Evolution of Concrete Pavement Design and Construction in the U.S. over the Last 100 Years

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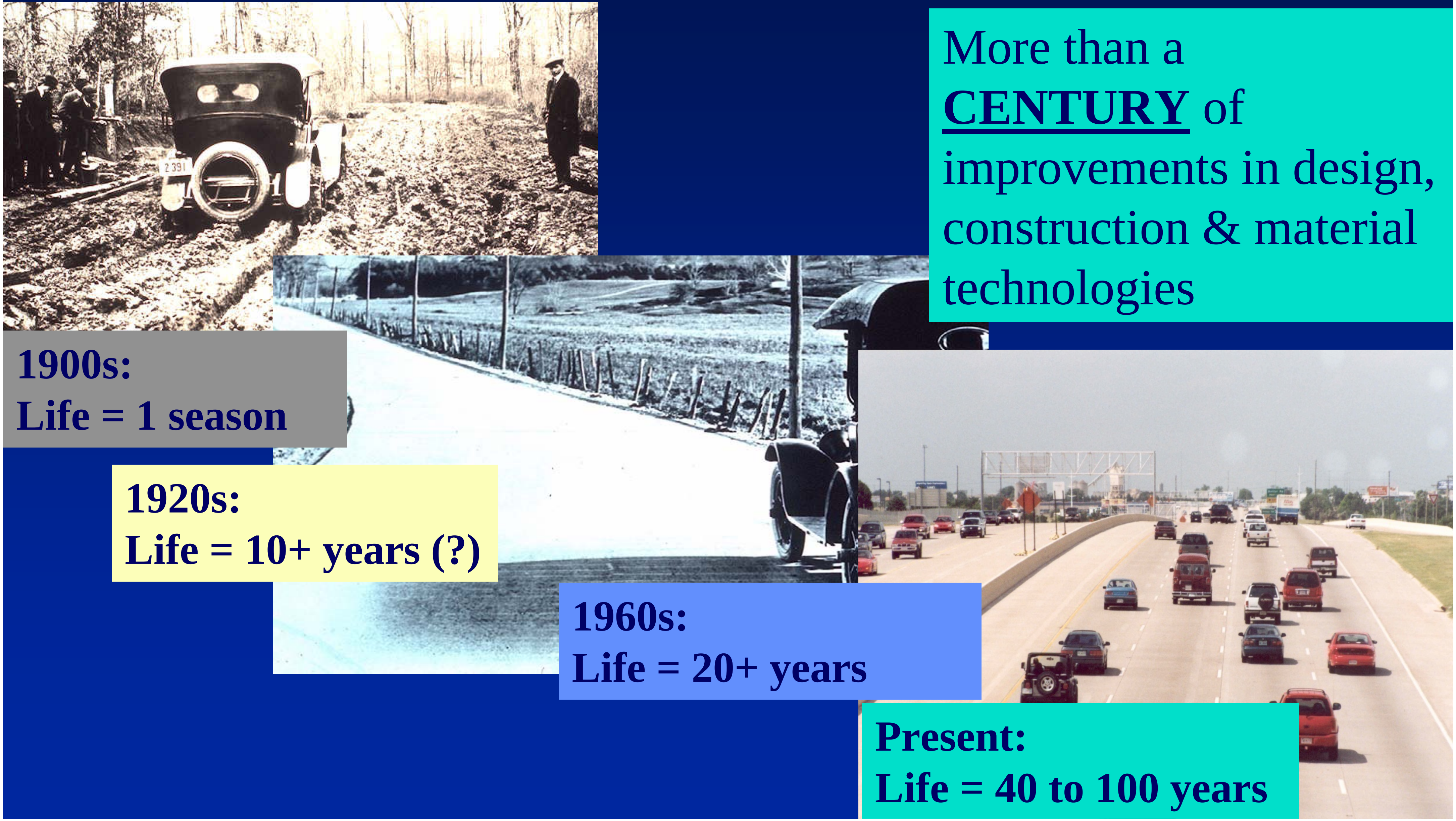
University of Pittsburgh, USA

50^0 Congresso Brasileiro do Concreto – IBRACON 2008

Salvador, Bahia, Brasil – 04 a 09 de Setembro, 2008

PCCP Evolution – A Long Journey



More than a **CENTURY** of improvements in design, construction & material technologies

1900s:
Life = 1 season

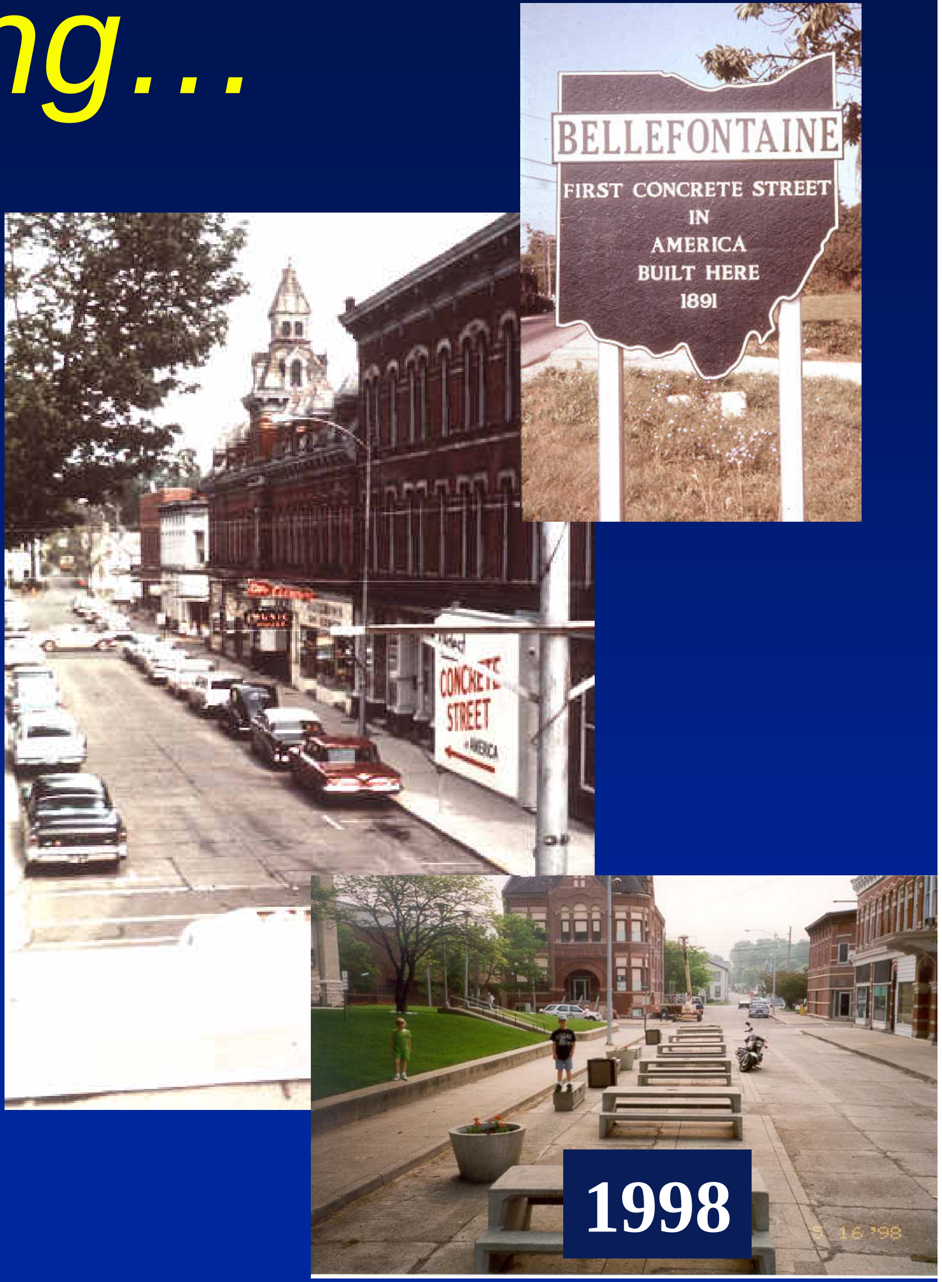
1920s:
Life = 10+ years (?)

1960s:
Life = 20+ years

Present:
Life = 40 to 100 years

In The Beginning…

- First U.S. concrete pavement constructed in 1891
- Two-course construction
  - Hard aggregate on top to resist horseshoe wear
  - Grooved in 100mm squares: surface friction for horses!
- George Bartholomew (builder) posted $5000 bond for 5-year guarantee
- Paved other 3 sides of square in 1893



US Concrete Industry – 1910s - Early Activities

“Seedling” Roads

- By 1916, there were 10,000 autos in the U.S., operating mostly on unpaved roads
- The industry built single-lane, 3-meter wide concrete pavements, hoping that motorists would like them and would lobby for more miles of concrete roads

1910s to 1950s

(Understanding the behavior of concrete pavements)

- Advances in
  - Pavement analysis – understanding the behavior of concrete pavements
  - Early road tests
  - Concrete materials improvements
  - Began to use design features – joints, load transfer, base/subbase

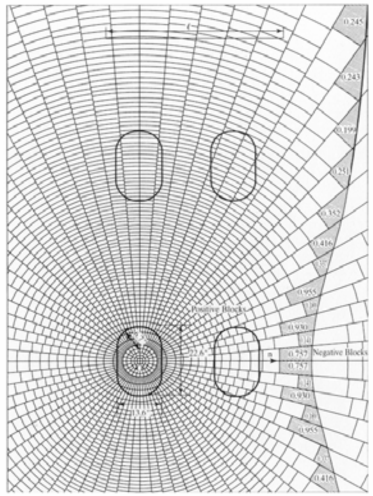
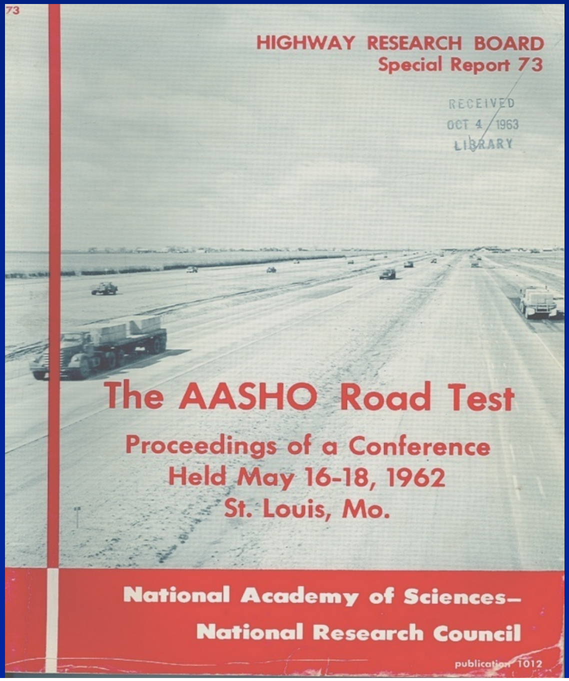


FIGURE 4.12

Application of influence chart for determining moment (1 in. = 25.4 mm) (After Pickett and Ray (1951).)

1956 Interstate Highway Act.

- A 41,000 miles network was planned
- Mostly constructed in the 1960s and 70s; last original segment completed in the 1990s.
- More than 50% concrete (original construction)
- Led to the AASHO road test



73

HIGHWAY RESEARCH BOARD
Special Report 73

The AASHO Road Test

Proceedings of a Conference
Held May 16-18, 1962
St. Louis, Mo.

National Academy of Sciences—
National Research Council

publication 1012


ALASKA
ATLANTIC OCEAN
MEXICO
The National System of INTERSTATE and DEFENSE HIGHWAYS
HOW TO USE THIS MAP
00
100
200
00
YOUR GUIDE TO BETTER MOTORING

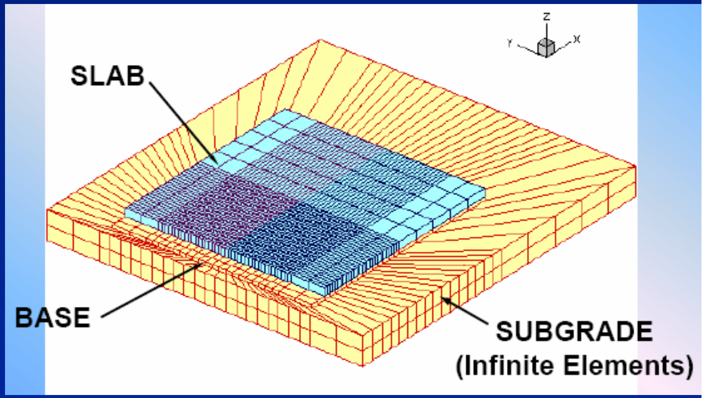
1960s to 1980s - Era of Advancements

(US Interstate Highway Construction)

- Advances in
  - Slip-form paving
  - Concrete mixture improvements
  - Improved design features – good bases, dowels at joints, good drainage, concrete shoulders, etc
  - Finite element analysis techniques – KENSLAB, ILLI-SLAB, JSLAB

1990s to Present

Focus on Rehabilitation & Reconstruction



- Heavier loadings
  - o Highway truck loadings
  - o Heavier aircraft loadings
  - o Heavier off-highway loadings
- Advances in
  - o 3-D finite element analysis
  - o M-E pavement designs
  - o Advances in concrete materials
  - o Advances in construction equipment
  - o Advances in repair & rehab technologies
  - o Advances in process control and acceptance testing

US Concrete Pavement Types

- Jointed plain concrete pavement (most popular)
- Jointed reinforced concrete pavement (infrequent use)
- Continuously reinforced concrete pavement

- Roller compacted concrete pavement
- Whitetopping (resurfacing of distressed asphalt pavement)

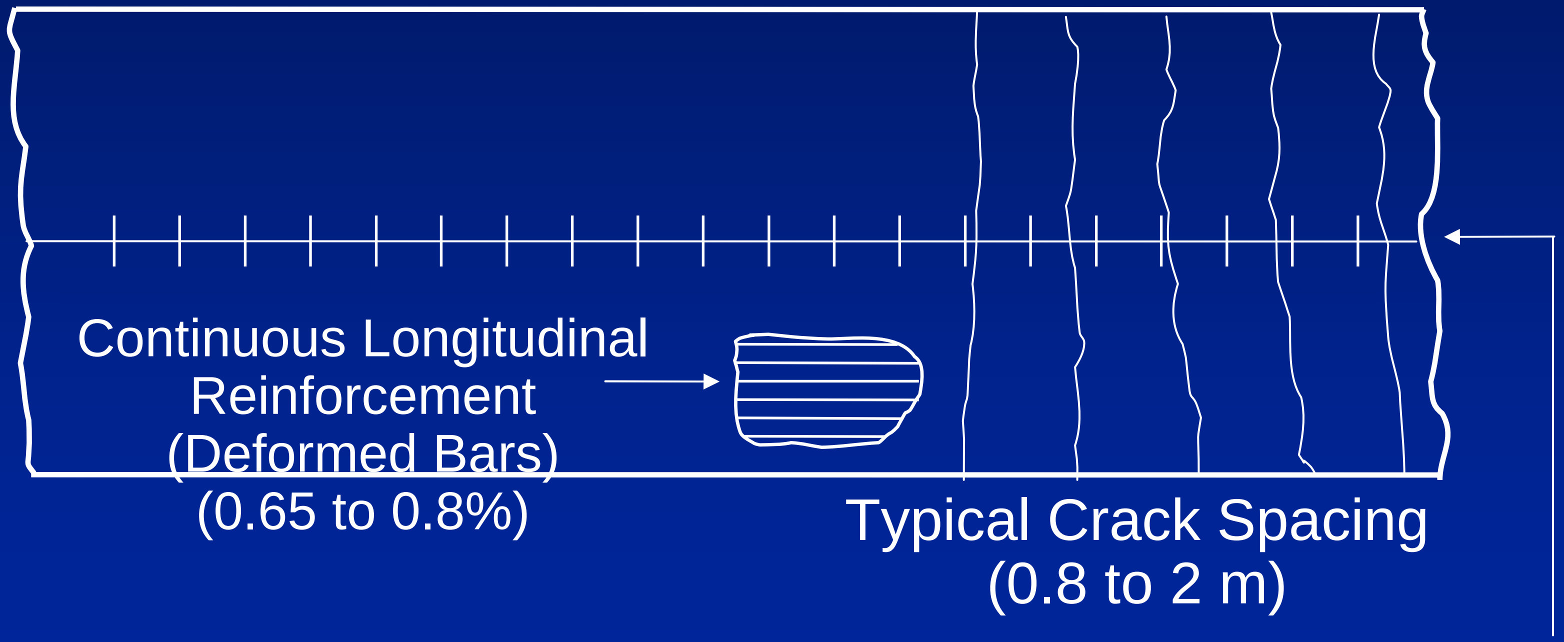
- Prestressed concrete pavement
- Precast concrete pavement

US Jointed Concrete Pavements

- Jointed plain concrete pavement
  - ~ 4.6 m joint spacing
  - t = 150 mm (streets) to 200 to 250 mm (secondary roads) to 300 to 350 mm (primary & interstate systems)
  - Dowels for medium/heavy volume of truck traffic
- Jointed reinforced concrete pavement (not widely used now)
  - 12 to 25 m joint spacing
  - mid-slab cracking anticipated
  - steel: 0.15 to 0.20%;
  - Dowel bars at all transverse joints

US Continuously Reinforced Concrete Pavements

PLAN VIEW



Continuous Longitudinal Reinforcement (Deformed Bars) (0.65 to 0.8%)

Typical Crack Spacing (0.8 to 2 m)

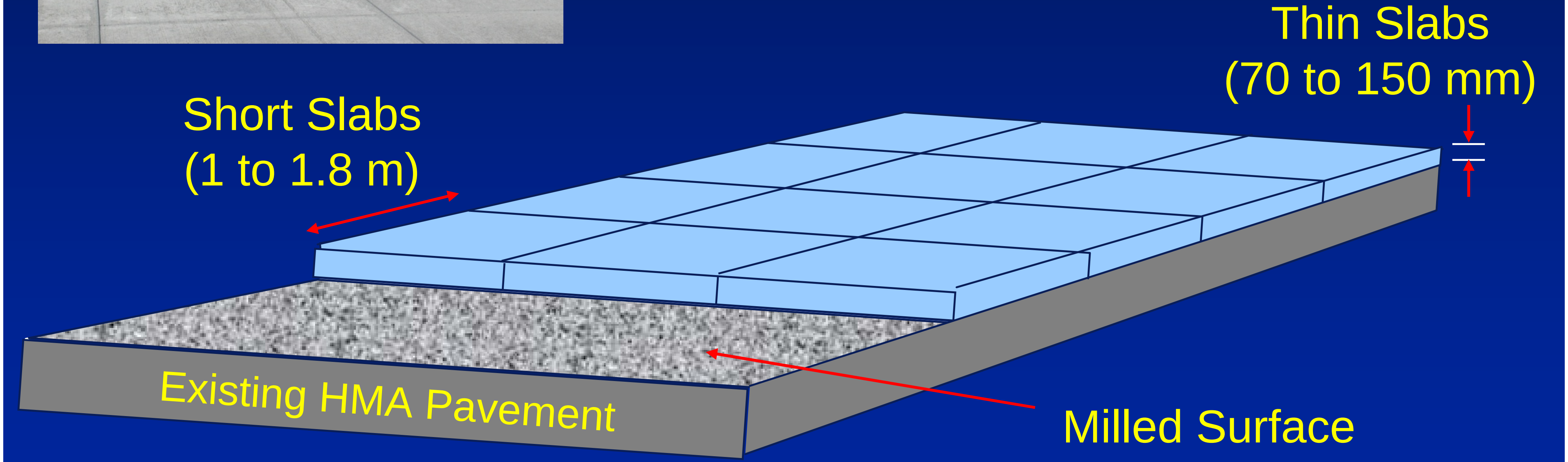
Longitudinal Joint (with tiebars)

Chicago CRCP
Construction - 2006

California CRCP: >50-years old

Concrete Overlays
(Over existing PCCP or ACP)

Thin Whitetopping



100+ Years of Concrete Pavement Technology Evolution

Concrete Pavement Analysis and Design

Pavement Engineering

"…the art of molding materials we do not wholly understand into shapes we cannot precisely analyze, so as to withstand forces we cannot assess, in such a way that the community at large has no reason to suspect our ignorance."

Credits: ERES Consultants, Inc./ ARA, Inc.

Harald Malcolm Westergaard
(1888-1950)

H. Malcolm Westergaard and his daughter Mary, with the family's 1928 Hupmobile

Harald M. Westergaard

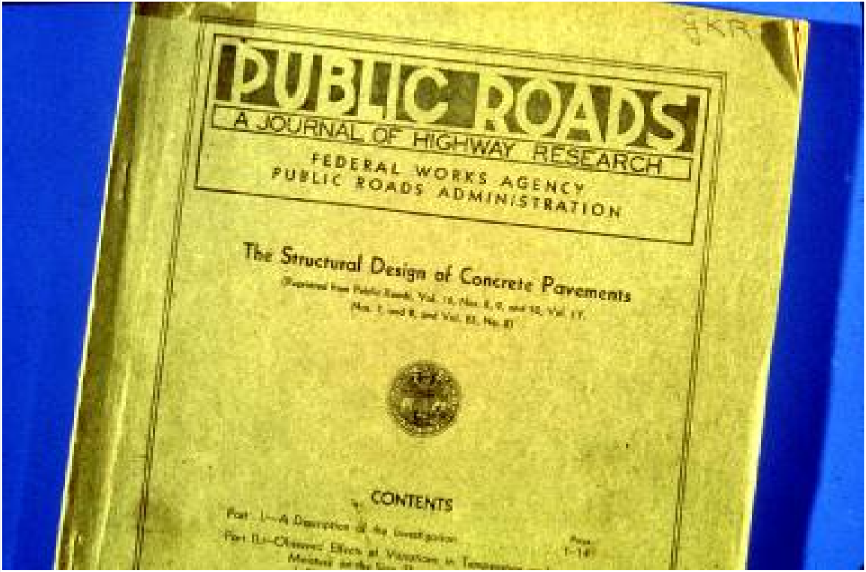
Credits: U of Illinois,
Tasos Ioannides

The ‘Father’ of Modern Pavement Mechanics

First Design Equations (1920s, 1930s)

- In 1926, Prof. Westergaard, University of Illinois, published equations for stresses and deflections of concrete pavement

- To test Westergaard's equation, the Bureau of Public Roads (forerunner of FHWA) conducted four years of testing and published a very complete report on the "Structural Design of Concrete Pavements".



PUBLIC ROADS
A JOURNAL OF HIGHWAY RESEARCH
FEDERAL WORKS AGENCY
PUBLIC ROADS ADMINISTRATION

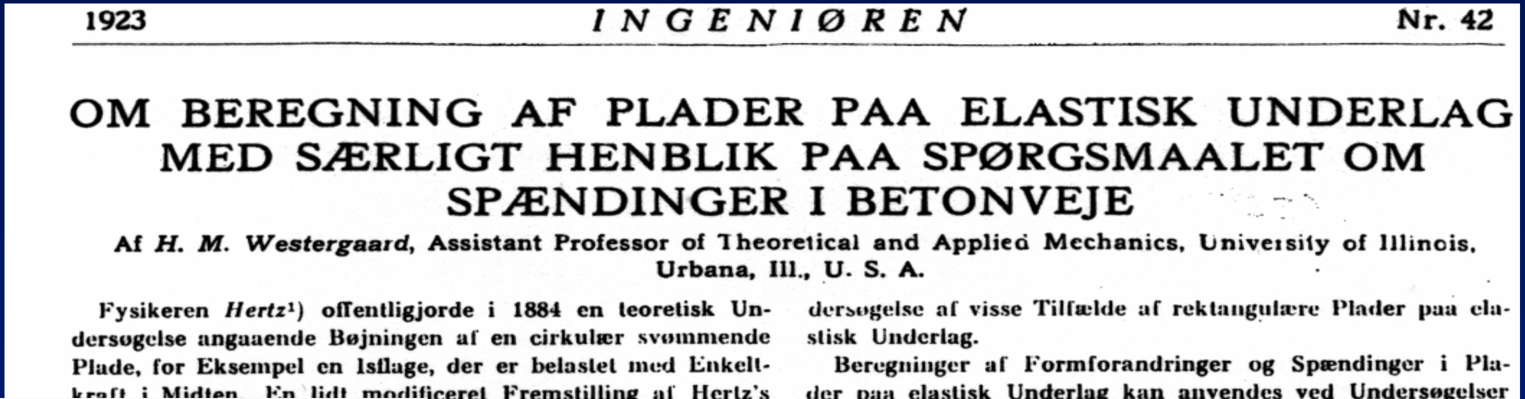
The Structural Design of Concrete Pavements

CONTENTS

$$d = \sqrt{\frac{cp}{s}}$$

d = thickness
c = stress coefficient
p = wheel load
s = allowable tensile stress

Westergaard (1923, 1948)



1923 INGENIØREN Nr. 42

OM BEREGNING AF PLADER PAA ELASTISK UNDERLAG MED SÆRLIGT HENBLIK PAA SPØRGSMAALET OM SPÆNDINGER I BETONVEJE

Af *H. M. Westergaard*, Assistant Professor of Theoretical and Applied Mechanics, University of Illinois, Urbana, Ill., U. S. A.

