Review of 10 Years of Concrete Airport Pavement Studies at the NAPTF

and Next 10 Year Plan

Federal Aviation Administration

Presented to: 2nd International Conference on Best Practices for Concrete Pavements
Florianópolis, Brasil

By: David R. Brill, P.E., Ph.D.

Date: 3 November 2011

Outline of Presentation

- **Concrete Failure Model Studies**
  - Historical background of the rigid pavement failure model in FAA design
  - One- and Two-Stage Failure Models
  - Concept of "Three-Stage" failure
- **Field Studies**
  - Understanding "Total Stress" - the true killer of rigid pavements
  - Rigid Pavement Curling Studies
  - Field Instrumentation Research at Denver, Atlanta and JFK
- **Plan for Next 10 Years**
  - Extending Pavement Life to 40 Years
  - Looking Ahead for FAA PAVEAIR

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  - Dr. Yuanguo Chen
- **Consultants:**
  - Dr. Edward H. Guo
  - Roy D. McQueen
  - Richard Ahlvin

Federal Aviation Administration
Airport Technology R&D Program

- **Research conducted at the FAA William J. Hughes Technical Center, Atlantic City, NJ, USA.**
- **Sponsor: FAA Office of Airport Safety and Standards (AAS-100), Washington, DC.**
- **Provide support for development of FAA pavement standards (Advisory Circulars).**

National Airport Pavement Test Facility (NAPTF)

FACTS:

- **Fully enclosed facility for accelerated traffic testing of airport pavements.**
- **Full-scale pavement structures and landing gear loads with programmed wander.**
- **Opened in 1999.**
- **Total construction contract was $21M.**
  - $14M from FAA
  - $7M from Boeing Co. under FAA/Boeing CRDA.

Pavement Software Products

2011	**FAA PAVEAIR**	Web-based airport pavement management system.
2010	**FAARFIELD 1.305**	**FAA R**igid and **F**lexible **I**nteractive **E**lastic **L**ayered **D**esign: Standard thickness design software. Incorporated in AC 150/5320-6E.
2011	**FEAFAA 1.2**	**3D Finite Element** analysis of rigid pavements, runs on desktop PC.
2010	**COMFAA 3.0**	Computes pavement strength and thickness for reporting PCN. Incorporated in AC 150/5335-5B.
2008	**ProFAA**	Computes pavement elevation profile roughness indexes from profile data. Incorporated in AC 150/5380-9.
2003	**LEDFAA 1.3**	**L**ayered **E**lastic **D**esign **– FAA.** Previous FAA thickness design standard, but still supported.
2002	**BAKFAA**	Backcalculation of elastic properties using **LEAF**. Also used for **LEAF** development.
2001	**LEAF**	**L**ayered **E**lastic **A**nalysis – **FAA**: Layered elastic analysis program for 32-bit Windows, replaces JULEA.

Concrete Failure Model Studies

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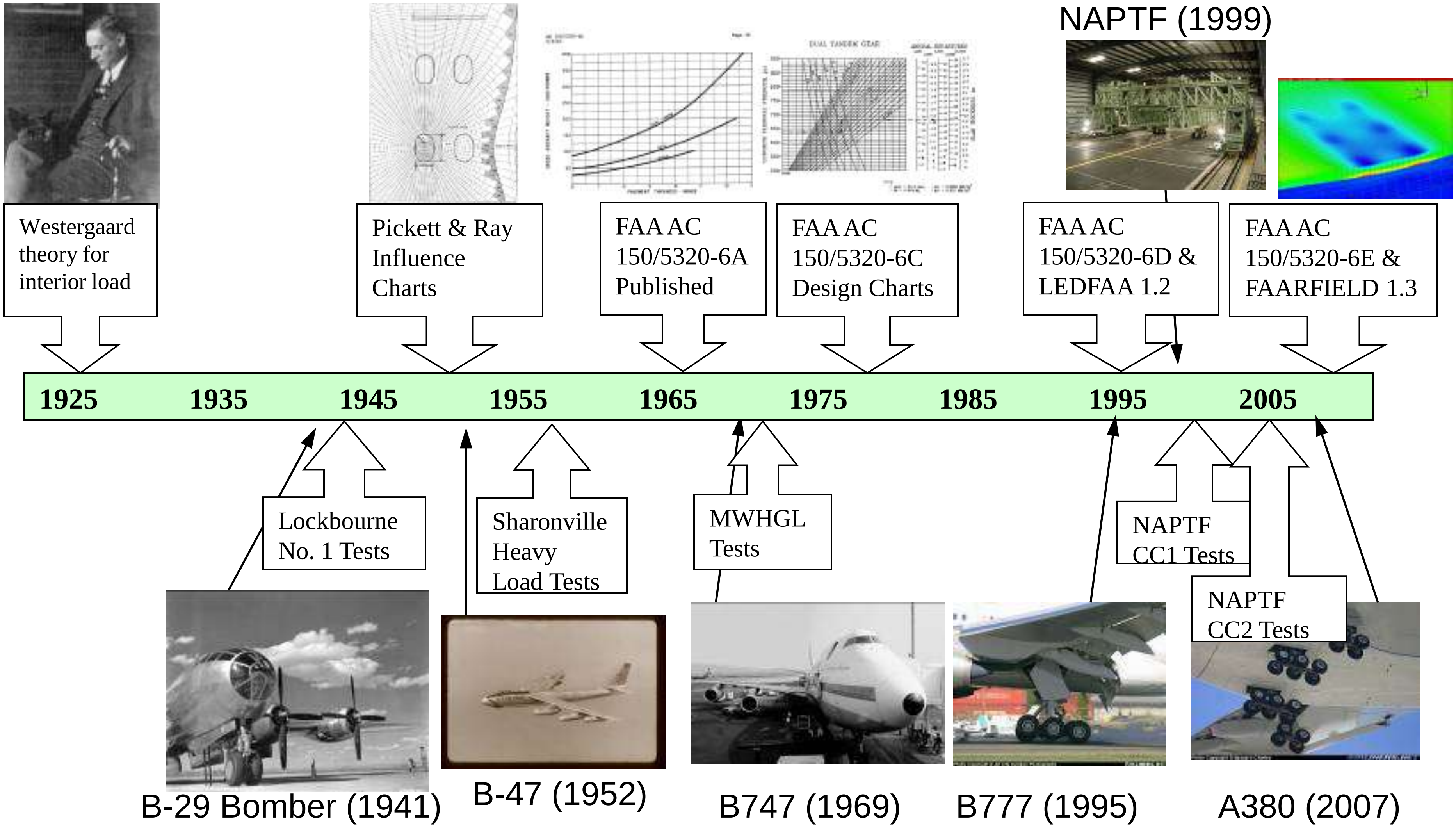
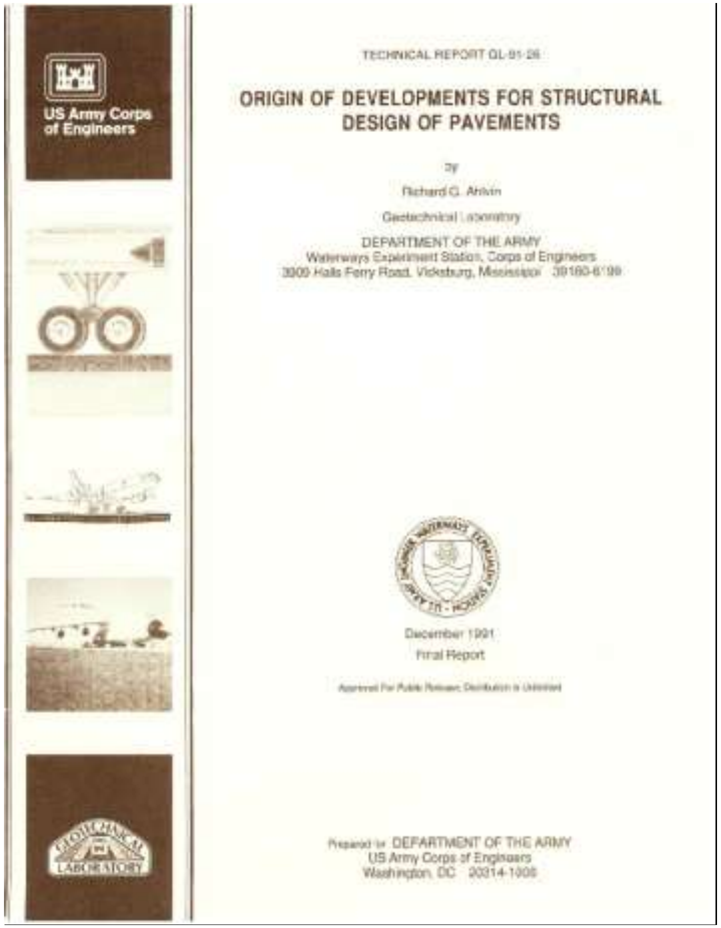
Timeline of Rigid Airport Pavement Design



Learning from History (1)

- **Beginning in the early 1940's, the U.S. Army Corps of Engineers conducted a series of traffic tests to check Westergaard's interior load criteria.**
- **These tests established some well-known principles of rigid airport pavement design:**
  - Edge loads are more critical than interior loads for rigid slabs.
  - 25% load transfer at joints is reasonable.
  - Important to consider load repetitions, not just load magnitude.
  - High-strength subgrade support extends rigid pavement life, especially after first crack.


US Army Corps of Engineers

TECHNICAL REPORT GL-91-26

ORIGIN OF DEVELOPMENTS FOR STRUCTURAL DESIGN OF PAVEMENTS

by

Richard G. Ahlvin

Geotechnical Laboratory

DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
3909 Halls Ferry Road, Vicksburg, Mississippi 39180-6199

December 1991
Final Report

Approved For Public Release; Distribution is Unlimited

Prepared for DEPARTMENT OF THE ARMY
US Army Corps of Engineers
Washington, DC 20314-1000

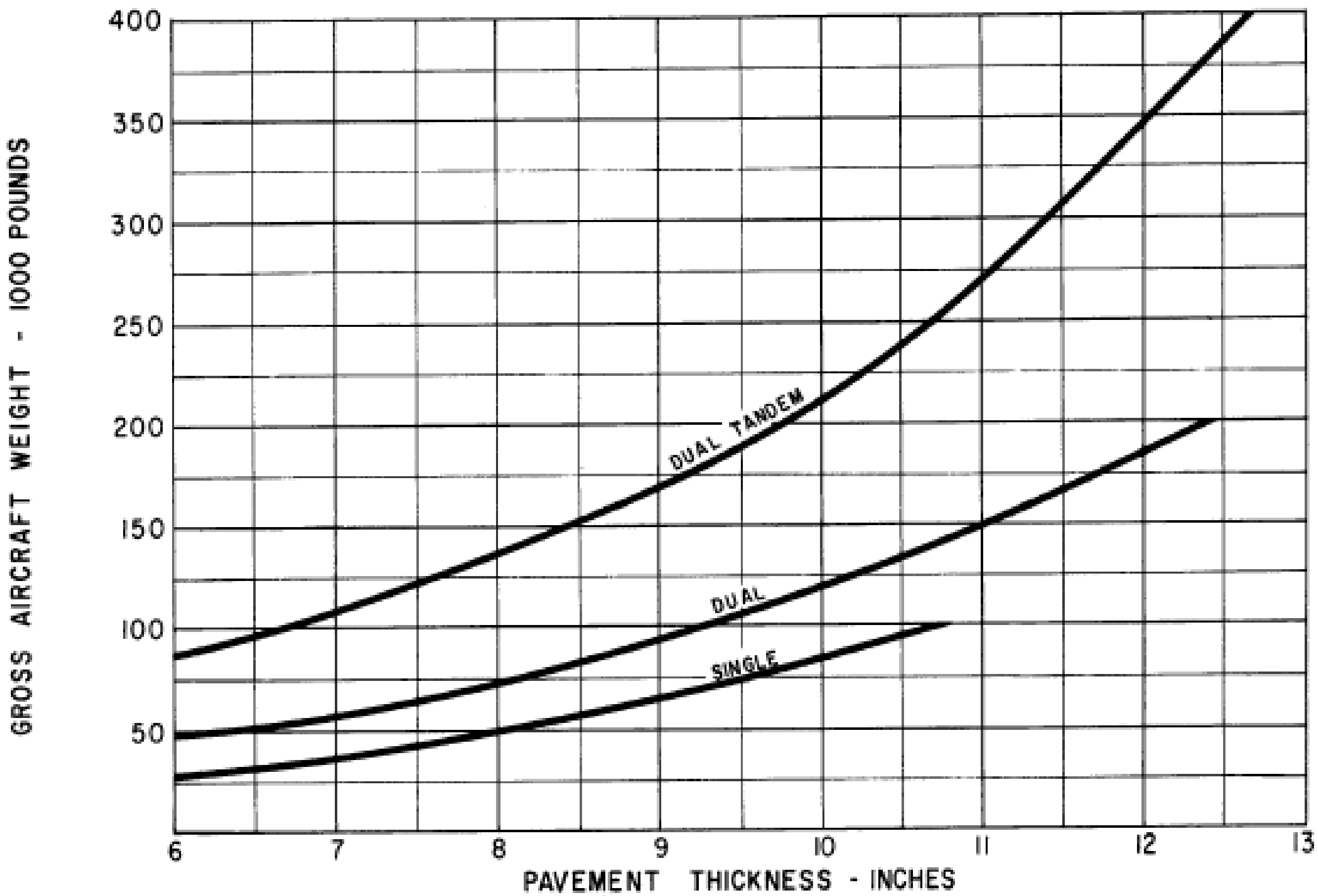
GEOTECHNICAL LABORATORY

Learning from History (II)

