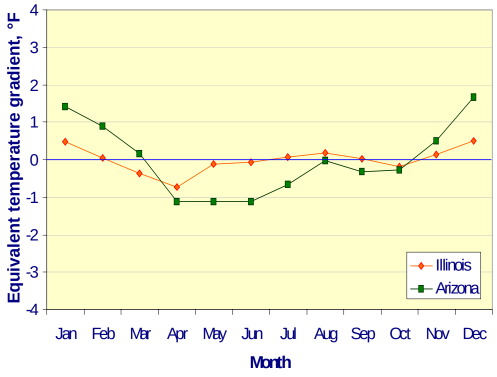


$$TG_{BuiltIn} = f\left(Design \,\&\, Site\ Factors\right)$$

Empirical relationship based on calibration results

Moisture Gradient





Effects of monthly variation in R.H. expressed as equivalent temperature gradient

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PCC Field Fatigue Model (NCHRP 1-26)

$$Log_{10}N = [\ (-R^{-b}\ Log_{10}\ (1-P))\ /\ a\ ]^{\ 1/c}$$

Where

N = number of stress repetitions to 50% slab cracking

R = tensile stress / flexural strength

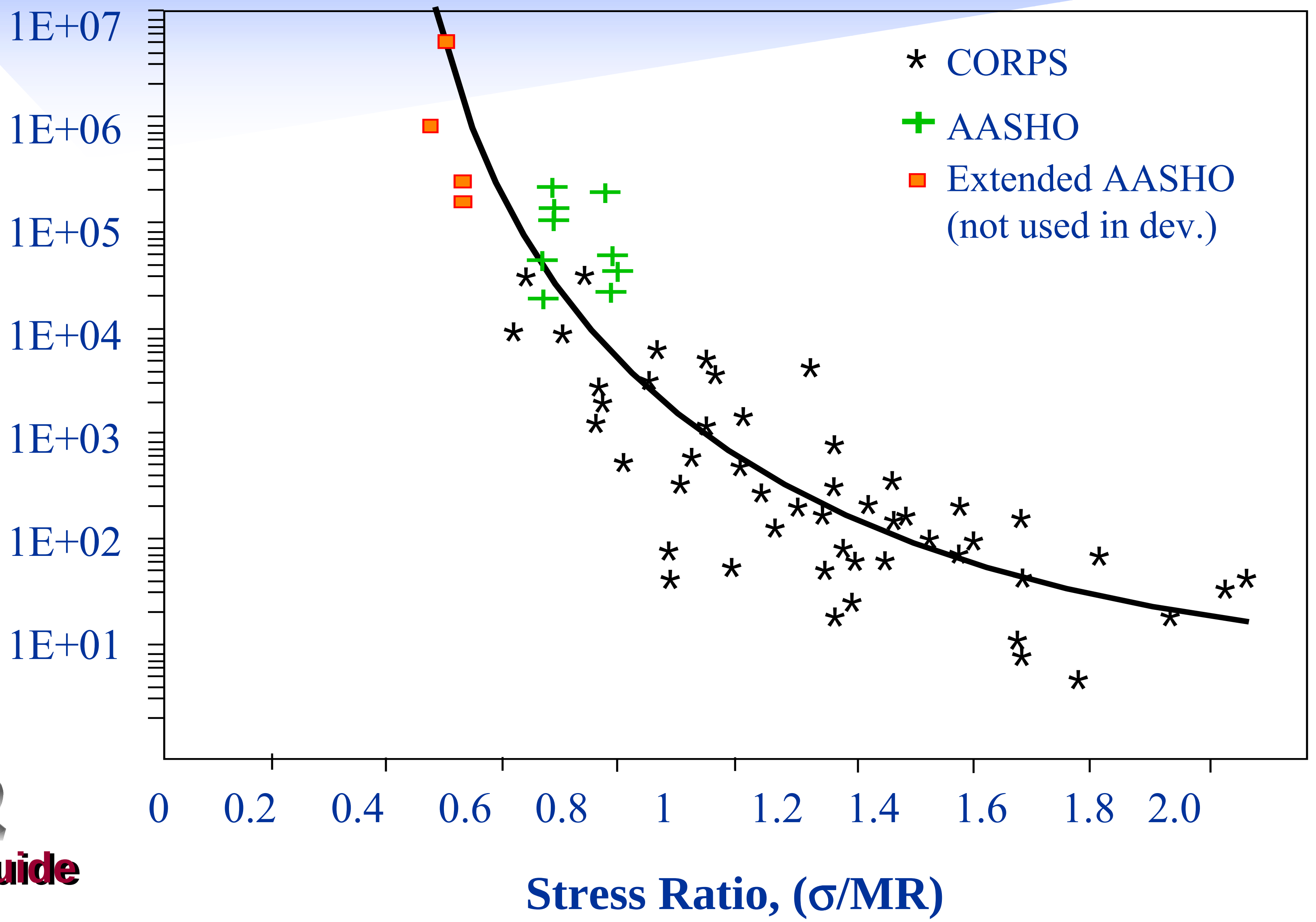
P = probability of cracking

a = 0.0032 b = 5.367 c = 4.394 (field calibration)

R^2 = 0.87

No. test sections = 62

Number of Stress Repetitions



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JPCP Design Procedure

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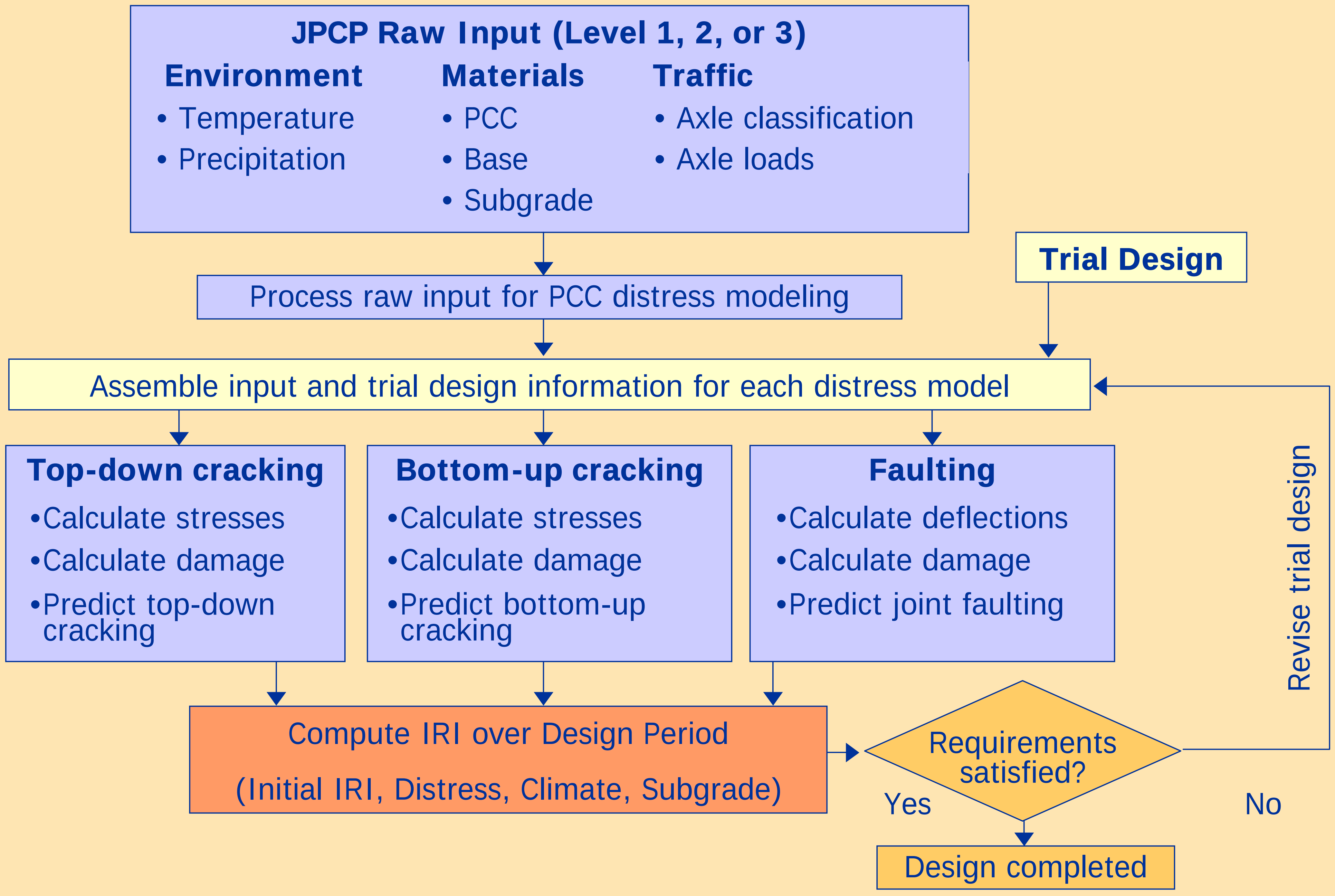
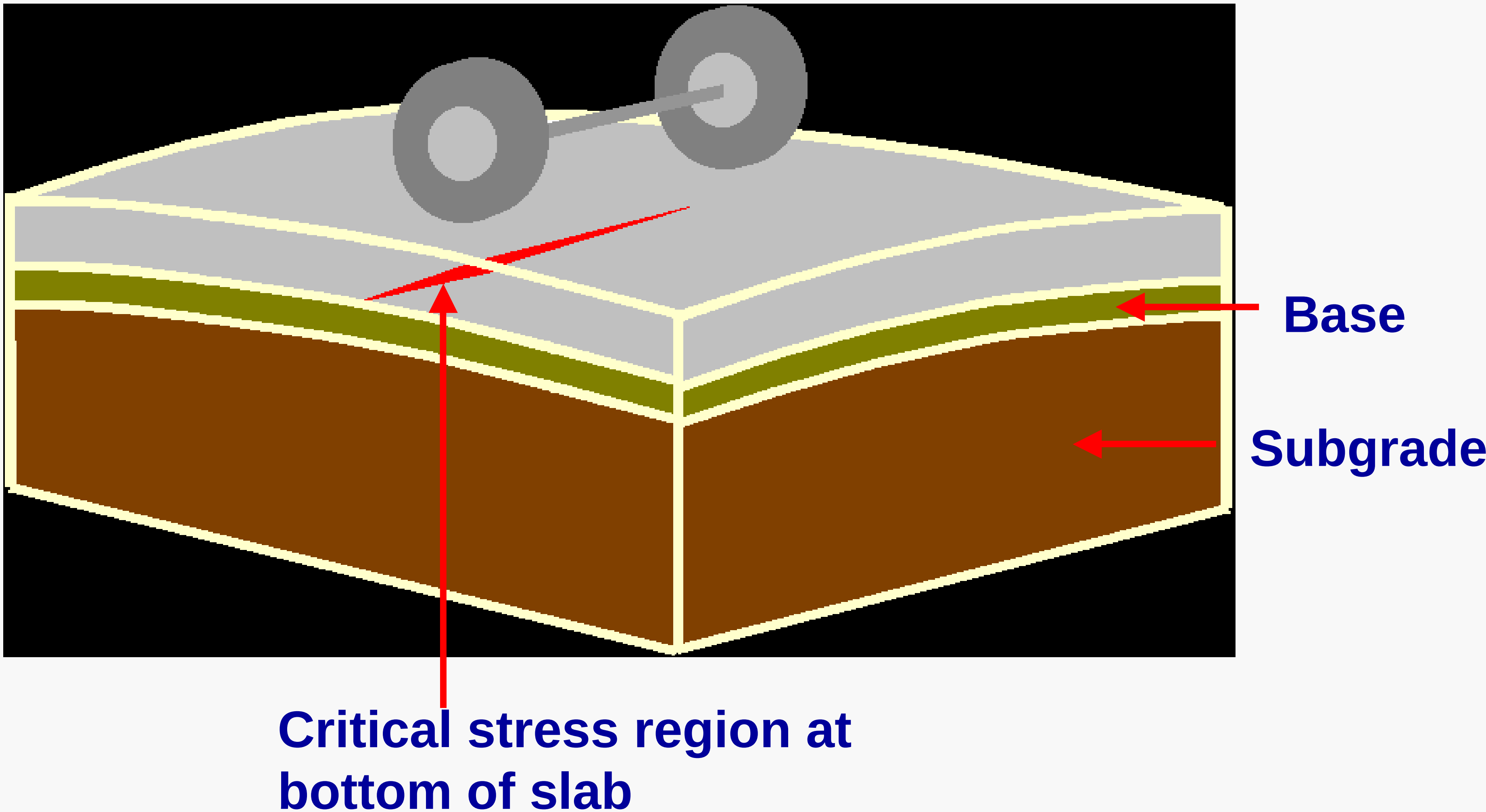
Prediction Models

- Development of mechanistic based models of key distresses
  - ✓ JPCP bottom-up cracking
  - ✓ JPCP top down cracking
  - ✓ JPCP joint faulting
- Development of empirical IRI model
  - ✓ IRI = f — distress, site conditions, patching


JPCP Raw Input (Level 1, 2, or 3)
Environment
• Temperature
• Precipitation
Materials
• PCC
• Base
• Subgrade
Traffic
• Axle classification
• Axle loads
Process raw input for PCC distress modeling
Trial Design
Assemble input and trial design information for each distress model
Top-down cracking
•Calculate stresses
•Calculate damage
•Predict top-down cracking
Bottom-up cracking
•Calculate stresses
•Calculate damage
•Predict bottom-up cracking
Faulting
•Calculate deflections
•Calculate damage
•Predict joint faulting
Revise trial design
Compute IRI over Design Period
(Initial IRI, Distress, Climate, Subgrade)
Requirements satisfied?
Yes
No
Design completed