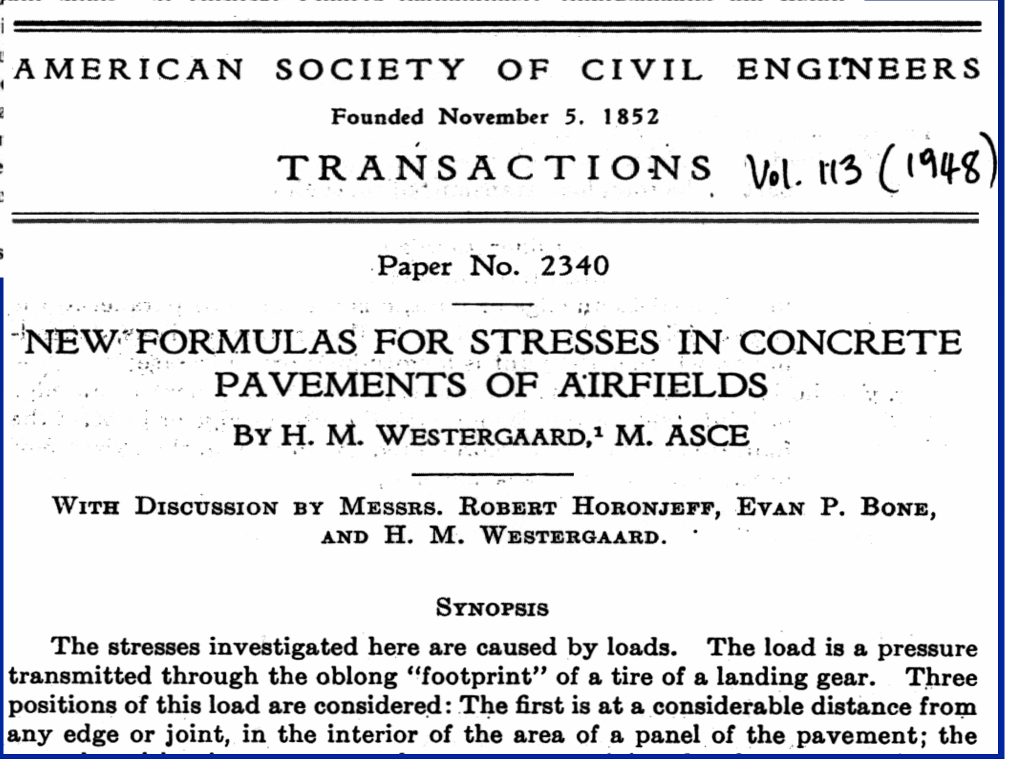
Fysikeren *Hertz*¹) offentligjorde i 1884 en teoretisk Undersøgelse angaaende Bøjningen af en cirkulær svømmende Plade, for Eksempel en Isflage, der er belastet med Enkeltkraft i Midten. En lidt modificeret Fremstilling af Hertz's
Technische Mechanik. Föppl
t Hertz's Teori finder direkte
en cirkulær Plade, der hviler
lsat at Modtrykket fra Under-
dbøjningen; et saadant Mod-
len Tilvækst i Opdri
n svømmende Plade
er paa elastisk Unde
nan udtrykte Nedbø
Koefficienter beregn
æt lineære Ligninge
en kvadratisk Plade

regning, der egner s

dersøgelse af visse Tilfælde af rektangulære Plader paa elastisk Underlag.

Beregninger af Formforandringer og Spændinger i Plader paa elastisk Underlag kan anvendes ved Undersøgelser angaaende *Fundamentpladers og Betonvejes Styrkeforhold*; og paa Grund af Analogien mellem visse statiske og dynamiske Virkninger er der tillige, hvis man foretager visse Modifikationer, Mulighed for Anvendelser ved Beregninger af *elastiske Pladers Svingninger*. Spørgsmaalet om Beton-

H. Malcolm Westergaard, 1928



AMERICAN SOCIETY OF CIVIL ENGINEERS

Founded November 5, 1852

TRANSACTIONS Vol. 113 (1948)

Paper No. 2340

NEW FORMULAS FOR STRESSES IN CONCRETE PAVEMENTS OF AIRFIELDS

By H. M. Westergaard,¹ M. ASCE

With Discussion by Messrs. Robert Horonjeff, Evan P. Bone, and H. M. Westergaard.

Synopsis

The stresses investigated here are caused by loads. The load is a pressure transmitted through the oblong "footprint" of a tire of a landing gear. Three positions of this load are considered: The first is at a considerable distance from any edge or joint, in the interior of the area of a panel of the pavement; the

Credits:
U of Illinois

Tasos Ioannides

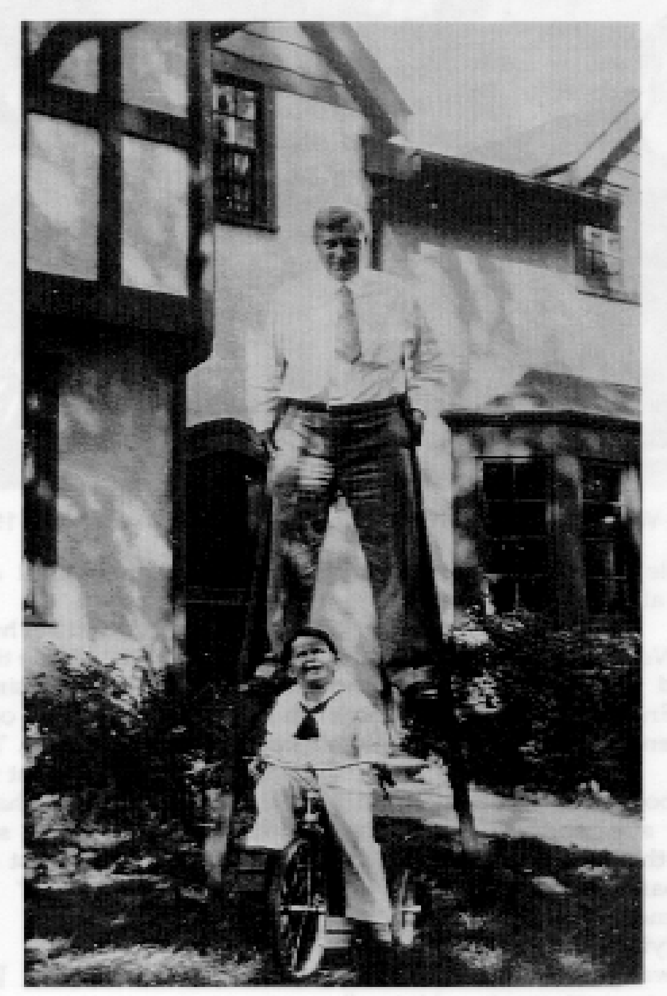
Westergaard's Equations

$$\sigma_i = \frac{0.3162\left(W\right)}{h^2}\left[4\log_{10}\left(\frac{l}{b}\right)+1.069\right]$$

$$\sigma_e = \frac{0.572\left(W\right)}{h^2}\left[4\log_{10}\left(\frac{l}{b}\right)+0.359\right]$$

$$\sigma_c = \frac{3\left(W\right)}{h^2}\left[1-\left(\frac{a\sqrt{2}}{l}\right)^{0.6}\right]$$

Westergaard's Assumptions


H. Malcolm Westergaard and his son Peter, 1934

1. **Uniform Support – No curling**
2. **One slab - No load transfer**
3. **Single Wheel Load - No mulitple wheel loads**
4. **Single Placed Layer - No base**
5. **Infinite Slab**
6. **Semi Infinite Foundation - No rigid bottom**

Credits: Tasos Ioannides

NL Temperatures: Thomlinson (1940)

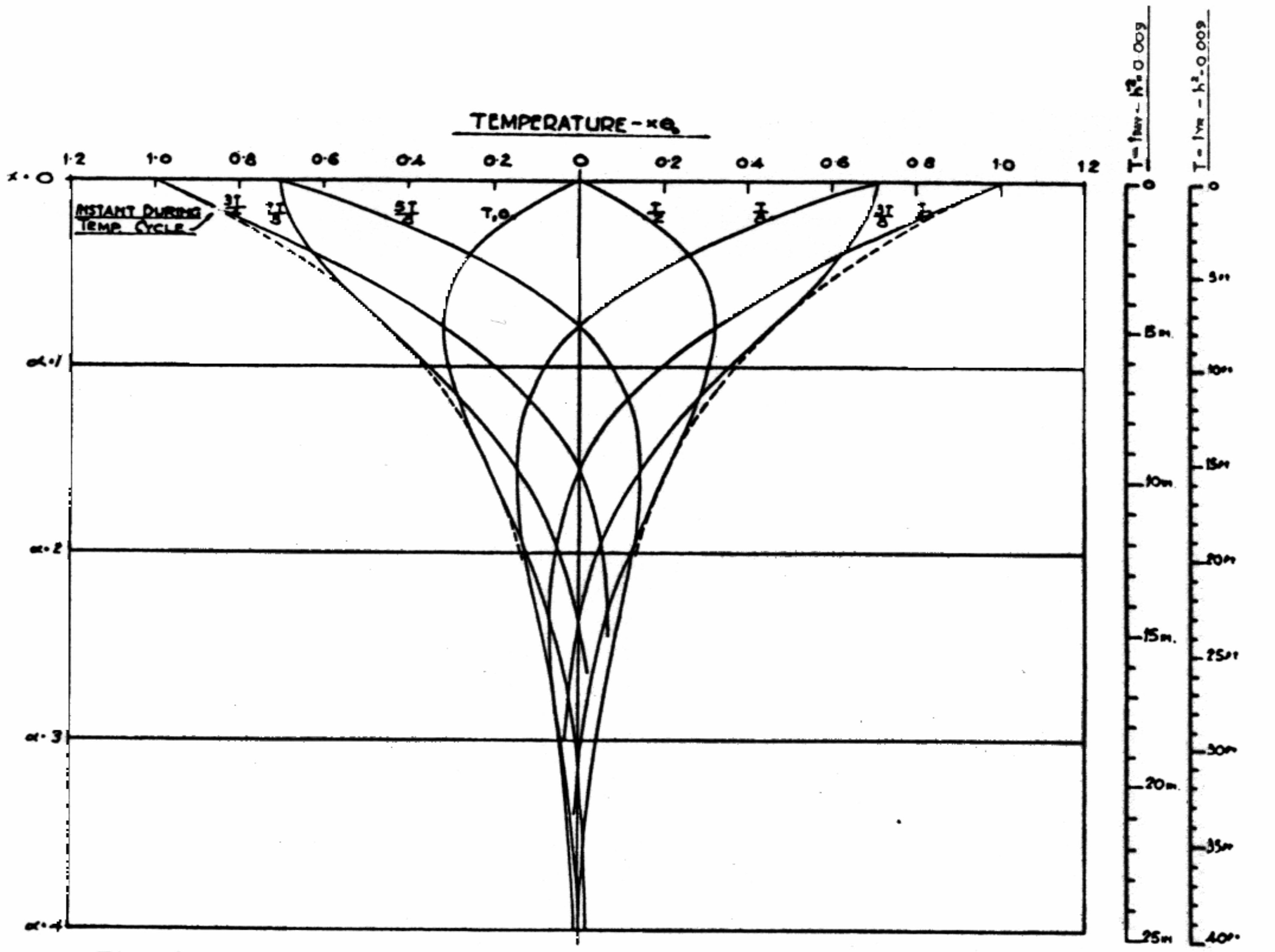
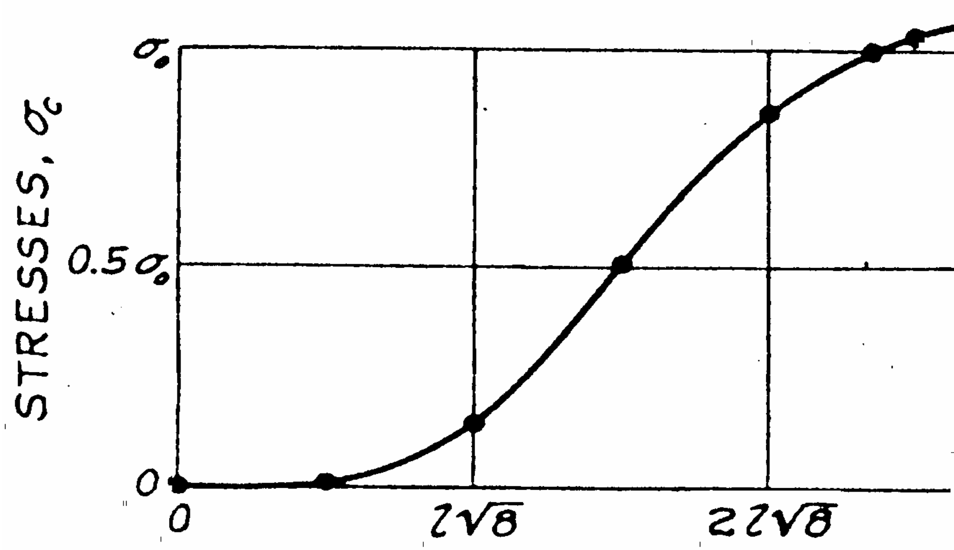


Fig. 2.—Variation of Temperature with Depths at Various Times.

The “No Curling” Assumption



After Westergaard (1927)

After Bradbury (1938)

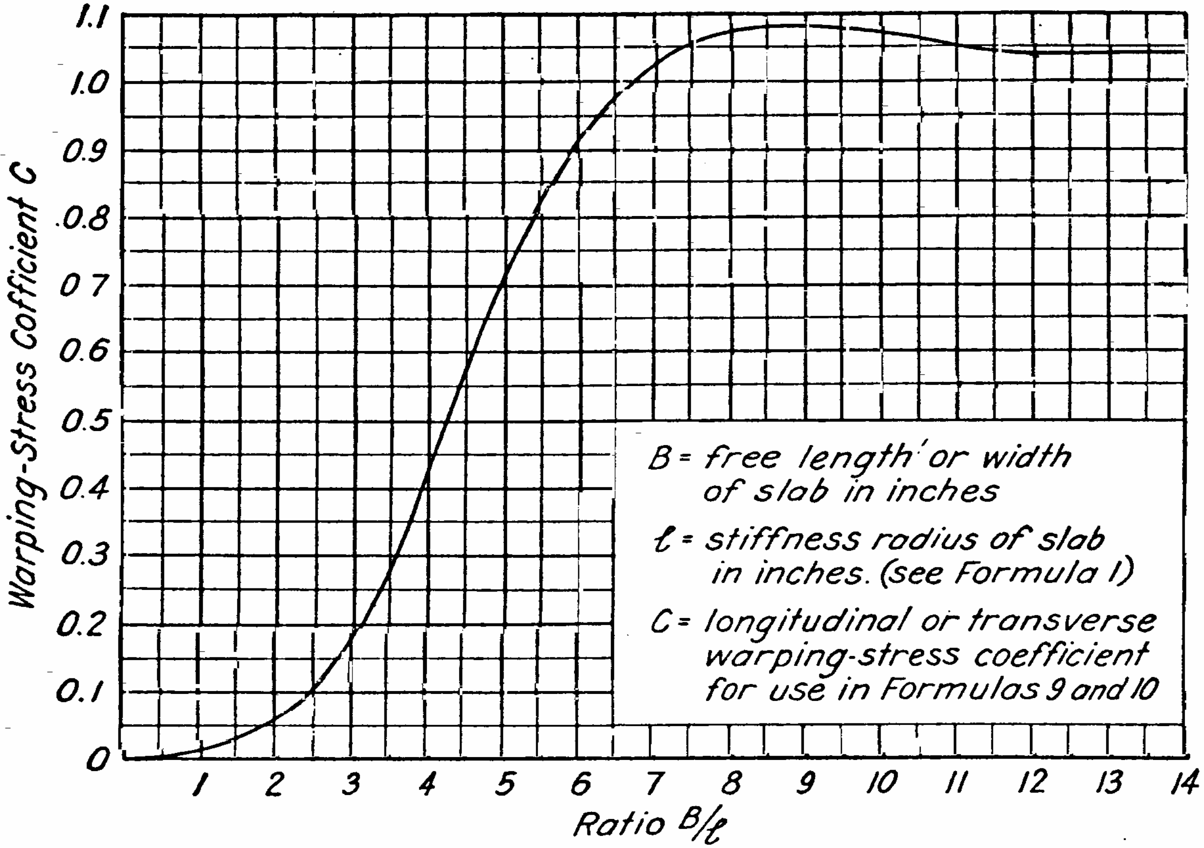
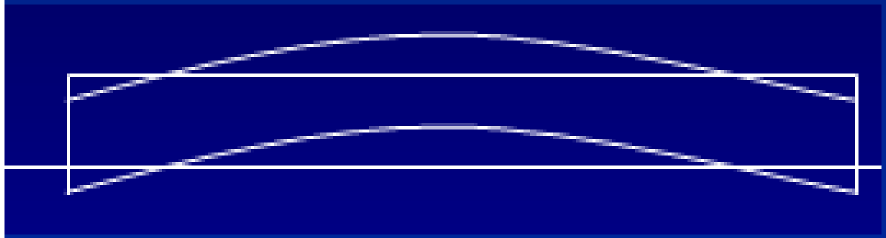


FIG. 2.—CURVE SHOWING VARIATION IN THE DIFFERENTIAL TEMPERATURE STRESS COEFFICIENT C FOR DIFFERENT VALUES OF THE CURLING RATIO B/l.



Credits: Tasos Ioannides
and Shiraz Tayabji

The SWL Assumption

After Pickett and Ray (1951)

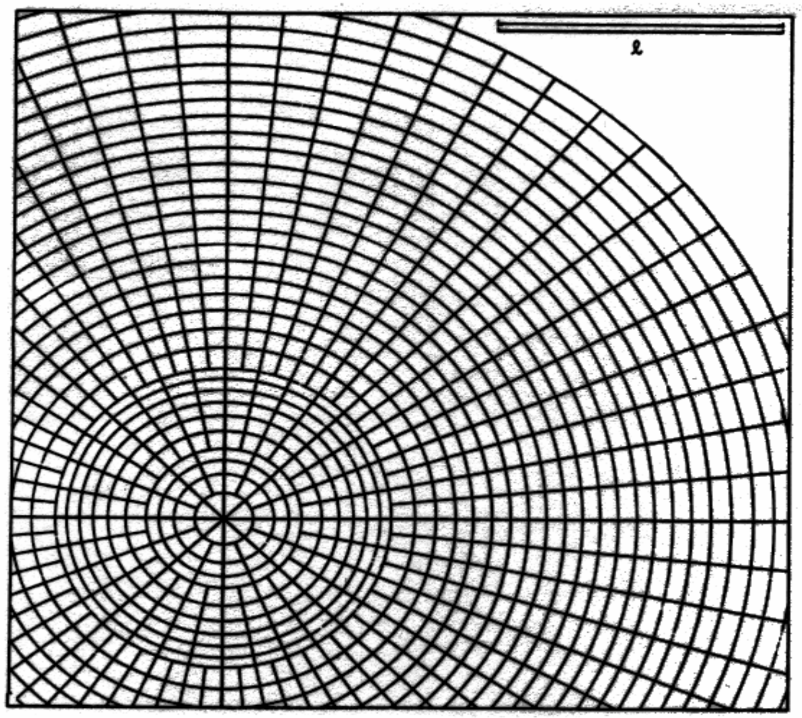


Figure 4.13 Influence chart for deflection due to interior loading. (After Pickett and Ray (1951).)

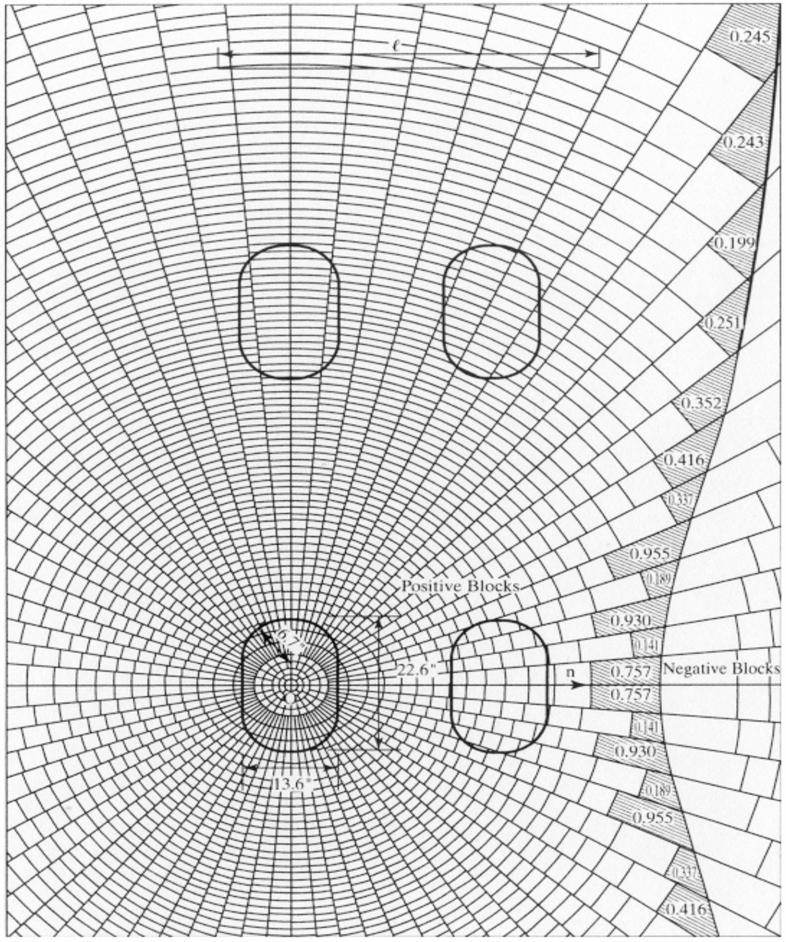
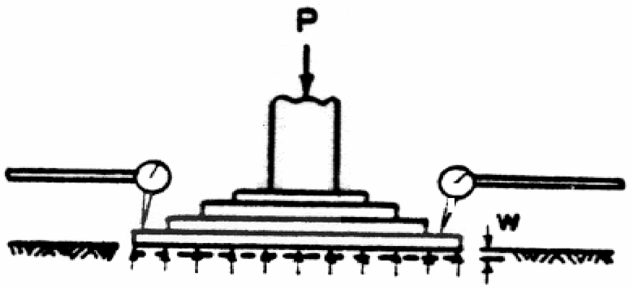


FIGURE 4.12

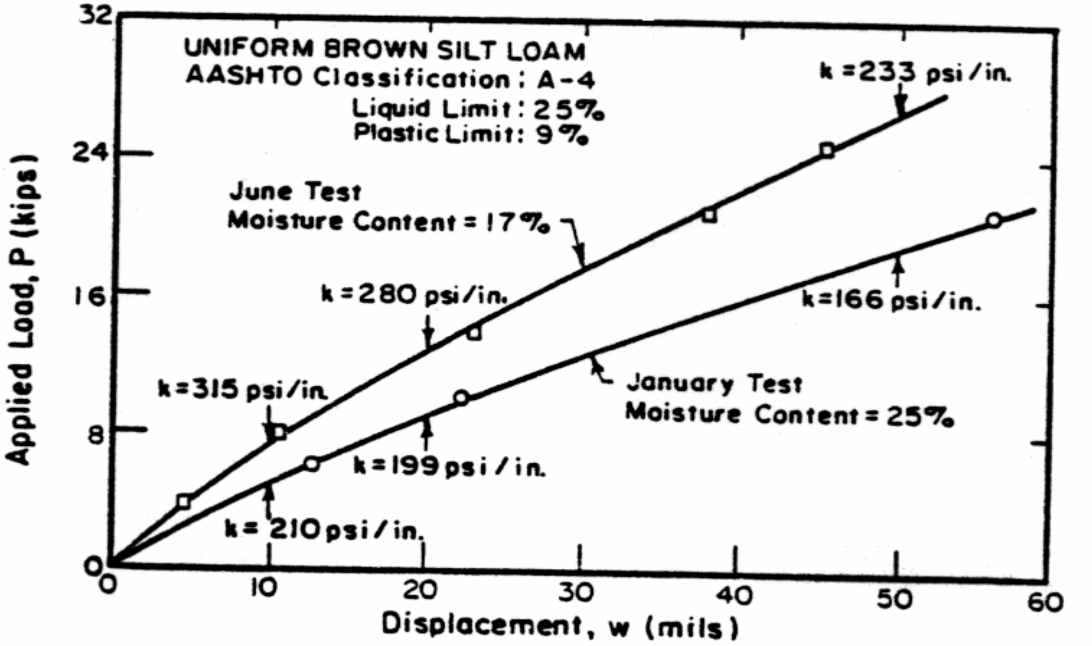
Application of influence chart for determining moment (1 in. = 25.4 mm). (After Pickett and Ray (1951).)

