Long-Life and Sustainable Concrete Pavements

by

Mang Tia

Professor of Civil Engineering

Engineering School of Sustainable Infrastructure and Environment

University of Florida

Presentation at

3rd International Conference on Best Practices for Concrete Pavements

Bonito, Brazil

October 29, 2015

Acknowledgments

Graduate Research Assistants: David Verdugo
Ohhoon Kwon

Project Manager: Abdenour Nazef

Reviewers: James Greene
Charles Holzschuher
Emmanuel Uwaibi
Sean Masters

Background and Study Objective

- In Florida, the initial design for new construction for both asphalt and concrete pavements in Florida is 20 years. While the rehabilitation period for asphalt pavements varies from 8 to 20 years, that of concrete pavements varies from 20 to 25 years.
- Increased traffic on roadways, costs due to maintenance-related traffic delays, and increasing construction costs have led the Florida Department of Transportation (FDOT) to evaluate various concrete pavement designs which would yield service lives of 50 years or more.

US 1 (northbound), Daytona, Florida

Constructed in 1959. 8 inches (203 mm) of plain, unreinforced PCC. Little repair work done since 1959.

US1 (southbound), Daytona, Florida

Constructed in 1959. 8 inches (203 mm) of plain, unreinforced PCC. Little work done since 1959. Pavement is still in good condition.

US 17/92, Deland, Florida

Constructed in 1939. Reinforced PCC, 7 inches (178 mm) thick. Very few cracks. Ride quality became deficient in 2002 after 63 years of service.

US 17/92, Winter Park, Florida

Constructed in 1936.

Reinforced PCC 7 inches (178 mm) thick.

Condition of pavement before diamond grinding

US 17/92, Winter Park, Florida

Constructed in 1936.

Reinforced PCC 7 inches (178 mm) thick.

Condition of pavement after diamond grinding

Premature failure of concrete pavement on I-10 in Florida

Transverse cracking on I-75 concrete pavement in Florida

Major Tasks in the Study

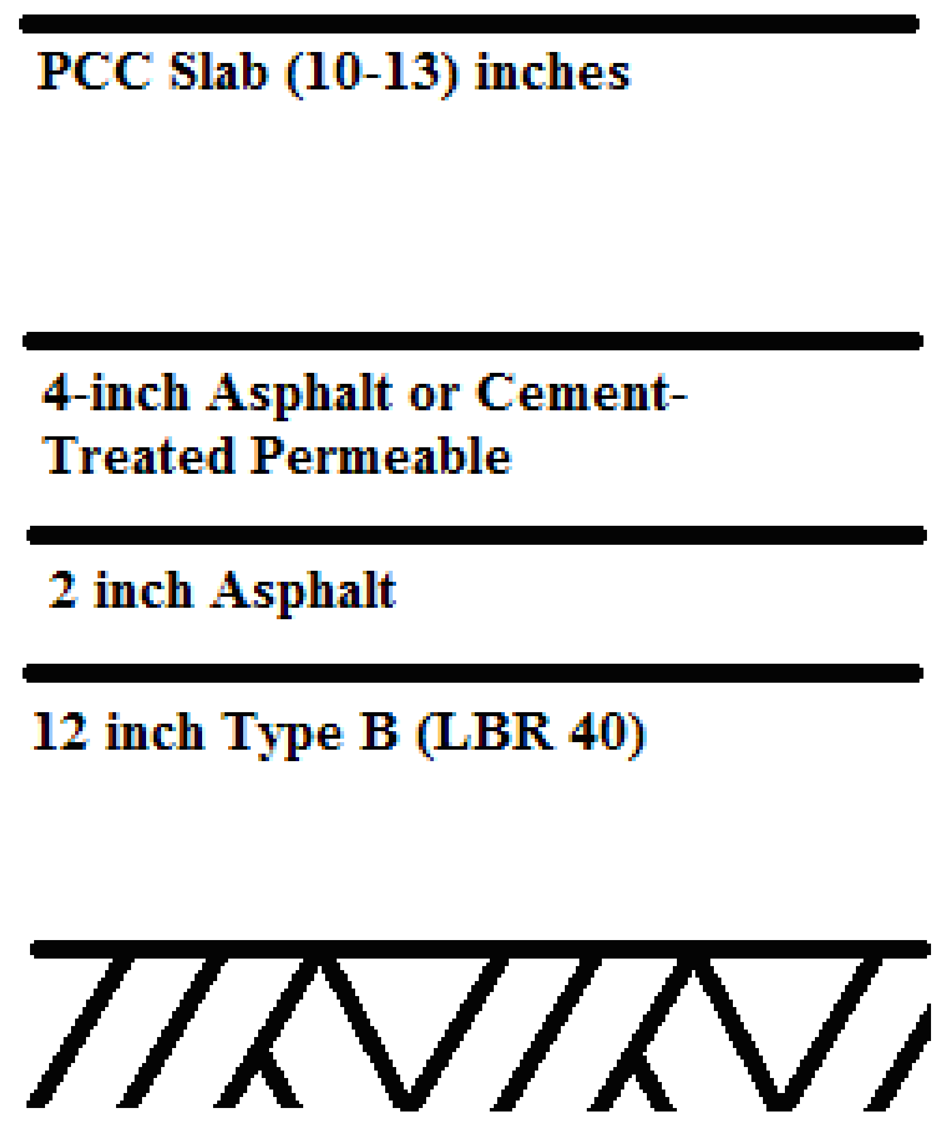
1. Evaluating long-life pavement designs using MEPDG model
2. Evaluating drainage
3. Evaluating performance-related factors using LTPP data and Critical Stress Analysis
4. Examining life-cycle costs of concrete pavements in Florida
5. Recommending long-life concrete pavement designs for Florida