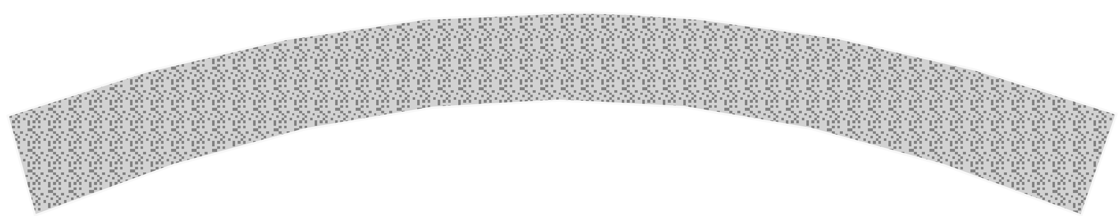
Transverse Cracking--JPCP

Bottom-Up Cracking
Mid-slab Loading—Positive Curl/Warp

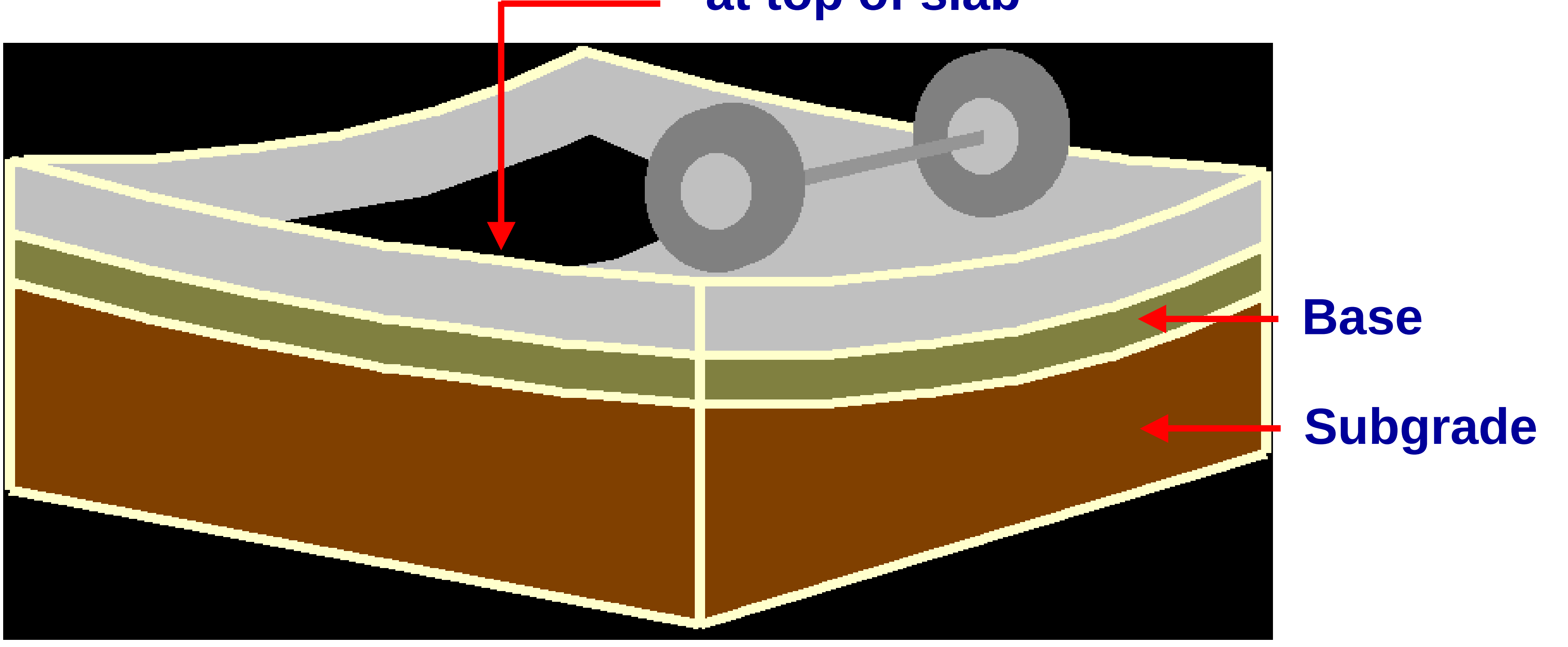


Downward Curling Situation

- Combination of
  - Positive (+) day time thermal gradient
  - Negative (- day placement) or positive (+ night placement) built-in temperature gradient
  - Negative (-) moisture gradient from shrinkage
- Combined gradients can result in downward curling of slab causing tensile stress at bottom of slab and potential bottom-up cracking when combined with traffic load



Top Down Cracking
Joint Loading -- Negative Curl/Warp



Upward Curling Situation

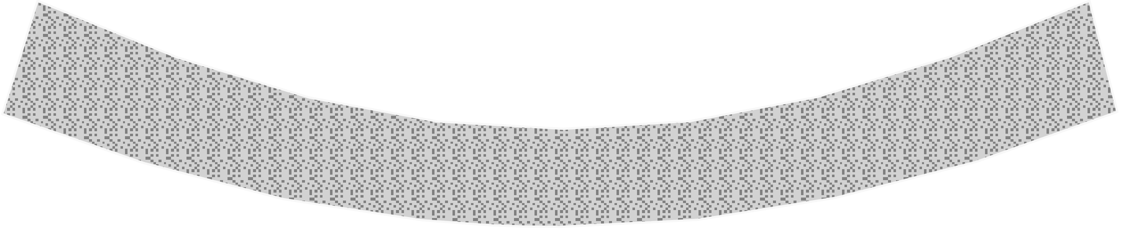
- Combination of

  Negative night time thermal gradient

  Negative or positive built-in temperature gradient

  Negative moisture gradient from shrinkage

- Combined gradients results in upward curling of slab causing tensile stress at top of slab and potential top-down cracking when combined with traffic load



Slab Curling

Top of slab (crack initiation)

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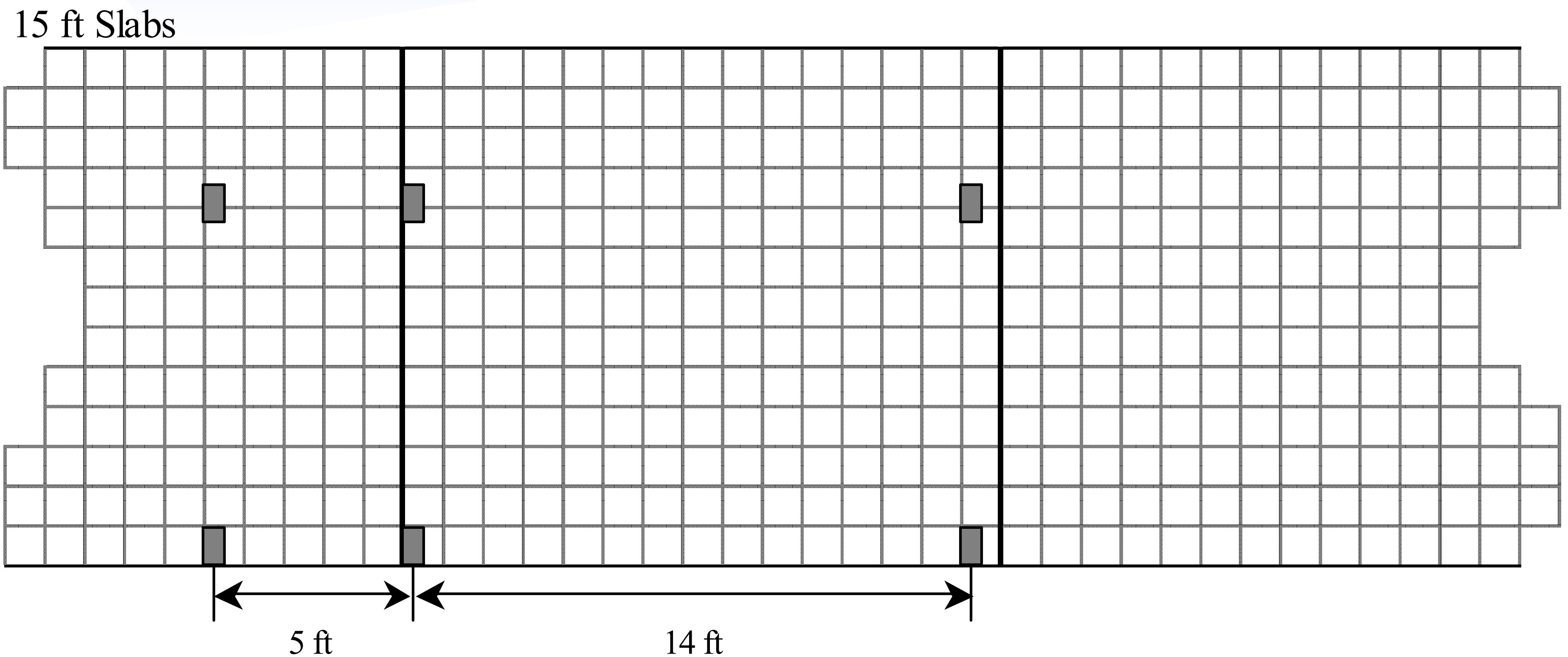
Top-down cracking



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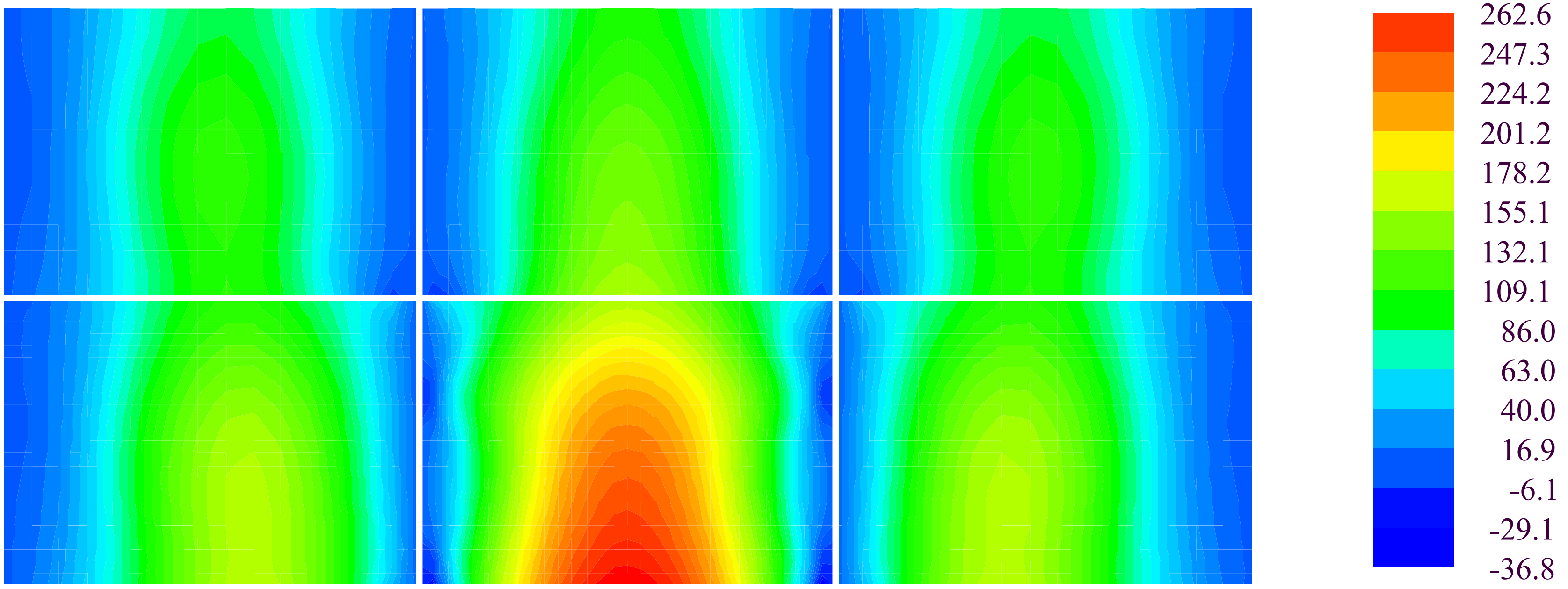
ISLAB2000 Longitudinal Stresses

Stresses in Y-direction



Key Inputs for Cracking (L+M+H)

- Axle type, loading, lateral position, number
- Slab thickness, E, strength, coefficient of thermal exp.
- Base thickness, E
- Slab/base friction
- PCC material properties (strength, E, shrinkage, ...)
- Joint spacing and longitudinal joints LTE
- Slab width
- Permanent curl/warp (built-in temp., perm. Shink)
- Transitory curl/warp (thermal gradients, relative humidity)

Increments for Cracking

Factor	Varies Over Design Life?	Varies Seasonally?	Varies Over Day/Night?
Axle loads	Yes	Yes	Yes
PCC f'r, Ec	Yes	No	No
PCC Shrink	Yes	Yes	No
Temp. Grad.	No	Yes	Yes
Joint LTE	Yes	Yes	Yes
Subgrade E	No	Yes	No

Incremental Damage Accumulation

$$Fatigue\ \ Damage = \sum_i \sum_j \sum_k \sum_l \sum_m \sum_n \frac{n_{ijklmn}}{N_{ijklmn}}$$

where:

n_{ijklmn} = Applied number of load applications at condition i,j,k,…

N_{ijklmn} = Allowable number of load applications at condition i,j,k,…

i = Age | j = Season

k = Axle combination | l = Load level

m = Temperature gradient | n = Traffic path

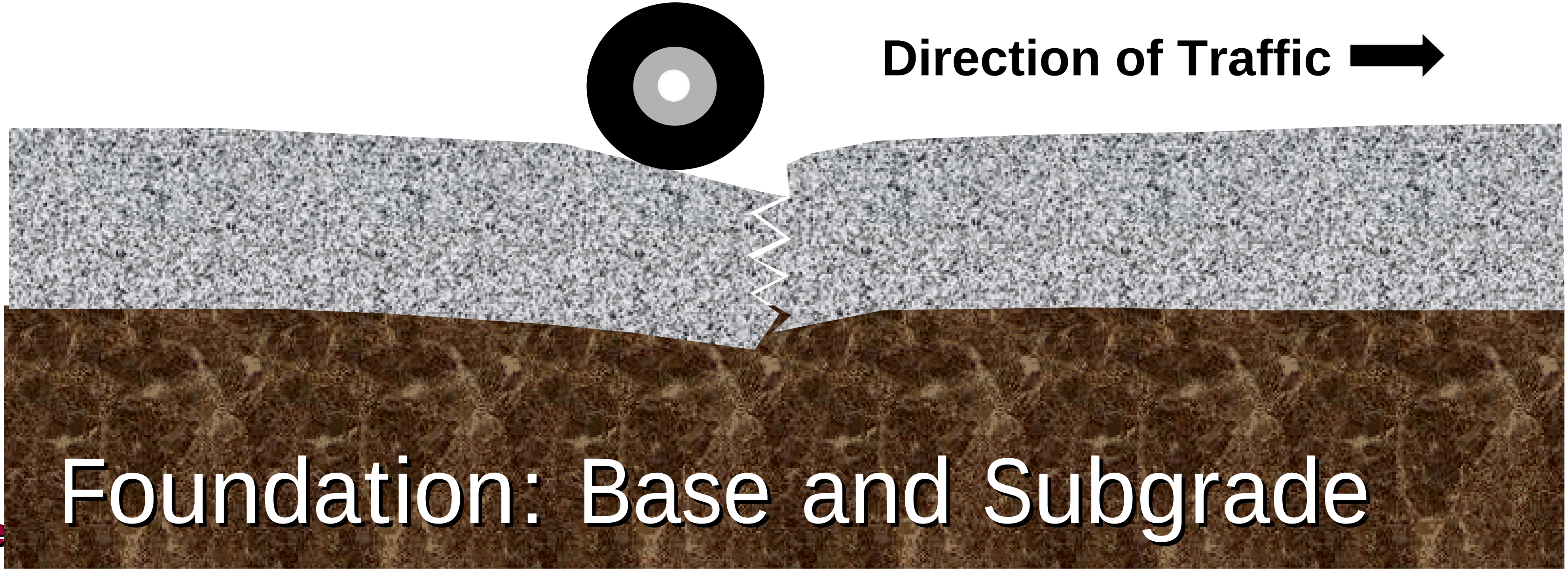
Joint Faulting

Joint Faulting

- Conditions favorable for joint faulting development
  - ✓ High loaded corner deflection
  - ✓ Low joint load transfer efficiency
  - ✓ Erodable base/subbase
  - ✓ Heavy repeated axle loads
  - ✓ Upward curling of slab corners

High Differential Deflection at Joint

- High foundation differential energy and faulting potential
- High differential deflections (and stresses)