Credits: Yang H. Huang

Determination of k-value



(a) Typical Setup for the Plate Load Test

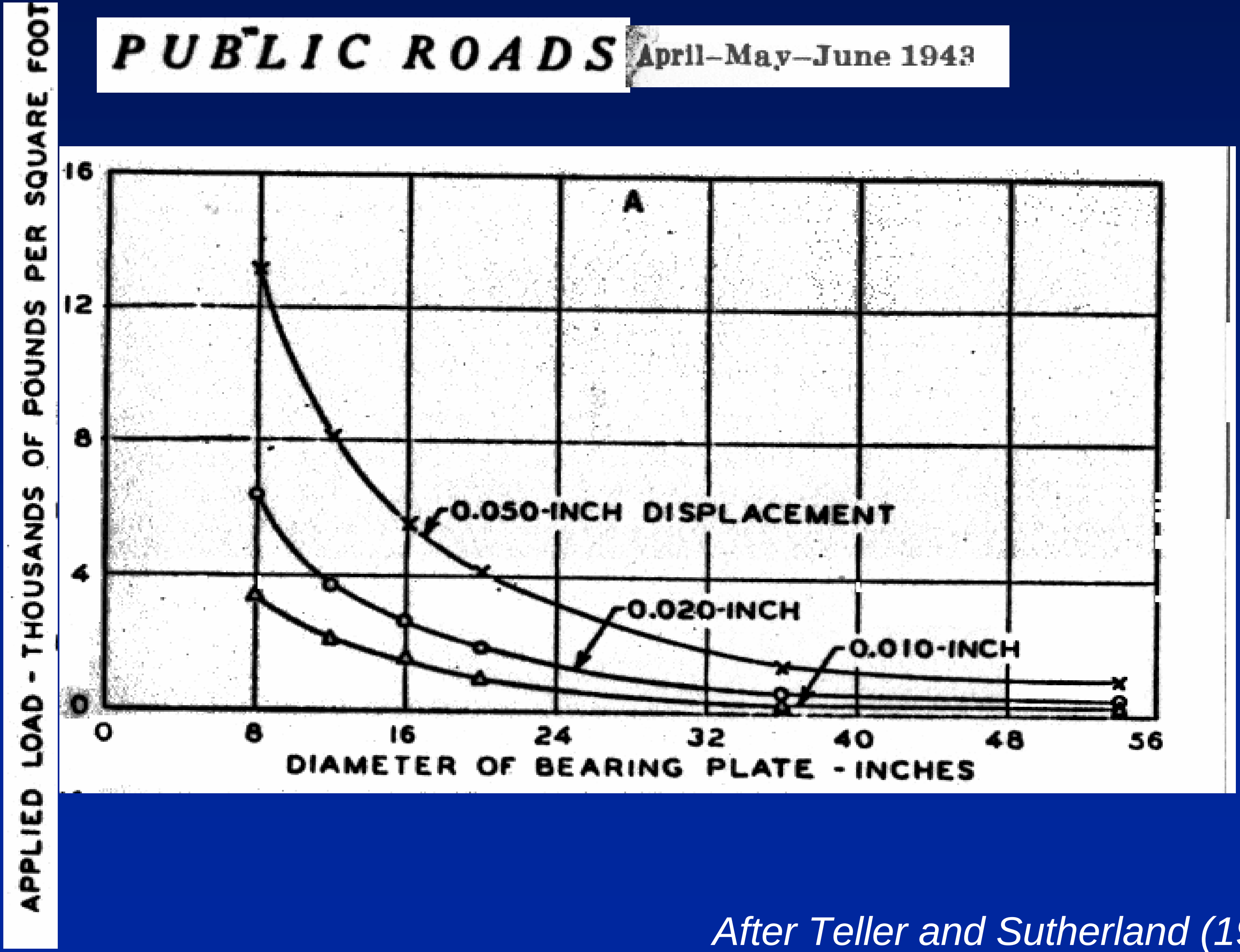


(b) Typical Plate Load Test Results
(After Teller and Sutherland [29]

After Ioannides (1984)

Effect of Plate Size

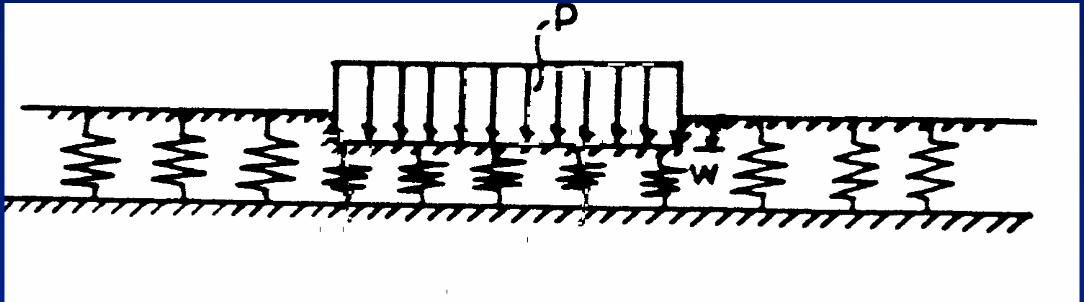
PUBLIC ROADS April–May–June 1943



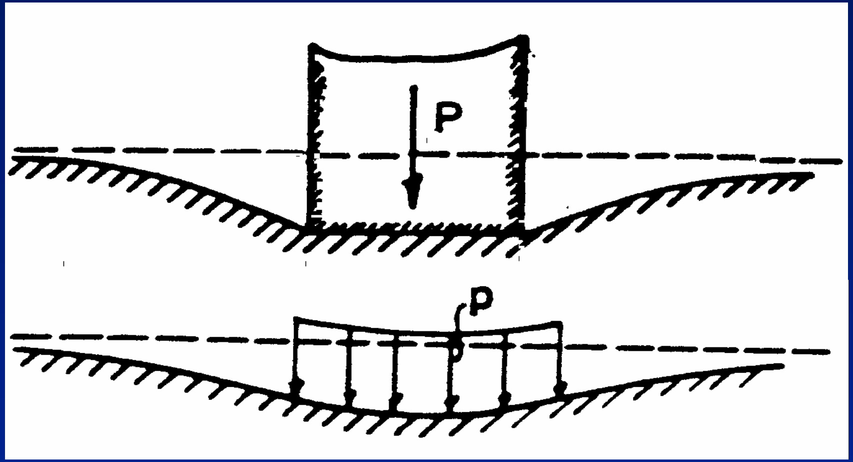
After Teller and Sutherland (1943)

Winkler (1867) and Boussinesq (1885)

Dense Liquid (DL)



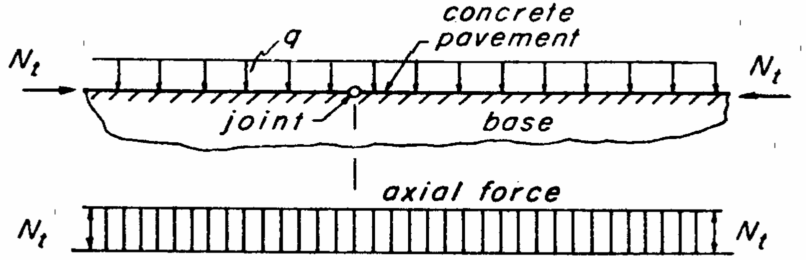
Elastic Solid (ES)



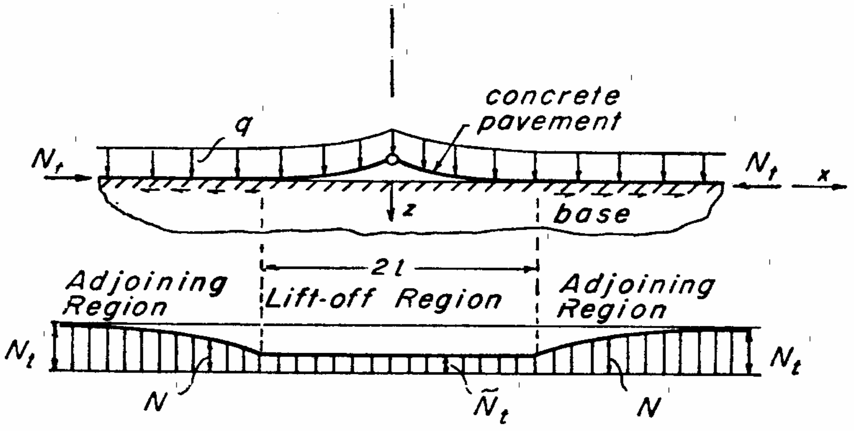
Credits: Arnold D. Kerr

Edges and Corners: Blowups

Fig. 1. Blowup of concrete highway pavement in Ohio, 1975 (courtesy Prof. A. M. Richards [2])



(a) BEFORE BUCKLING



(b) AFTER BUCKLING

Fig. 3. Axial forces in a concrete pavement

After Kerr (1989)

$$w = 1.5 \frac{p \cdot a}{E_s} \cdot F_w$$

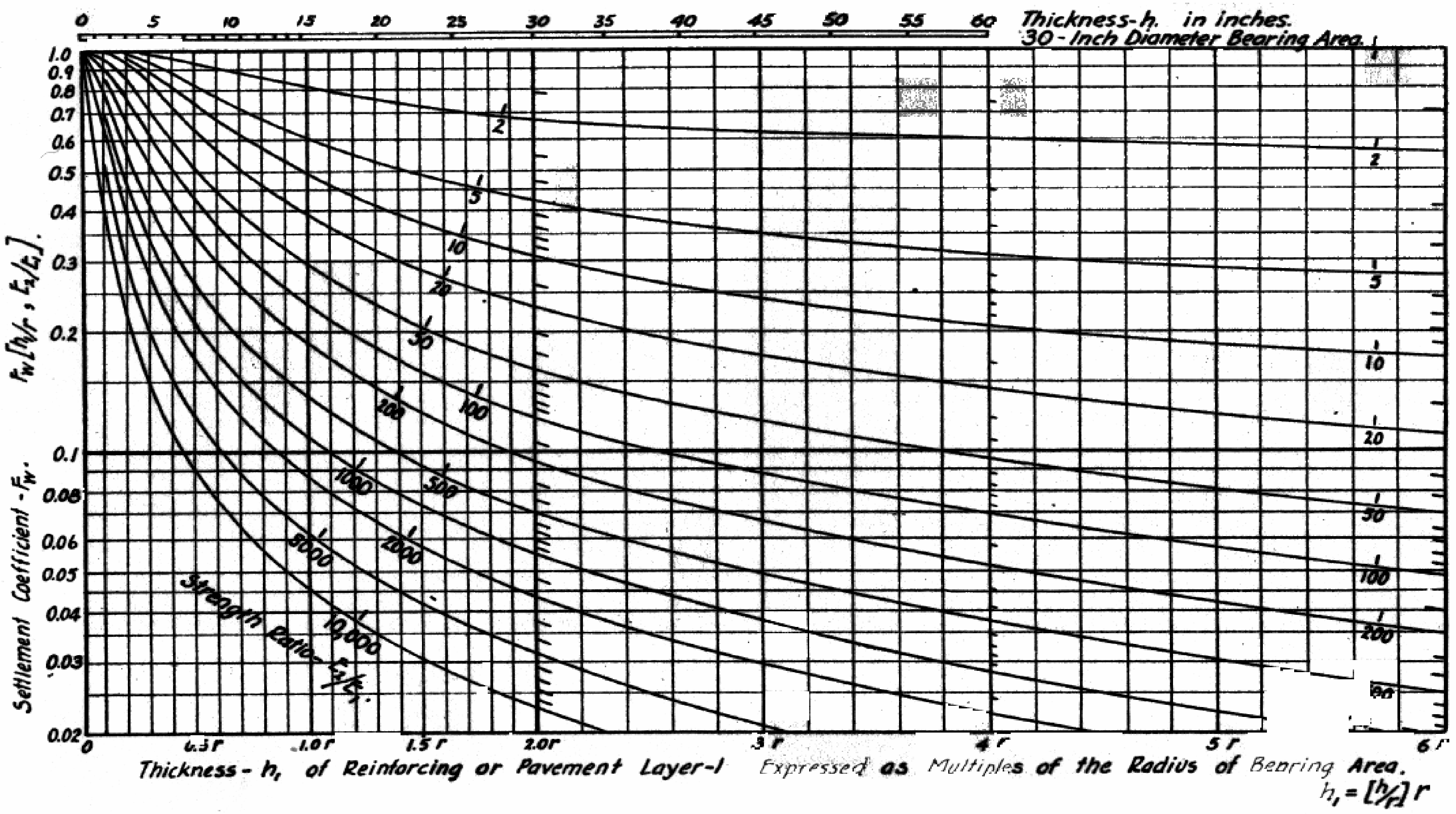


Figure 4. Influence Curves of the Settlement Coefficient $-F_w$ for the Two-Layer System. Basic Load-Settlement Relation

$$W_c = 1.5 \frac{P \cdot r}{E_2} \cdot F_w . \qquad F_w = \frac{W E_2}{1.5\, P r}$$

Design Advancements

- In the 1950’s, Dr. Gerald Pickett and Gordon Ray developed influence charts
  - Calculated pavement stresses for any wheel configuration,
- PCA prepared design charts for individual aircraft.
  - With the advent of multi-wheel gear, 747 has 16 wheels in it’s main gear, the use of Influence Charts became quite tedious

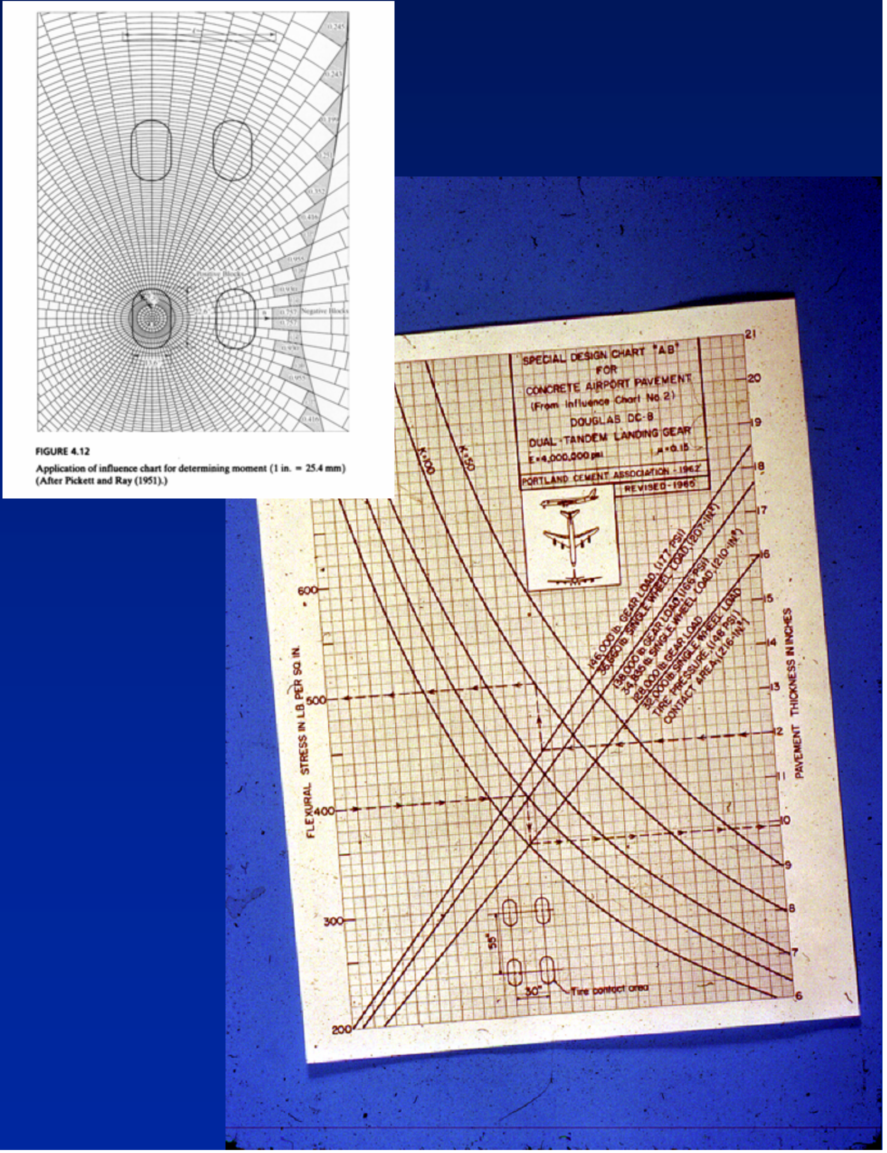


FIGURE 4.12

Application of influence chart for determining moment (1 in. = 25.4 mm) (After Pickett and Ray (1951).)

Empirical Design Approaches

INPUTS
Slab thickness
k-value
ESAL
PCC M_r

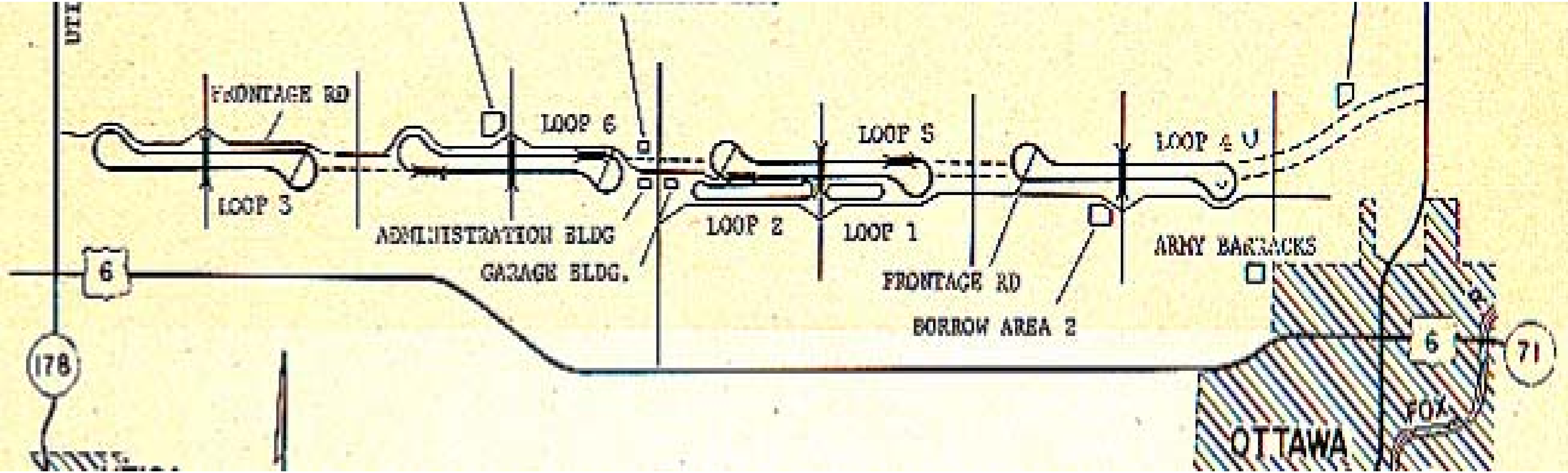
STATISTICAL
REGRESSION
MODEL

OUTPUTS
PSI

AASHTO Road Test

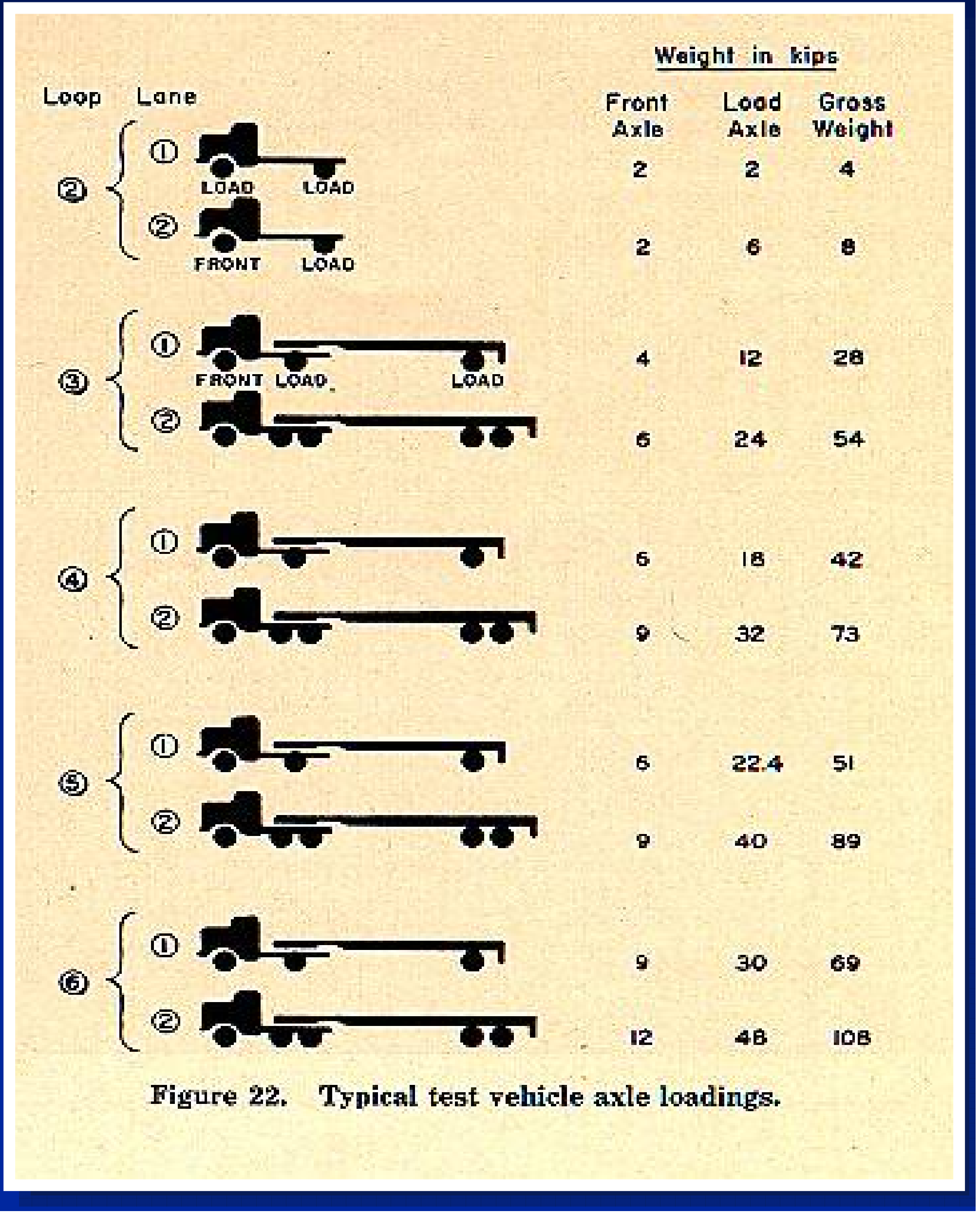
The AASHO Road Test was conceived and sponsored by the American Association of State Highway Officials to study the performance of pavement structures of known thickness under moving loads of known magnitude and frequency.