- AC 150/5320-6A was published in 1967.
- For rigid pavements, the FAA adopted a simplified Westergaard-type analysis using the Pickett and Ray charts.
- Design curves were prepared for single, dual and dual-tandem aircraft based on limiting stress.

Design Curve in 150/5320-6A (1967)

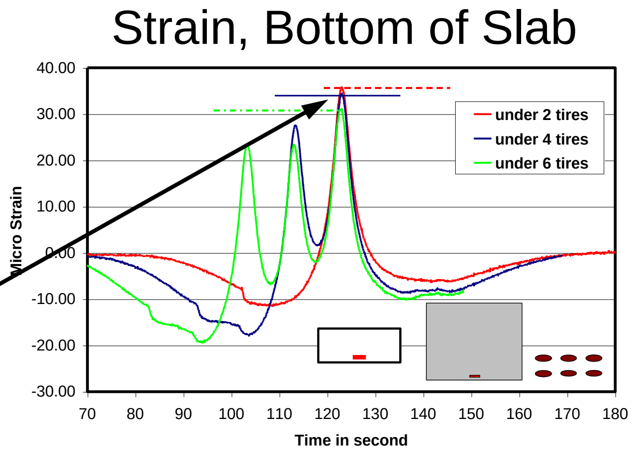
Critical stress was not directly involved in the thickness design.

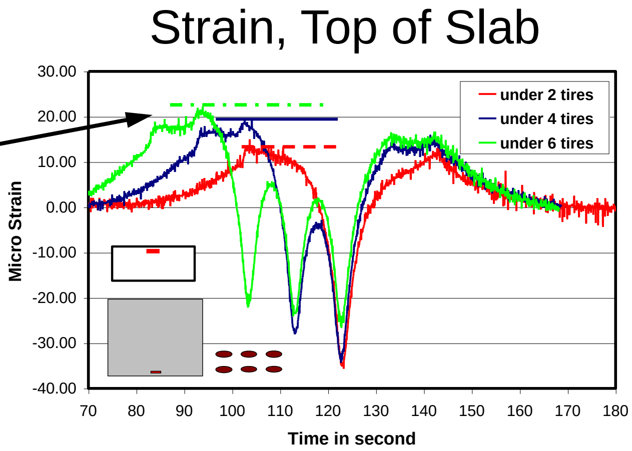


Full Scale Test Results, CC1

(1999-2000)

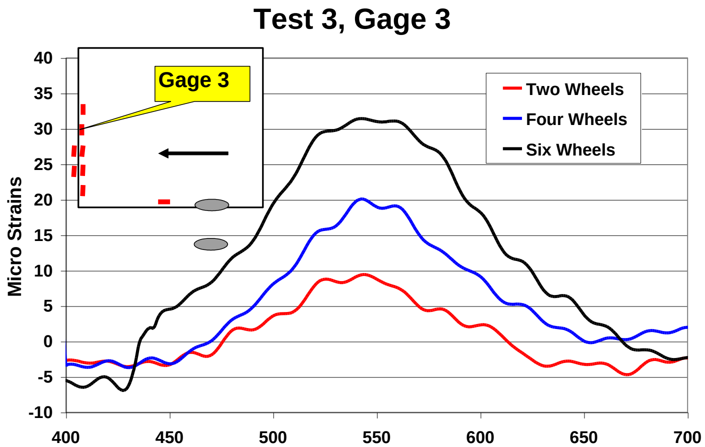
- **The critical stress is not necessarily controlled by the gross weight, as implied by the 1967 design curve.**
- **Bottom of slab – maximum tensile strain for 2-wheel gear.**
- **Top of slab – maximum tensile strain for 6-wheel gear.**



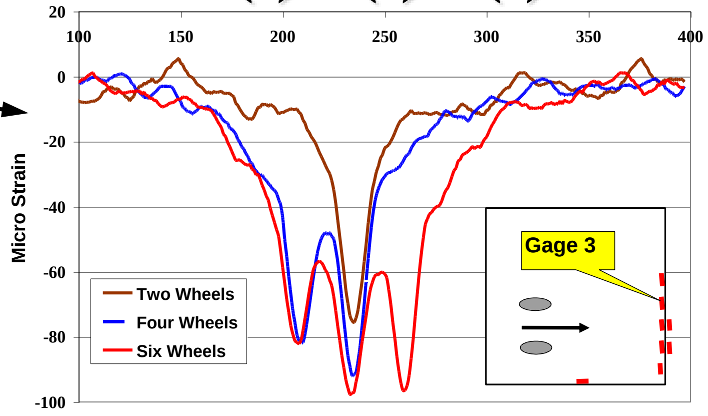


Surface Strain Gage Full-Scale Tests
January 2005

- **Tensile strains tending to cause top-down cracks at the transverse joint are strongly dependent on the total gear load.**
- **Strains related to bottom-up cracking also depend on the number of wheels, but to a lesser degree.**

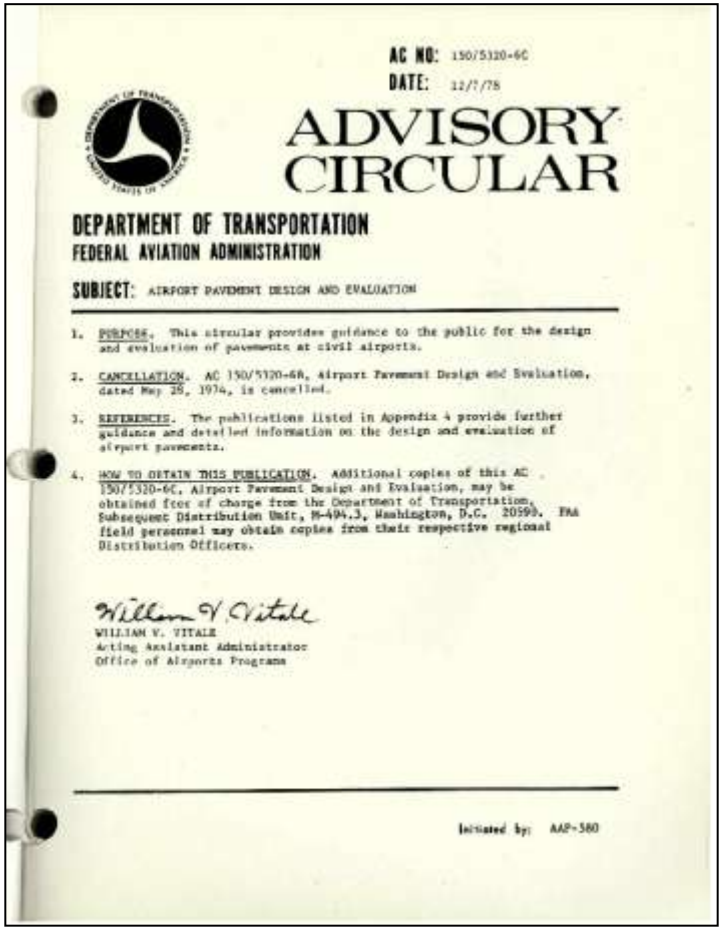


$\sigma(6) > \sigma(4) > \sigma(2)$



Learning from History (III)

- **AC 150/5320-6C was in effect from 1978 to 1995.**
- **The critical stress to determine slab thickness was calculated by a mechanistic procedure.**
  - The prediction follows a “one-stage” failure model.
  - The whole period from new pavement to the end of service life is treated as one continuous phase.



AC NO: 150/5320-6C
DATE: 12/7/78

ADVISORY CIRCULAR

DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION

SUBJECT: AIRPORT PAVEMENT DESIGN AND EVALUATION

1. PURPOSE. This circular provides guidance to the public for the design and evaluation of pavements at civil airports.

2. CANCELLATION. AC 150/5320-6B, Airport Pavement Design and Evaluation, dated May 28, 1974, is cancelled.

3. REFERENCES. The publications listed in Appendix 4 provide further guidance and detailed information on the design and evaluation of airport pavements.

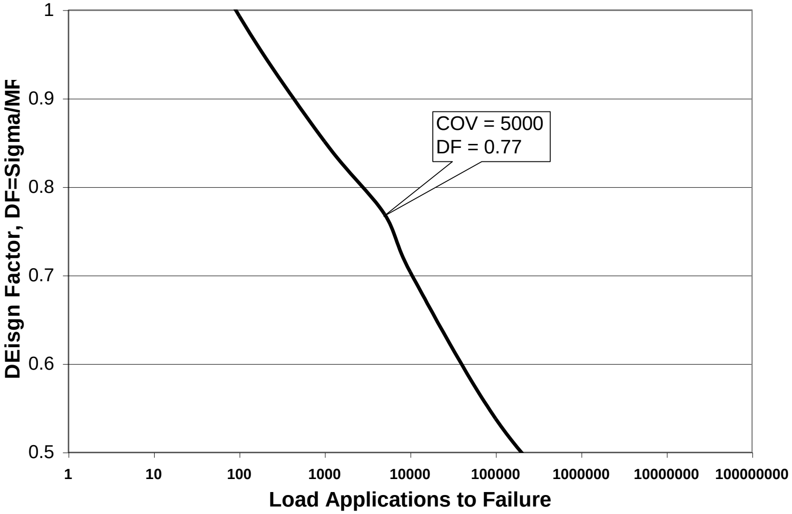
4. HOW TO OBTAIN THIS PUBLICATION. Additional copies of this AC 150/5320-6C, Airport Pavement Design and Evaluation, may be obtained free of charge from the Department of Transportation, Subsequent Distribution Unit, M-494.3, Washington, D.C. 20590. FAA field personnel may obtain copies from their respective regional Distribution Officers.