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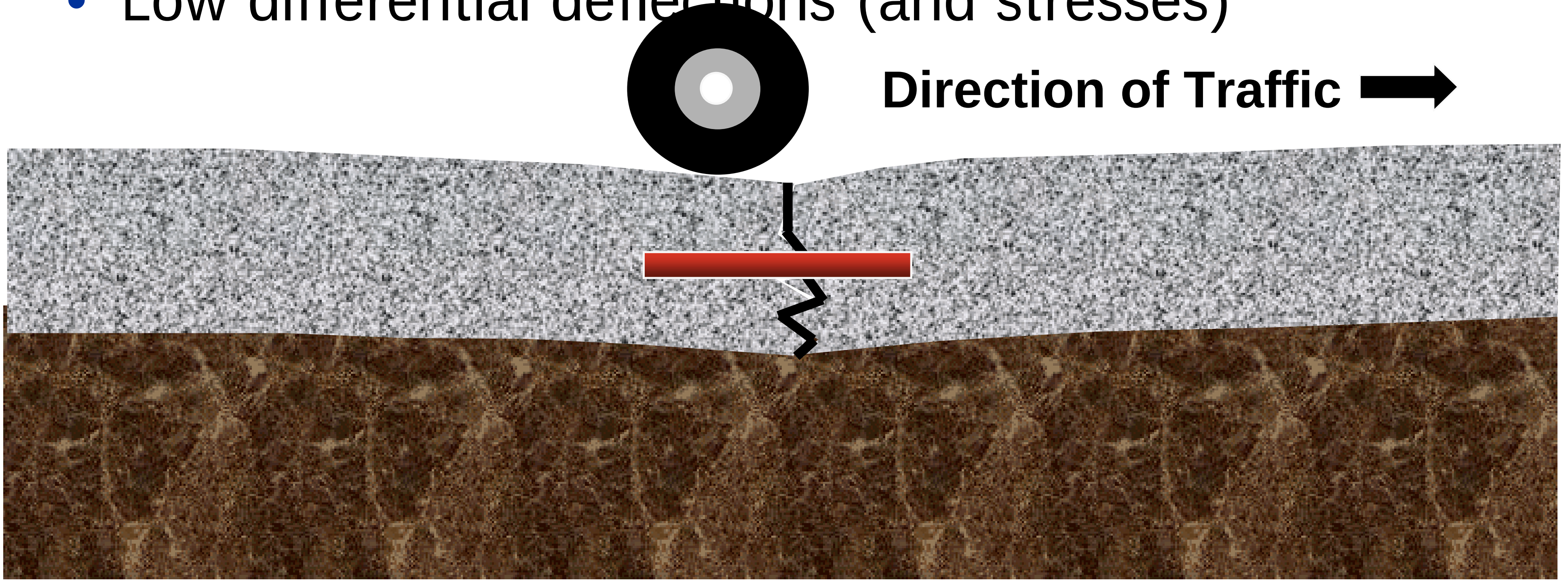
Low Differential Deflection at Joint

- Low foundation differential energy and faulting potential
- Low differential deflections (and stresses)



Joint Faulting Inputs

- Axle type, loading, lateral position, number
- Permanent curl/warp (temp. & moisture)
- Transitory curl/warp (temp. & moisture)
- Slab thickness, E, strength, coefficient of thermal exp.
- Base thickness, E, erodobility
- Subgrade modulus and P200
- Joint spacing, slab width, and dowel spacing/diameter
- Transverse joint LTE, longitudinal joint LTE
- Various climatic parameters

Joint Faulting

- Three mechanisms of load transfer efficiency (LTE)
  - ✓ Aggregate interlock LTE
  - ✓ Dowel LTE
  - ✓ Base/subgrade support LTE

Joint Faulting

- PCC Aggregate Interlock LTE
  - ✓ Depends on aggregate type, maximum size, and joint opening.
  - ✓ Deteriorates with load and time.
  - ✓ Calculated for each increment of time

Joint Faulting

- Dowel LTE
  - ✓ Depends on dowel diameter
  - ✓ Depends on consolidation around dowel
  - ✓ After initial deterioration remains relatively stable with time

Dowel Diameter	LTE
1 in	50-69%
1.25 in	70-84%
1.5 in	85-95%

Joint Faulting

- Base/Subgrade LTE
  - ✓ Depends on base type/stiffness
  - ✓ Depends on base durability
  - ✓ Base Type / LTE

Base Type	LTE
AGG	20-29%
Stabilized	30-49%
Old PCC pvt	50-70%

Joint Faulting

- Combined load transfer efficiency
  - ✓ LTE = 100 -

$$100*(1-LTE_{PCC}/100)*(1-LTE_{Dowel}/100)*(1-LTE_{Base}/100)$$

where

- LTE_{PCC} - PCC aggregate interlock LTE, percent
- LTE_{Dowel} - LTE due to dowels, percent
- LTE_{Base} - LTE due to base/subgrade, percent

Joint Faulting

- Structural response parameter: differential energy density of subgrade deformation, DE

- $DE = k/2\ (Def^2_{loaded} - Def^2_{unloaded})$

- IF LTE=100%, DE=0 (no faulting accum.)
- IF LTE=0 DE= $k\ Def^2_{loaded}$
  (faulting accumulates at maximum rate)

Increments Defined — Faulting

Factor	Varies Over Design Life?	Varies Within Season?	Varies Over Day/Night?
Axle loads	Yes	Yes	Yes
PCC f'r, Ec	Yes	No	No
PCC Shrink	Yes	Yes	No
Temp. Grad.	No	Yes	Yes
Joint LTE	Yes	Yes	No
Subgrade E	No	Yes	No

Faulting Prediction

- Calculate maximum potential faulting (LTE= 0):

$$FAULTMAX = C * D_i * (\log(1 + B * 5^{EROD}))^{0.4} * (\log(\frac{P200 * WetDAYS}{p_s}))^{0.4}$$

- where

C = model parameter =2.5 (calibration)

B = model parameter =100 (calibration)

Di = corner deflection due to curling only, in

P200 = subgrade percentage passing of #200 sieve

EROD - erodobility index (base)

p_s = subgrade overburden pressure, lbf/ft[3]

$$p_s = \gamma_{eff} h_e$$

Faulting Prediction (cont.)

- Calculate faulting increment at the end of each month:

$$DFAULT = A * (FAULTMAX - FAULT)^2 * \sum_{ij} n_{ij} * DE_{ij}$$

DFAULT = faulting increment
FAULTMAX = maximum faulting (zero LTE)
FAULT = current cumulative faulting at month beginning
DEij = differential energy (axle type i and load level j)
nij = number of load repetitions
A = 0.000014 (calibration)

Faulting Prediction (cont.)

- Calculate faulting level at the end of each month:

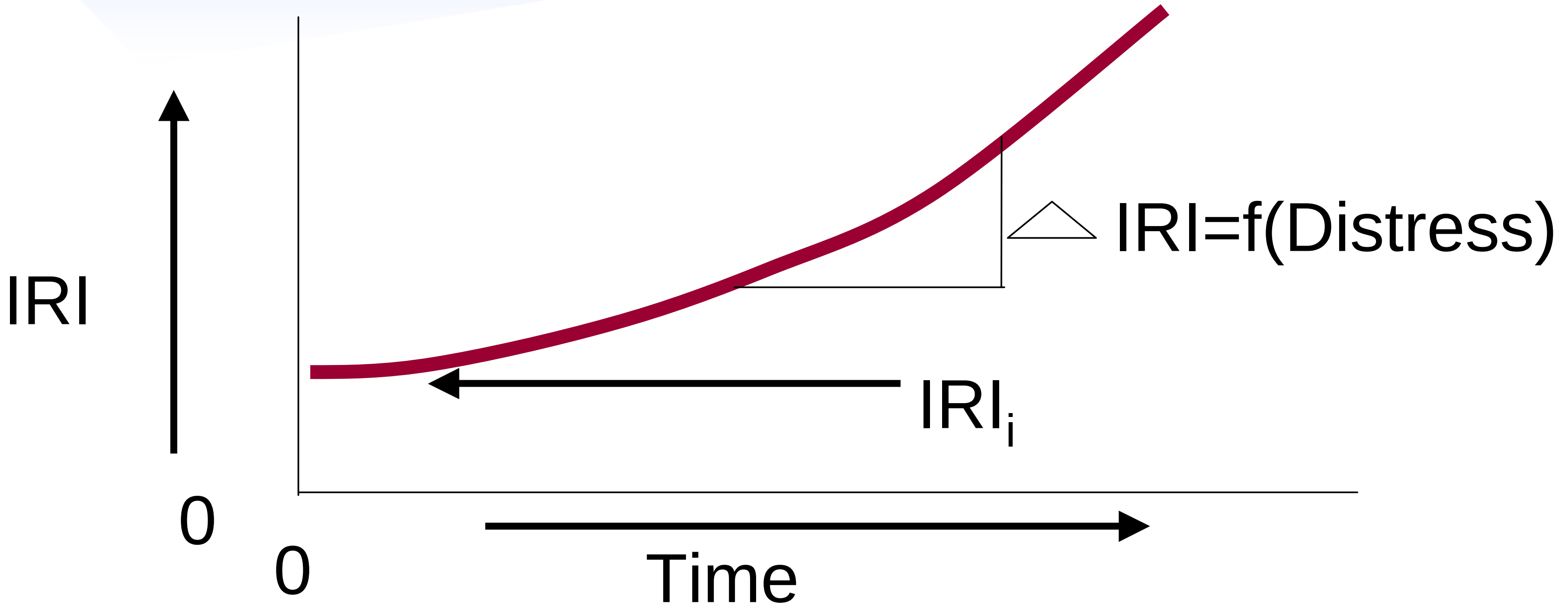
$$FAULT_{l+1} = FAULT_l + DFAULT$$

where

$FAULT_{l+1}$ = faulting level at the end of the month
$FAULT_l$ = faulting level at the beginning of the month
DFAULT = faulting increment

Smoothness Prediction

- Smoothness depends on:
  - ✓ Initial smoothness — specifications
  - ✓ Change in distress — faulting, cracking, spalling
  - ✓ Effect of maintenance activities — patching
  - ✓ Effect of site conditions — subgrade and climate
- Model predicts smoothness loss incrementally (month by month)



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JPCP Smoothness Model

$$IRI = IRI_I + 0.0137CRK + 0.007SPALL + 0.005PATCH + 0.0015TFAULT + 0.04SF$$

where

- IRI_I = Initial IRI, m/km
- CRK = percent slabs with cracking (transverse and corner breaks [all severities])
- SPALL = percentage of joints with spalling (medium and high severities)
- PATCH = area with flexible or rigid patching (all severities), m^2
- TFAULT = total joint faulting, mm/km

JPCP Smoothness Model, cont'd

$$SF = \text{site factor} = AGE^*(1 + FI^{1.5})(1 + P_{0.075})/10^6$$

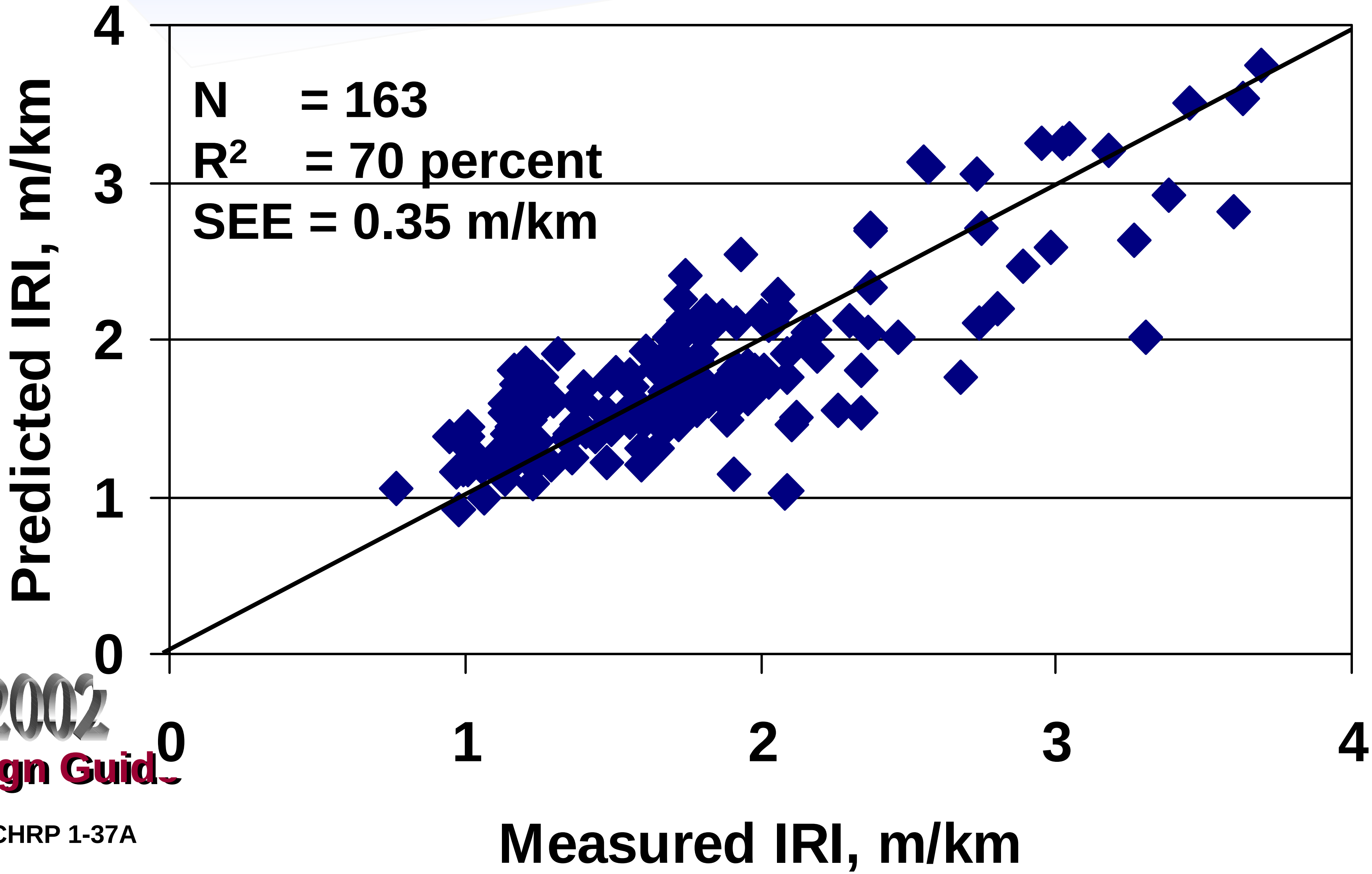
where

AGE = pavement age, yr

FI = Freezing index, °C days

$P_{0.075}$ = percent subgrade material passing 0.075-mm sieve

Measured vs. Predicted IRI for JPCP



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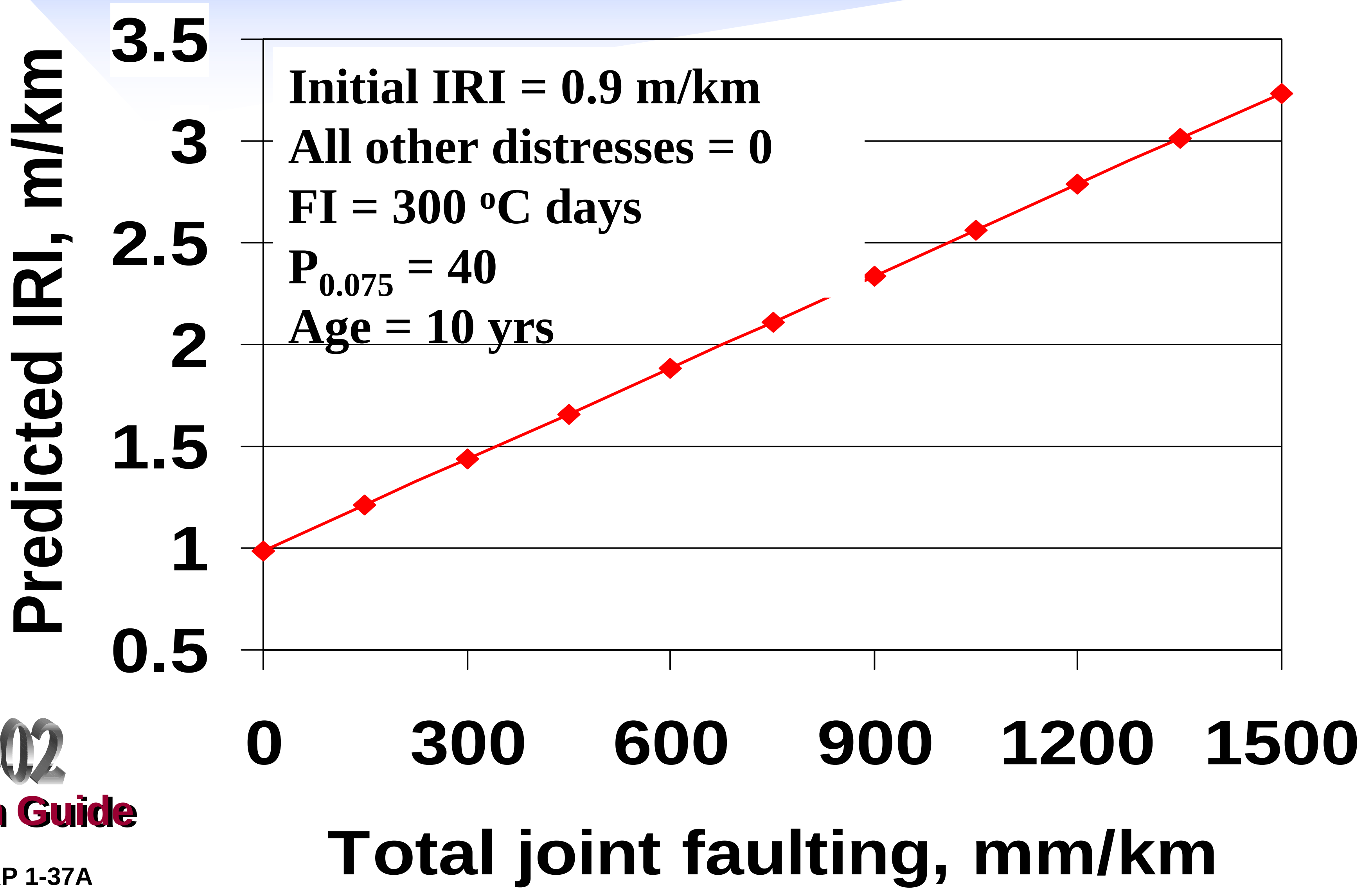
JPCP Smoothness Model Sensitivity Analysis