AASHO Test Loops Layout



AASHO Test Traffic

- Started Nov. 1958
- Loops 3-6:
  - 6 veh/lane
  - 10 veh/lane (Jan '60)
- Operation
  - 18 hr. 40 min. @ 35 mph.
  - 6 days/wk
- Total Loads
  - 1,114,000 Applications
  - Avg. ESAL - 6.2 million
  - Max ESAL - 10 million (Flex)

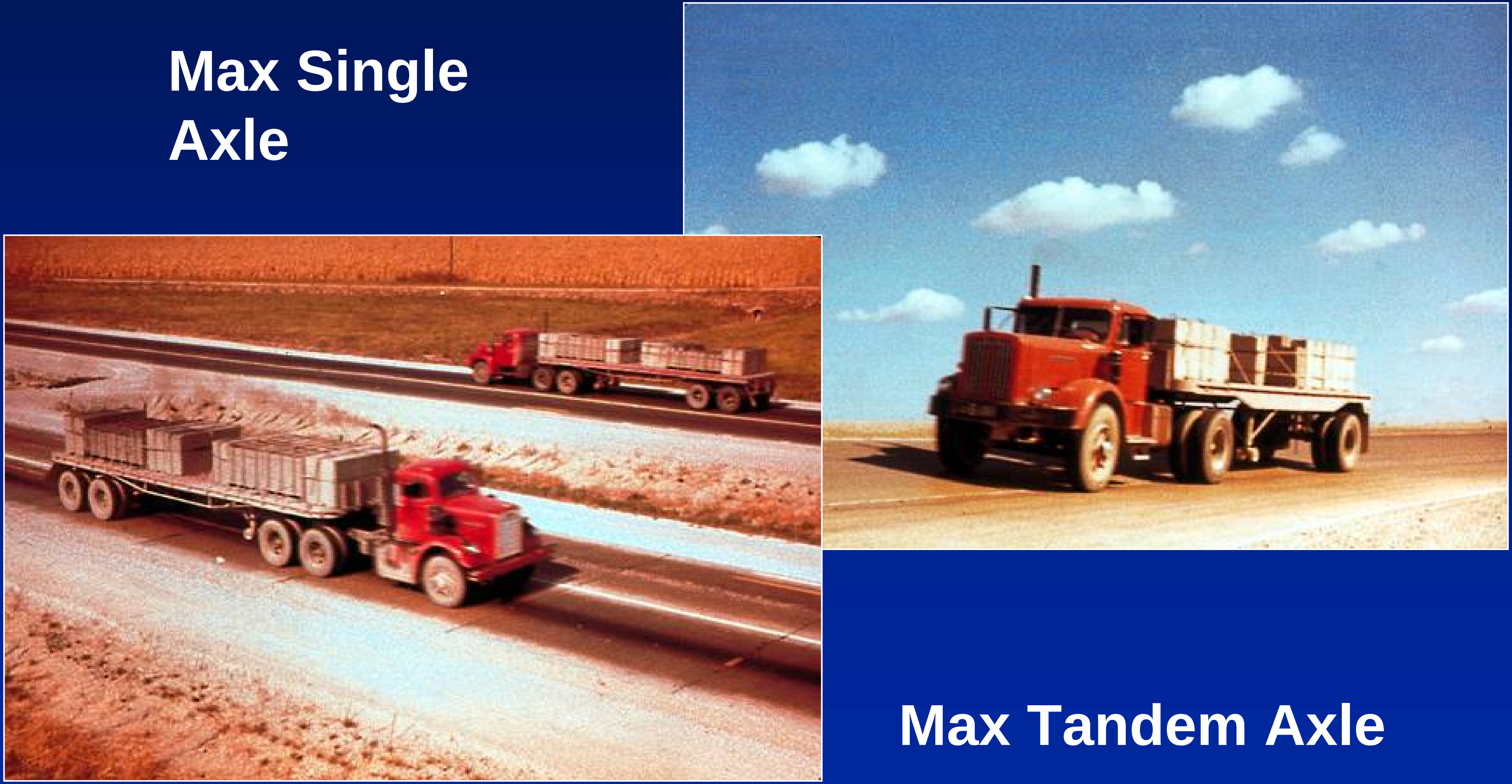


Loop	Lane	Weight in kips		
		Front Axle	Load Axle	Gross Weight
②	①	2	2	4
	②	2	6	8
③	①	4	12	28
	②	6	24	54
④	①	6	18	42
	②	9	32	73
⑤	①	6	22.4	51
	②	9	40	89
⑥	①	9	30	69
	②	12	48	108

Figure 22. Typical test vehicle axle loadings.

AASHO Test Traffic

Max Single Axle



Max Tandem Axle

AASHO Road Test

Empirical Loop Equation:

$$\text{Log}(W) = \text{Log } R + \frac{G}{F}$$

$$\text{Log } R = 5.85 + 7.35 * \log (D+1) - 4.62 * \log (L1+L2) + 3.82 * \log L2$$

$$F = 1.00 + \frac{3.63 * (L1+L2)^{5.2}}{(D-1)^{8.46} * L2^{3.52}}$$

$$G = \text{Log} \left[\frac{(P1-P2)}{(P1-1.5)} \right]$$

D = Concrete slab thickness, in
L1 = Load on single/tandem axle, kips
L2 = Axle code
P1 = Initial serviceability
P2 = Terminal serviceability

AASHO Road Test
Extended Design Equation

- Not everybody used the same concrete
- Some used reinforced or CRC designs
- Developed mechanistic-empirical relationship between Log W and stress ratio.

$$\mathrm{Log}(W) = A + B\ \mathrm{Log}\frac{S'c}{\sigma}$$

W = Number of axle loads to terminal serviceability
(from main loop equation)
A = Regression constant
B = Slope of Log W vs. Log $S'c/\sigma$ curve
S'c = 28-day flexural strength, 3rd point loading
σ = Spangler's corner stress

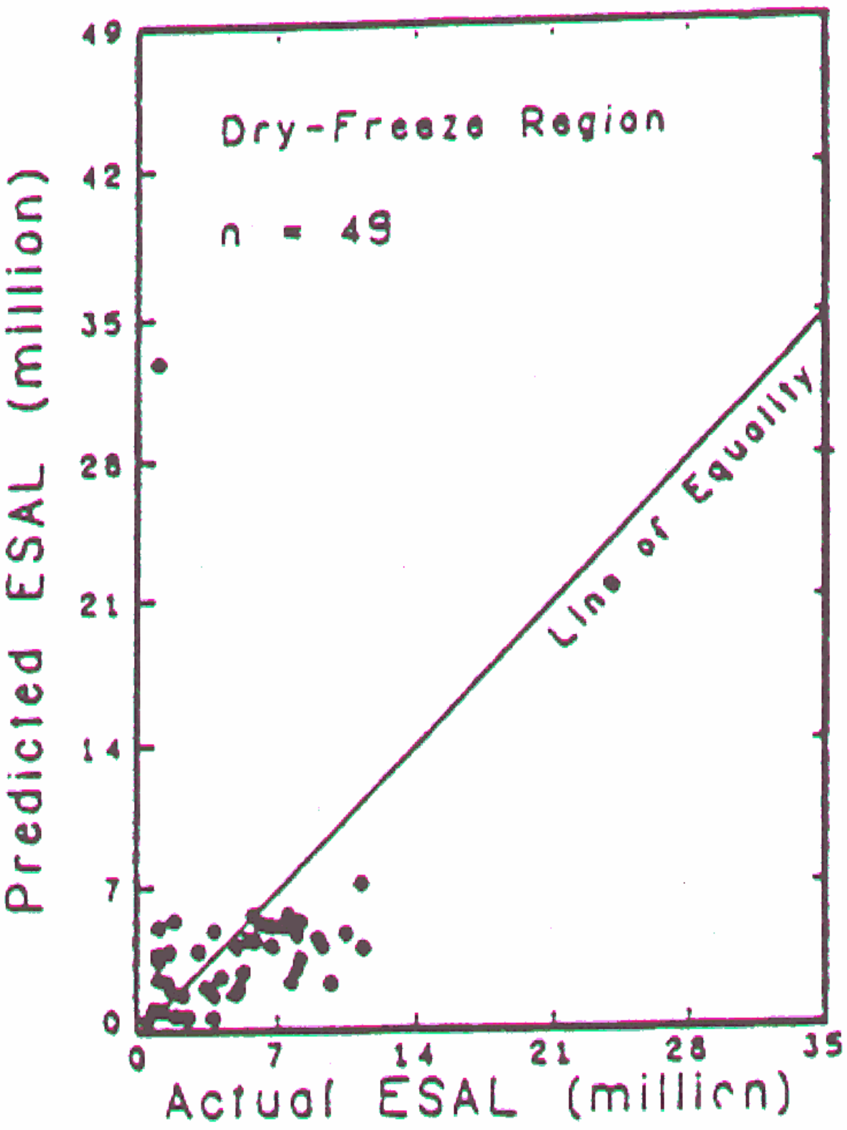
1962 Rigid Pavement Design Equation

$$\mathrm{Log(ESAL)} = 7.35 * \mathrm{Log}(D + 1) - 0.06 + \left[\frac{\mathrm{Log}\left[\dfrac{4.5 - 1.5}{4.5 - 1.5} \right]}{1 + \dfrac{1.624 * 10^{7}}{(D + 1)^{8.46}}} \right]$$

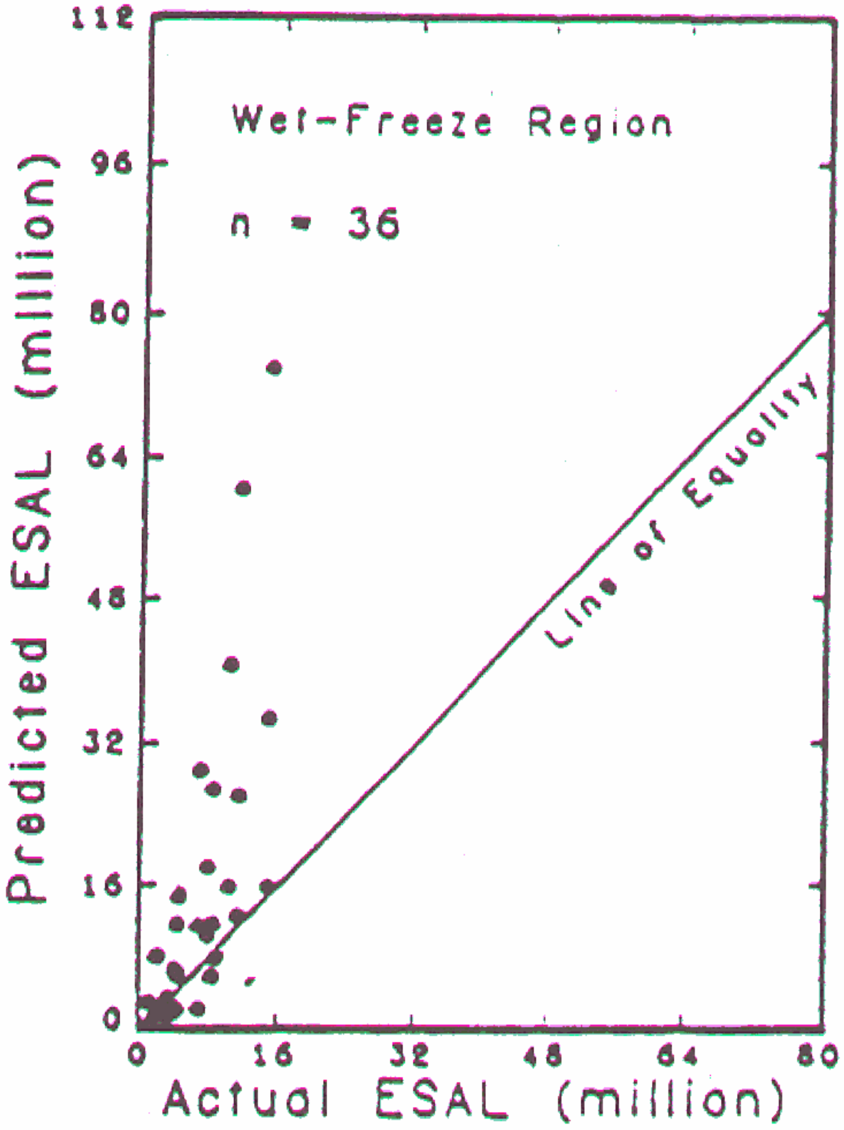
$$+ (4.22 - 0.32p_{t}) * \mathrm{Log}\left[\frac{S'_{c}}{(215.63 * J)} \; \frac{\left[D^{0.75} - 1.132 \right]}{\left[D^{0.75} - \dfrac{18.42}{(E_{c} / k)^{0.25}} \right]} \right]$$

AASHTO Design Procedure Limitations

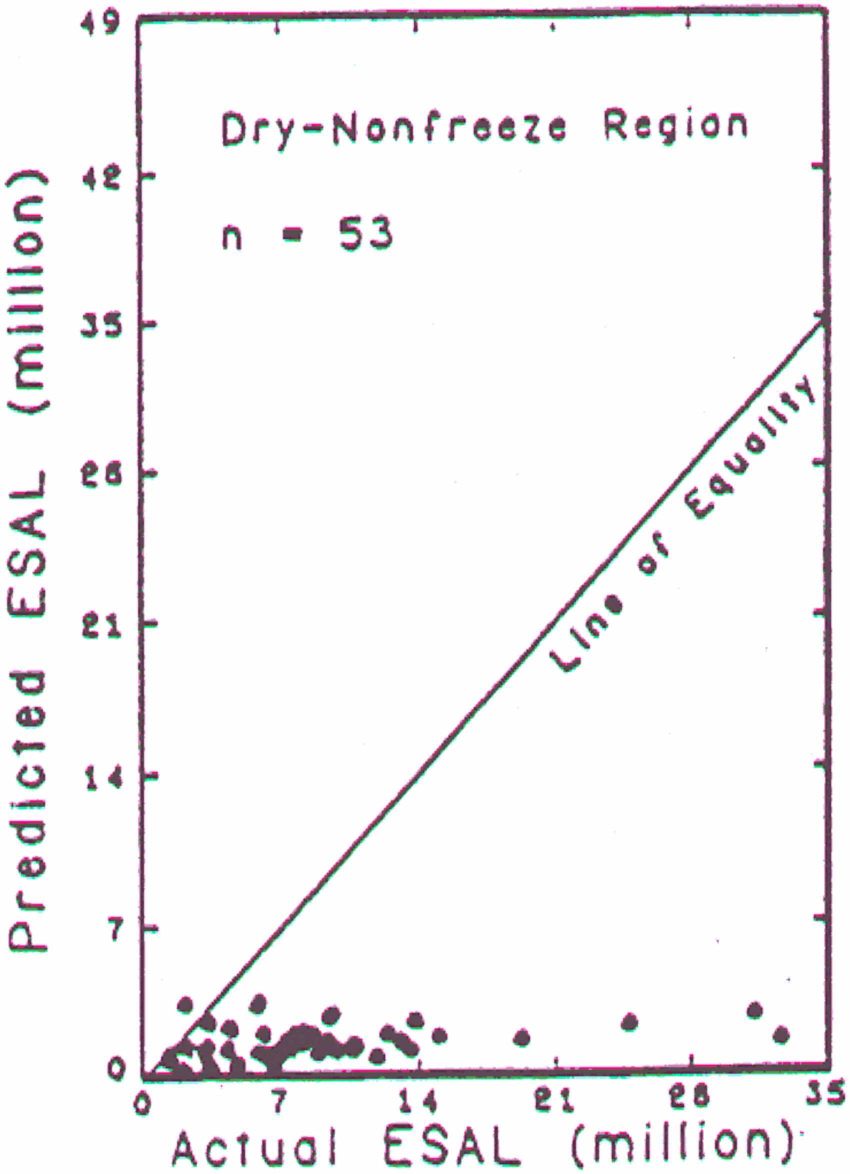
- One subgrade type
- One environment
- Only 2 years of service
  - Limited truck traffic
  - Limited environmental effects
- One PCC mixture
- 1950s materials & paving technology
- Limited innovations


Dry-Freeze Region
n = 49
Line of Equality
Predicted ESAL (million)
Actual ESAL (million)
0
7
14
21
28
35
42
49
0
7
14
21
28
35

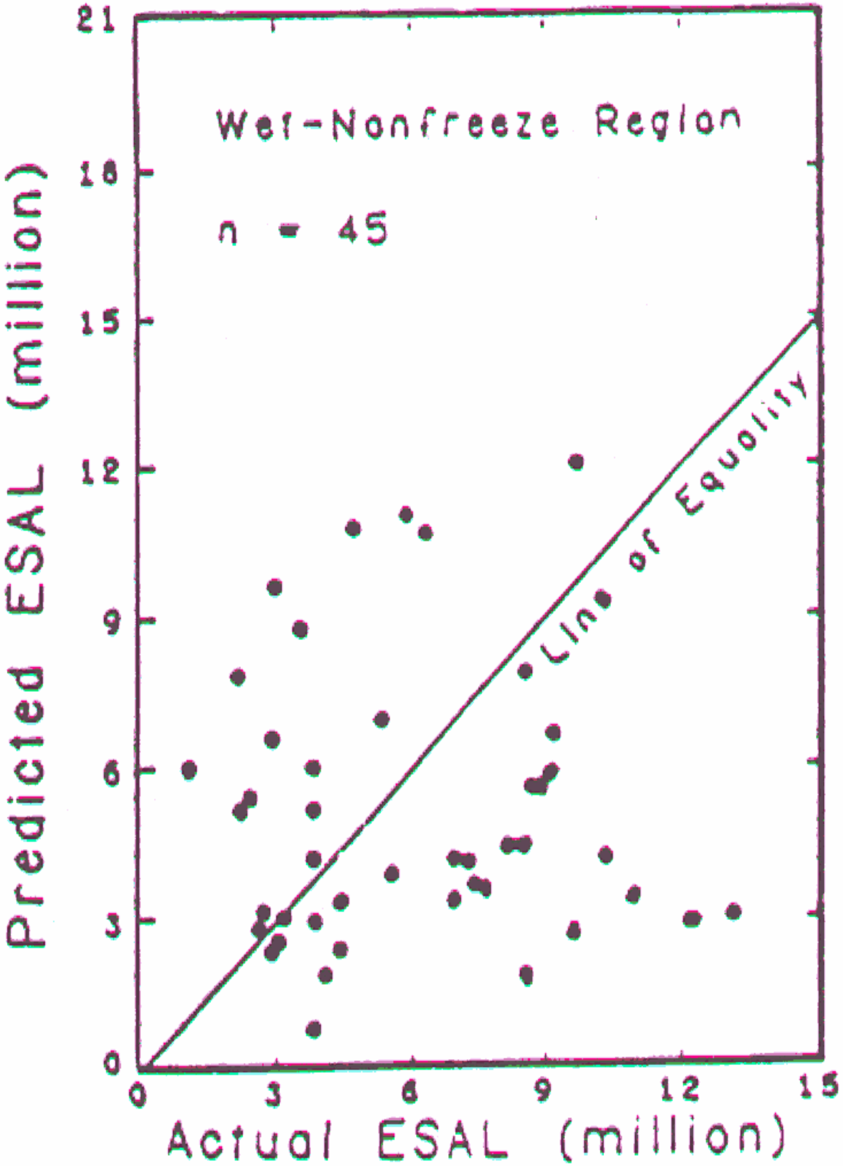
(a)


Wet-Freeze Region
n = 36
Line of Equality
Predicted ESAL (million)
Actual ESAL (million)
0
16
32
48
64
80
96
112
0
16
32
48
64
80

(b)

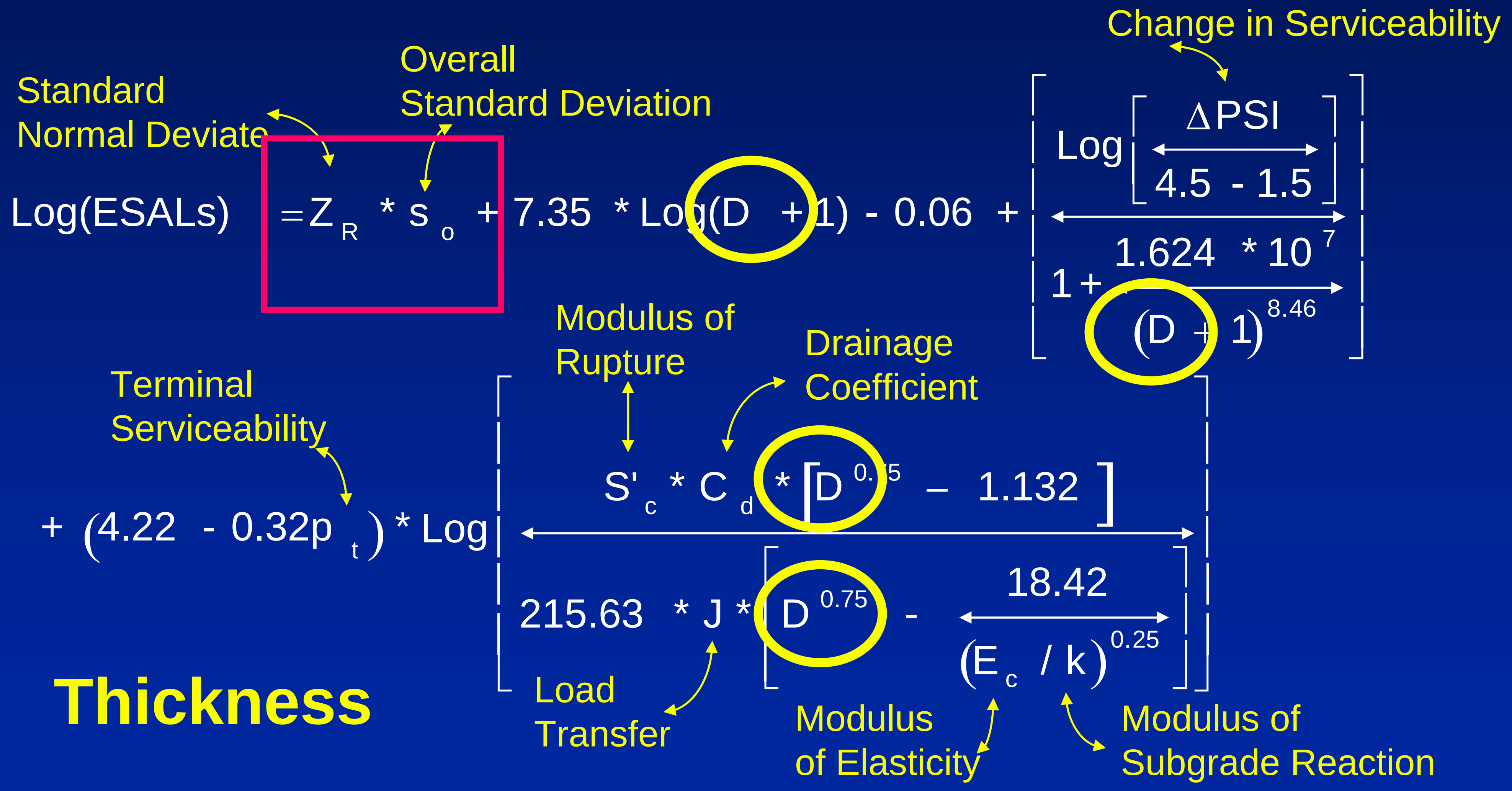

Dry-Nonfreeze Region
n = 53
Line of Equality
Predicted ESAL (million)
Actual ESAL (million)
0
7
14
21
28
35
42
49
0
7
14
21
28
35

(c)


Wet-Nonfreeze Region
n = 45
Line of Equality
Predicted ESAL (million)
Actual ESAL (million)
0
3
6
9
12
15
18
21
0
3
6
9
12
15

(d)

1986/1993 Rigid Pavement Design Equation



$$\text{Log(ESALs)} = Z_R * s_o + 7.35 * \text{Log}(D+1) - 0.06 + \frac{\text{Log}\left[\frac{\Delta PSI}{4.5-1.5}\right]}{1+\frac{1.624 * 10^7}{(D+1)^{8.46}}} + (4.22 - 0.32p_t) * \text{Log}\left[\frac{S'_c * C_d * \left[D^{0.75} - 1.132\right]}{215.63 * J * \left[D^{0.75} - \frac{18.42}{(E_c / k)^{0.25}}\right]}\right]$$