WILLIAM V. VITALE
Acting Assistant Administrator
Office of Airports Programs

Initiated by: AAP-580

One-Stage Failure Model

- The "one-stage" failure model was adopted in AC 150/5370-6C (1978).
- The design factor, defined as *R*/σ, is used as the independent parameter for fatigue-based design (where *R* is the beam flexural strength).
- Design assumes that the pavement fatigue strength is similar to *R* for 5000 coverages (COV).
- The safety factor is 1.3.
- Different equations are used for COV < 5000 or COV > 5000.



$$\frac{\sigma(Final)}{MR} \le \frac{1}{1.3 \times \alpha^2}$$

$$\alpha = 1 + 0.15603 \times Log_{10}\left(\frac{COV}{5000}\right) \quad (COV \ge 5000)$$

$$\alpha = 1 + 0.07058 \times Log_{10}\left(\frac{COV}{5000}\right) \quad (COV < 5000)$$

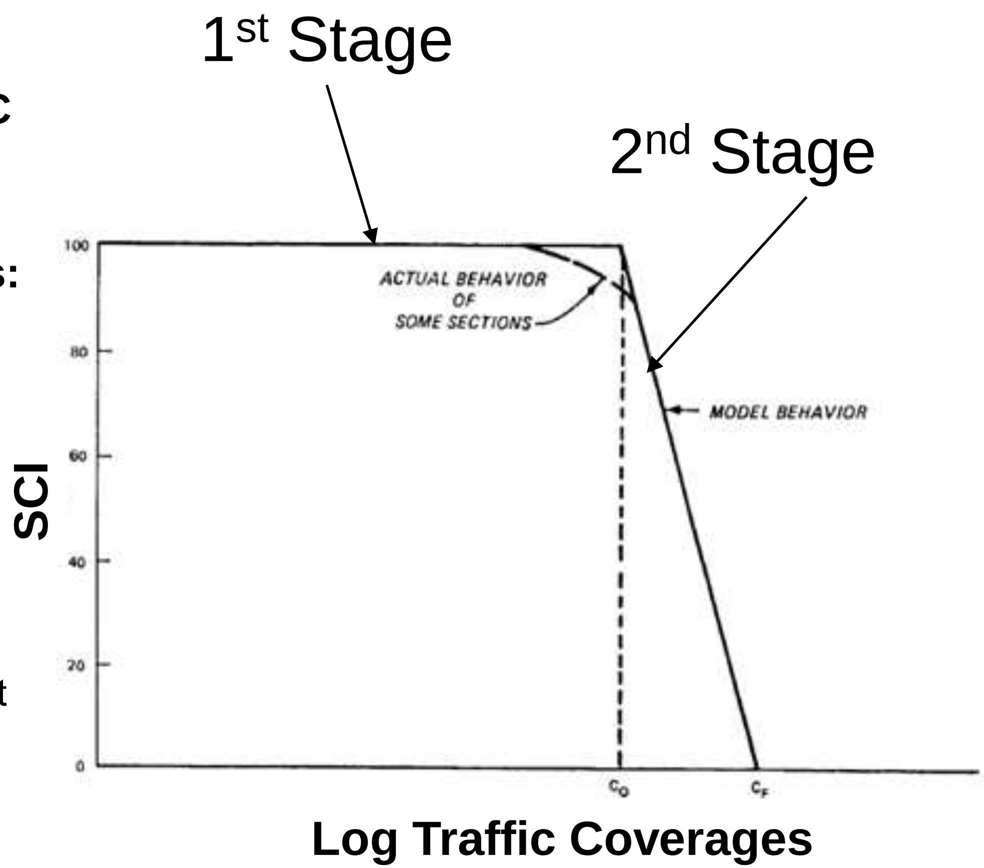
Expression of "one-stage" failure model

Two-Stage Failure Model

- **Beginning with LEDFAA (1995) and continuing with AC 150/5320-6E and FAARFIELD, the FAA adopted a "two-stage" failure model.**
  - Stage 1: New slab to development of the first full-depth crack.
  - Stage 2: From 1st crack to the end of the pavement service life.
- **The parameters of the failure model are fitted to existing full-scale data.**

Two-Stage (Rollings) Failure Model

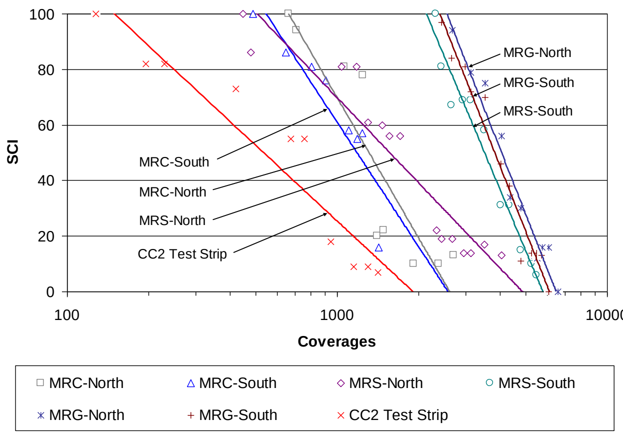
- **A "two-stage" rigid failure model was adopted by FAA in 1995 in AC 150/5320-16 (LEDFAA).**
- **The original idea was provided by Witczak, 1976. Consists of 3 steps:**
  1. "Initial fracture prediction"
  2. Consideration of "rate of crack propagation"
  3. Modeling the "distress to performance relationship"
- **The procedure was first proposed by Rollings, 1988.**
  - "Design of Overlays for Rigid Airport Pavements," DOT/FAA/PM-87/19
- **Model continues to be used in FAARFIELD, with some modifications for stabilized bases.**

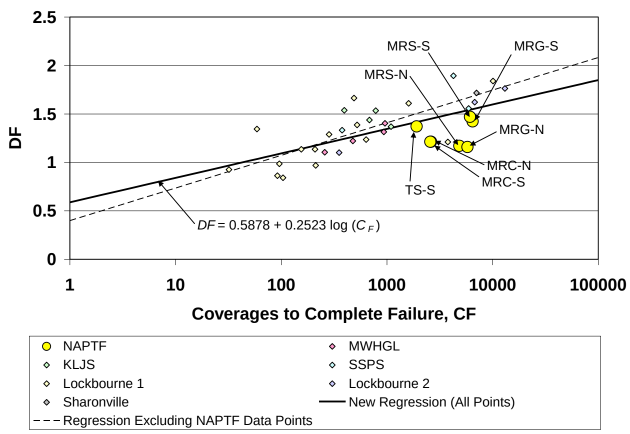


(Rollings, 1988, p. 47)

Refining the Two-Stage Model (CC2)

- **CC2 rigid pavement tests were conducted in 2004 at the NAPTF.**
- **6 test items with different combinations of subbase material and loading:**
  - Stabilized subbase.
  - Conventional subbase.
  - Slab on grade.
- **Slabs trafficked to full failure (shattered slab).**





What We Learned From CC2:

- **Linear model of SCI vs. log of coverages is reasonable for stabilized and conventional bases.**
- **High proportion of cracks were top-down – need to consider curling/top-down cracks in future model.**
- **Revised rigid pavement failure model for FAARFIELD:**

$$\frac{DF}{F_c} = \left[\frac{F_s'bd}{(1-\alpha)(d-b)+F_s'b}\right] \times \log C + \left[\frac{(1-\alpha)(ad-bc)+F_s'bc}{(1-\alpha)(d-b)+F_s'b}\right]$$

- **Parameters:**

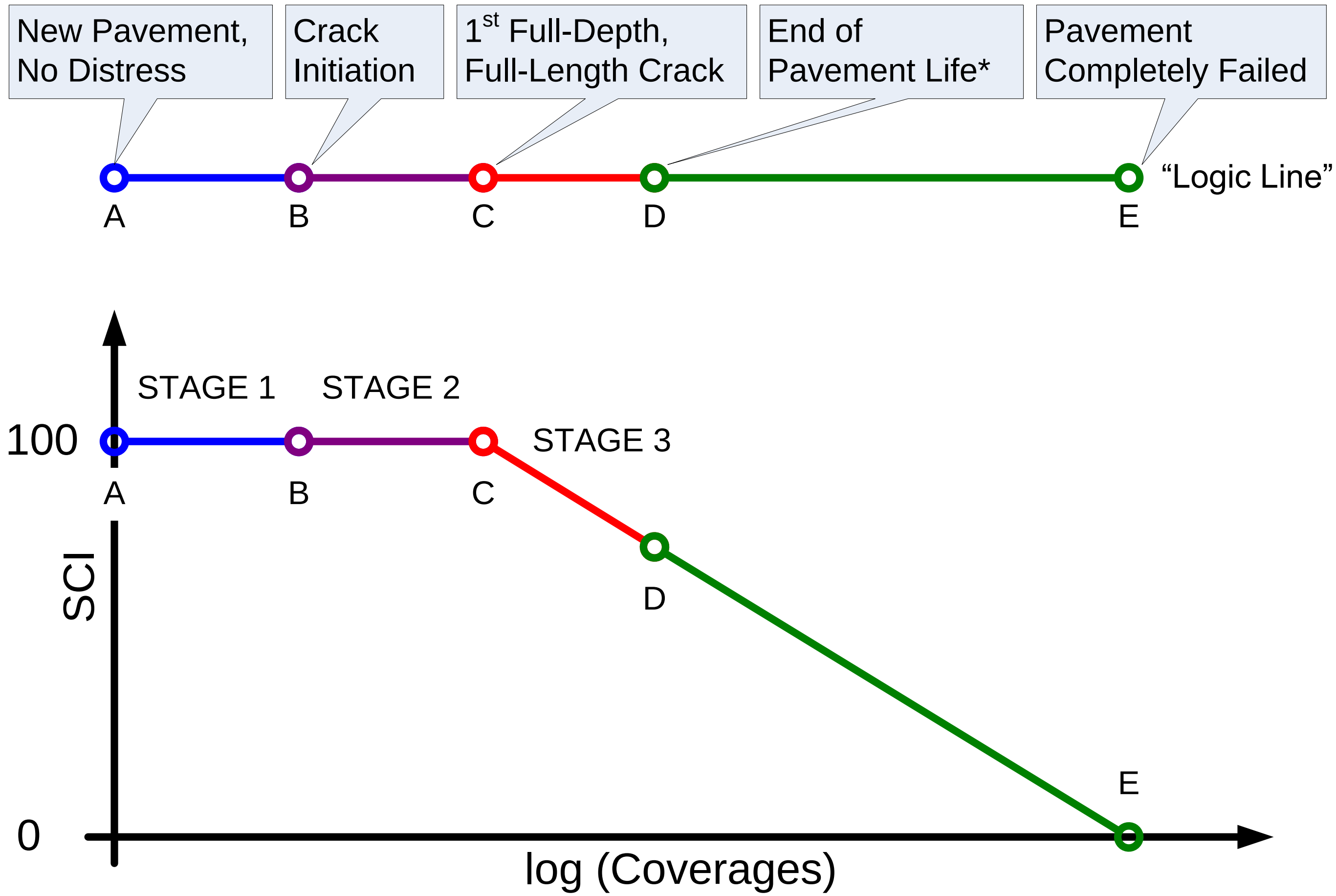
$a = 0.5878$
$b = 0.2523$
$c = 0.7409$
$d = 0.2465$

$\alpha = 0.8$ for failure criterion SCI = 80
F'_s = stabilized base factor
F_c = calibration factor (1.12)

Need for a “Three-Stage” Model

- A significant percentage of the total life is consumed in the 1st (flat) part of the curve, where SCI=100. However, there is very little description of the deterioration in that stage.
- Up to now, most data analysis has concentrated on the falling part of the curve (Stage 2), only because that is where data were available. At the NAPTF we now have considerable data on Stage 1 from embedded sensors. In particular, we have full-scale data on different rates of crack propagation under traffic for top-down and bottom-up cracks. A three-stage model is needed to capture these differences.
- As design software (FAARFIELD) becomes more integrated with PMS (FAA PAVEAIR), we will need models to better quantify consumed life before significant damage appears.

Concept of “Three-Stage” Model



*Major rehabilitation or reconstruction is needed.