- Initial IRI
- Cracking (transverse & corner)
- Transverse joint spalling
- Patching
- Joint faulting
- Freezing index
- Percent passing 0.075-mm sieve

Effect of Joint Faulting on JPCP IRI



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Calibration of JPCP Models

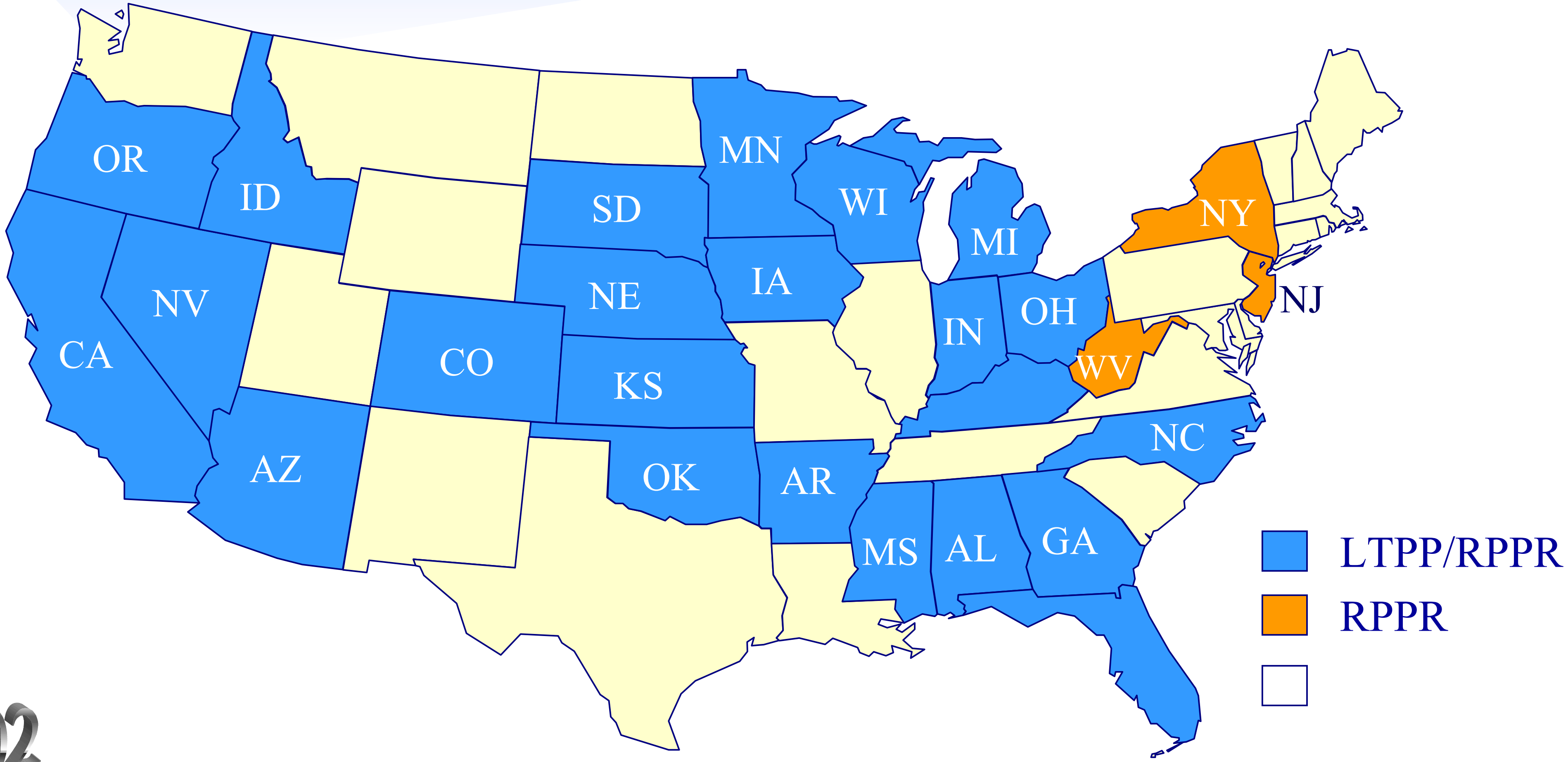
Overview of Model Calibration

- Calibrated performance models:
  Relate calculated damage to actual
  field performance
- Calibration procedure:
  - ✓ Assemble performance database (80/20)
  - ✓ Obtain missing data
  - ✓ Determine model coefficients
  - ✓ Run sensitivity analyses
  - ✓ Modify the model as needed
- Repeat calibration as needed until all problems solved

Calibration of JPCP Models

- Cracking
  - ✓ Total number of cells = 128
  - ✓ 70 percent (89 of the 128 cells) were non-zero
  - ✓ The 89 cells consisted of 295 pavement sections
- Faulting
  - ✓ Total number of cells = 144
  - ✓ 65 percent (93 of the 144 cells) were non-zero
  - ✓ The 93 cells consisted of 295 pavement sections
- 80% data calibration, 20% data validation

JPCP Calibration States (LTPP Data from 23 States)



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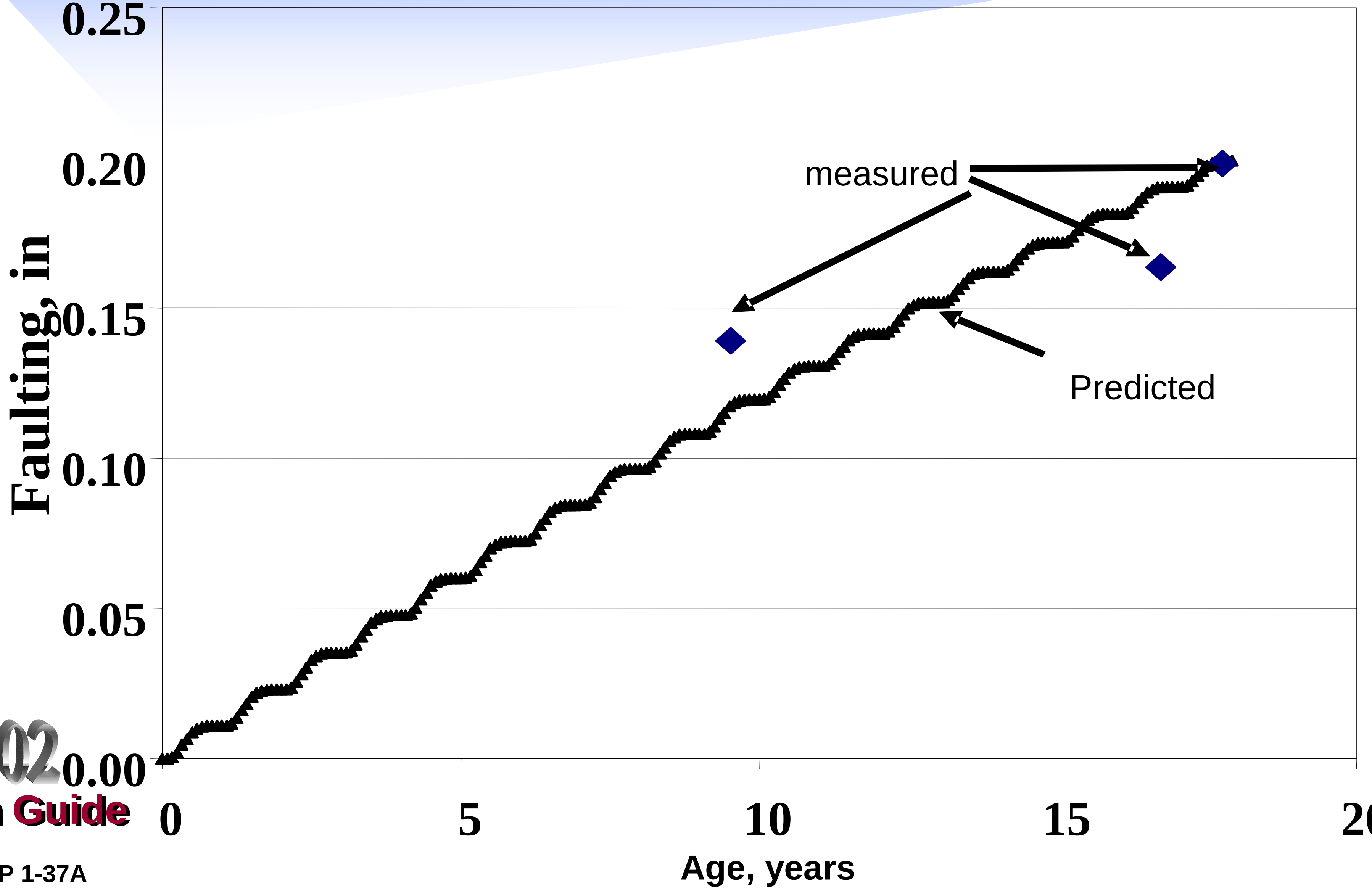
		Climate:	Dry					
			Nonfreeze			Freeze		
		Base Type:	G	S	P	G	S	P
Slab Thick.	Dowels	Edge Support	Faulting					
Low	None	No	0	20	2	5	3	0
		Yes	0	2	0	1	1	0
	Small	No	1	1	1	6	2	2
		Yes	1	1	1	5	2	2
	Large	No	0	0	0	0	0	0
		Yes	0	0	0	0	0	0
High	None	No	0	3	0	3	2	0
		Yes	4	2	0	0	1	0
	Small	No	0	1	0	1	0	0
		Yes	0	1	0	0	2	1
	Large	No	1	1	1	2	2	2
		Yes	1	1	1	2	2	2

		Climate:	Wet					
			Nonfreeze			Freeze		
		Base Type:	G	S	P	G	S	P
Slab Thick.	Dowels	Edge Support	Faulting					
Low	None	No	3	19	1	6	9	5
		Yes	1	4	1	7	3	4
	Small	No	4	7	0	11	7	3
		Yes	0	2	0	8	1	3
	Large	No	1	1	1	1	0	0
		Yes	0	1	0	0	0	0
High	None	No	2	10	0	7	0	0
		Yes	0	4	0	14	2	1
	Small	No	0	7	0	1	3	0
		Yes	2	1	0	3	0	1
	Large	No	1	1	1	4	4	3
		Yes	1	2	1	3	0	4

Sensitivity Study

- Base design - LTPP section 323010 (Nevada)
- PCC thickness = 9.7 in
- CTB base (class C erodobility) = 5.6 in
- Joint spacing = 15.5 ft
- Non-doweled
- P200= 19.45
- Initial AADTT/lane=600
- AADTT/lane=1250 after 15 years
- percentage of trucks = 45 percent

LTPP Section 323010



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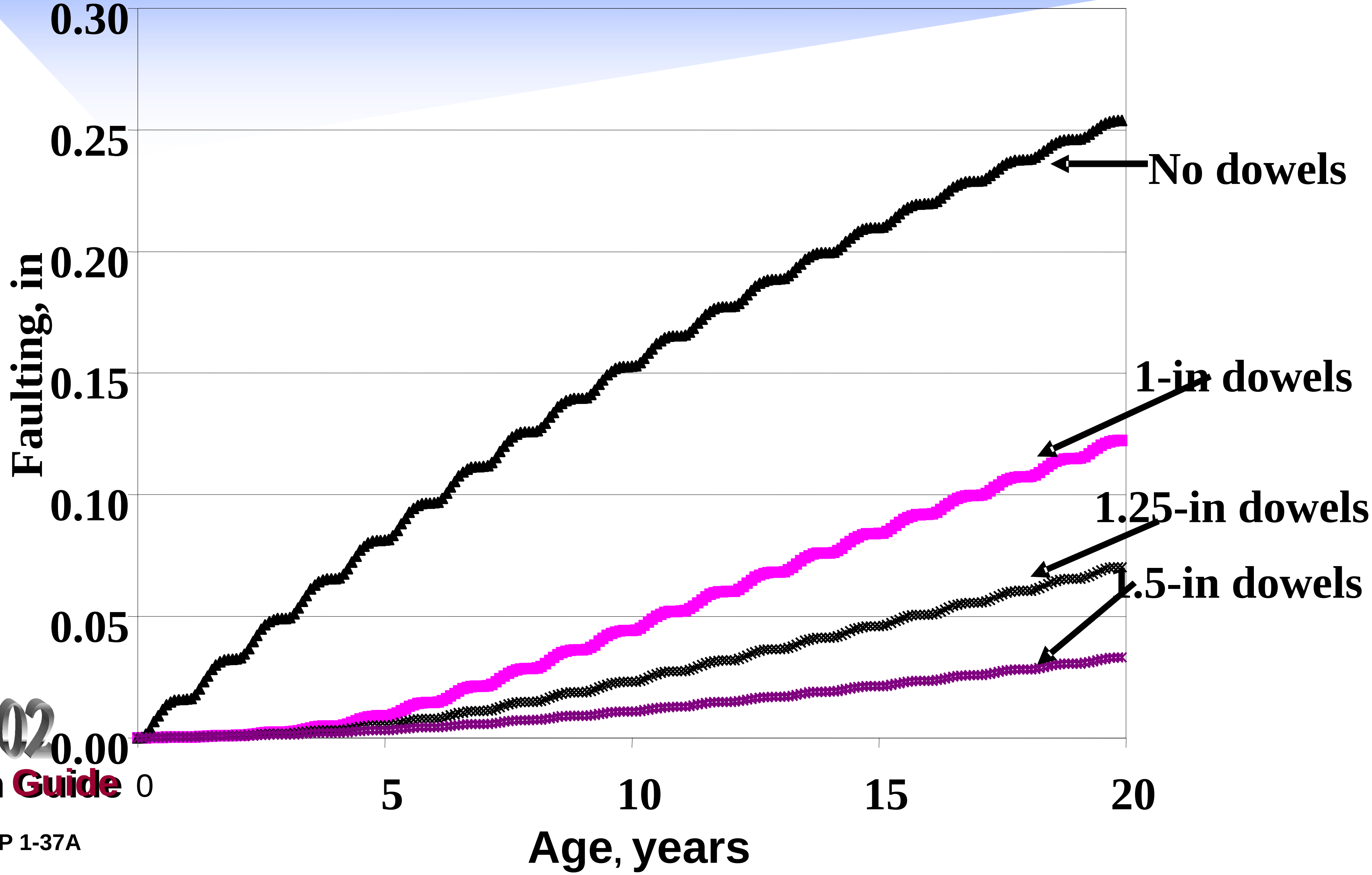
Effect of dowel diameter