1. Evaluation of Concrete Pavement Designs Using MEPDG Model

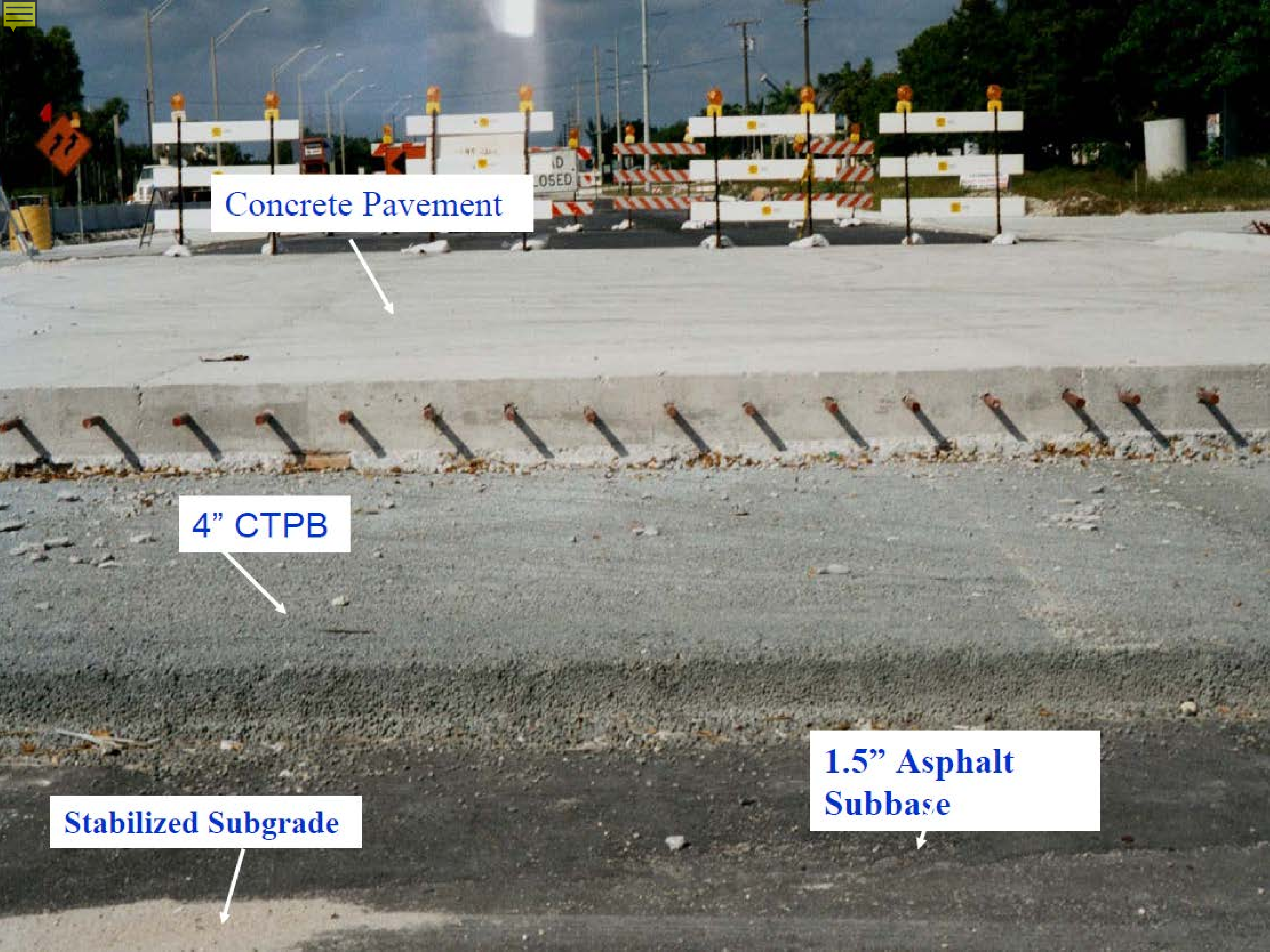
The MEPDG (Mechanistic-Empirical Pavement Design Guide) model which has been calibrated for the Florida conditions was used to analyze