Future Developments

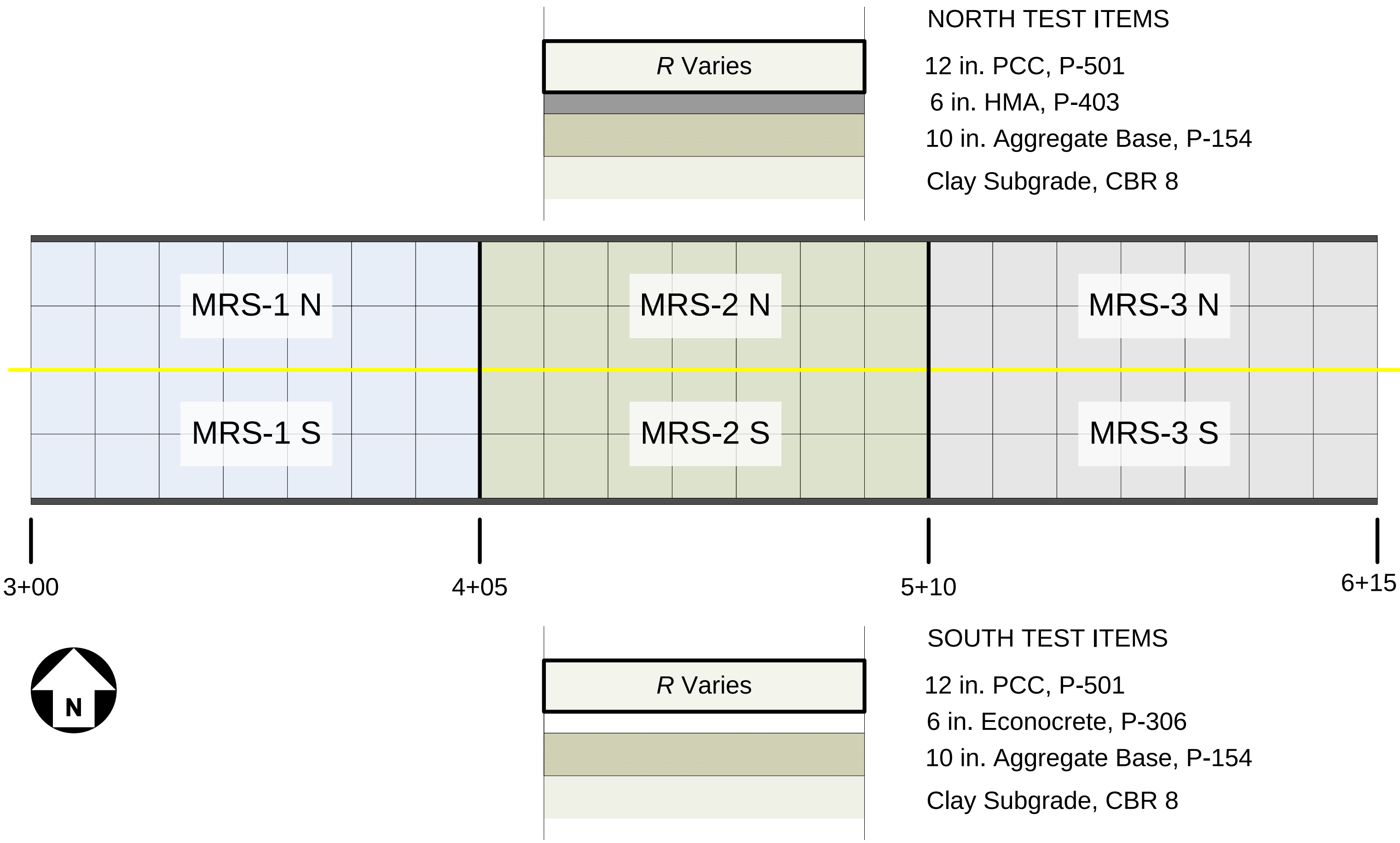
- A "three-stage" failure model has been proposed to better represent the progressive failure mechanism of airport concrete pavements.
- The 3-phase model describes a new Stage 2 between point B, where cracking initiates, and point C, where the 1st full-depth crack is identified at the surface that causes the SCI to fall below 100.
- Relationships among the three failure stages can be different depending on whether the cracking mode is bottom-up or top-down.

Current Full-Scale Test – CC6

- **6 combinations of concrete strength & subbase type.**
- **Primary Test Objectives:**
  - Investigate the relative effect of concrete strength on test item performance.
    - Will concrete that is “too strong” perform poorly (embrittlement)?
    - Is the current flexural strength limitation in AC 150/5320-6E justified by objective full-scale test data?
  - Investigate the effect of subbase material (cement stabilized vs. asphalt stabilized) on performance.
    - Will test items on econocrete prove more susceptible to top-down cracks (e.g., corner breaks) than HMA stabilized base?
    - Is the stiffness of the subbase the key subbase parameter affecting life (as assumed in the FAARFIELD model)?

CC6 Test Item Structure Summary

"Low Strength"	"Medium Strength"	"High Strength"
Target 500 psi	Target 750 psi	Target 1000 psi



Field Studies

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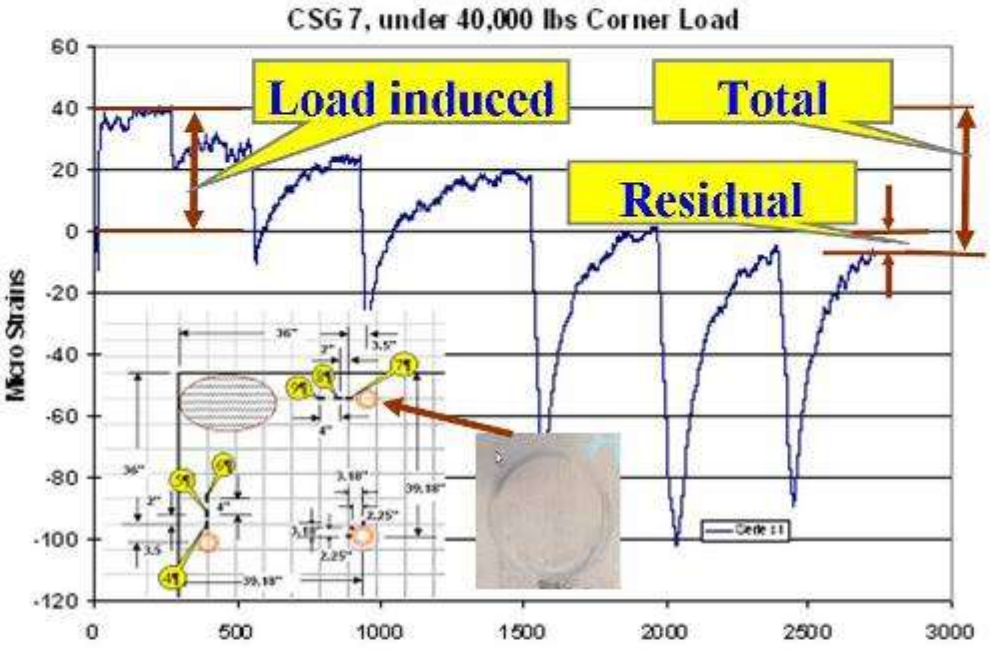
Understanding Total Stress

- **From CC1 through CC6 at the NAPTF we have used almost 1000 concrete strain gages, both embedded and surface applied types.**
- **As a surrogate for stress, strain measurements are important for:**
  - development of design procedures.
  - pavement analysis and evaluation.
- **We have come to understand that the total stress (not just the load-induced component) drives cracking in slabs. Hence, our emphasis since 2008 on developing a reliable residual stress test.**

Measurement of Residual Stress in Concrete Pavements - Concept

- **Developed by Dr. Edward Guo.**
  - Procedure extends a method originally used for metals.
  - Strain gages are applied to the slab surface in the region of interest.
  - A cut is made and the change in the strain gage response is observed.
- **Dr. Guo's original concept tested at the NAPTF in 2008 used coring-ring drills.**
- **An FAA-CEAT research project at the University of Illinois used a portable circular saw instead of the core ring.**

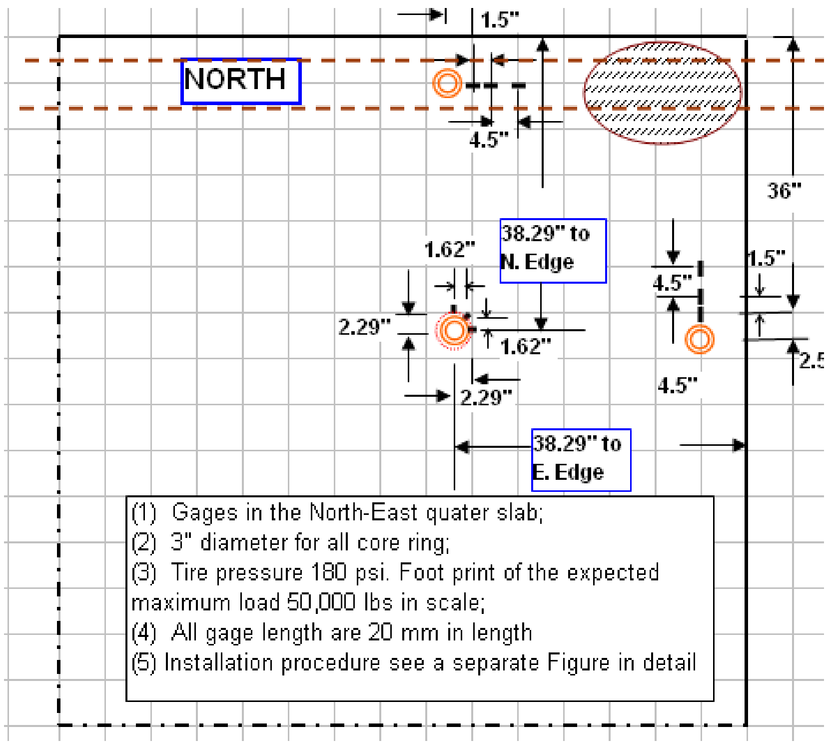


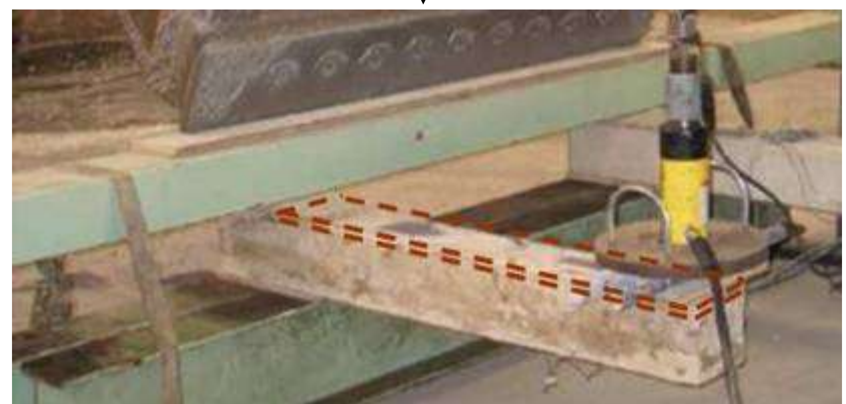
Original Concept Testing - NAPTF

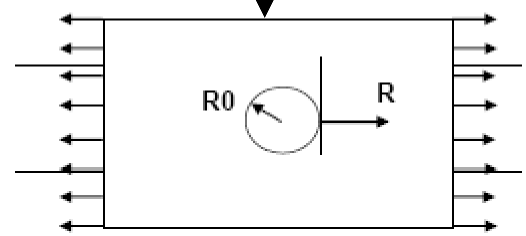
Cantilever Beam Tests

Single Slab Tests

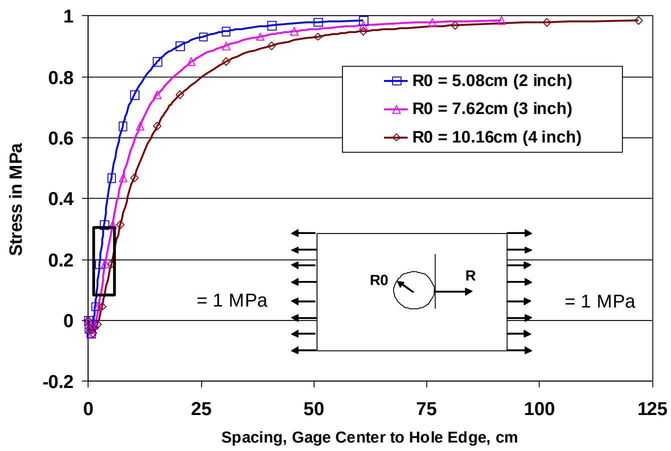
Initial Modeling Using Thin Plate Theory