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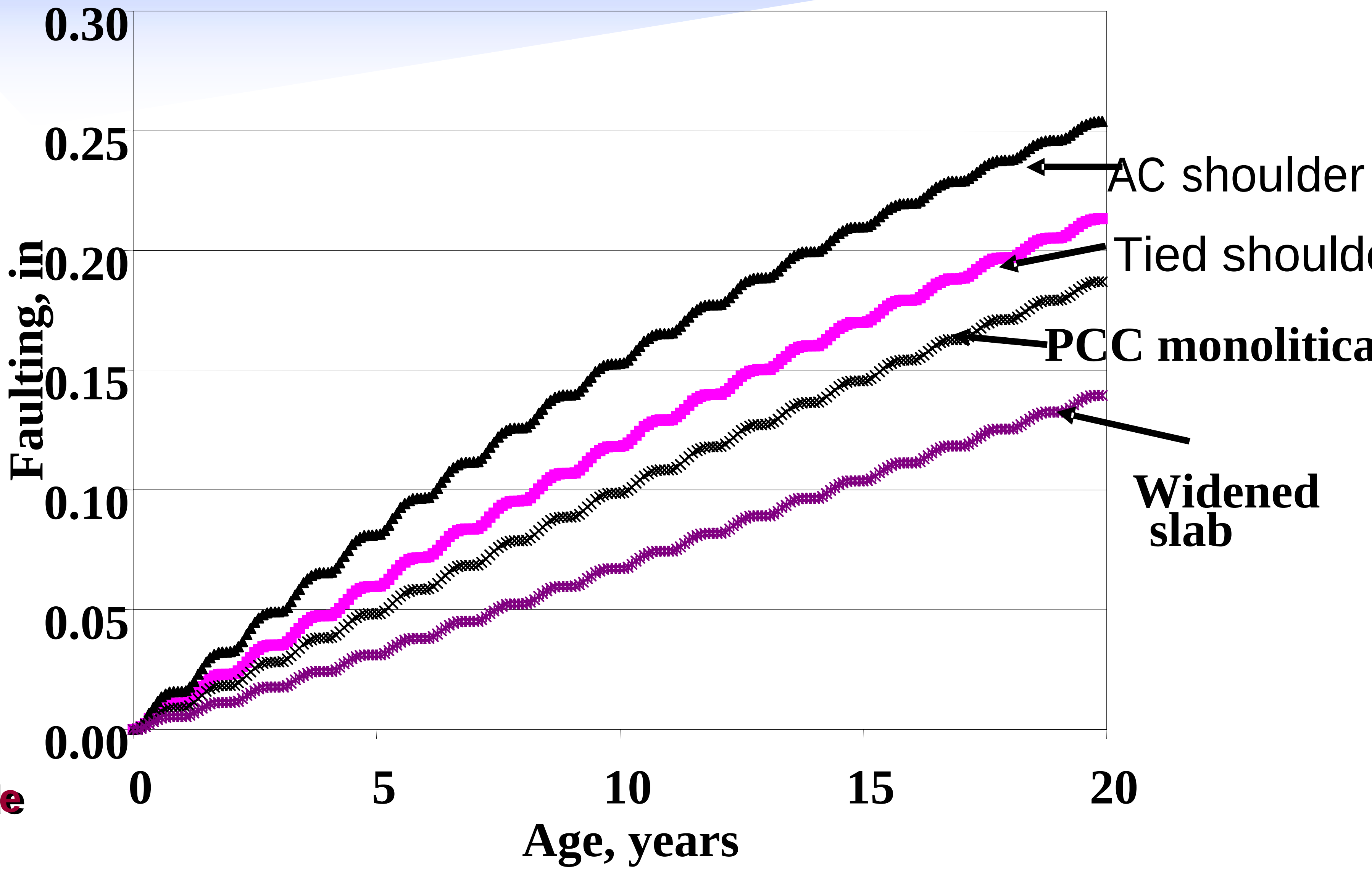
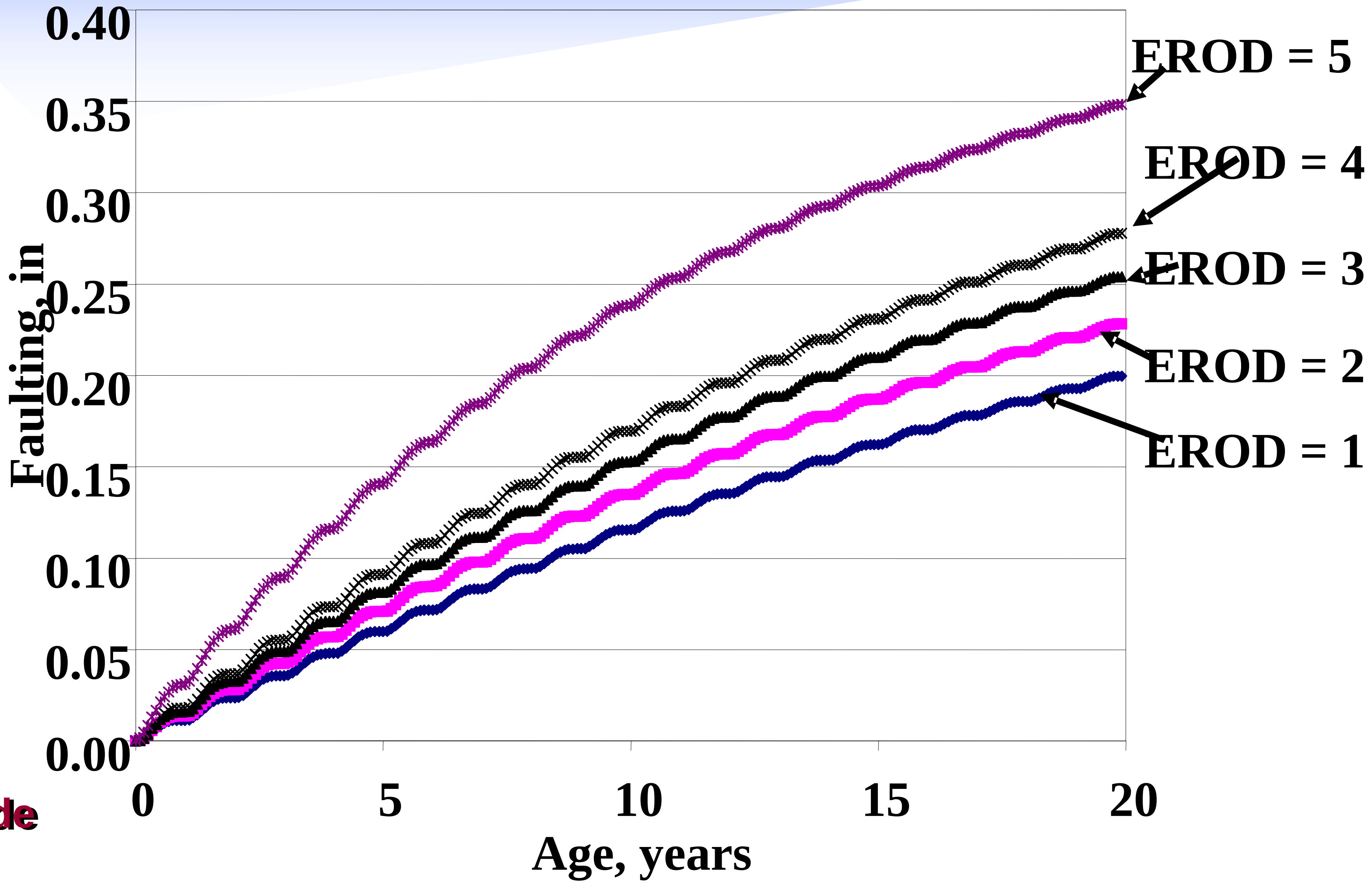
Effect of edge support(non-dowel)



Effect of erodobility (non-dowel)



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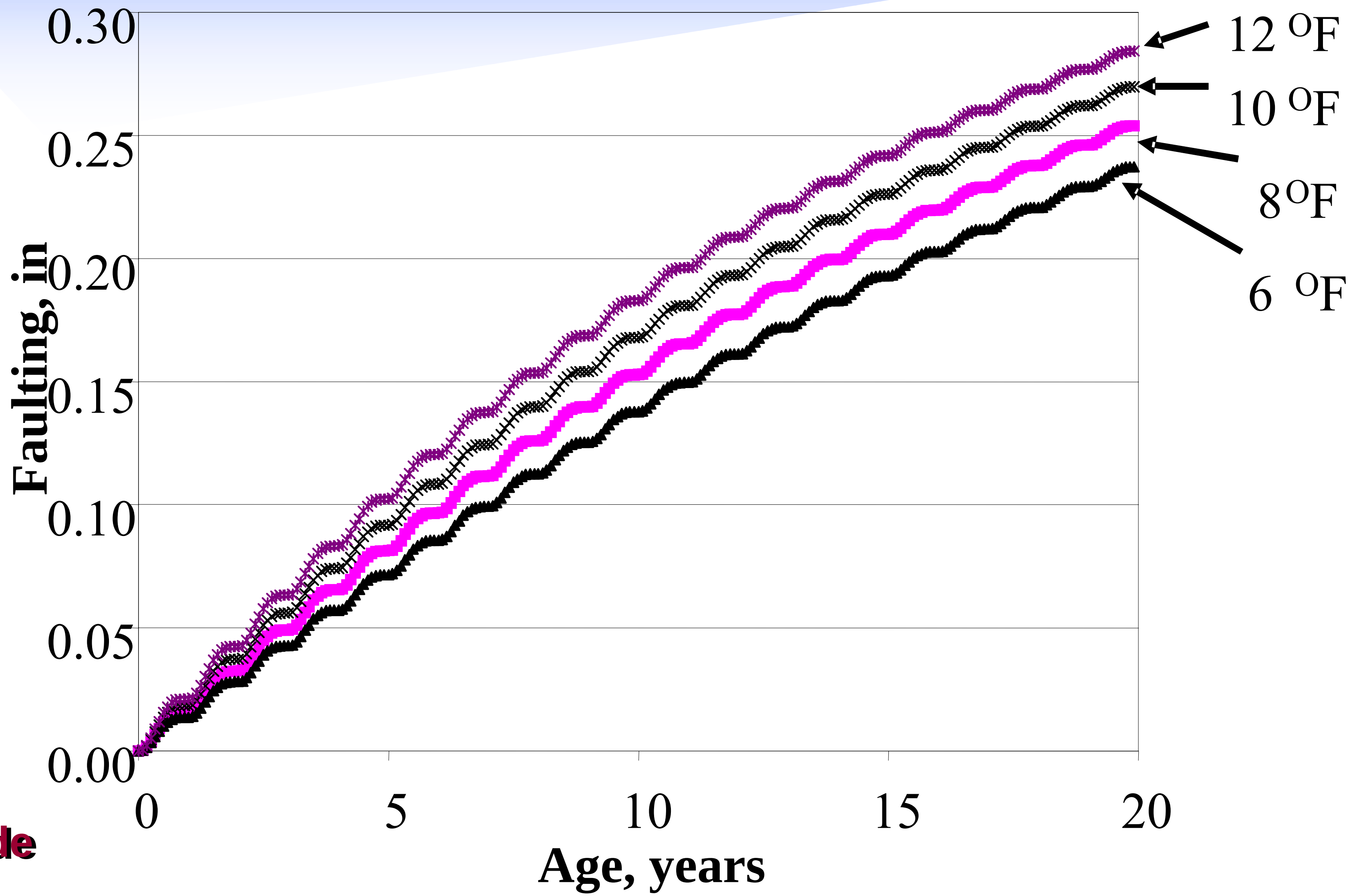
Effect of Built-in Curling



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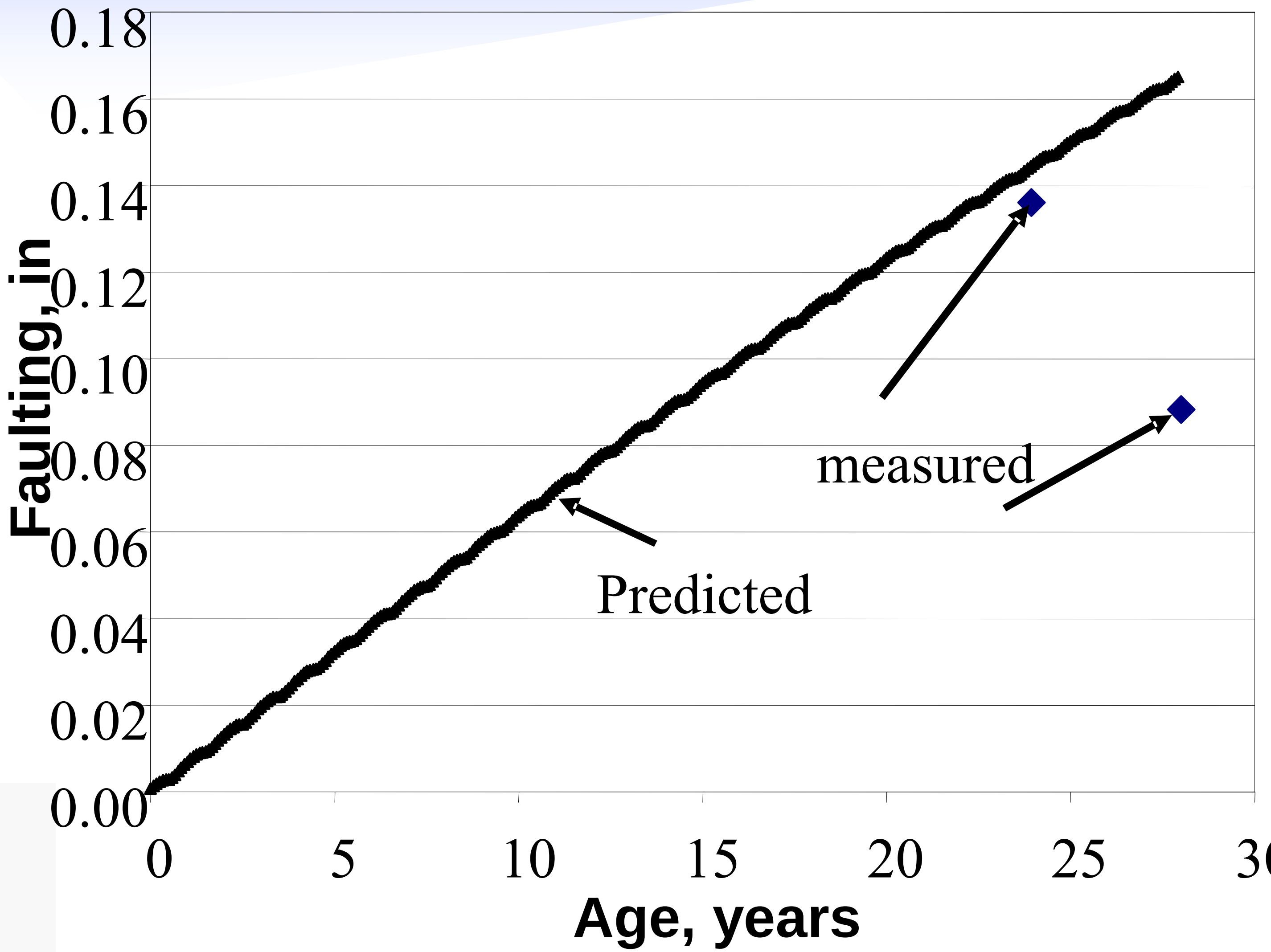
Design Input Parameters
WA Example — LTPP section 533013)

- Trial slab thickness — 8 inch
- Shoulder type — PCC shoulder
- PCC material properties — E_{28} =3,463,000psi
- PCC thermal coefficient — $6.9x10^{-6}$
- PCC ultimate shrinkage — 1326 microstrains
- Base elastic modulus — AGG, 30,600 psi