(1)the performance of three typical concrete pavement designs in Florida to evaluate their suitability for use as long-life concrete pavements and

(2) the effects of various design parameters on their performance.



Type I-A Design

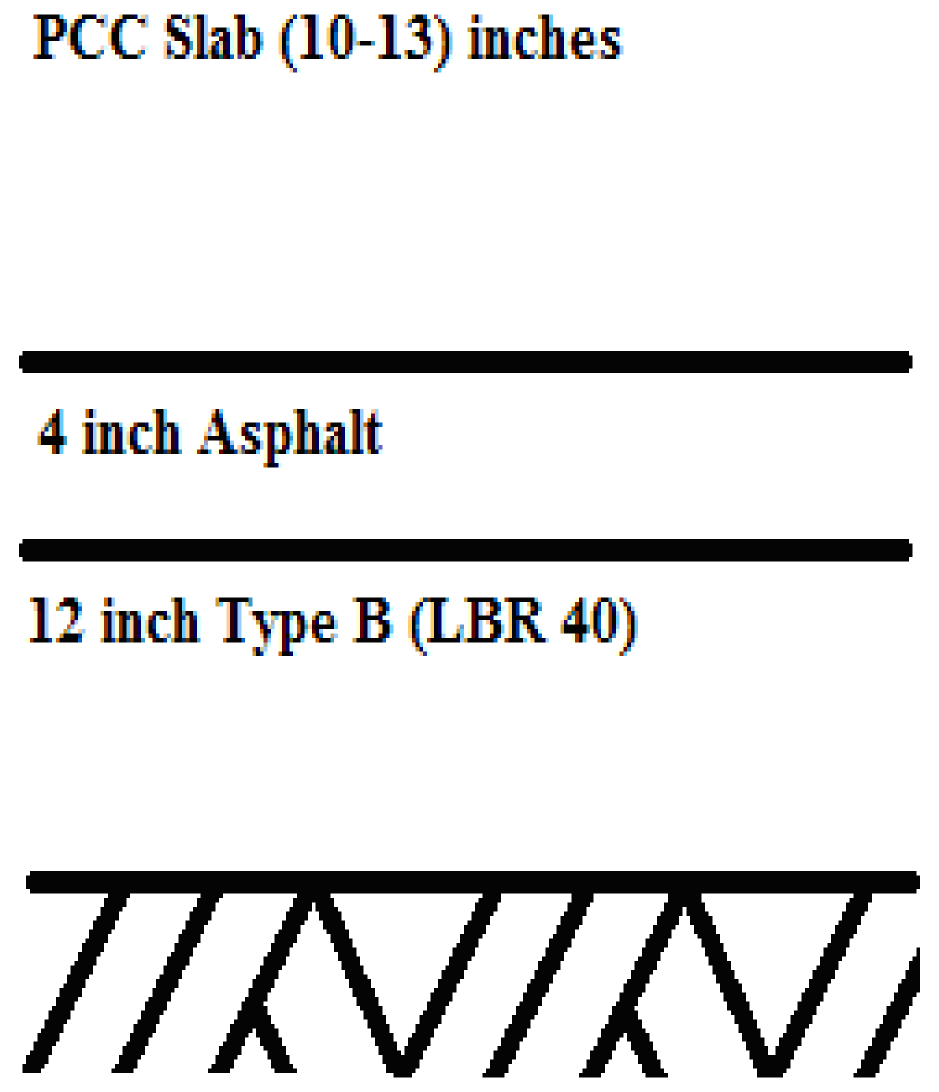


Concrete Pavement

4” CTPB

1.5” Asphalt Subbase

Stabilized Subgrade

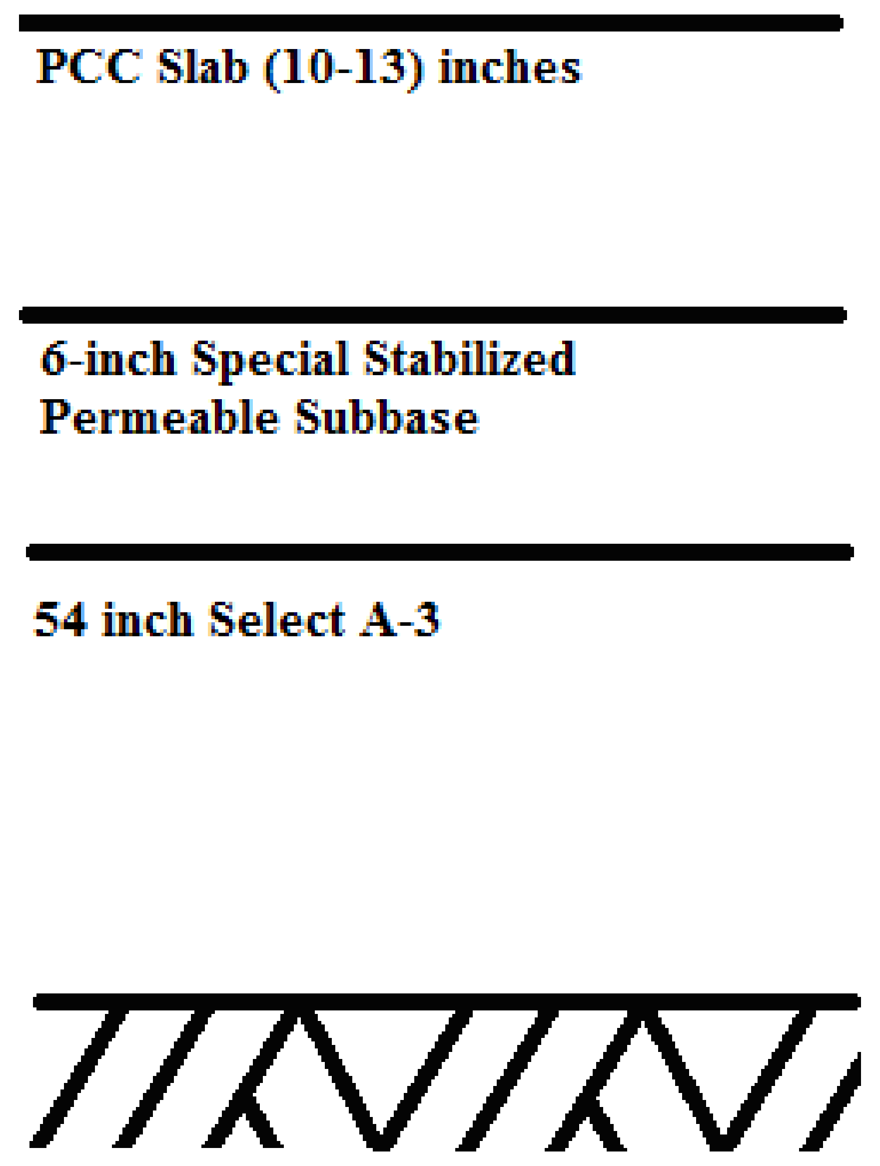


Type I-B Design

22nd Street- Tampa

11.5" PCC

4" AC base on stabilized Subgrade



PCC Slab (10-13) inches

6-inch Special Stabilized Permeable Subbase

54 inch Select A-3

Type II Design

5’ A-3 Material: ≤10% (-200) stabilized w/ 57 stone. Edge drains provided

The input threshold values used in the MEPDG :

IRI = 180 in/mi (Initial IRI = 58 in/mi)
(2.84 m/km) (0.92 m/km)
Joint faulting = 0.12 in (3.0 mm)
Transverse cracking = 10%

The threshold values with 95% reliability level :

IRI = 123 in/mi (1.94 m/km)
Joint faulting = 0.034 in (0.86 mm)
Transverse cracking = 4.3%.