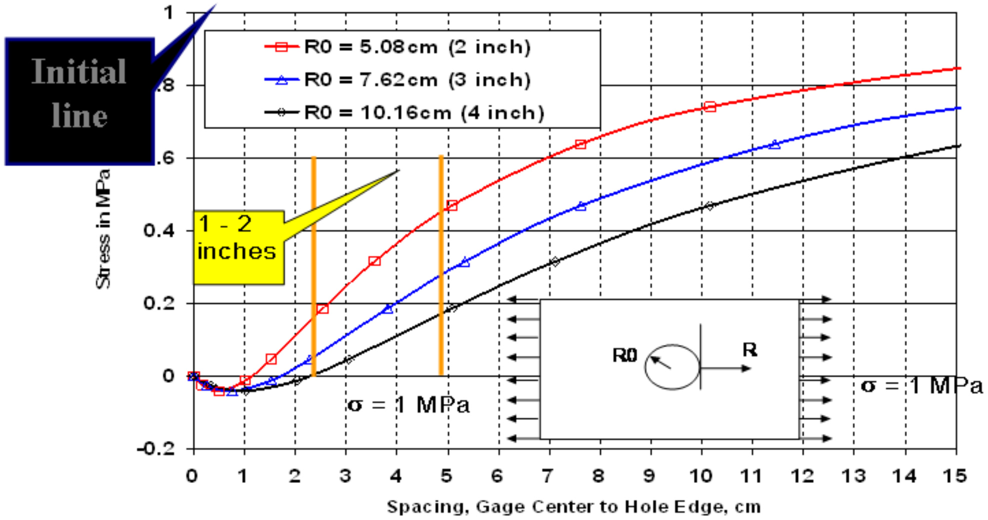






Studies to Determine Appropriate Coring Ring Size and Gage Spacing

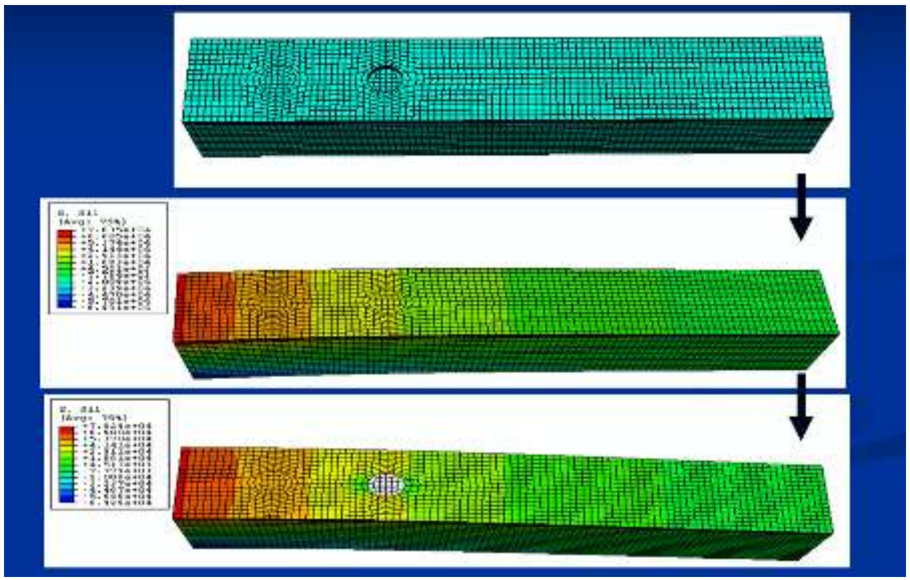




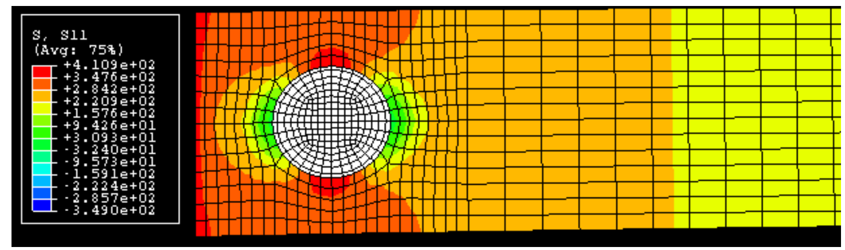
- **Findings from analytical studies:**
  - The appropriate core-ring diameter is equal to or greater than 3 in.
  - The appropriate spacing between gage and core-ring edges is 1 - 5 cm (0.4 to 2 inches).
  - The appropriate core-ring depth is about 2.5 cm (1 inch).
  - No essential difference between core-ring and blind hole model.

Additional Finite Element Modeling

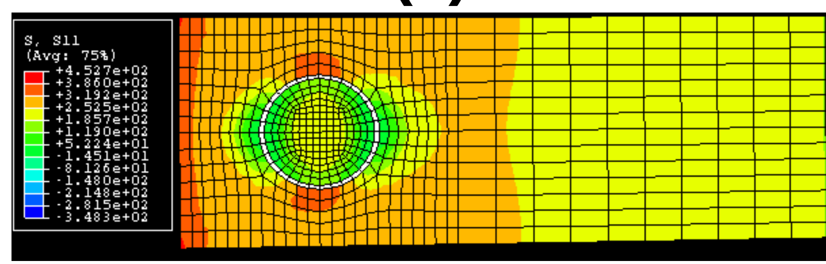
In Collaboration with Harbin Institute of Technology (HIT)



Blind Hole (a) and Core Ring (b) Models



(a)



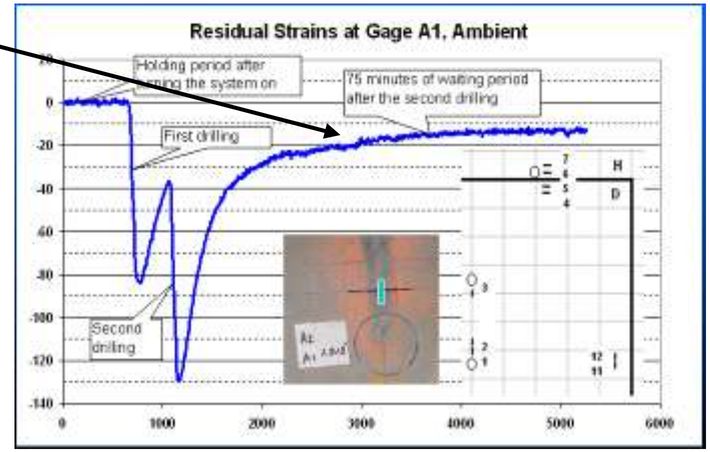
(b)

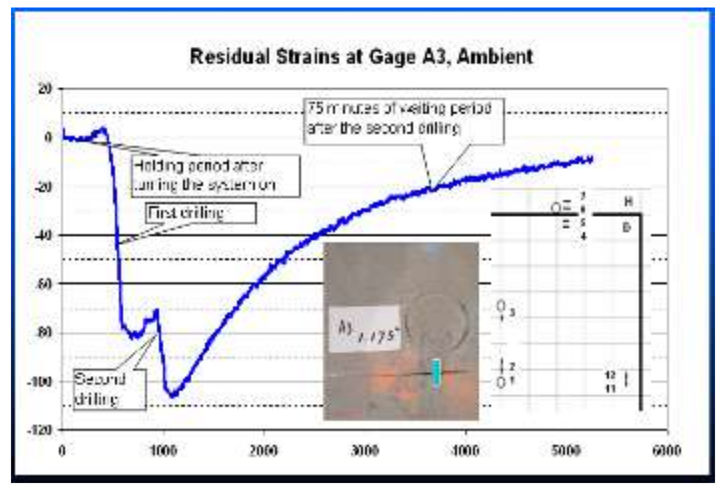
2009 Multiple Slab Tests at NAPTF

Temperature strain induced by heat of drilling dissipates after about 75 minutes

Site View

Typical Reponses





Findings From Measurements

- **Over 90% of the residual stress-related strain (RSRS) in a single slab was released by drilling a core ring near the strain gage.**
- **The measured RSRS under 40,000 lbs. load was relatively stable under NAPTF ambient conditions.**
- **The range of surface RSRS found by this method was 7-15 microstrains.**
  - Corresponds to residual stress in the 37-82 psi range.

Future Studies

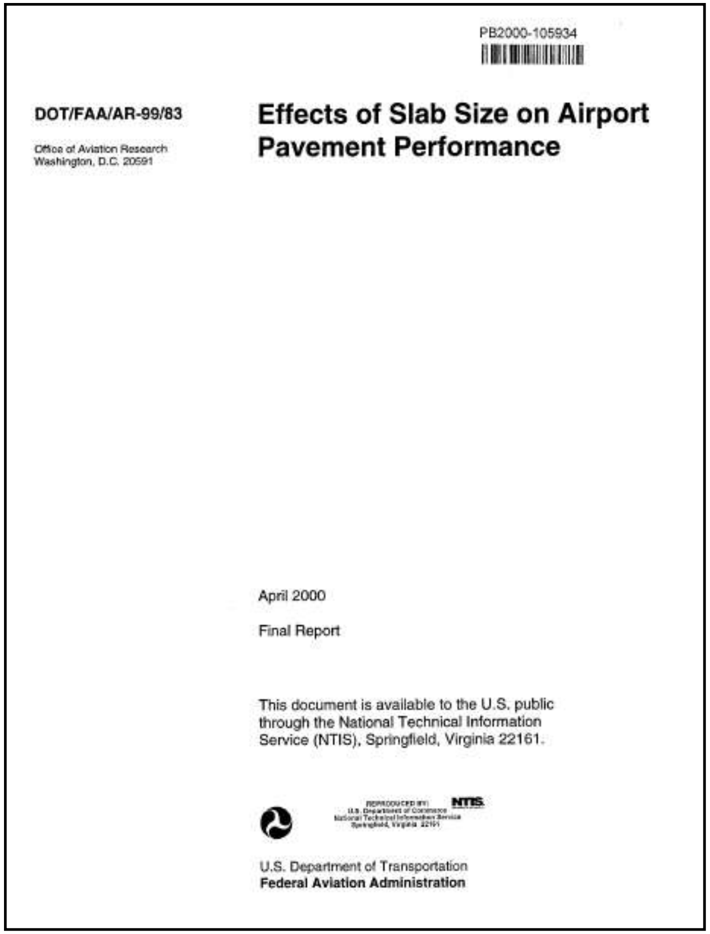
- Find the range of residual stresses in concrete pavements under different environmental conditions.
- Define the relationship among the residual stress, load induced stress and the total stress.
- Determine the range of slab thicknesses within which the total stress (as opposed to load-induced stress only) should be considered for designing the slab thickness.
- Field studies (Atlanta, Denver, JFK, etc.) are an essential part of meeting these objectives.