Standard Normal Deviate

Overall Standard Deviation

Change in Serviceability

Modulus of Rupture

Drainage Coefficient

Terminal Serviceability

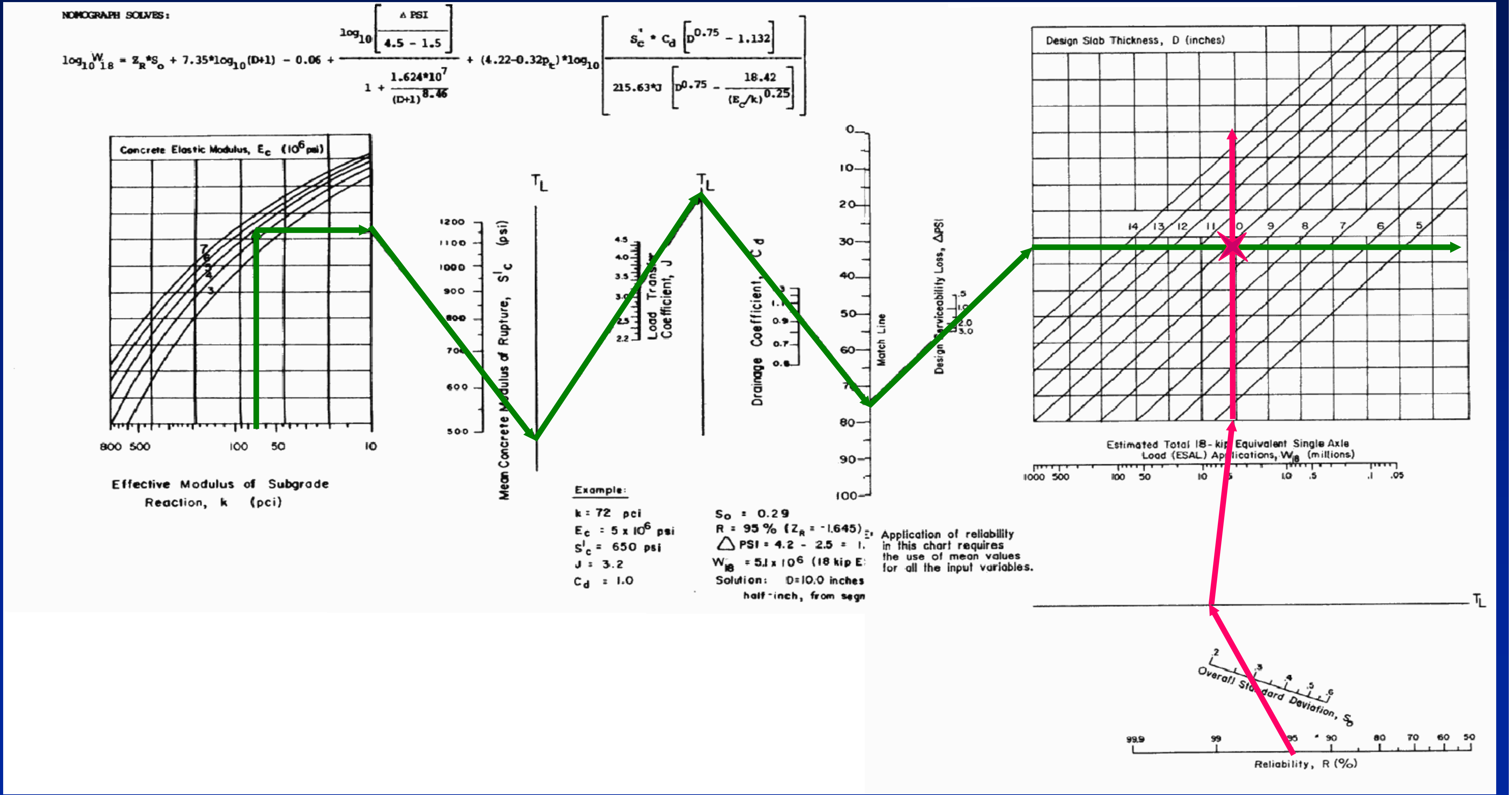
Load Transfer

Modulus of Elasticity

Modulus of Subgrade Reaction

Thickness

Rigid Design Nomograph



NOMOGRAPH SOLVES:

$$\log_{10}W_{18} = Z_R*S_o + 7.35*\log_{10}(D+1) - 0.06 + \frac{\log_{10}\left[\frac{\Delta PSI}{4.5-1.5}\right]}{1+\frac{1.624*10^7}{(D+1)^{8.46}}} + (4.22-0.32p_t)*\log_{10}\left[\frac{S_c' * C_d\left[D^{0.75}-1.132\right]}{215.63*J\left[D^{0.75}-\frac{18.42}{(E_c/k)^{0.25}}\right]}\right]$$

Example:

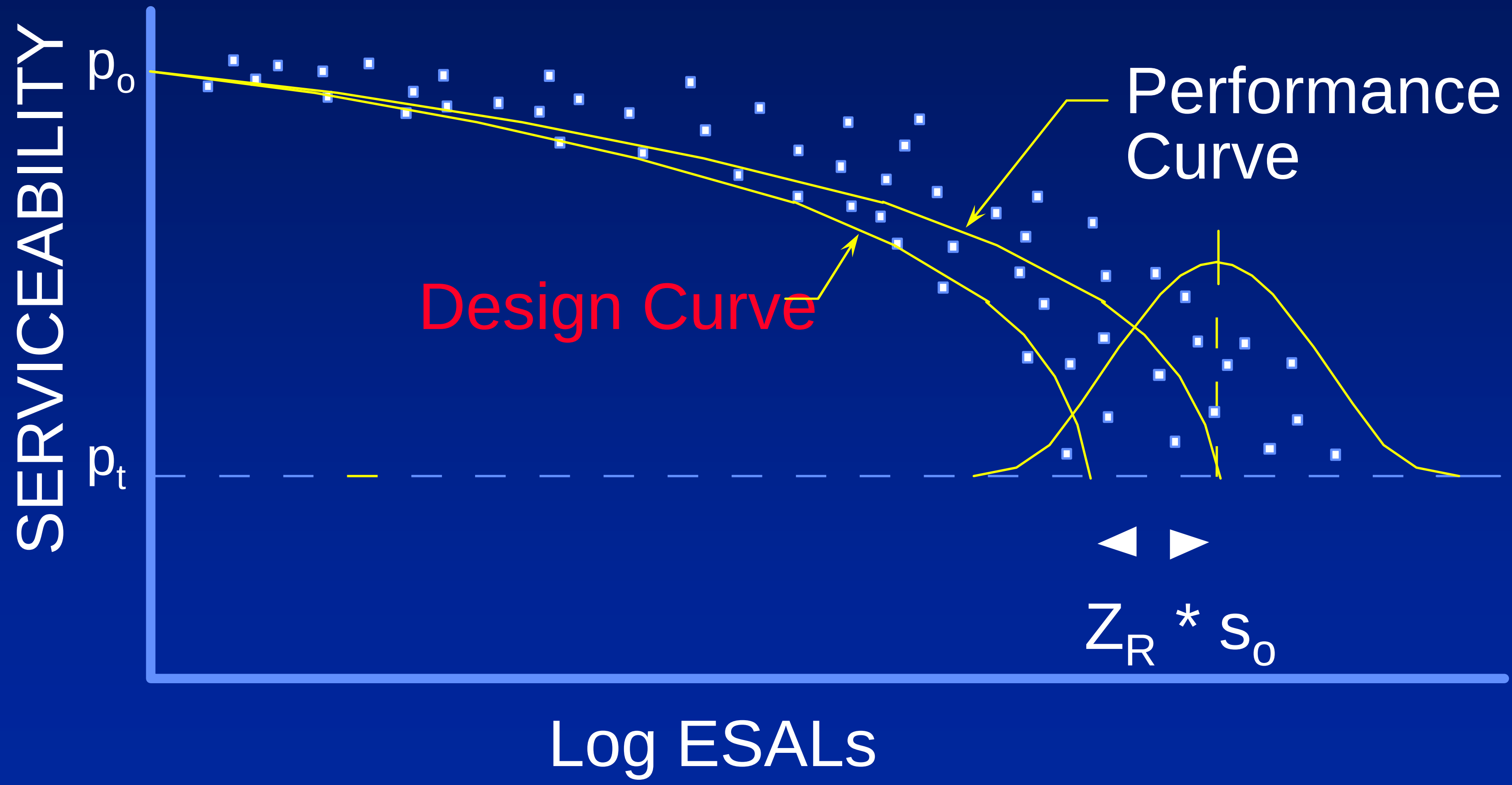
$k = 72$ pci
$E_c = 5 \times 10^6$ psi
$S'_c = 650$ psi
$J = 3.2$
$C_d = 1.0$

$S_o = 0.29$
$R = 95\%$ ($Z_R = -1.645$)
$\Delta PSI = 4.2 - 2.5 = 1.$
$W_{18} = 5.1 \times 10^6$ (18 kip E
Solution: D=10.0 inches
half-inch, from segn

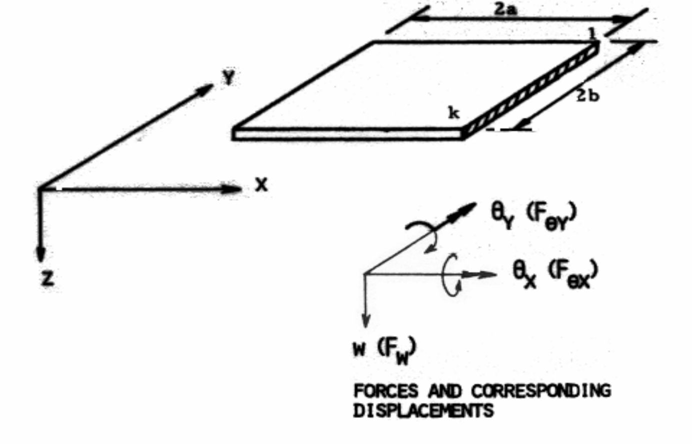
Application of reliability in this chart requires the use of mean values for all the input variables.

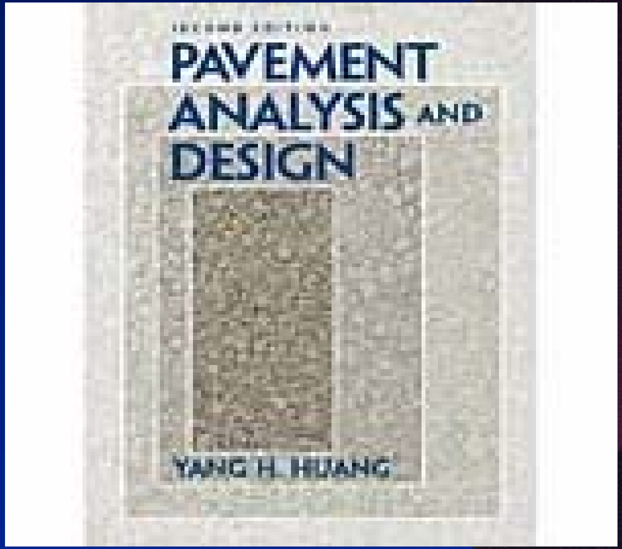
AASHTO DESIGN

Reliability



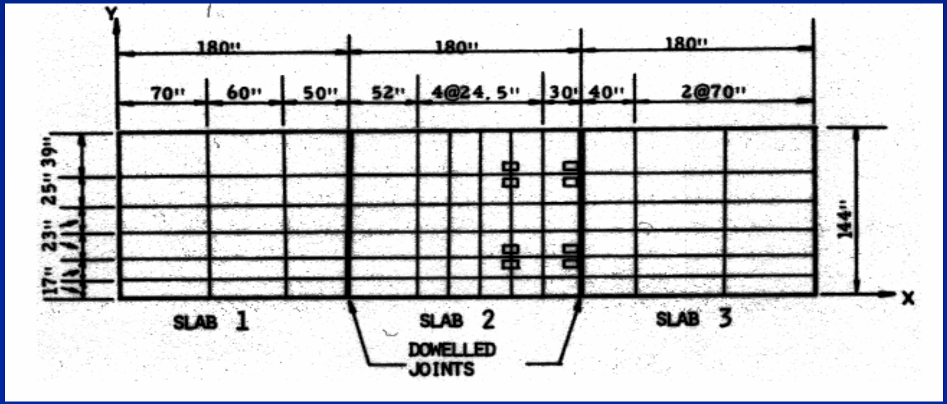
2-D FE Analysis (1970's)




SECOND EDITION

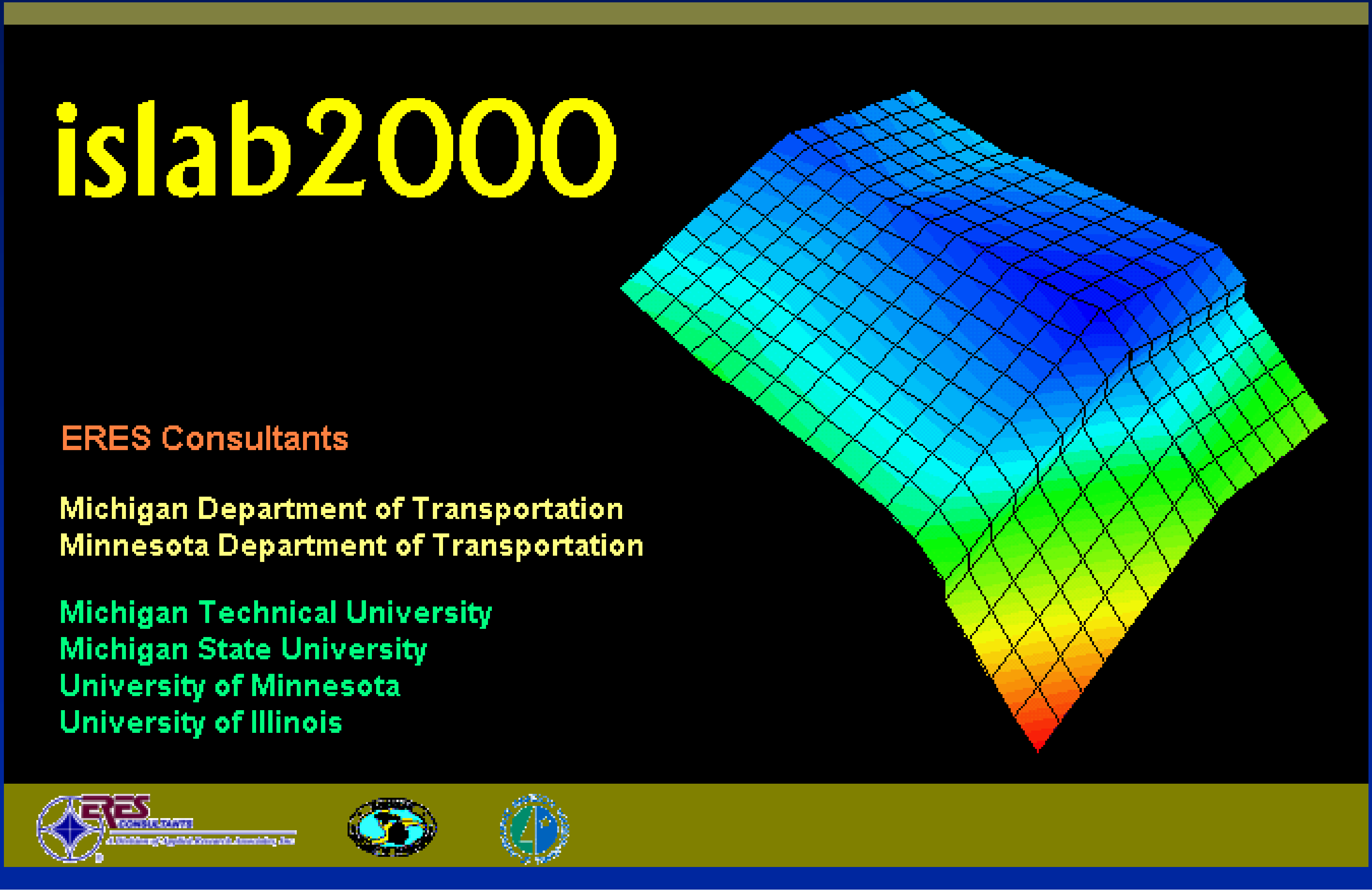
PAVEMENT ANALYSIS AND DESIGN

YANG H. HUANG



Yang Hsien Huang (b. 1927)

ISLAB2000 - 2D FEM



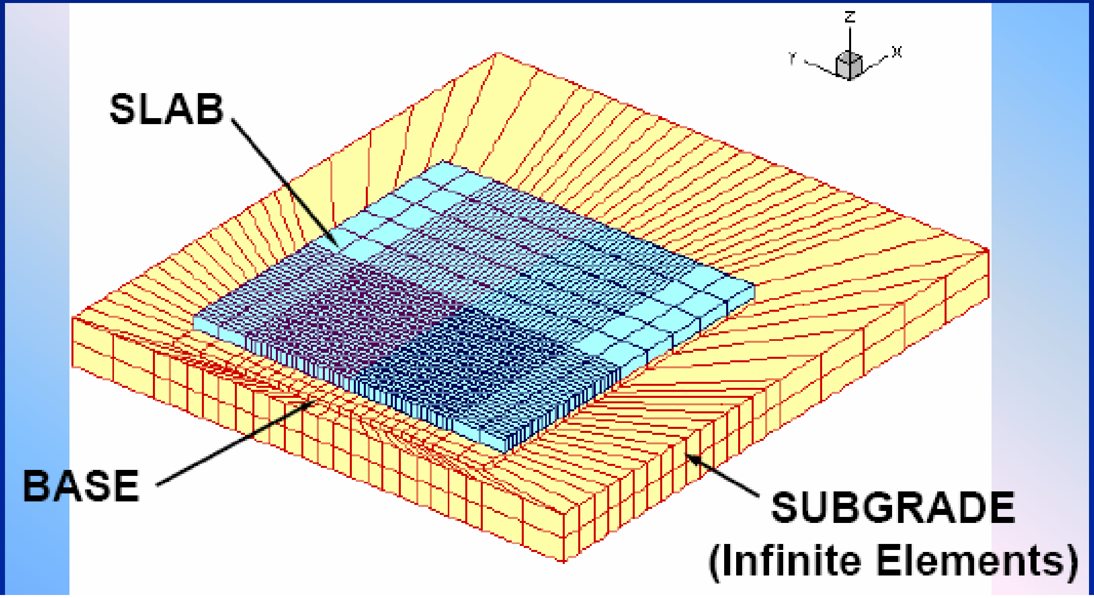
islab2000

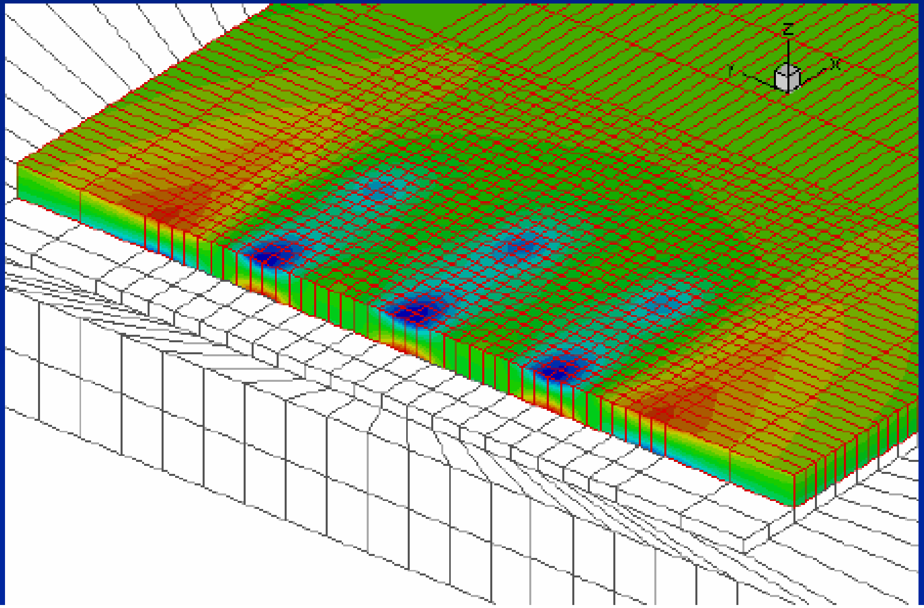
ERES Consultants

Michigan Department of Transportation
Minnesota Department of Transportation

Michigan Technical University
Michigan State University
University of Minnesota
University of Illinois