Factors Evaluated in MEPGD Analysis

- Slab thickness
- Concrete flexural strength
- Aggregate used in concrete
- Types of base material
- Stiffness of base material
- Thickness of base
- Erodibility of base material
- Friction between base and concrete

Three Most Significant Factors:

- Concrete slab thickness
- Concrete flexural strength
- Aggregate used in concrete (which affects the elastic modulus and coefficient of thermal expansion of the concrete)

Coefficient of Thermal Expansion of Concretes using Different Aggregates

Condition	Aggregate	CTE (x 10^{-6} /°F)
28-day	Brooksville	5.68
	Calera	5.99
	River Gravel	7.2

(Source: “Coefficient of Thermal Expnsion of Concrete Used in Florida” by Tia et al, 1991)

Elastic Modulus of Concretes Made with Different Aggregates

Equation	Condition	Aggregate	[w] Unit weight	[f_r] Modulus of Rupture	[E] Elasticity
$E = 4.20\ (w^{1.5})\ f_r$	**28-day**	Brooksville	145 pcf	650 psi	4,767,000 psi
$E = 4.09\ (w^{1.5})\ f_r$		Calera	152	650	4,982,000 psi
$E = 3.69\ (w^{1.5})\ f_r$		River Gravel	150	650	4,406,000 psi

650 psi = 4.48 MPa

(Source: *Field and Laboratory Study of Modulus of Rupture and Permeability of Structural Concretes in Florida* by Tia et al., 1990)

Required Slab Thickness for 50-year Service Life with Initial AADTT of 4000

		Type I-A			**Type I-B**			**Type II**		
Aggregate		Brooksville	Calera	River Gravel	Brooksville	Calera	River Gravel	Brooksville	Calera	River Gravel
Slab Thickness (inches)		**13**	**15**	**16**	**13**	**15**	**16**	**13**	**16**	**16**
Modulus of Elasticity (x 10^6 psi)		4.8	5.0	4.4	4.8	5.0	4.4	4.8	5.0	4.4
Pavement Distress	**Terminal IRI (in/mi)**	74	63.4	63.6	62.7	65.4	62.1	66.6	63.2	80.8
	Transverse Cracking (% slabs cracked)	3.1	4.3	2.4	4.2	4.2	2.4	2.3	1.2	2.5
	Mean Joint Faulting (in)	0.013	0	0.001	0.001	0.001	0.001	0.004	0.001	0.028

Note: Flexural strength of concrete used = 650 psi
Initial AADTT = 4000

Effects of Modulus of Rupture on Required Slab Thickness (for Type II Concrete Pavement Design)

Brooksville Aggregate

Modulus of Rupture 600 psi (E=4,400,000 psi)

Pavement Distress		**Slab Thickness (in)**			
Type	**Measurement**	**10**	**11**	**12**	**13**
Terminal IRI	(in/mi)	75.2	124.2	80.3	76.3
Transverse Cracking	(% slabs cracked)	89.3	70.3	56.8	6.8
Mean Joint Faulting	(in)	0.006	0.007	0.004	0.013
Pass/Fail		**Fail**	**Fail**	**Fail**	**Fail**

Modulus of Rupture 700 psi (E=5,133,000 psi)

Pavement Distress		**Slab Thickness (in)**			
Type	**Measurement**	**10**	**11**	**12**	**13**
Terminal IRI	(in/mi)	56.4	80.5	64.6	65.3
Transverse Cracking	(% slabs cracked)	39.9	14.7	4.7	1.7
Mean Joint Faulting	(in)	0.008	0.009	0.009	0.003
Pass/Fail		Fail	Fail	**Pass**	**Pass**

Modulus of Rupture 800 psi (E=5,867,000 psi)

Pavement Distress		**Slab Thickness (in)**			
Type	**Measurement**	**10**	**11**	**12**	**13**
Terminal IRI	(in/mi)	65.8	63.6	70.9	71.3
Transverse Cracking	(% slabs cracked)	6.7	1.6	0.5	0.4
Mean Joint Faulting	(in)	0.001	0	0.016	0.015
Pass/Fail		Fail	**Pass**	**Pass**	**Pass**

Note: Initial AADTT = 4000 50-year service life

Predicted Service Lives of Concrete Pavements Using Type I-A, I-B and II Designs

Slab Thickness (inch)	Type I-A	Type I-B	Type II
	Predicted Life (years)		
10	27	24	28
11	33	30	36
12	42	40	43
13	51	50	56
14	56	53	60