Review of Field Studies 2000 – 2010

- **PCI of Rigid Airport Pavements**
  - Identify maintenance needs
  - Verify field performance vs. FAA design standards
- **Slab Curling Studies**
  - Monitoring test slabs at the NAPTF
  - FAA & U.S. Army ERDC Interagency Agreement
  - IPRF 05-2, *Joint Load Transfer in Concrete Airfield Pavements*.
- **Instrumented Pavement Projects**
  - Denver International Airport, Colorado, USA
  - Atlanta Hartsfield-Jackson I.A., Georgia, USA
  - John F. Kennedy Airport, New York, USA

FAA Research Report (2000)

- **DOT/FAA/AR-99/83, *Effects of Slab Size on Airport Pavement Performance.***
- **Considered data representing 288 million square feet of PCC pavement in 174 airports distributed in six FAA regions, plus Hawaii and Japan.**
- **Included 2820 features, equivalent to 192 standard size runways (3000 × 45 m^2).**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DOT/FAA/AR-99/83

Office of Aviation Research
Washington, D.C. 20591

Effects of Slab Size on Airport Pavement Performance

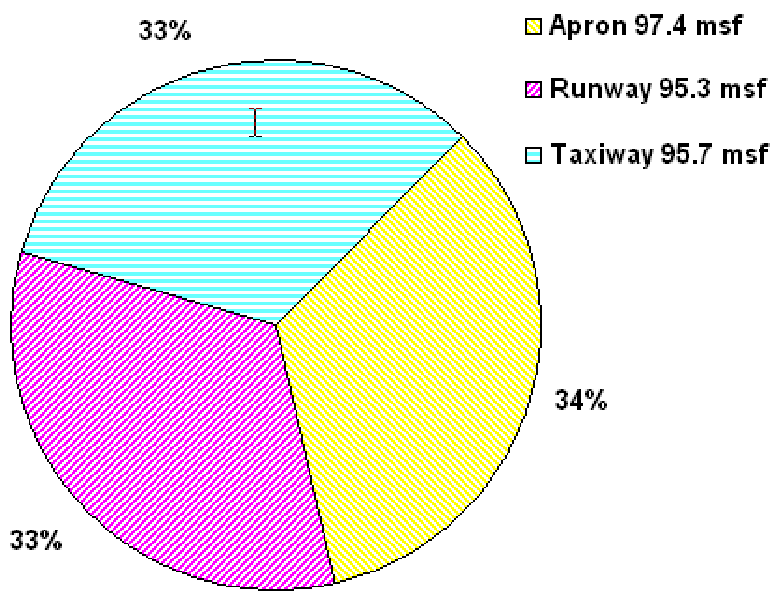
April 2000

Final Report

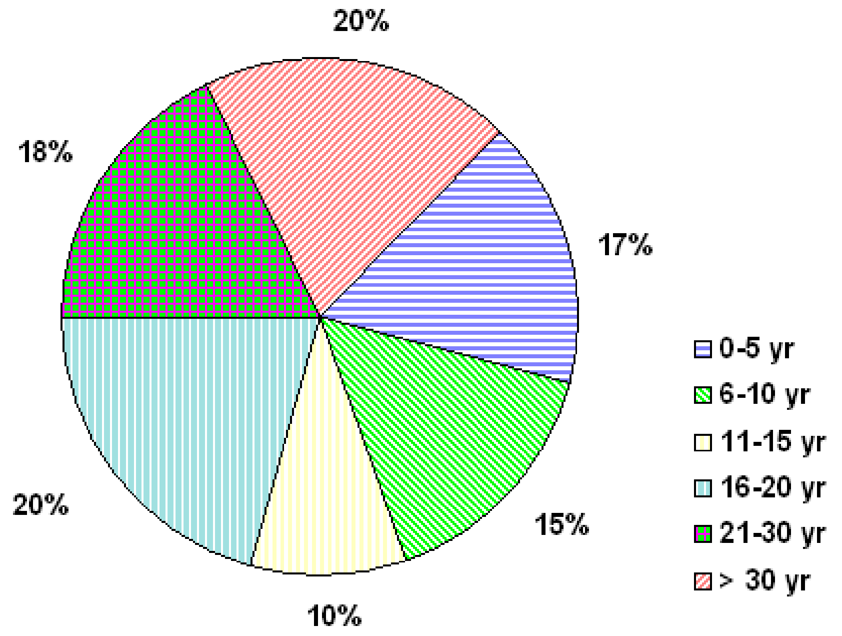
This document is available to the U.S. public through the National Technical Information Service (NTIS), Springfield, Virginia 22161.

U.S. Department of Transportation
Federal Aviation Administration

Multi-State Pavement Survey
Included 23 U.S. States and Japan

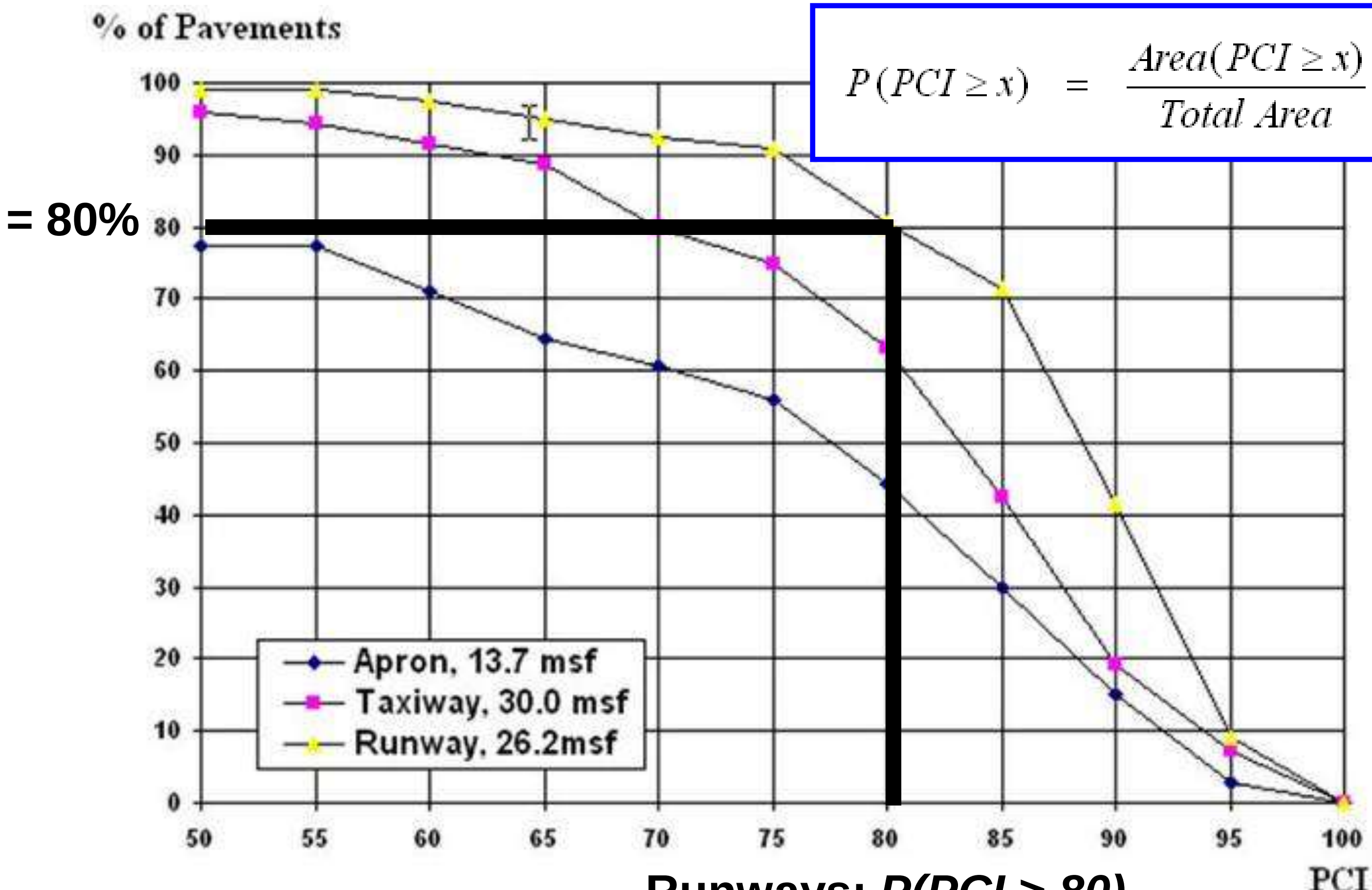


Distribution by Airport Feature



Distribution by Age

Probability Distribution of PCI for Surveyed Pavements in the 16-23 Year Age Range