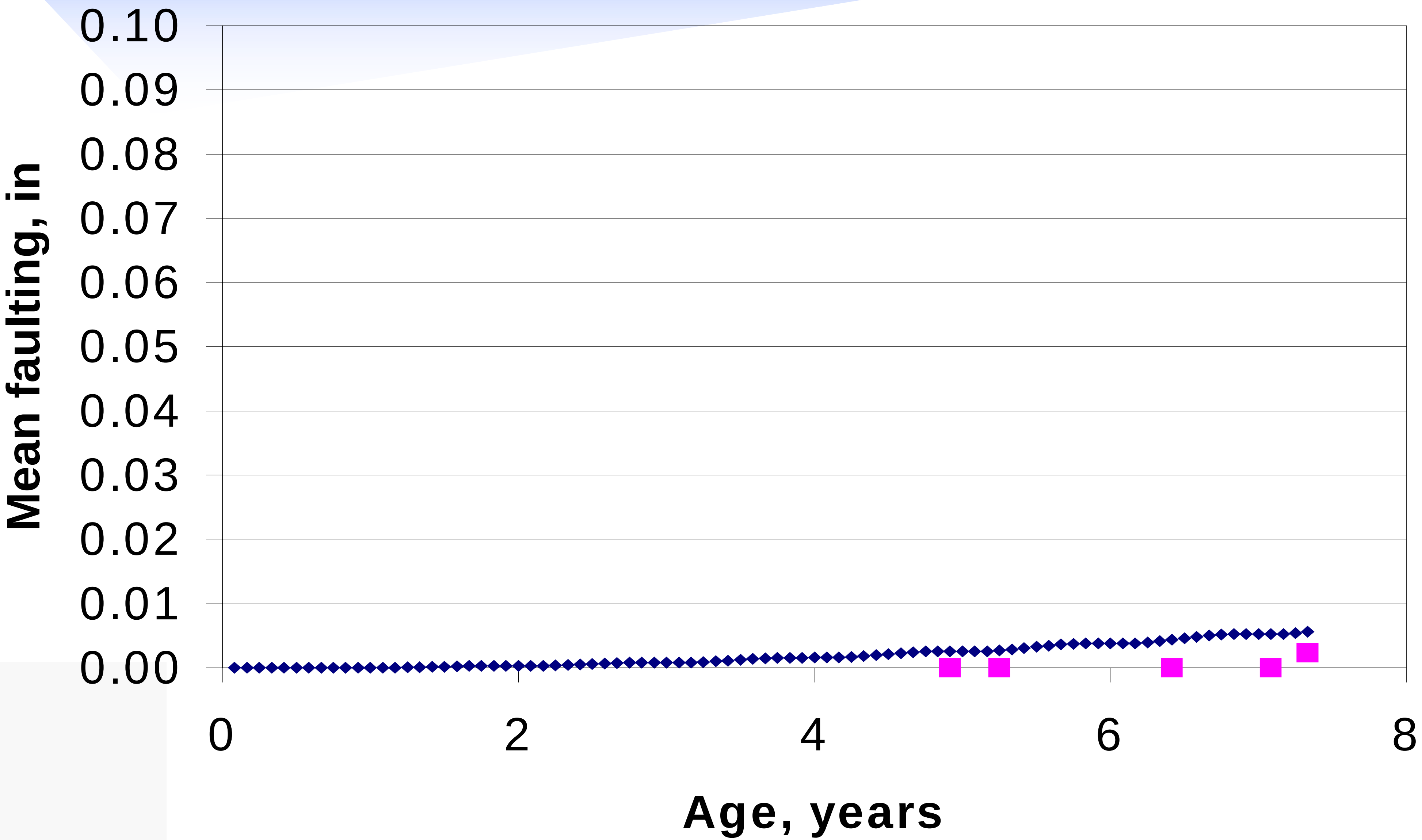
Design Input Parameters WA Example

- Time of construction — February
- PCC temperature at set time — Tset=100oF
- Average number of wet days — 134
- Subgrade % Passing #200 - 37.2
- No dowels

Faulting Prediction — WA Example



Faulting Prediction — Kansas Example

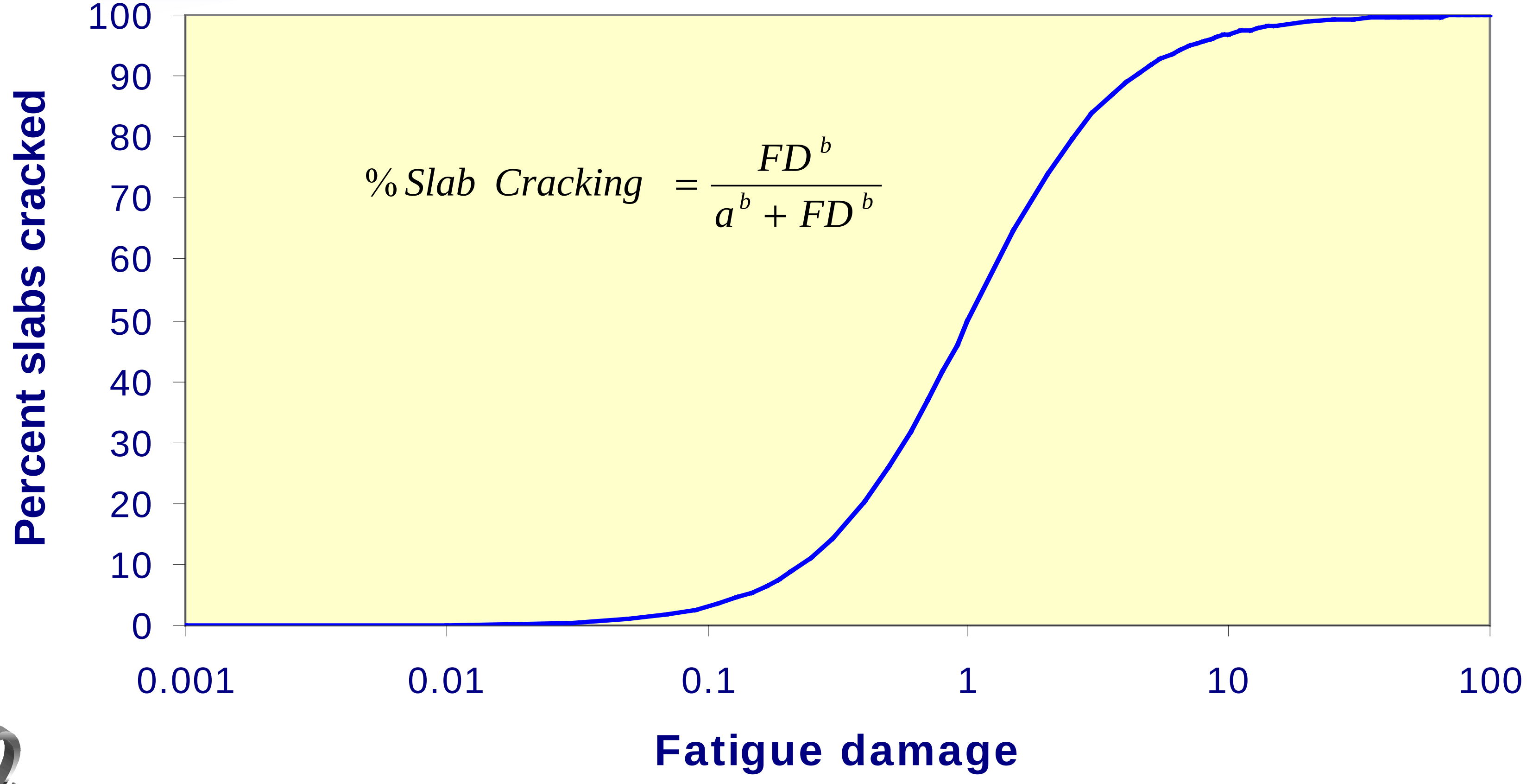


			Climate:	Wet			
				Nonfreeze		Freeze	
			Base Type:	Gran.	Stab.	Gran.	Stab.
Slab Length	Slab Thickness	Doweled	Edge Support	Cracking			
Low	Low	No	No	1	1	0	1
			Yes	1	1	2	0
		Yes	No	3	2	3	6
			Yes	0	1	1	2
	High	No	No	1	9	1	0
			Yes	0	3	0	0
		Yes	No	1	3	3	7
			Yes	1	2	2	1
High	Low	No	No	2	19	6	13
			Yes	0	4	5	7
		Yes	No	2	7	9	4
			Yes	0	2	7	2
	High	No	No	1	1	6	0
			Yes	0	1	14	3
		Yes	No	0	6	2	3
			Yes	2	2	4	4

Calibrated Cracking Model

- Relates the calculated fatigue damage to expected slab cracking
- Obtained by correlating field performance to calculated damage
  - ✓ Characteristic sinusoidal curve
  - ✓ NL optimization conducted to determine best-fit model coefficients

Characteristic Fatigue Curve



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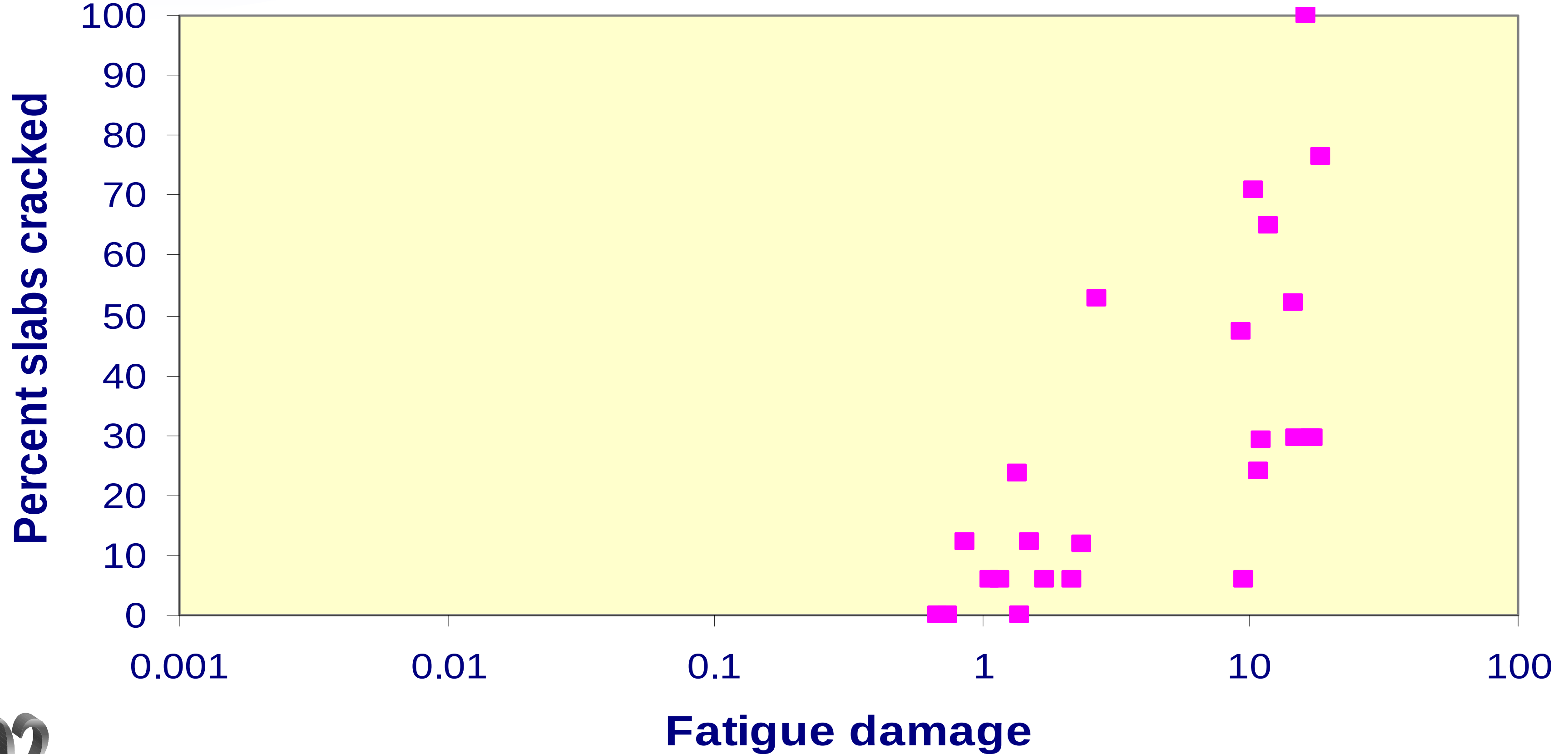
Damage vs. Observed Cracking



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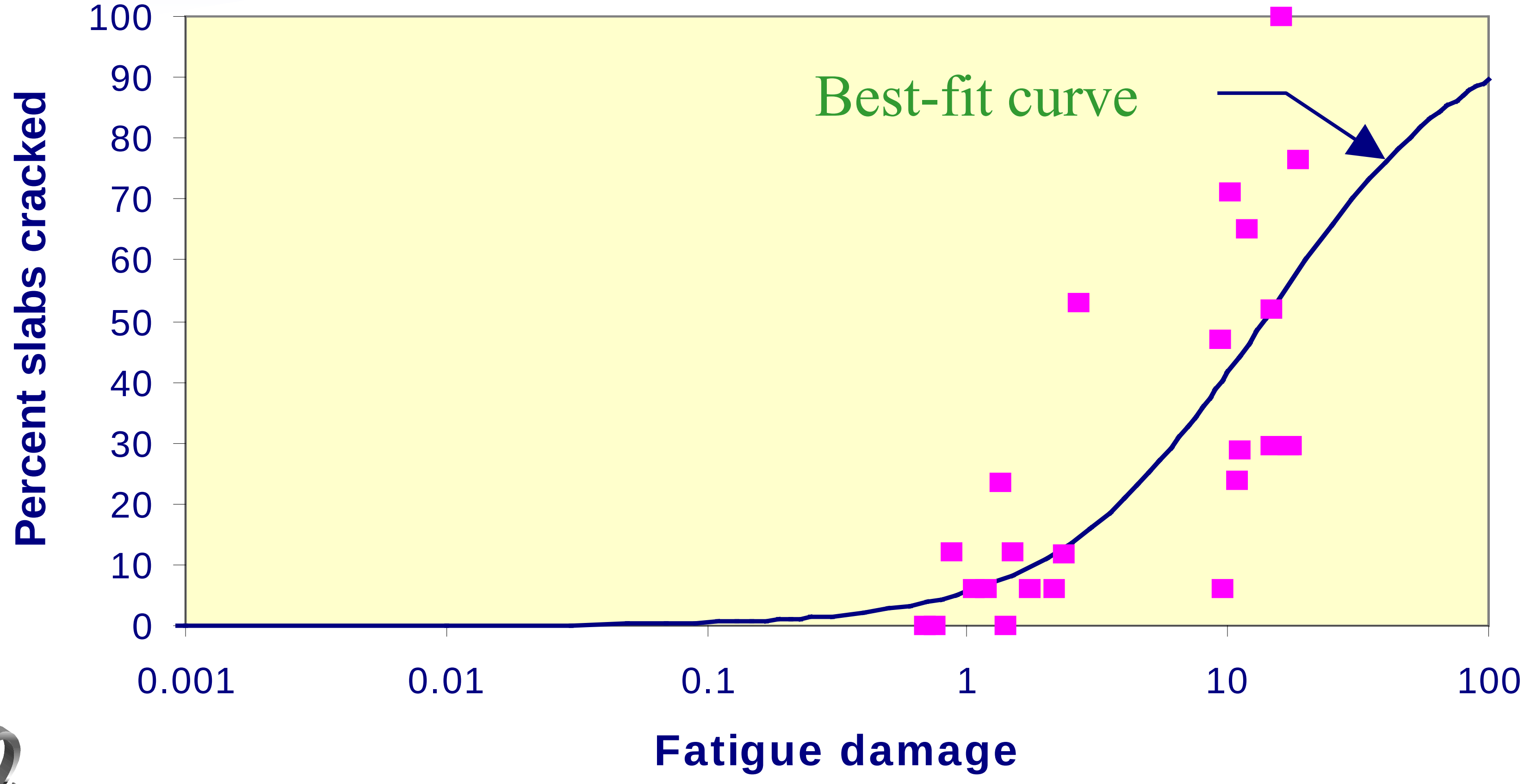
Calibration