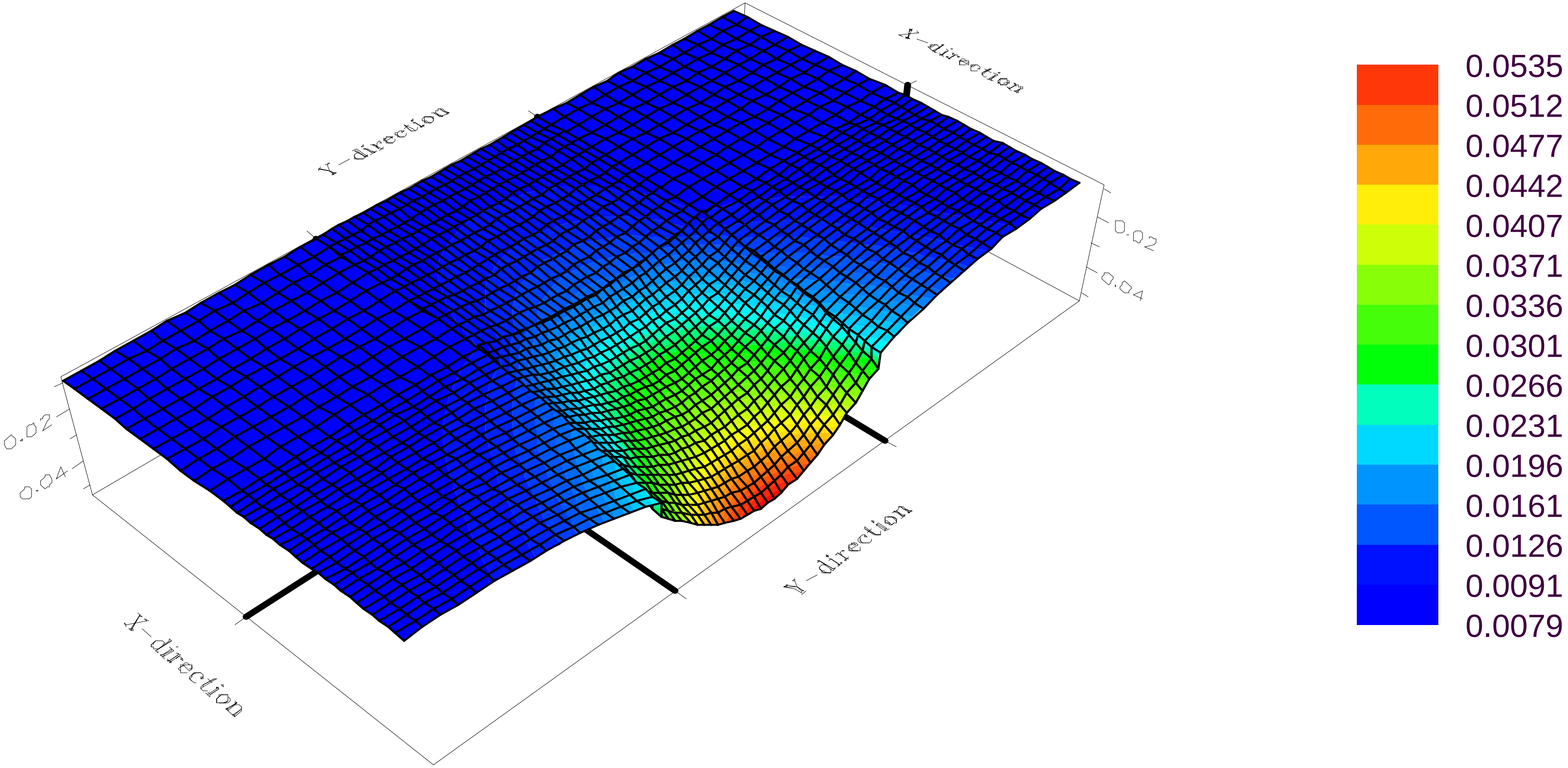
3-D FE Analysis



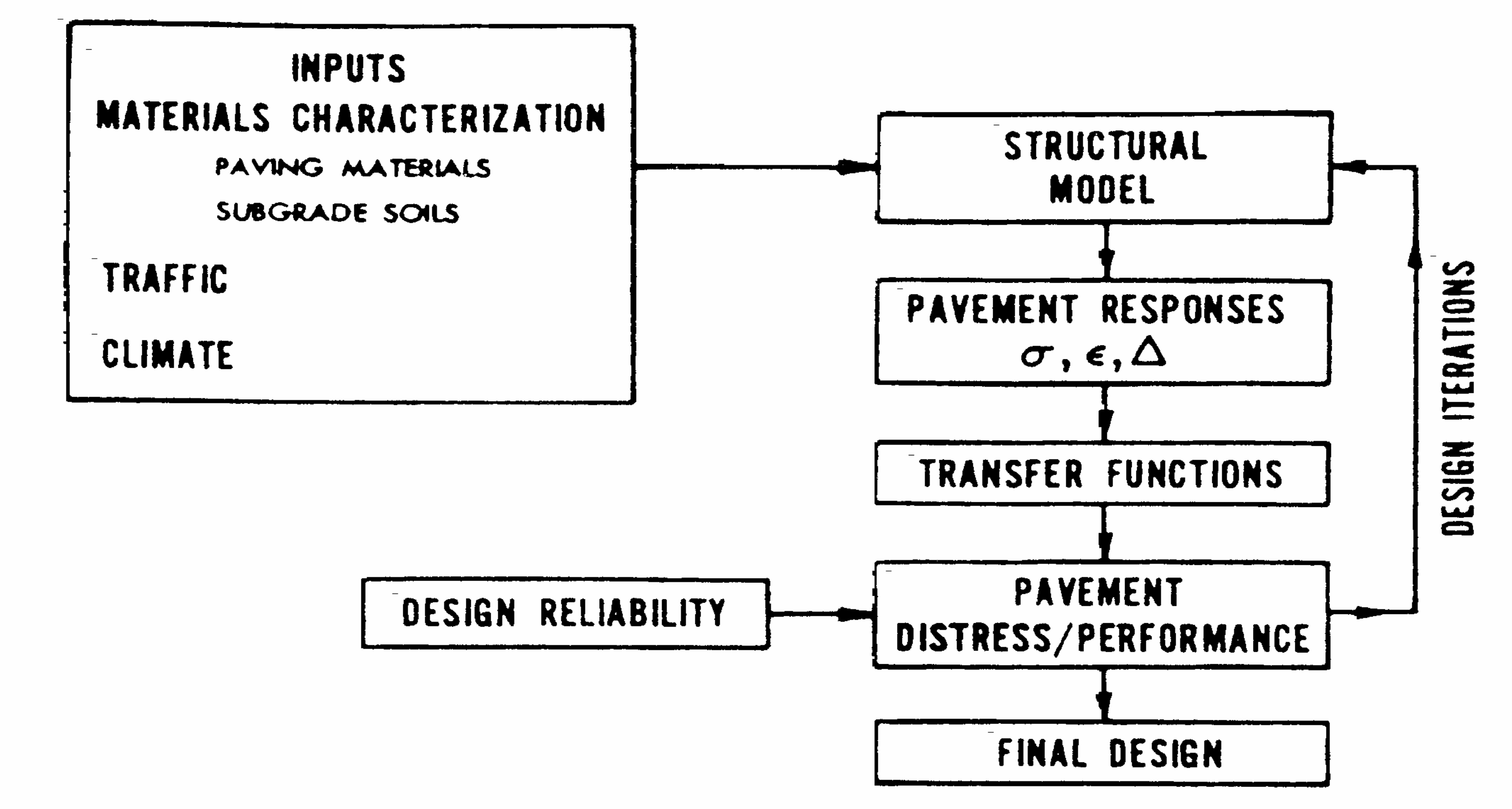


Flat Slab Condition, Tridem Axle Loading

Deflections



The Mechanistic-Empirical Design Procedure



After Thompson (2002)

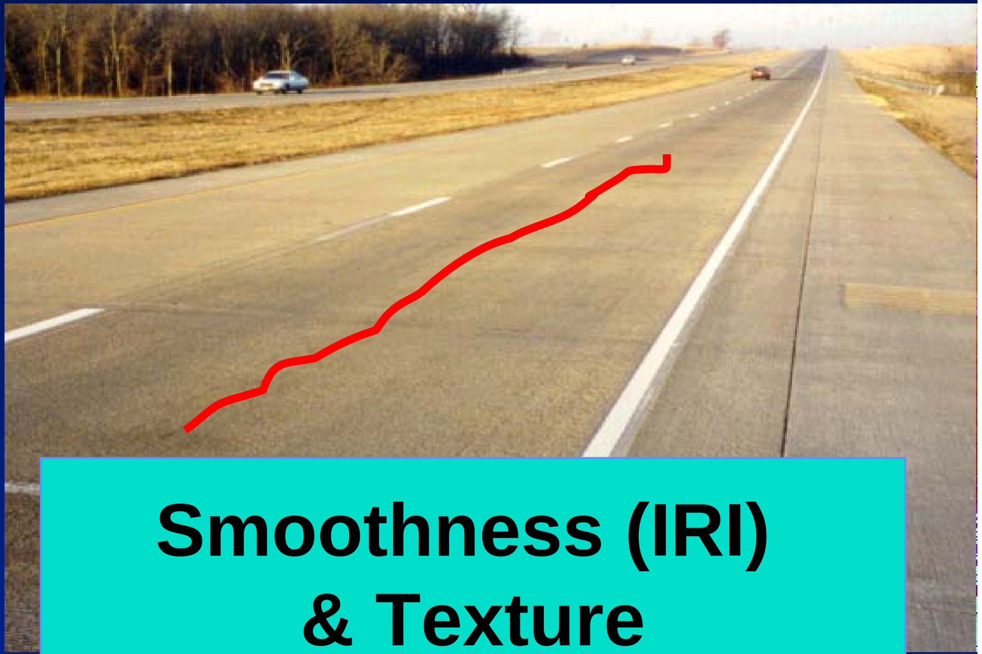
Benefits of M-E Design

- Ability to predict specific distress types and then improve design as needed
- Ability to extrapolate much better from limited field and laboratory results
- Evaluate new loading impacts
- Make better use of available materials
- Characterize materials changes with time
- Characterize seasonal effects
- Improved reliability of design

How do Concrete Pavements Fail?

Transverse Cracking

Some longitudinal cracking – typically early age



Smoothness (IRI) & Texture

Construction & in-service

Faulting

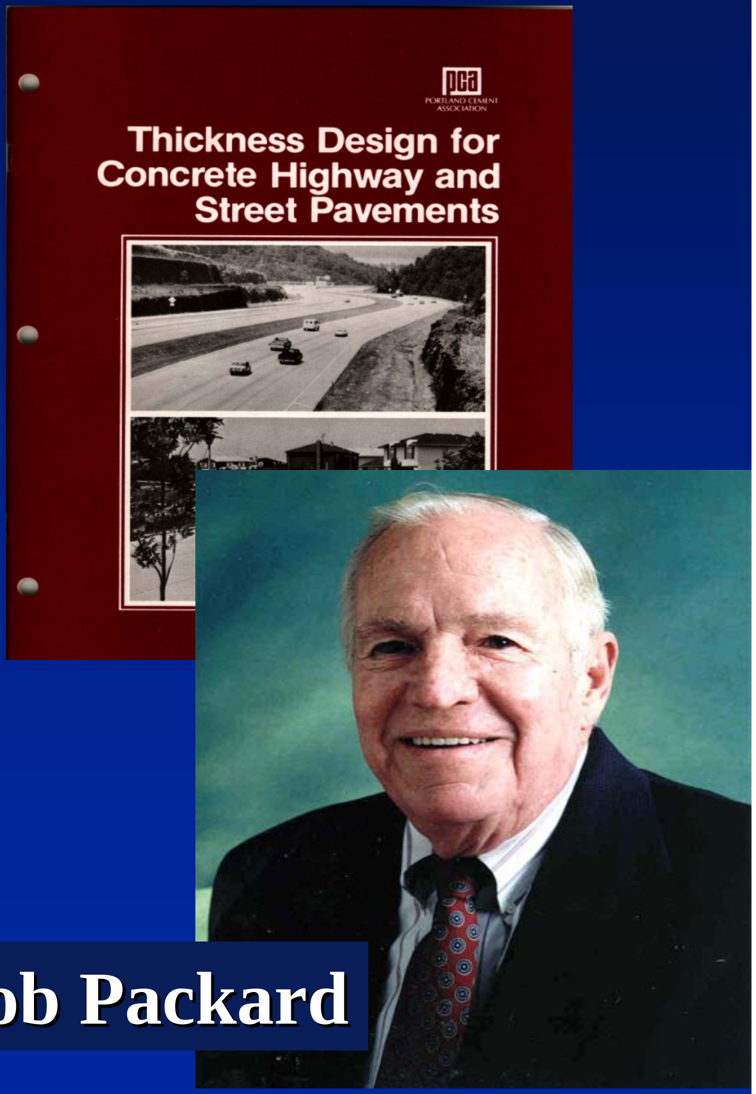
And, localized distresses (<u>spalling</u>) and materials related distresses (ASR, D-cracking, etc.)

M-E Design

PCA Thickness Design Procedure

- In 1966, PCA’s design was revised (Fordyce and Packard) based on AASHO Road Test, but with stresses computed mechanistically with edge load influence charts.

- Refined in 1984 (Packard & Tayabji) based on finite element based (JSLAB) mechanistic stress & deflection analysis



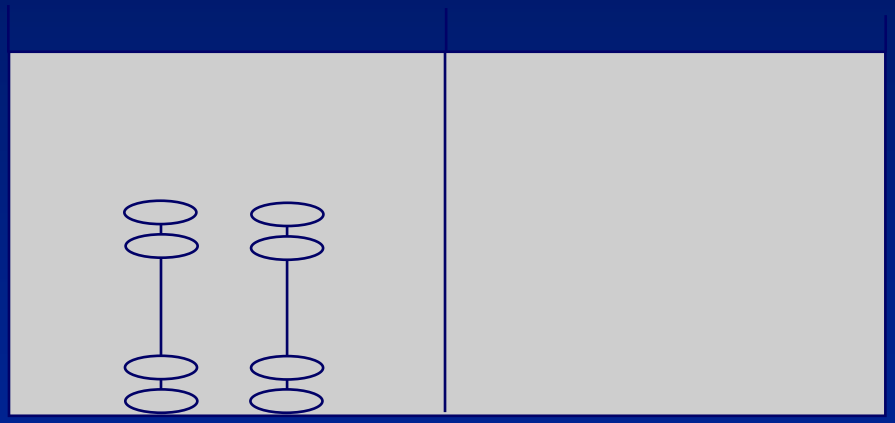
pca
PORTLAND CEMENT ASSOCIATION

Thickness Design for Concrete Highway and Street Pavements

Bob Packard

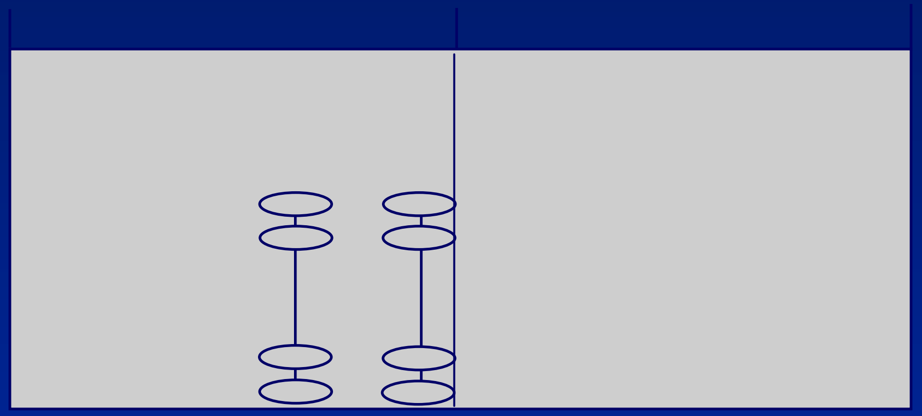
PCA Critical Loading Positions

Fatigue



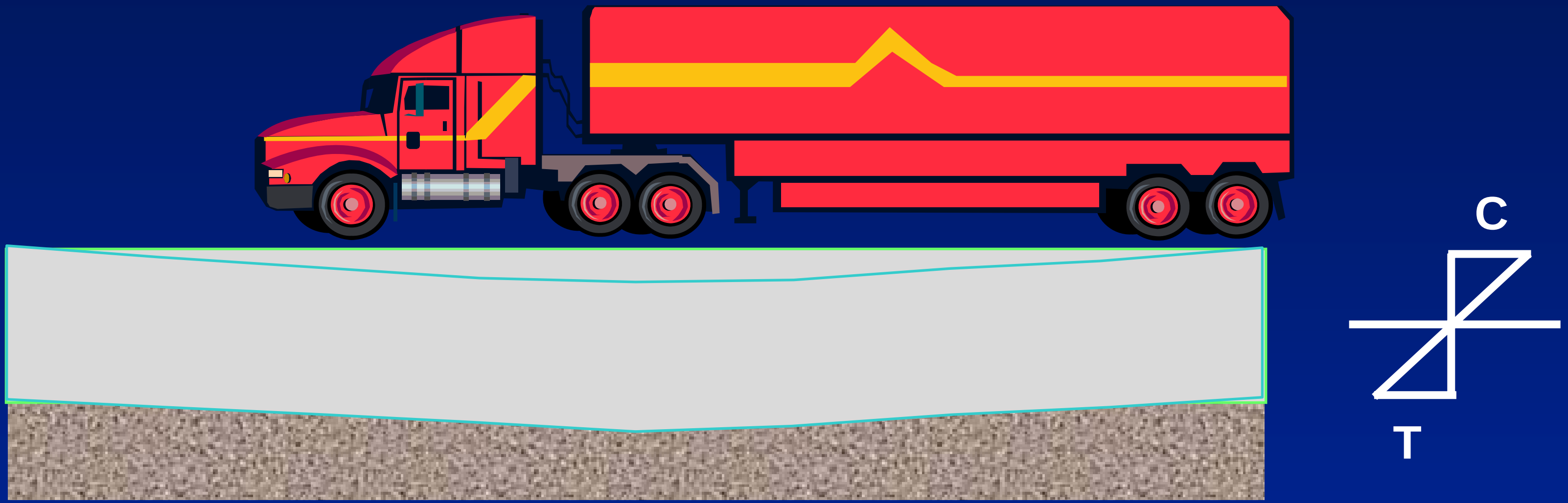
- Midslab loading away from transverse joint produces critical edge stresses

Faulting/Erosion/Pumping



- Corner loading produces critical pavement deflections

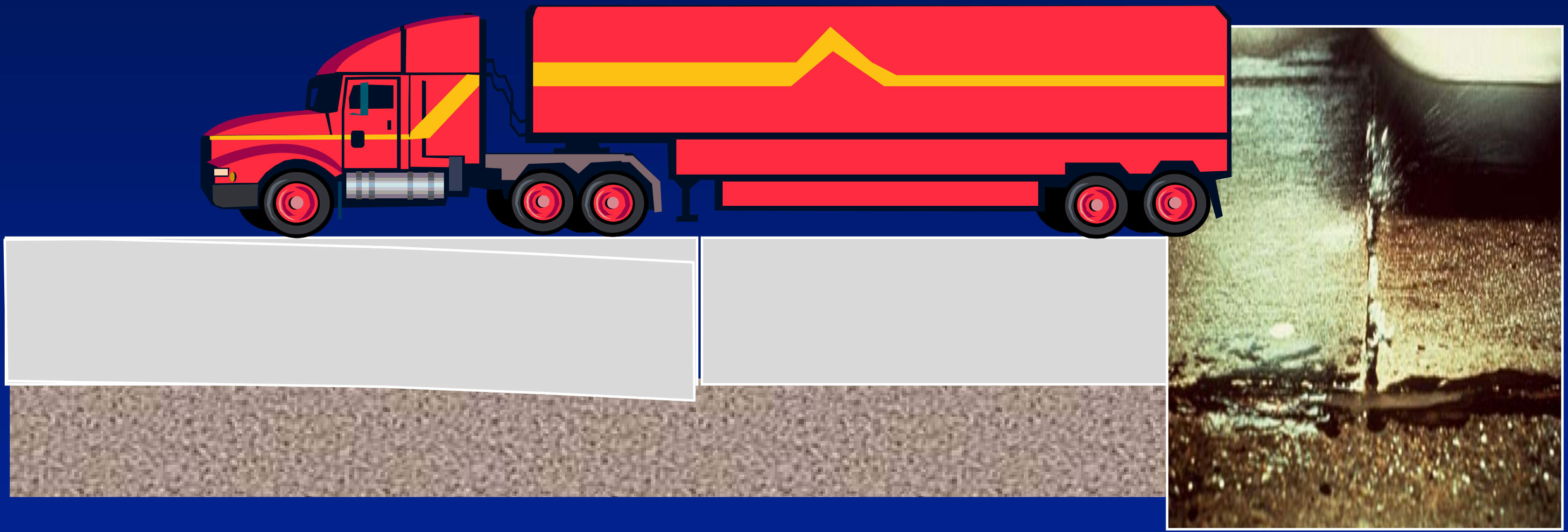
Basics of Thickness Design
(Edge Stress & Fatigue)



- Compressive strength: ~ 4000 psi
- Flexural strength: ~ 600 to 650 psi

Basics of Thickness Design

Corner Deflection / Erosion (pumping)/Faulting



- Higher k-value (stiffer support) will lower deflections
- Load transfer (dowel bars) will lower deflections
- Non-erodible base much better

PCA Design Traffic

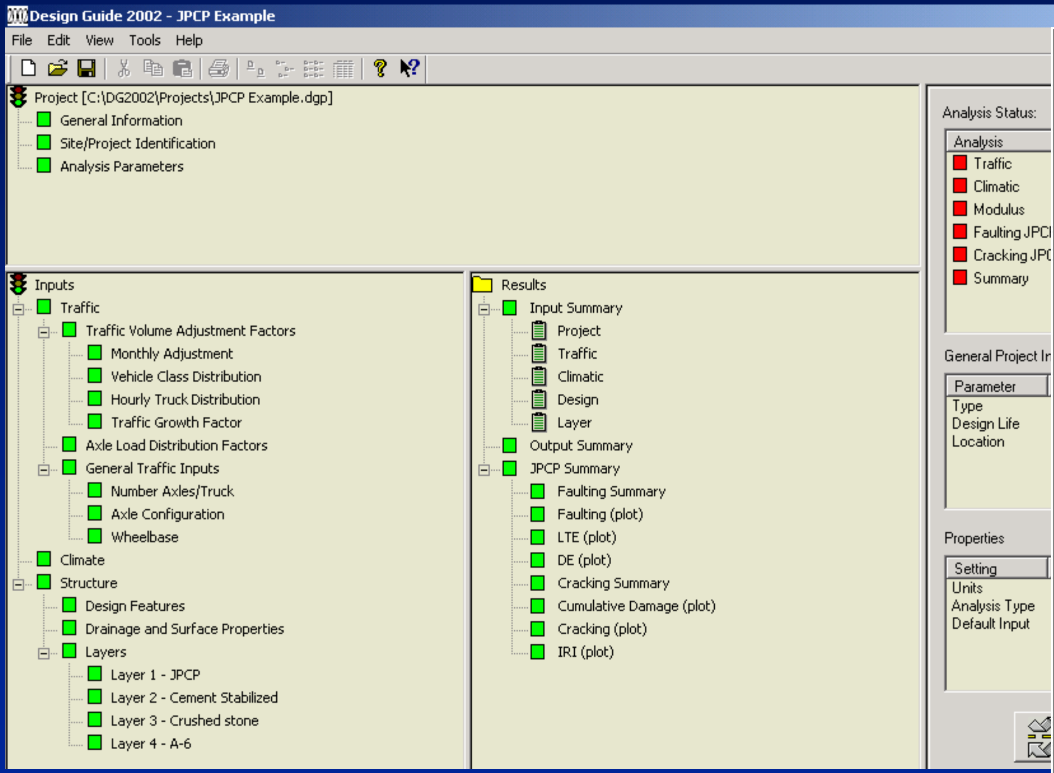
- Axle Load Distribution
  - The number of single and tandem axles over the design period
  - Expressed as Axles per 1000 trucks
  - Does not include panel and pickup trucks and other four-tire vehicles.

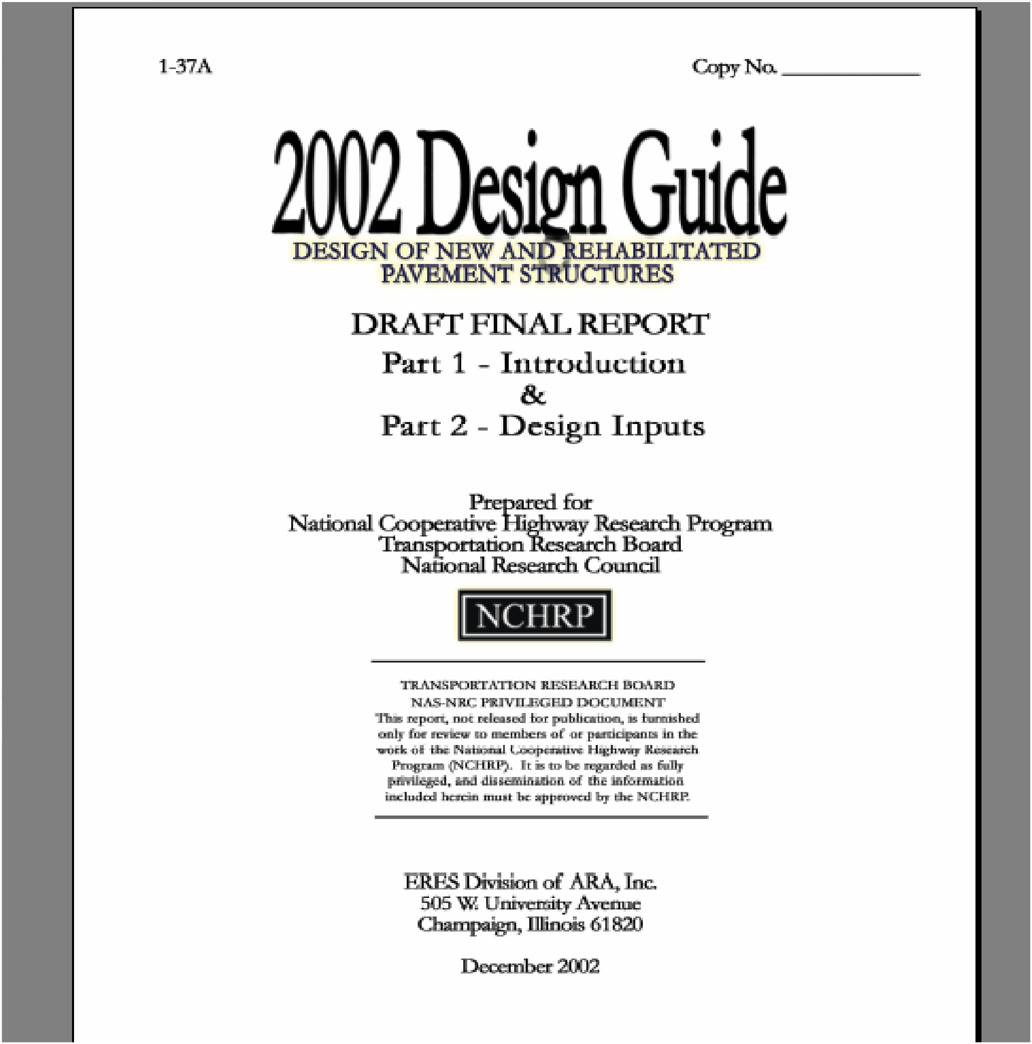
Axle load Kips	Axles/1000 Trucks	Axles in Design Period
Single Axles		
28-30	0.58	6,310
26-28	1.35	14,690
24-26	2.77	30,140
22-24	5.92	64,410
20-22	9.83	106,900
18-20	21.67	235,800
16-18	28.24	307,200
14-16	38.83	422,500
12-14	53.94	586,900
10-12	168.85	1,837,000
Tandem Axles		
48-52	1.96	21,320
44-48	3.94	42,870
40-44	11.48	124,900
36-40	34.27	372,900
32-36	81.42	885,800
28-32	85.54	930,700
24-28	152.23	1,656,000
20-24	90.52	984,900
16-20	112.81	1,227,000
12-16	124.69	1,356,000