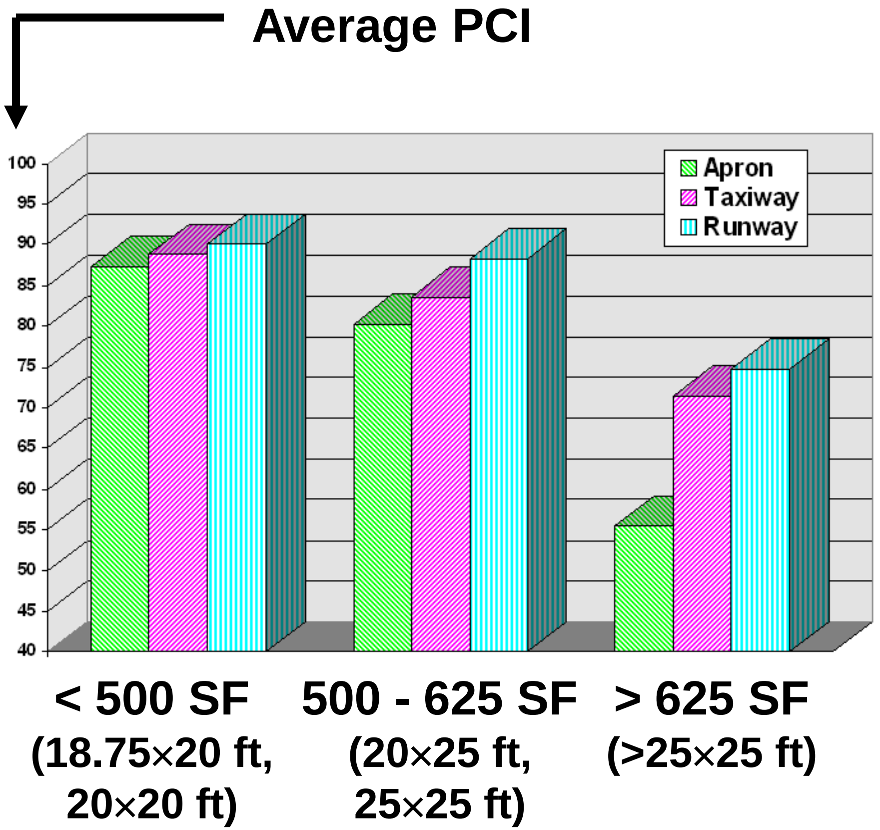


$$P(PCI \geq x) = \frac{Area(PCI \geq x)}{Total\ Area} \times 100\%$$

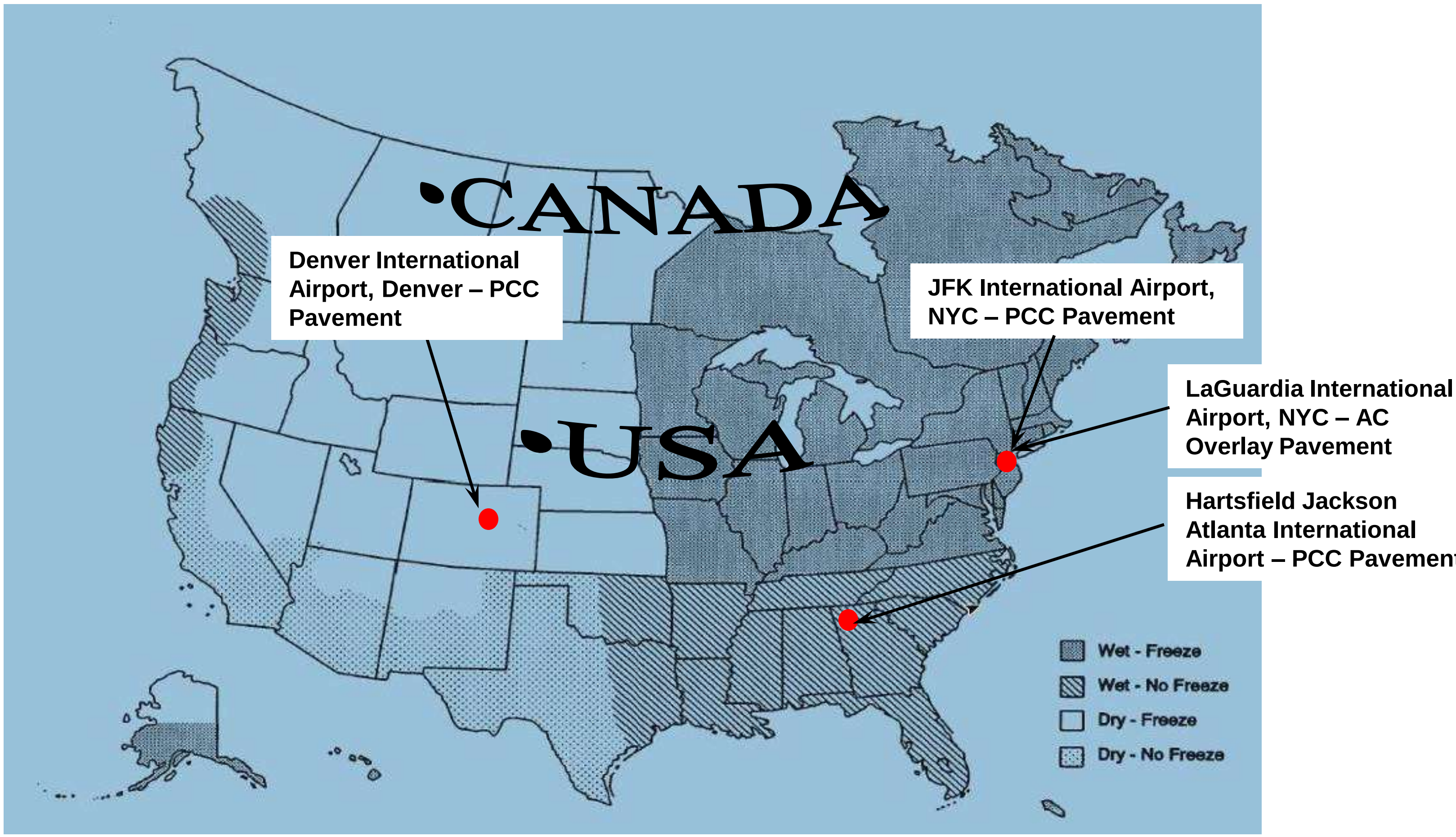
Runways; *P(PCI > 80)*

Slab Size Recommendations

- Slabs > 625 SF (25 × 25 ft) performed more poorly for all pavement types.
- Slabs in the 500 – 625 SF category tended to show more rapid deterioration after 20 years than smaller slabs.
- Based on the field PCI data, it was recommended that new slabs should not exceed 20 × 20 SF. This is the current FAA guidance.
- Smaller slabs for aprons.



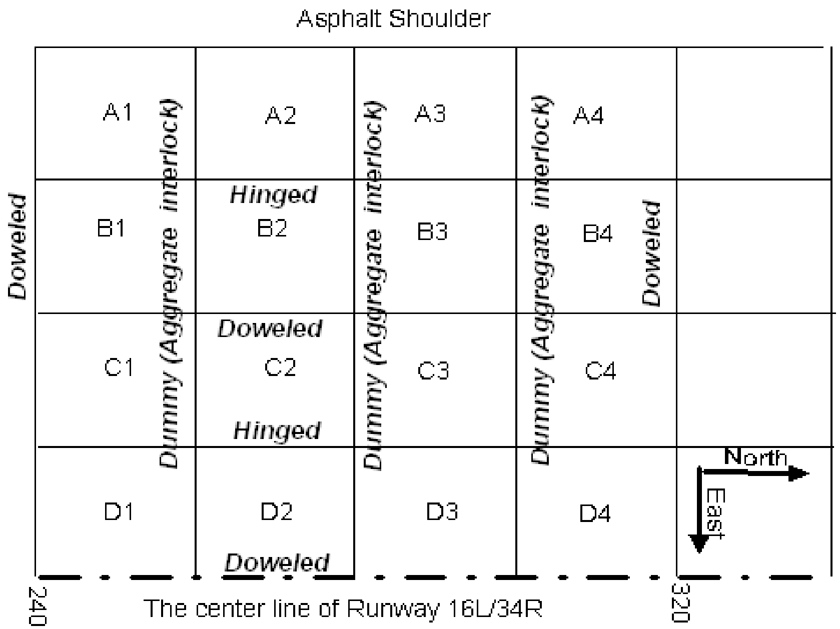
FAA Airport Instrumentation Projects



Denver Instrumented Runway Project

1996-1997 Data

- **Measured load transfer efficiency depends on:**
  - Load transfer device (dowel, tie bar, aggregate interlock).
  - Average temperature.
  - Load type (FWD versus rolling aircraft tire).



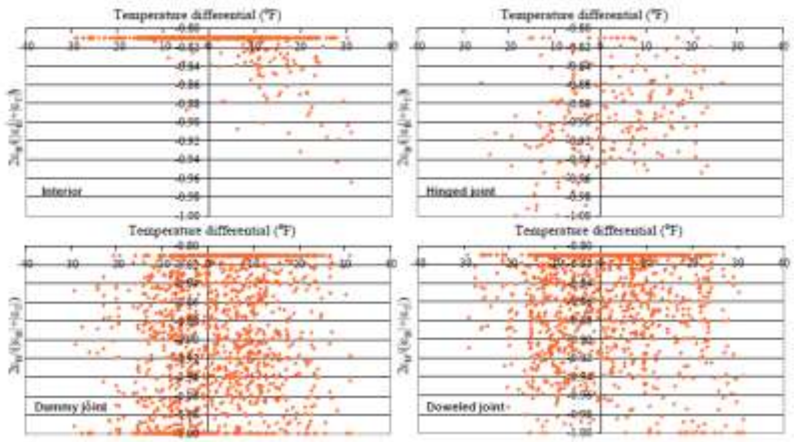
Avg. Deflection LTE based on FWD Tests

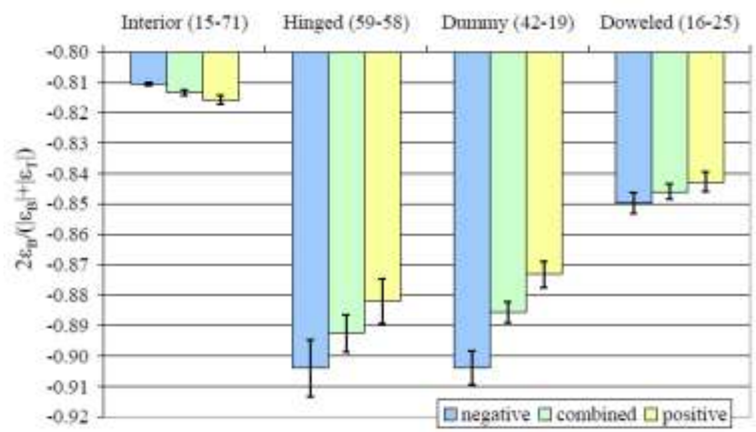
Joint Type \ Time Measured	March 96	April 97	August 97
Hinged(Tied)	88.7	84.4	84.3
Doweled	73.3	65.5	75.0
Dummy(Saw cut)	34.8	28.2	81.3

Denver Instrumented Runway Project
– In-Service Strain Data Analysis

- **Analysis of paired strain gages (top and bottom of slab) showed significant influence of:**
  - gage location (interior vs. edge)
  - joint type

  on effective slab-base interface behavior.
- **Slab interior was effectively bonded.**
- **CEAT Report: Rufino, Roesler & Barenberg (2004)**





JFK Runway 13R-31L Reconstruction Project
Taxiway Z
John F Kennedy International Airport, Queens, NY 11422
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
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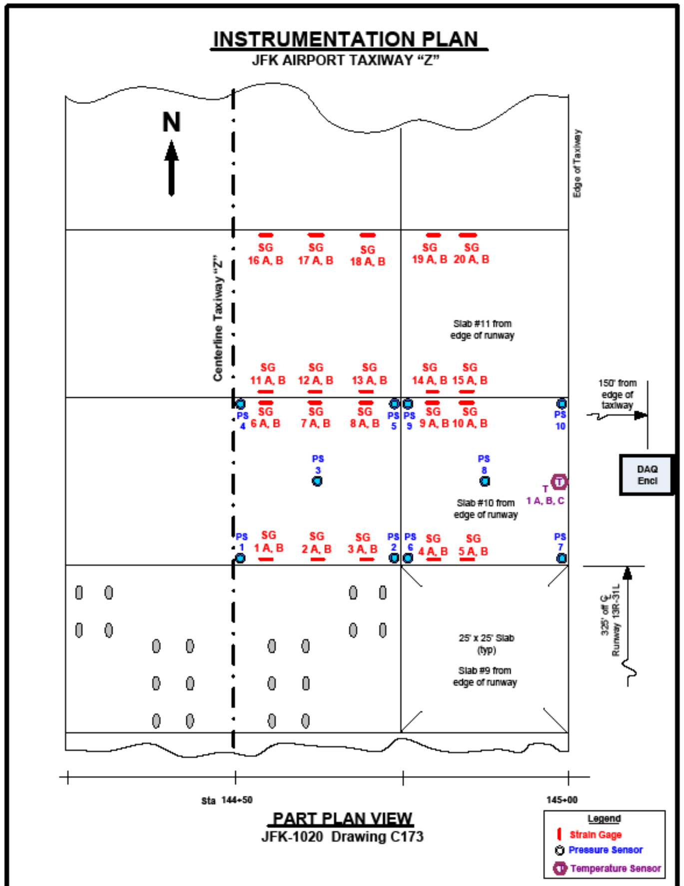
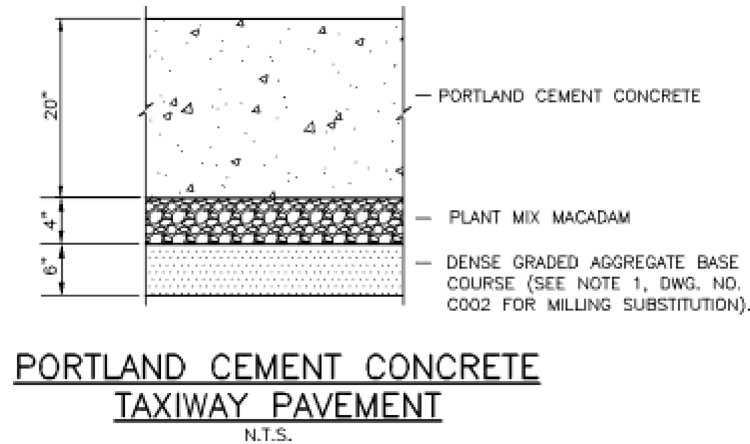
JFK Taxiway Z Instrumented Slabs