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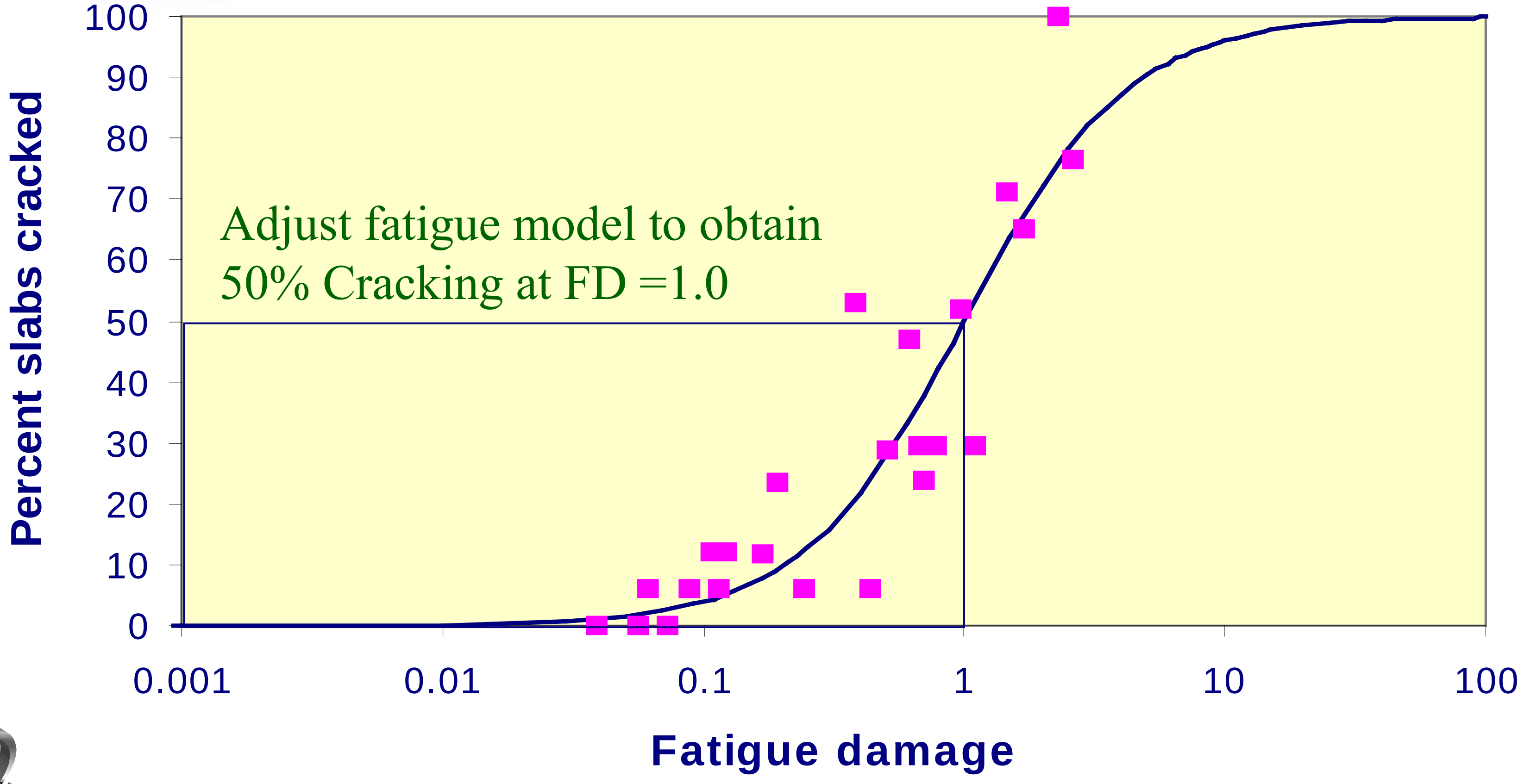
Develop Empirical Relationship to Predict Effective Built-In Curling

$$TG_{BuiltIn} = f\left(Design \ \& \ Site \ Factors\right)$$

- Design factors include
  - ✓ Slab thickness
  - ✓ Base type
  - ✓ Cement type and content
- Site factors include
  - ✓ Temperature
  - ✓ Annual rainfall
  - ✓ Relative humidity

Final Step in Cracking Model Development



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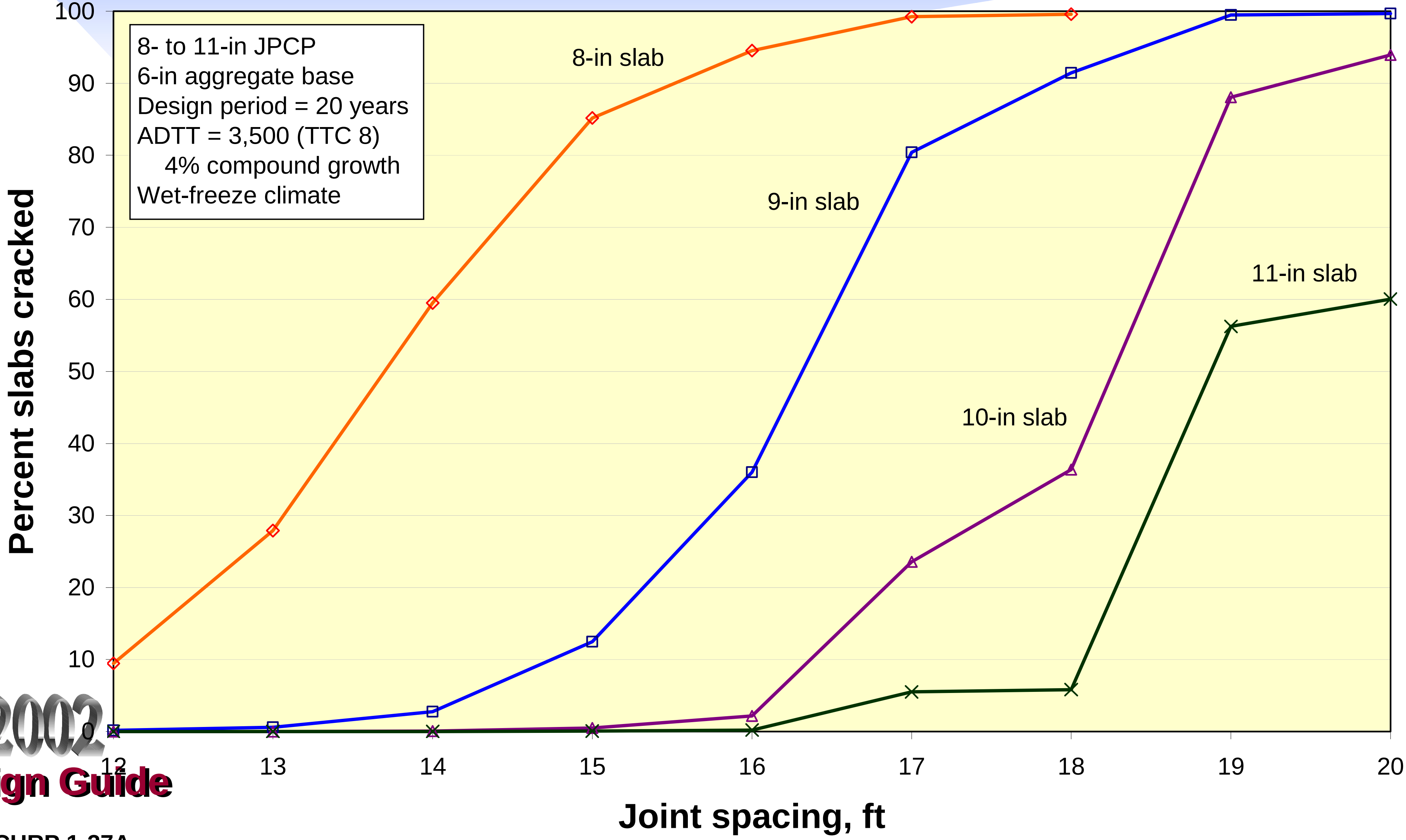
Validation of Performance Models

- Sensitivity study
- Case studies

JPCP Cracking Model Sensitivity

Effects of slab thickness and joint spacing



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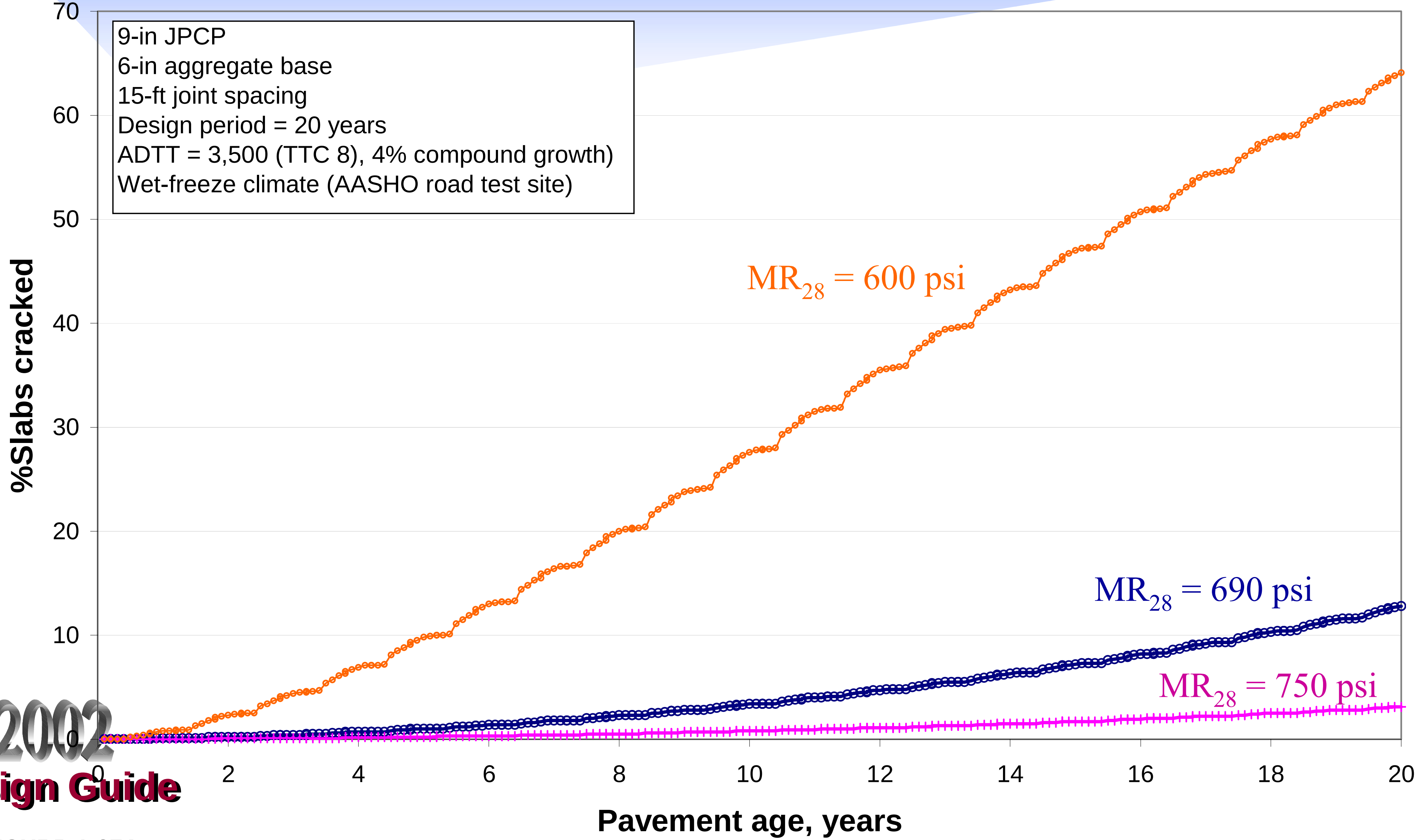
Effects of PCC strength



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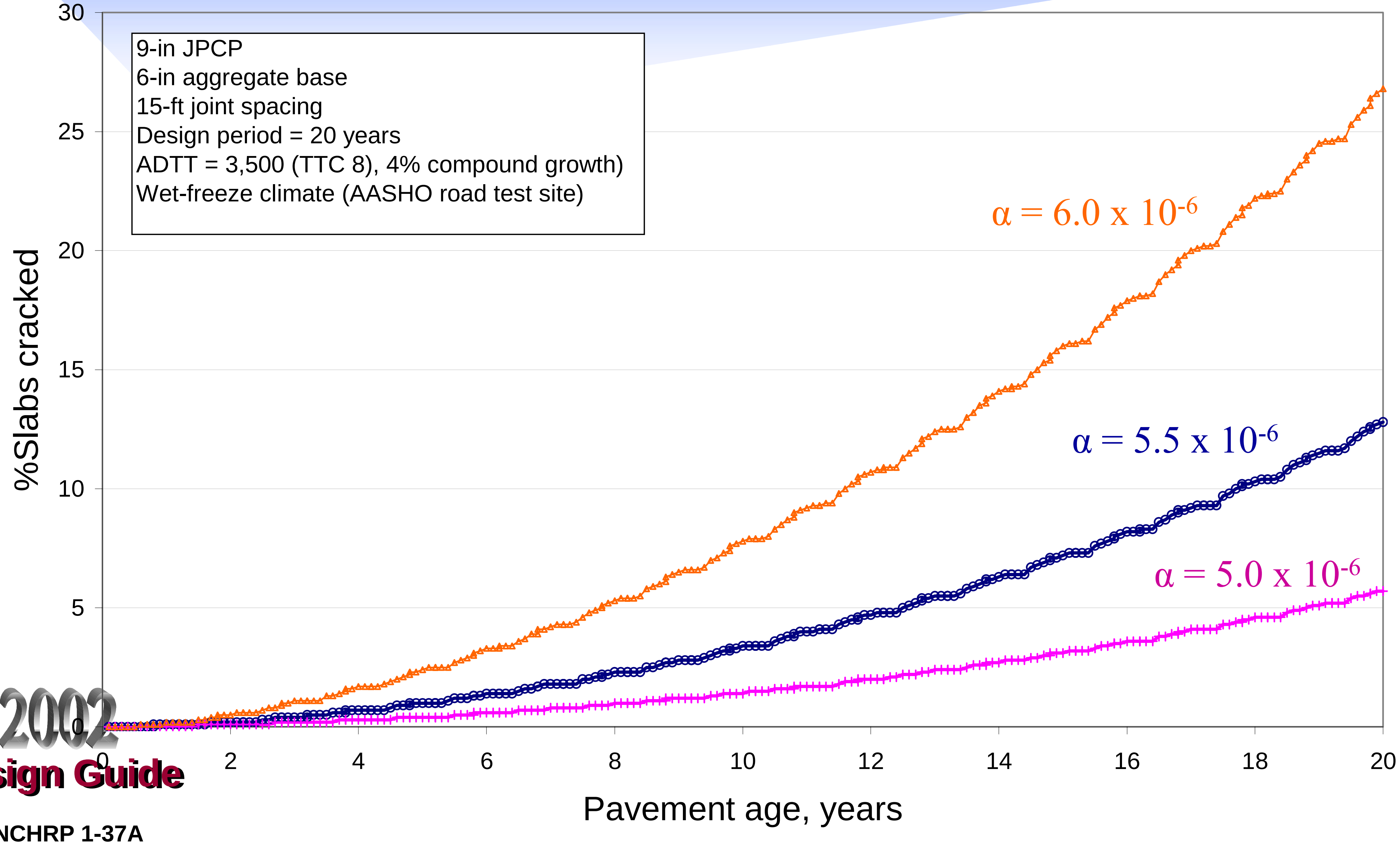
Effects of coefficient of thermal expansion