Other M-E Design Procedures

- U of Illinois study by Mike Darter and Ernie Barenberg (1977) – for FHWA
  - Westergaard-based analysis for plain, jointed pavements, single and tandem axle loads
  - Fatigue cracking
  - Consideration of curling stresses
  - Cumulative damage
  - Consideration of dowels
  - Referred to as “Zero- Maintenance Design”
- NCHRP 1-26 (Barenberg and Thompson)

AASHTO M-E Pavement Design Guide (MEPDG)





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2002 Design Guide

DESIGN OF NEW AND REHABILITATED
PAVEMENT STRUCTURES

DRAFT FINAL REPORT
Part 1 - Introduction
&
Part 2 - Design Inputs

Prepared for
National Cooperative Highway Research Program
Transportation Research Board
National Research Council

NCHRP

TRANSPORTATION RESEARCH BOARD
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ERES Division of ARA, Inc.
505 W. University Avenue
Champaign, Illinois 61820

December 2002

A 7-year, $6.5 million effort, completed March 2004

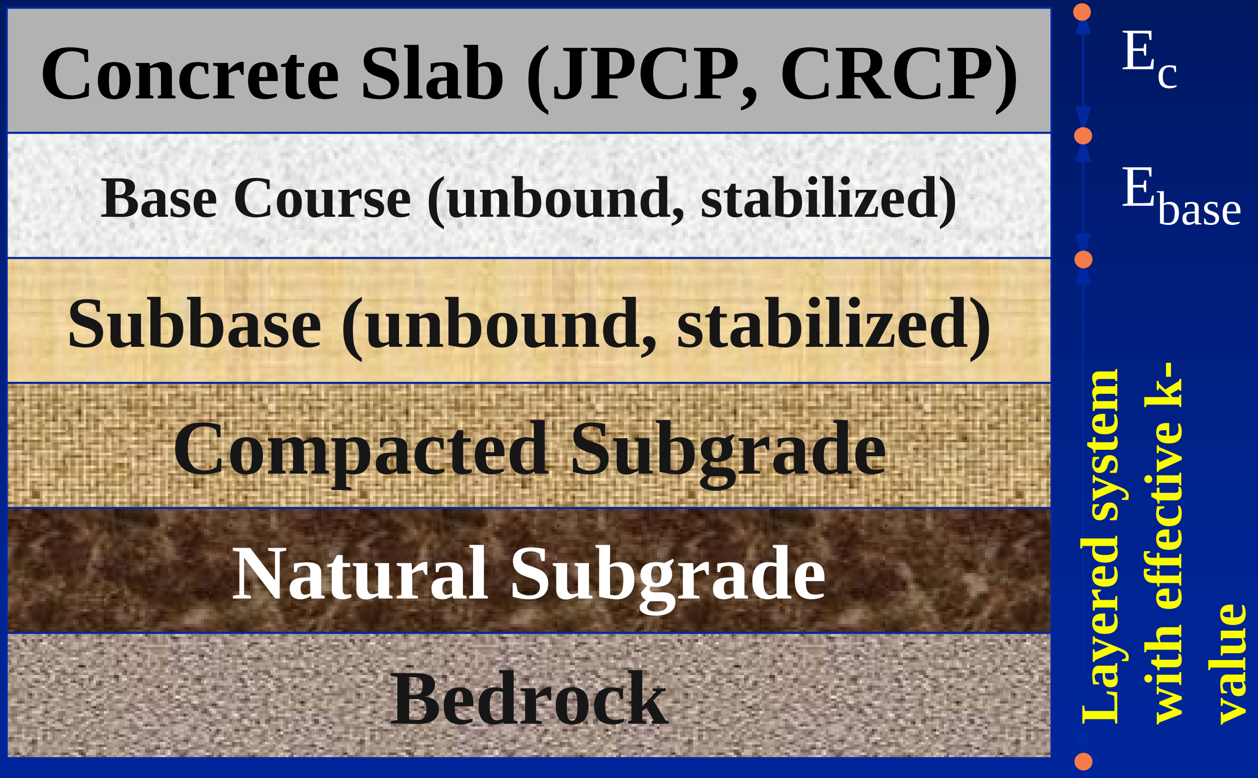
MEPDG Structural Analysis and Pavement Response

Calculate pavement responses

Stresses

Deformations

at critical locations



Concrete Slab (JPCP, CRCP)

Base Course (unbound, stabilized)

Subbase (unbound, stabilized)

Compacted Subgrade

Natural Subgrade

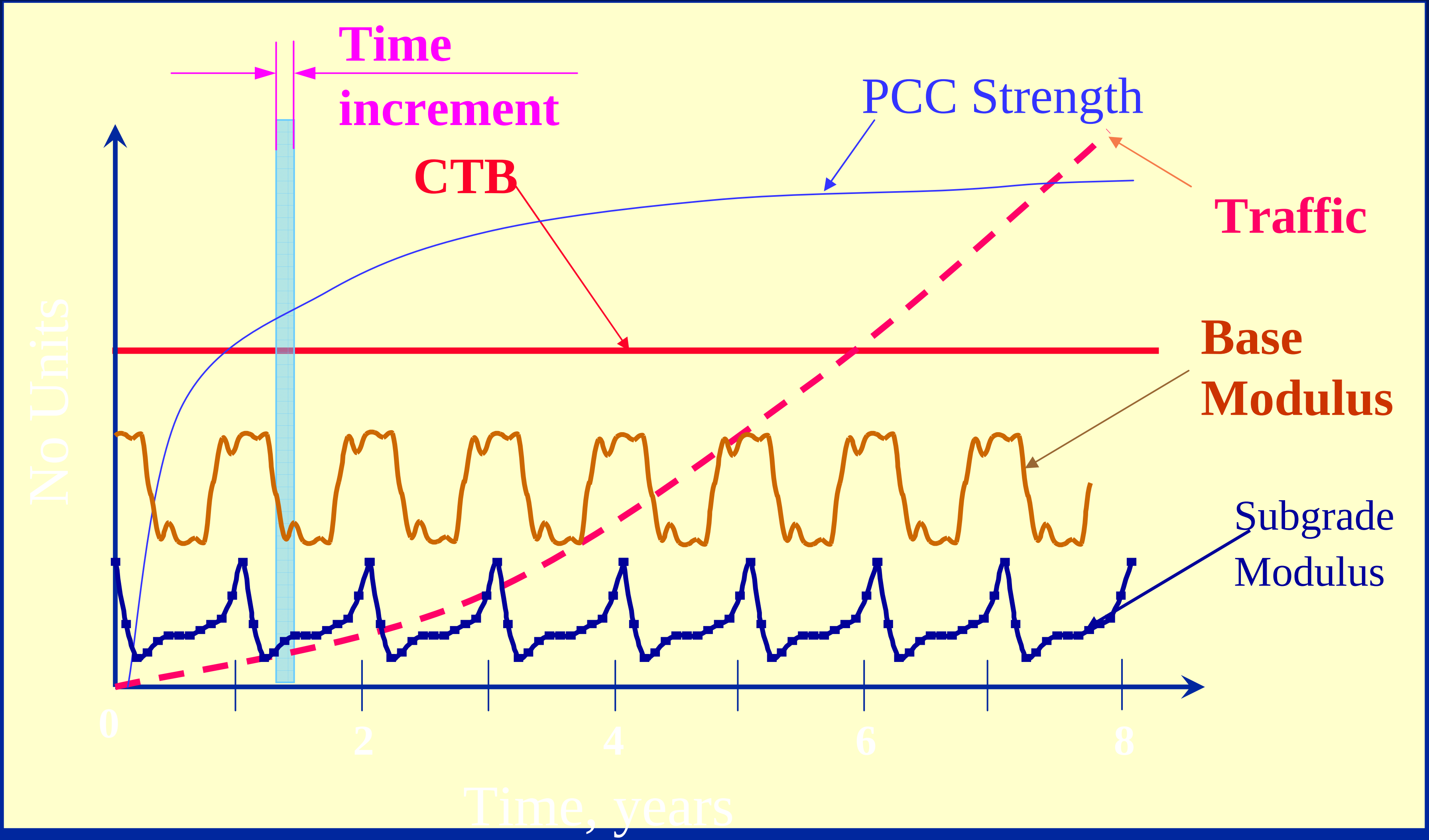
Bedrock

E_c

E_{base}

Layered system with effective k-value

Models Consider Changing Conditions



MEPDG Incremental Damage Approach (fatigue cracking example)

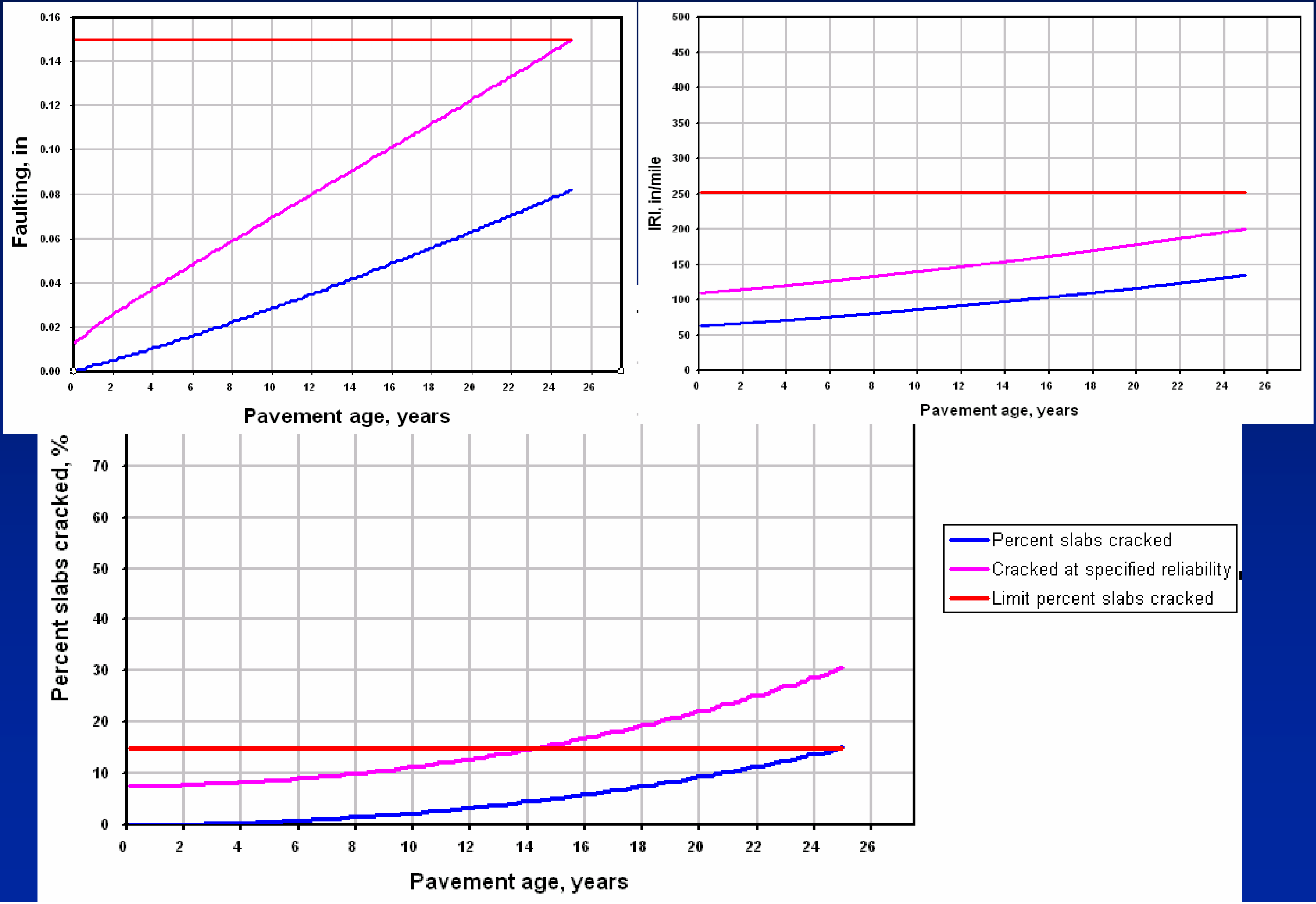
$$Fatigue\ \ Damage = \sum_{i} \sum_{j} \sum_{k} \sum_{l} \sum_{m} \sum_{n} \frac{n_{ijklmn}}{N_{ijklmn}}$$

$$Log(N) = 2.0 * \left(\frac{M_r}{\sigma_{total}} \right)^{1.22}$$

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

M-E Pavement Design Guide Results



Evaluate Performance

- Determine whether trial design satisfies
  - Cracking criterion
  - Faulting criterion
  - IRI criterion
- Modify design as needed
  - Run additional trials

2002 Guide Inputs for PCC (partial list)

- Performance Criteria (limits, reliability for cracking, faulting, IRI)
- Traffic:
  - No ESALs
  - Distribution by month, by hour
  - Distribution by Veh. Class
  - Axle Configuration and Load Dist. By Veh. Class
  - Growth Factors By Veh. Class
  - Wheel Path Location, Wander
- Site-specific Detailed Climatic Data, including seasonal variation of material properties
- Drainage path length, cross-slope
- Structural Design Features
  - Panel Dimensions
  - Joint Sealant Type
  - Dowel Size and Spacing
  - Edge Support Conditions
  - Bond Between Slab and Base
  - Erodability of Base, Subgrade
  - Built-in Curl/Warp
  - Layer Thickness and Properties
    - PCC Mix Design (including proportions, coarse aggregate type, w/c, etc.)
    - PCC Thermal Properties
    - PCC Shrinkage Potential
    - Change in PCC Props over Time
    - Unbound layer gradation, plasticity, strength, specific gravity, etc.
    - Resilient Modulus of Soil

MEPDG Performance Prediction: Correlate Damage to Distress

Distress models: Mechanistic-based, Calibrated with field data

- ***Faulting in JPCP***
- ***Transverse Cracking in JPCP***
  - Top–Down transverse cracking
  - Bottom–Up transverse cracking
- ***Edge Punchout in CRCP***
- ***IRI for Rigid Pavements***
  - IRI Models are Best-Fit from LTPP Data
  - IRI Accuracy depends upon predictive accuracy of all other Distress

National Field Calibration Factors
JPCP Joint Faulting

$$FaultMax0 = C_{12} * \delta_{curling} * \left[Log(1 + C_5 * 5^{erod}) \right] * Log(P_{200} * Wetdays / P_s)^{C_6}$$

$$\Delta Fault = C_{34} * (FaultMax - Fault)^2 * DE_n$$

$$C_{12} = C_1 + (C_2 * FR^{0.25})$$

$$C_{34} = C_3 + (C_4 * FR^{0.25})$$

$C_1 = 1.29$

$C_2 = 1.1$

$C_3 = 0.001725$

$C_4 = 0.0008$

$C_5 = 250$

$C_6 = 0.40$

$C_7 = 1.20$

$C_8 = 400$

JPCP IRI Model (Empirical)

$$IRI = IRI_I + 0.8203*cracking + 0.4417*Spalling + 1.4929*Faulting + 25.24*SF$$

where:

IRI_I = Initial IRI

PUNCH = Number of mid- to high-severity punchouts/km

PATCH = Number of mid- to high-severity flexible or rigid patching

SF = Site factor = $AGE*(1 + FI)(1 + P_{0.075})/10^6$

AGE = Pavement age, yr

FI = Freezing index, ^{o}C days

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

Data Analysis

- Local calibration will involve recalibrating the damage distress models using data collected from selected local sections

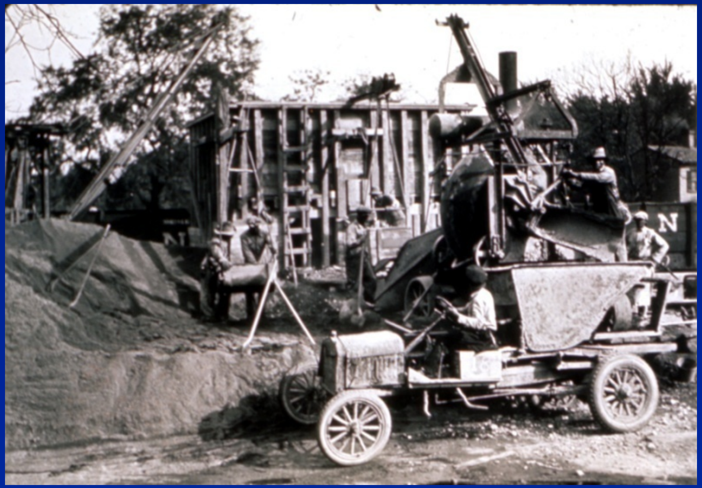
100+ Years of Concrete Pavement Technology Evolution

Construction Processes and Materials

Early Concrete Construction

First road construction was crude

Dry Batch and Dumped into Trucks



Mixed on Grade

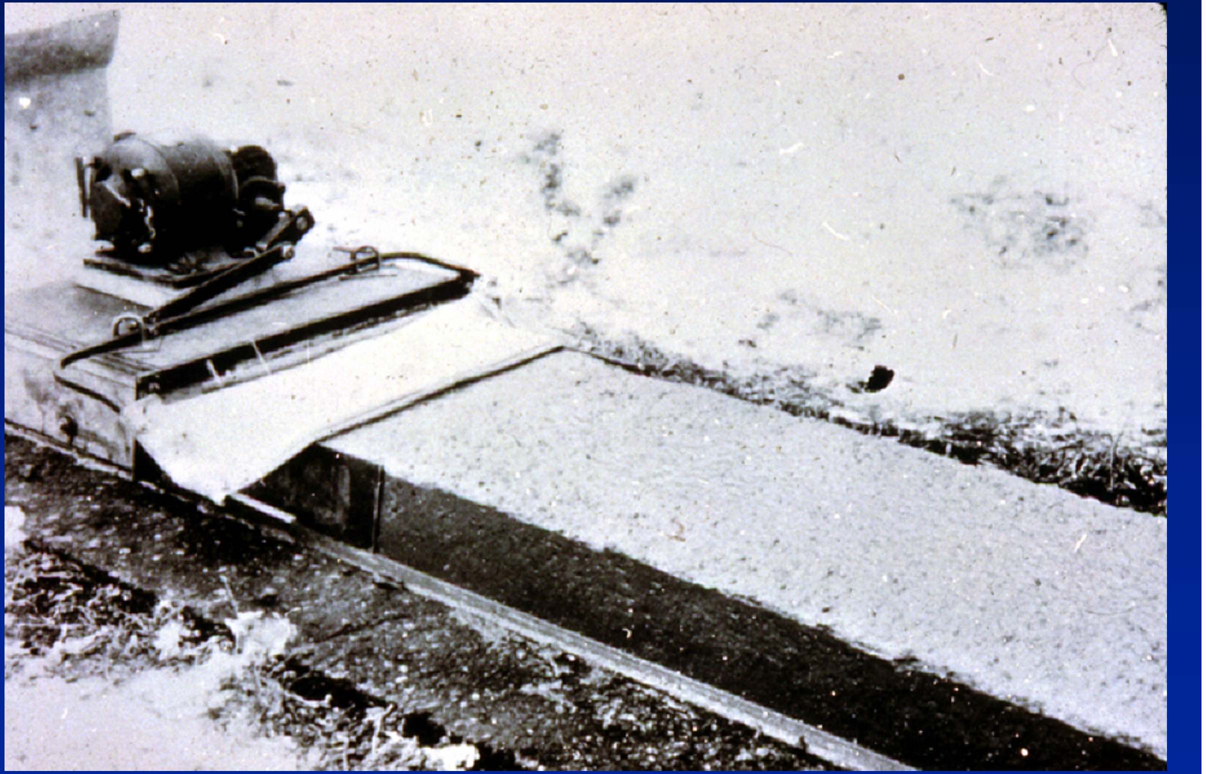
Construction Improvements

- 1920s until about 1960: all PCC pavements built with side forms
- Concrete was dry-batched and hauled out to a travelling mixer

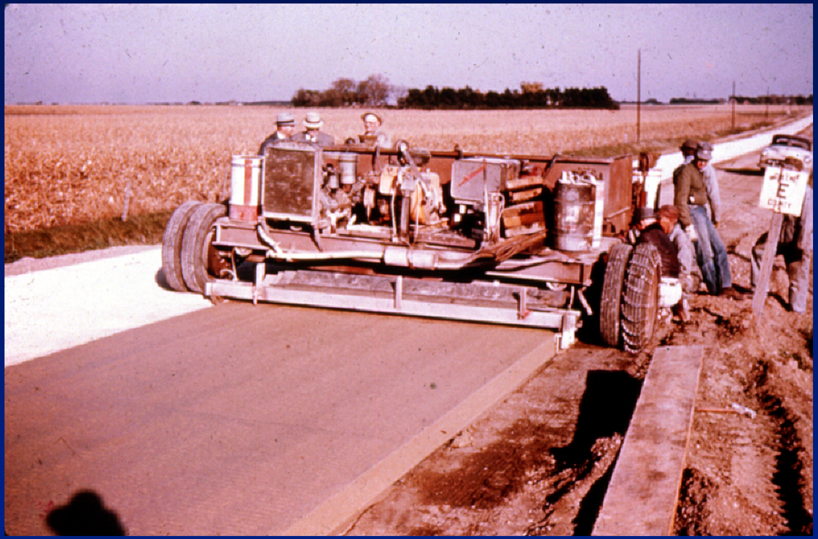
The 27E travelling mixer

Construction Improvements: Slip-form Paving

- In 1947, an Iowa DOT engineer built the first prototype slip-form paver
  - Laboratory demonstration
  - Paved 450 mm wide and 125 mm thick.



First Slipform Paving—1949
(Primghar, IA)



- 0.8-km county highway
  - 150-mm JPCP, 6.1 m wide
  - Paved in two passes
  - Cost: $1.76 / m^2 (vs. $2.64 / m^2 [estimated] for side-form paving)
- 1955: Development of self-propelled, track-mounted 7.3-m wide pavers

Construction Improvements: Central Plant Mixer

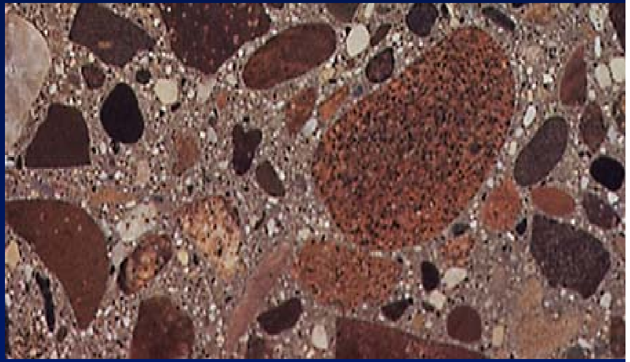
- Capacities of 6 to 9 cubic meters
- 10 times faster than 27E traveling mixer (dry-batch method).
- Made it possible to pave 1.6 two-lane km per day.

Poor Consolidation

Should we check for consolidation behind the paver?