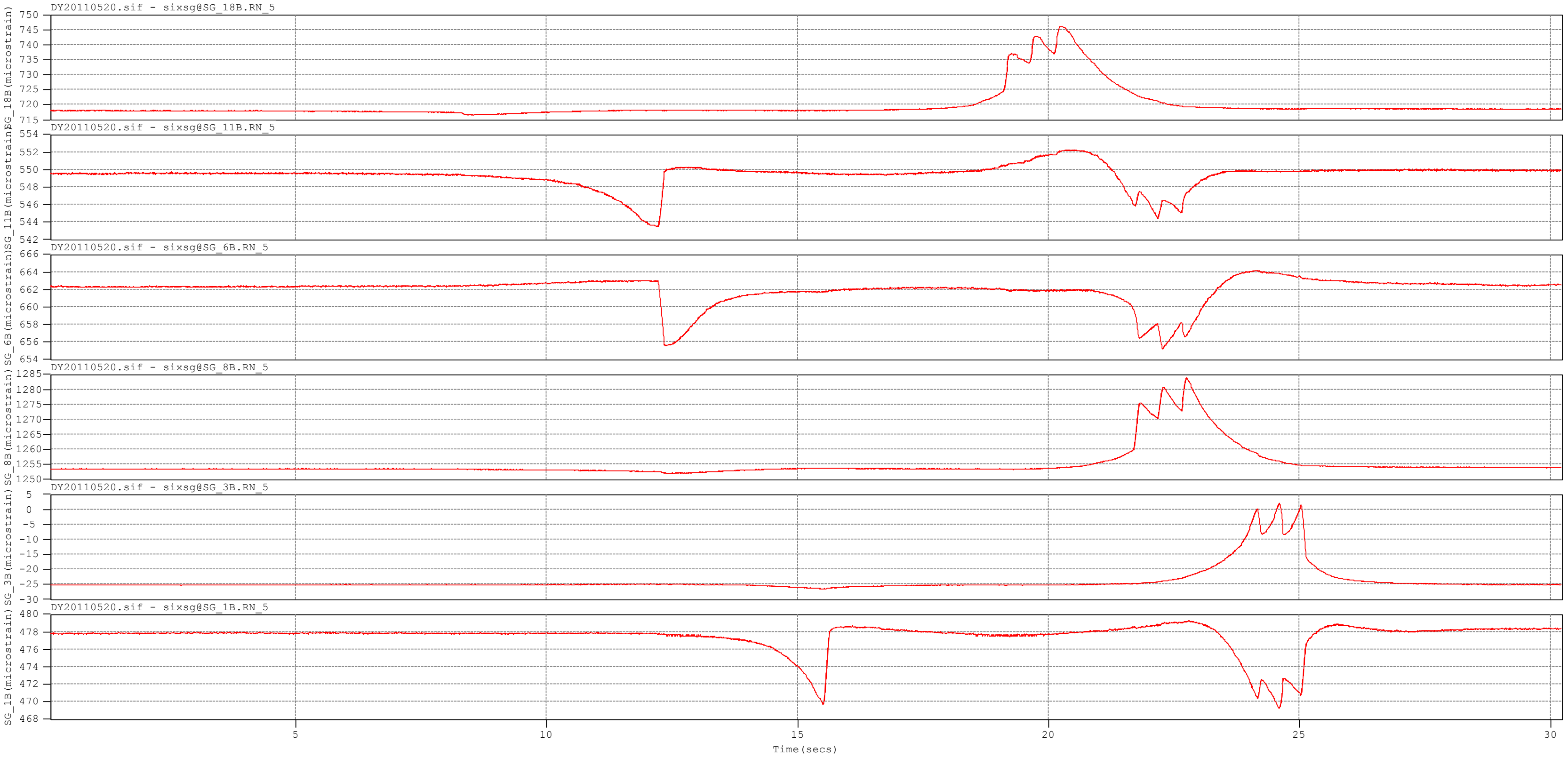


Typical Strain Gage Installation

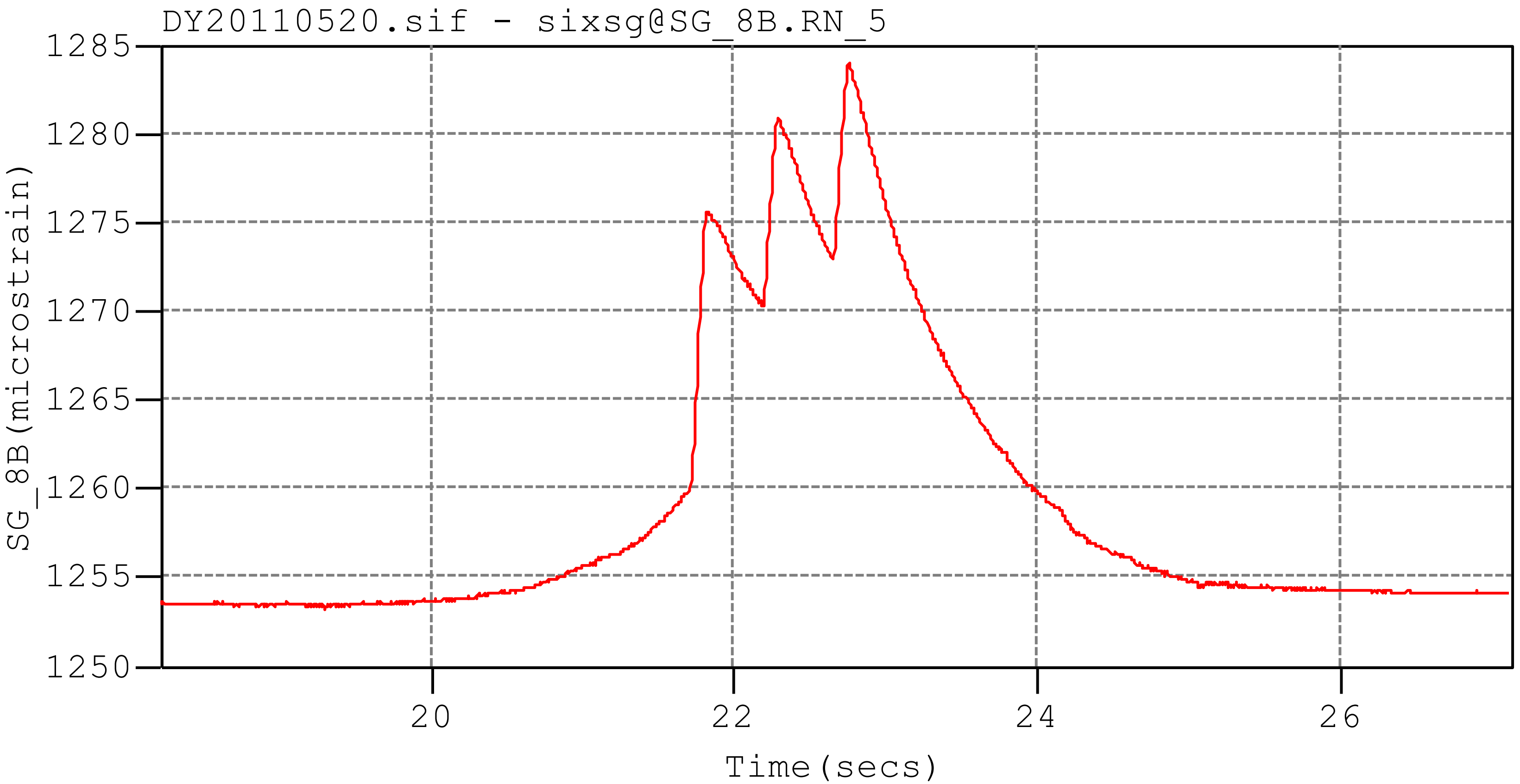
JFK Construction (August 2010)

JFK Camera Capture (July 11, 2011)

JFK – Typical Strain Responses (B777)



Detail – Gage 8B (B777 – Approach Slab)



Next 10-Year Plan

Presented to: 2nd International Conference on Best Practices for Concrete Pavements
Florianópolis, Brasil

By: David R. Brill, P.E., Ph.D.

Date: 3 November 2011

Key Elements of Next 10 Year Plan

- **Pavement life extension.**
  - FAA 40-year design life initiative envisions doubling of pavement life for runways at large hub airports.
  - Applies to rigid and flexible pavements.
- **Incorporate Life Cycle Cost Analysis (LCCA) in FAA design procedures.**
- **Software Integration.**

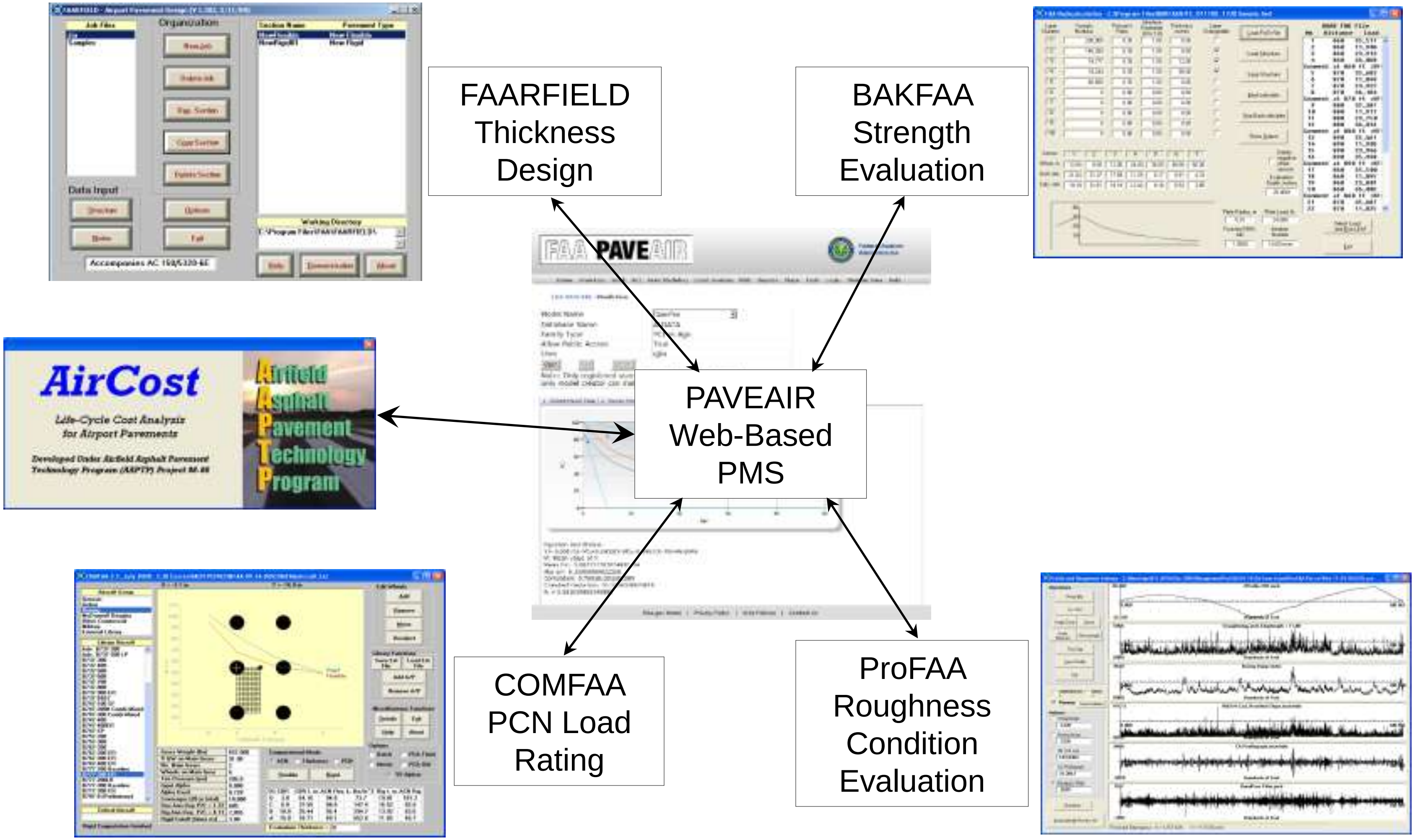
Issues in Extending Pavement Life

- **Current bidding process for AIP projects is based on "best" design to give 20-year structural life.**
- **Bidding process for extended life pavements must include functional failure as well as structural failure components.**
- **How to develop rational life cycle cost bidding guidelines?**
- **How to define pavement life anyway?**
  - Functional or structural failure? What SCI = "failure"?
  - Attributes of functional failure and structural failure do not develop at the same rate over a long period of time.

Pavement Life – Traffic or Time?

- **AC 150/5320-6E (Pavement Design) states:**
  - "The FAA design standard for pavements is based on a 20-year design life. The computer program [FAARFIELD] is capable of considering other design life time frames, but the use of a design life other than 20 years constitutes a deviation from FAA standards."
- **Structural design usually implies that time is unimportant except in that increasing time will increase the amount of traffic.**
- **No longer valid when we consider LCCA (cost of money and maintenance activities).**

PAVEAIR and Other Applications



Fully Funded Project Starting 2013

- Collect construction and maintenance data for new and recent AIP funded projects and deposit the data in PAVEAIR.
- Produce annual summaries for each project.
- Develop a comprehensive guide to LCCA for airport pavements, coupled with alternative thickness design strategies.
- Develop an automated procedure for LCCA which is compatible with PAVEAIR.
- Deliver recommended procedures for designing runway pavements for 40 years by 20??

Thank You! Obrigado!

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