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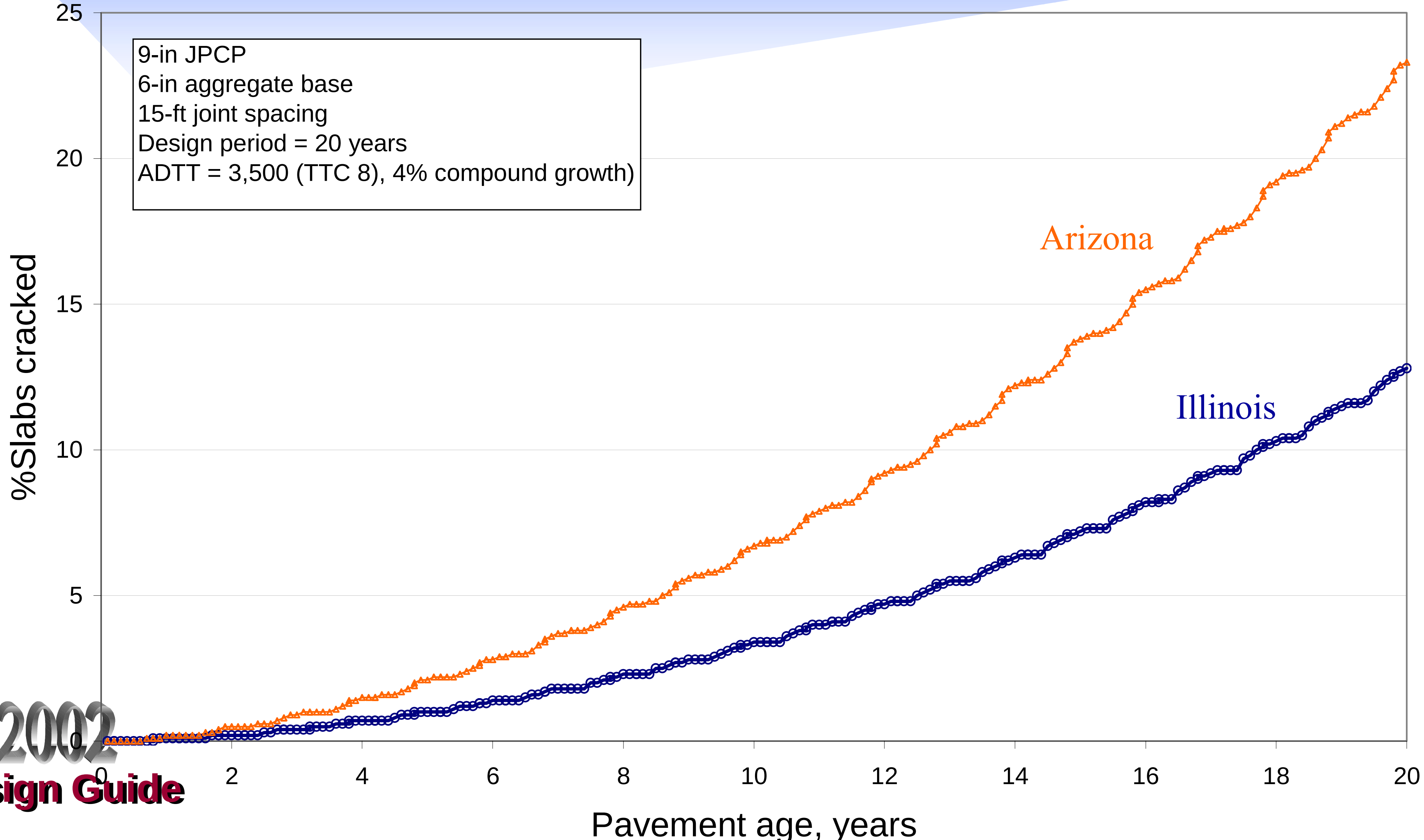
Effects of climate



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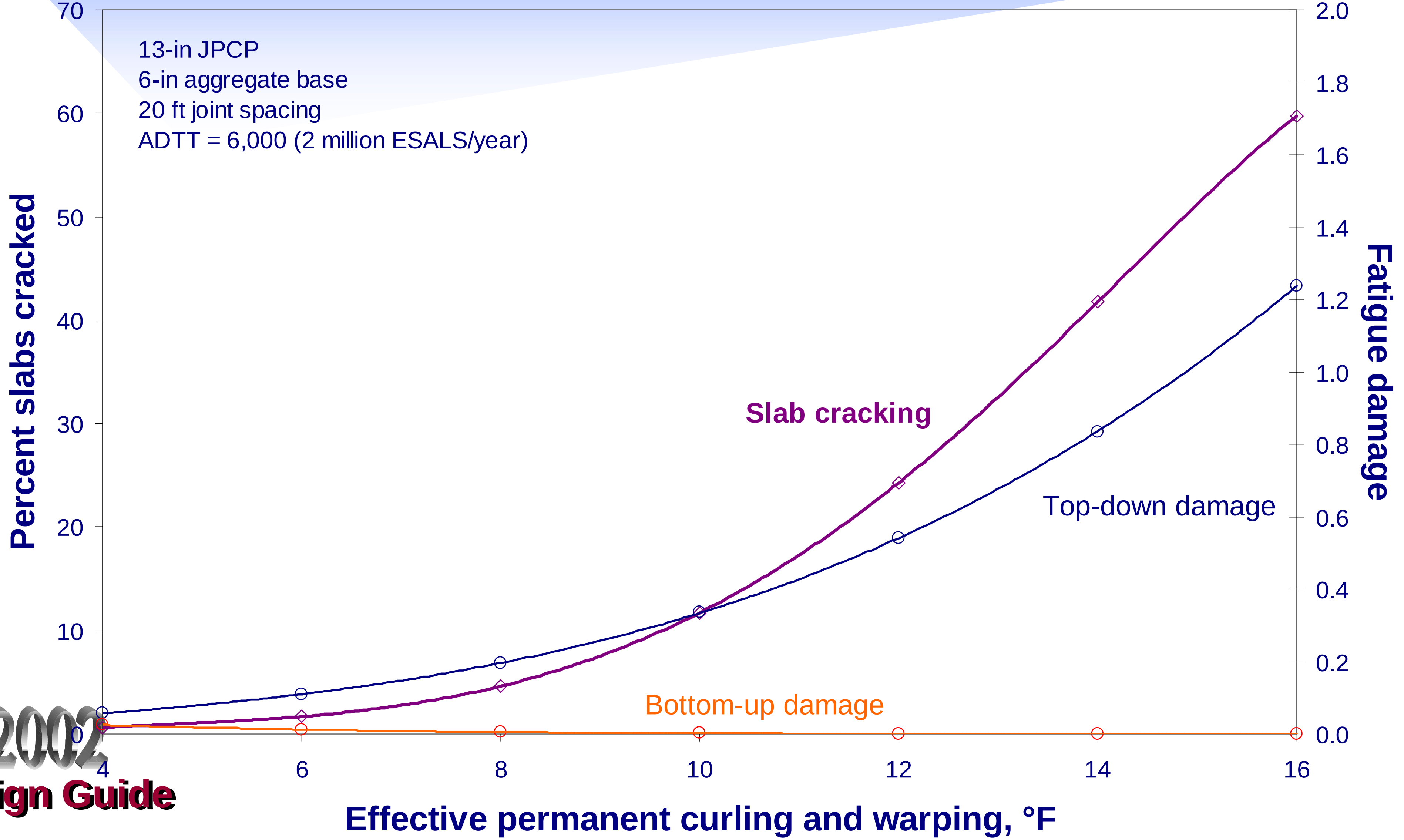
Effects of excessive joint spacing



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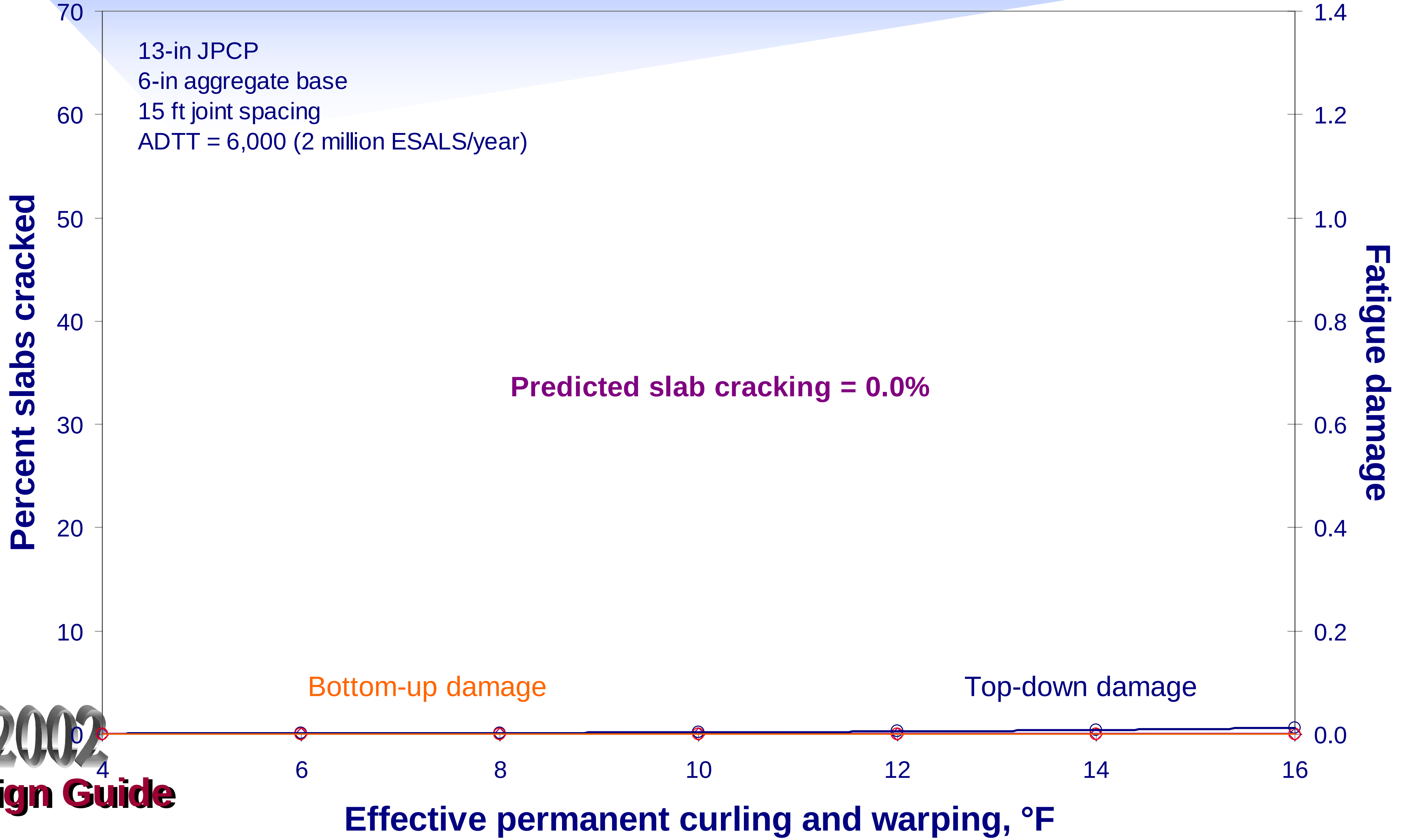
Effects of joint spacing – 15 ft joint spacing



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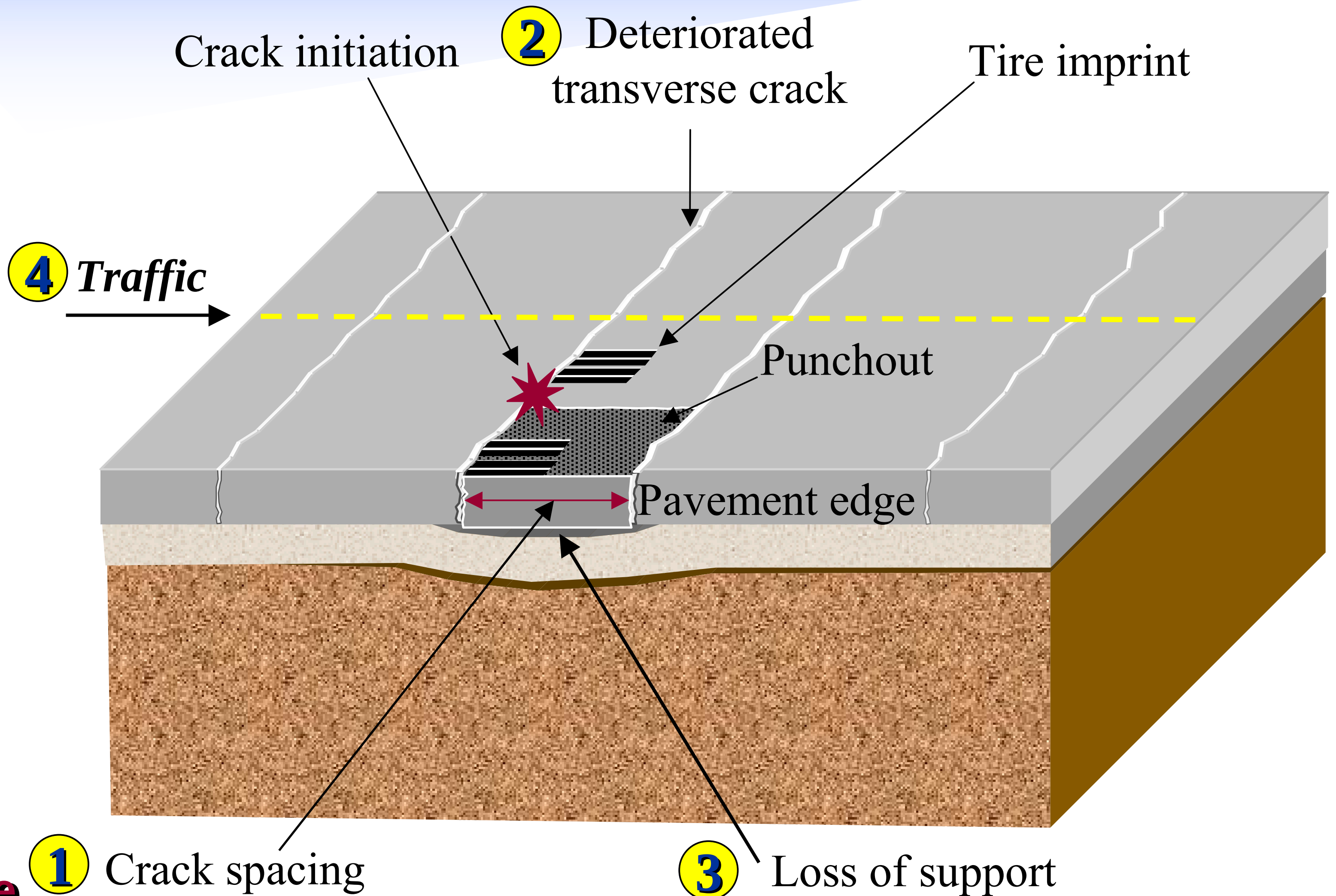
CRCP Design Procedure

Prediction Models

- Development of mechanistic based models of key distresses
  - ✓ Punchout (structural edge failure)
- Development of empirical IRI model
  - ✓ IRI = f — distress, site conditions, patching

CRCP Punchout – Major Structural Distress

CRCP Punchout Mechanism



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Summary

- **Design input levels** (from testing to estimating) provide flexibility. Level used will affect resulting design, reliability, and cost.
- **FEM structural model** has the capabilities to adequately structurally model the key design features, traffic loadings, climatic conditions, and subgrade support.

Summary

- **Incremental damage approach** makes design procedure extremely flexible and robust since material properties, traffic levels, seasonal climatic conditions, and joint load transfer can vary over life.
- **Key distress types** prediction provides a direct means to control them.
- **Estimation of smoothness** (IRI) over time based on initial smoothness and future development of distress and site factors directly considers the highway user.

Summary

- **Local validation and calibration** by lead states is highly recommended to ensure accuracy.