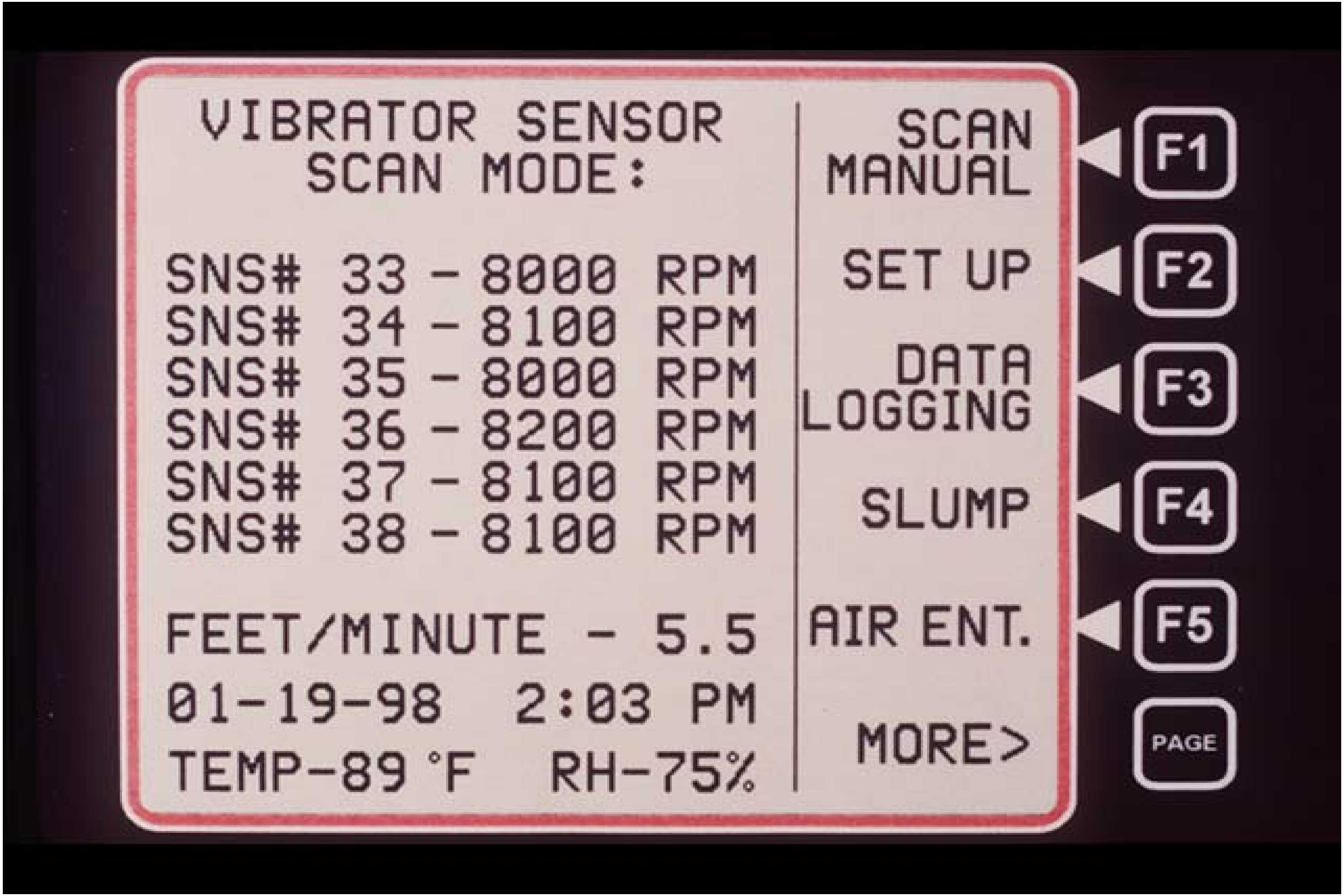
How?

Concrete Consolidation Understanding



- Inadequate consolidation:
    - Honey-combing
    - Reduced strength
- Over-consolidation:
    - Segregation
    - Poor air void system

- Solution: continuous monitoring of vibrator system



VIBRATOR SENSOR
SCAN MODE:

SNS# 33 – 8000 RPM
SNS# 34 – 8100 RPM
SNS# 35 – 8000 RPM
SNS# 36 – 8200 RPM
SNS# 37 – 8100 RPM
SNS# 38 – 8100 RPM

FEET/MINUTE – 5.5

01-19-98 2:03 PM

TEMP-89 °F RH-75%

Construction Improvements: Joint Sawing

- Prior to 1940s, joints were hand grooved in plastic concrete
  - Created a bump at most joints.
- Use of diamond blade saws started in the 1940s.
  - Standard practice since the 1950s

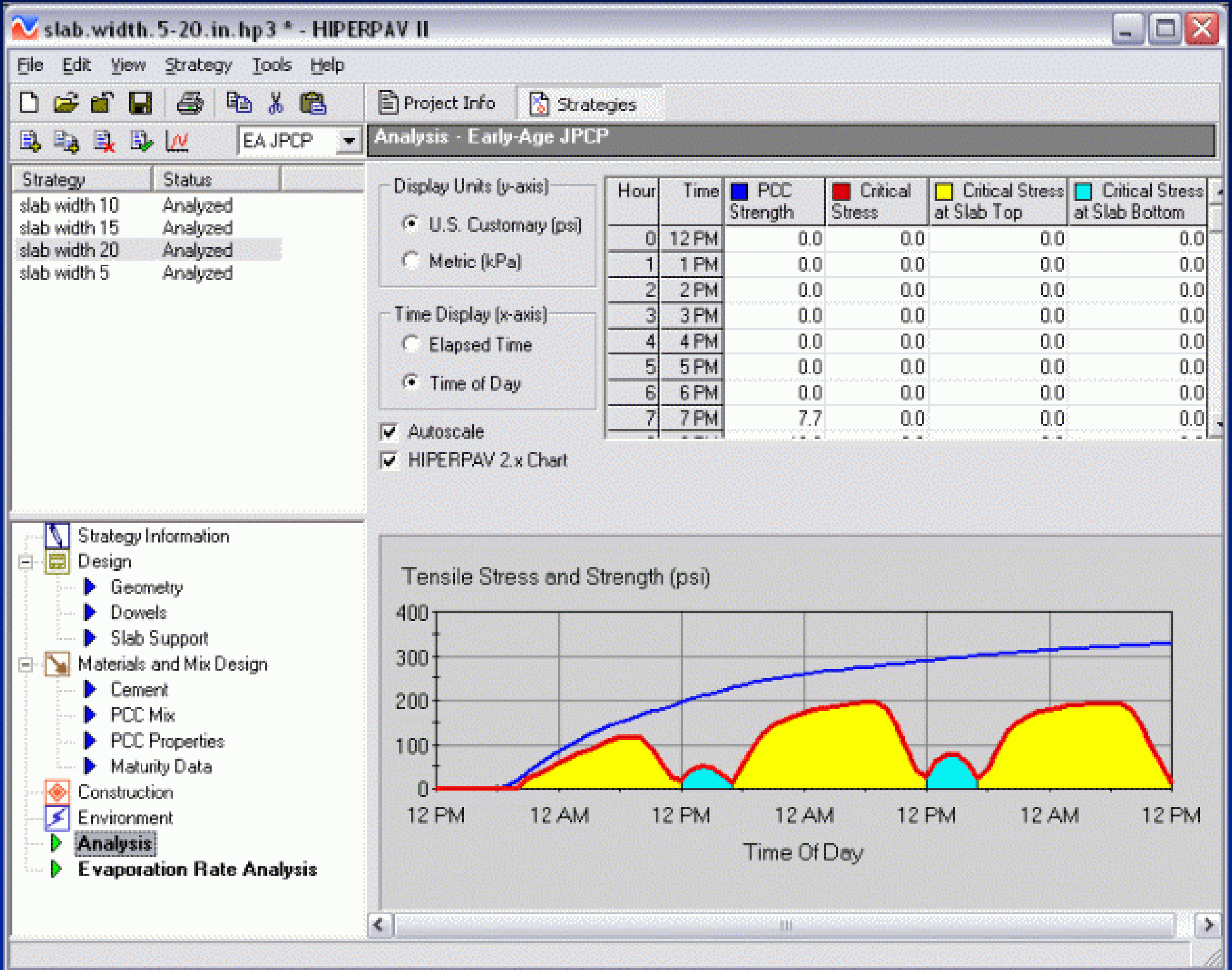
Joint Sawing/Sealing Approaches

- Traditional approach
  - Initial saw cut: 3 to 4 mm wide, D/4 or D/3 deep
  - Widening cut for sealant reservoir – shape factor

- Newer approach for short panels
  - single-cut, 2 to 3 mm wide
    - Unsealed
    - Sealed
    - Filled

Several US studies examining this issue. Findings: late 2008

HIPERPAV^{TM}



Strategy	Status
slab width 10	Analyzed
slab width 15	Analyzed
slab width 20	Analyzed
slab width 5	Analyzed

Display Units (y-axis)

● U.S. Customary (psi)
○ Metric (kPa)

Time Display (x-axis)

○ Elapsed Time
● Time of Day

☑ Autoscale
☑ HIPERPAV 2.x Chart

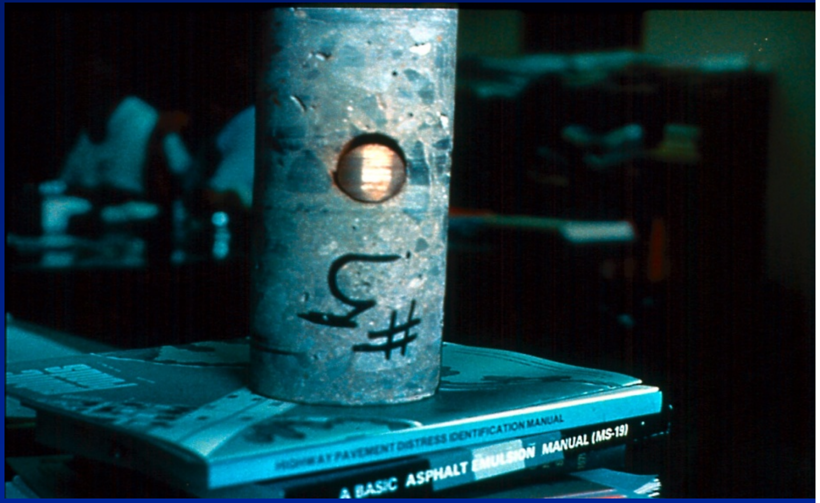
Hour	Time	🟦 PCC Strength	🟥 Critical Stress	🟨 Critical Stress at Slab Top	🟦 Critical Stress at Slab Bottom
0	12 PM	0.0	0.0	0.0	0.0
1	1 PM	0.0	0.0	0.0	0.0
2	2 PM	0.0	0.0	0.0	0.0
3	3 PM	0.0	0.0	0.0	0.0
4	4 PM	0.0	0.0	0.0	0.0
5	5 PM	0.0	0.0	0.0	0.0
6	6 PM	0.0	0.0	0.0	0.0
7	7 PM	7.7	0.0	0.0	0.0

Evolution of Concrete Pavement Joints

- Originally - aggregate interlock
- Then, various shapes of dowel bars (I-shaped, star lug, etc)
- Now, round dowel bars
  - Pre-positioned using baskets
  - Automatically placed using DBIs

Dowel bars

- Length: ~ 450 mm
- Spacing: ~300 mm in wheel paths
- ~150 mm minimum embedment length for outside 3 bars
- Diameter:
  - Highways: 32 to 38 mm
  - Airfields: 50 mm or more
- Corrosion-resistant or protected dowels
  - Epoxy coatings
  - Stainless Steel or Zinc Alloy Clad
  - MMFX steel



Evolution of Concrete Pavement Surface Texture

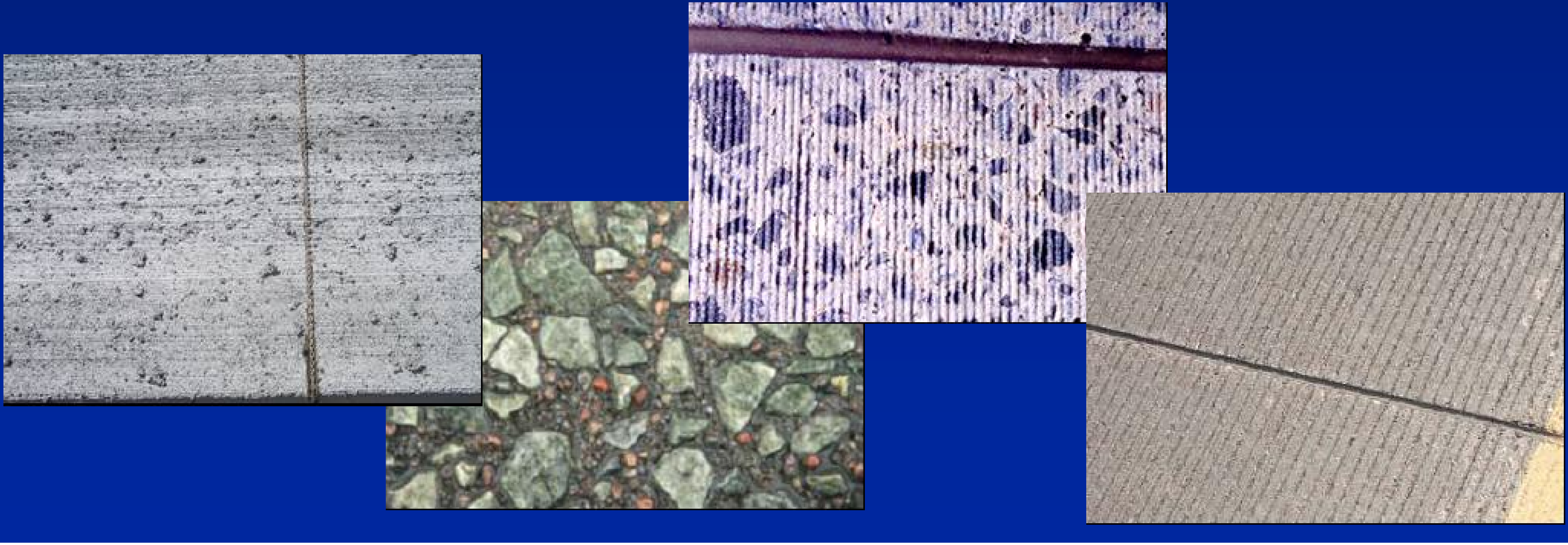
Balancing Safety and Noise

- Early pavements: no texture, burlap drag, brush texture
- 1970s – 2000s: transverse tining (noisy!)

Evolution of Concrete Pavement Surface Texture

Balancing Safety and Noise

- Now : moving towards “Astroturf drag”, longitudinal tining, grinding, exposed aggregate surface (European-style)



Construction Improvements: Curing Methods

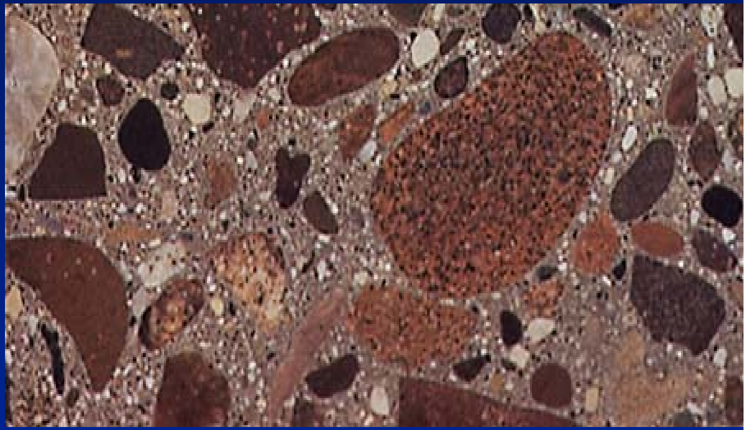
- Past techniques
  - Ponding/continuous sprinkling
  - Burlap/cotton mats
  - Plastic sheeting
- Modern technique - curing compounds

Recent Evolution of Design Features

- Improved durability for long life
  - Mix Designs
    - Ternary Blends
    - Aggregate Gradation
    - Increased Use of Recycled Materials
  - Corrosion-Resistant Dowels and Reinforcing
- Widened lanes and tied shoulders
- Precast concrete paving systems
- Pervious concrete

Concrete Mixture Design: Focus on Durability, Workability

- Design philosophy – concrete pavement failure should be due to traffic loading and not due to concrete material failure



- Concrete mixture technology has improved significantly
  - Avoid early materials-related failures
  - Higher concrete strengths can be attained, as needed

Typical US Paving Concrete Mixtures

- Cement - Type I or II: ~300+ kg/m3
- Fly Ash/Slag: 10 – 50% cement replacement
- Coarse Aggregate: ~1,080 kg/m3
- Fine Aggregate: ~720 kg/m3
- Water: ~ 130 kg/m3
- Admixtures - AEA, WRA
    - (Air: 4 to 7% in freeze areas)
- Fibers: not common
- Also: Well-graded aggregates

POZZOLANS AND SLAG USE

- Class F (siliceous) fly ash: 15% - 25%
- Class C (cementitious) fly ash: 15% - 35%
  (used with caution)
- Gran. Blast Furnace Slag: 25% - 50%
- Silica fume: 6% - 10%
  (not common in US for paving applications)
- Ternary Blends = Class F + GBFS

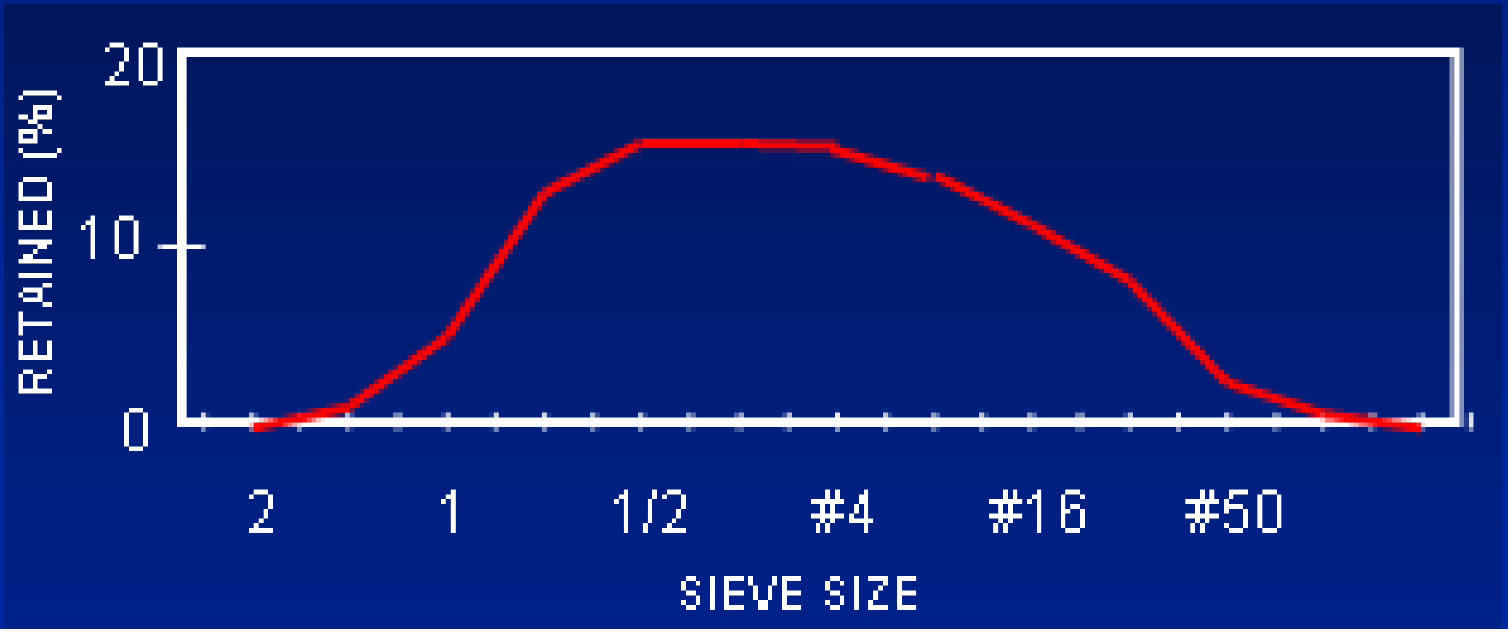
Also, blended cement use is allowed and is common

Aggregate Gradation

(From Gap-Graded to Shilstone's Combined Gradation)

- Combined gradation
  - Better for slip-form paving
  - Dense mixture
  - Less sensitive to consolidation effort
  - Less cement; more economical

- Gap graded
  - Possibly poorer concrete performance
  - Segregation is a big concern



Widened Slab/Tied Shoulder

- Widened Lane
  - Slab paved 0.6 m wider than usual
  - Lane striped at normal 3.65 m width
  - Reduces edge and corner stress/deflections

- Tied concrete shoulder
  - Reduces edge stress/deflections
  - Reduces moisture infiltration
  - Emergency/future traffic lane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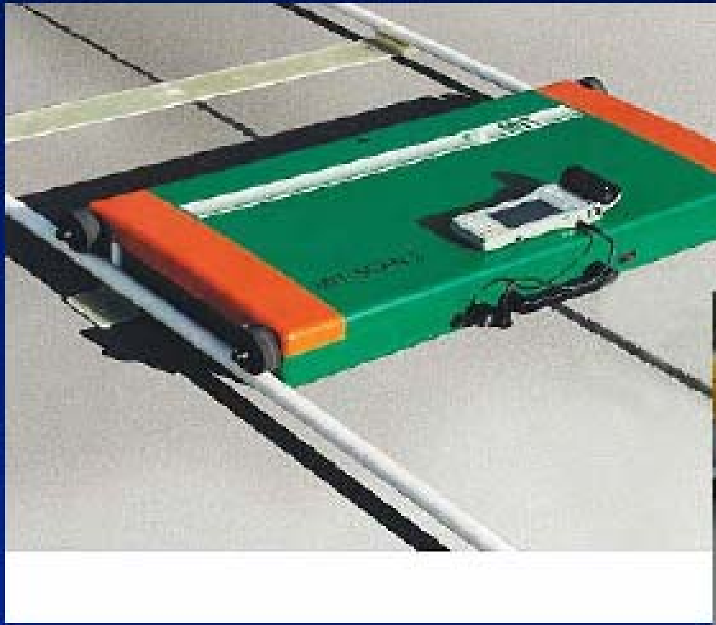
Some New Developments

- Stringless grading and slip-form paving
  - Laser/GPS Elevation Control
  - No stringlines or forms required

Some New Developments:
Dowel Bar Alignment Testing



German MIT SCAN Device

Precast Concrete Pavement

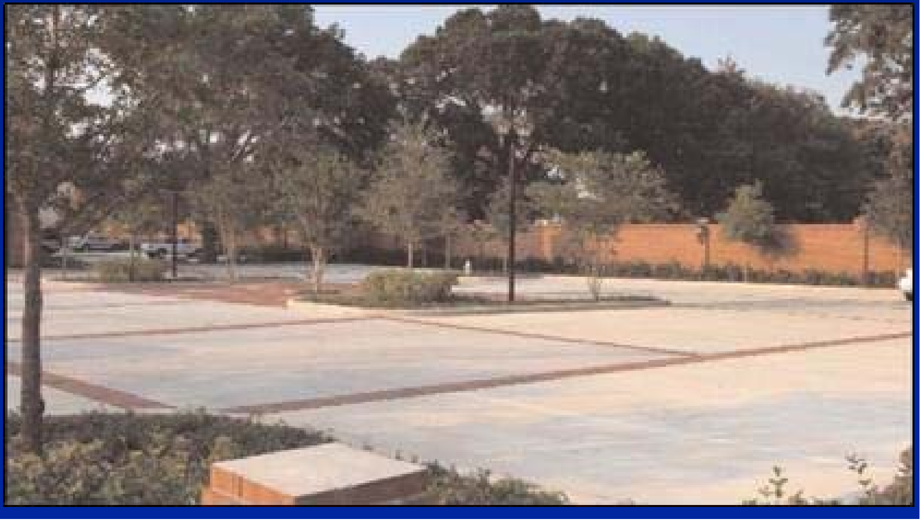
(For Accelerated Repair & Construction)

- Individual panel repairs – plain concrete panels
  - Full-depth full panel replacement
- Reconstruction or repair of larger areas
  - Conventional panels
  - Prestressed panels – fewer active joints

Newer Development: Pervious Concrete

(Environmentally Friendly Concrete)

- An older material ("no-fines" concrete) now being reconsidered for parking areas, low-volume streets & driveways



- Rapid flow of water through the pavement into the ground

Current Hot Issues

- Sustainability
  - Green concrete construction
  - Recycled concrete & other material use
  - Reducing carbon dioxide load
- Construction quality – reducing early failures
- Long-life pavements – low life cycle costs

US Future Directions

- Many incremental improvements in design, materials & construction processes
- More emphasis on construction quality & durability
- Emphasis on END PRODUCT REQUIREMENTS
- M-E procedures will allow optimum designs
  - Design lives of 40, 50 or 100+ years will be more common and reliable
  - Use of design catalogs will become more common

- NO RADICAL CHANGES IN DESIGN EXPECTED

Acknowledgments

- American Concrete Pavement Association
- Carl Monismith, Univ. of California – Berkeley
- ERES Consultants/ARA, Inc.
- Kurt Smith, Applied Pavement Technology
- Mike Plei (formerly with CRSI)
- Portland Cement Association
- Randell Riley, Illinois Chapter of ACPA
- Shiraz Tayabji, Fugro Consultants
- Tasos Ioannides, University of Cincinnati
- … and many more

Concrete Pavements - A 100+ Year Journey

Obrigado!