Note: Initial AADTT = 17,000

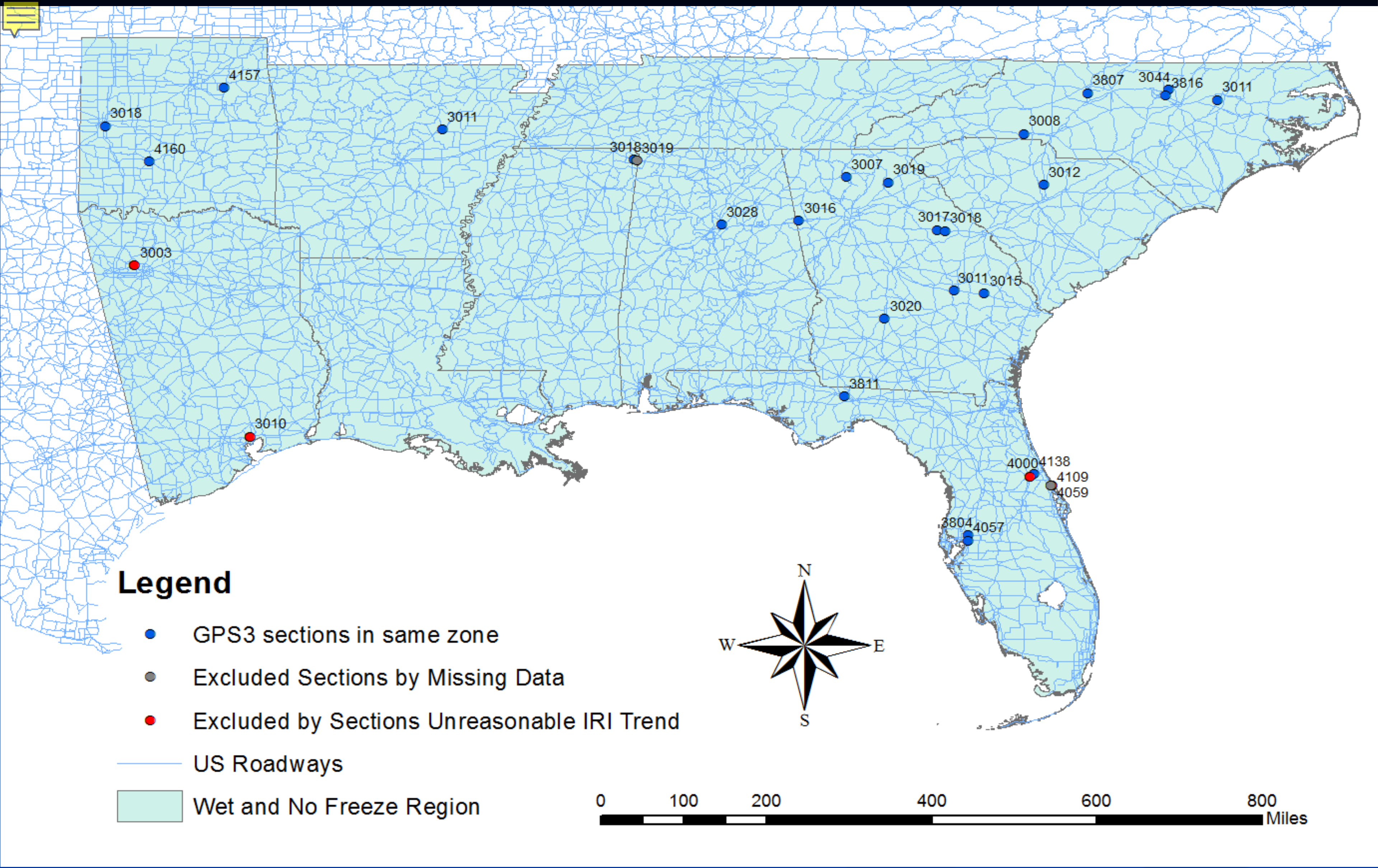
Concrete using Brookville aggregate used: modulus of rupture of concrete = 650 psi

The Effects of Other Factors from MEPDG Analysis Results

- The predicted performance of the pavement appeared to have improved slightly with an increase in base thickness.
- The type of base material and the stiffness of the base material appeared to have no significant effect on the predicted performance.
- Using different erodibility factor and friction factor for the base materials appeared to have no significant effect on the predicted performance according to the results of the MEPDG analyses.

3. Evaluating performance-related factors using LTPP data and Critical Stress Analysis

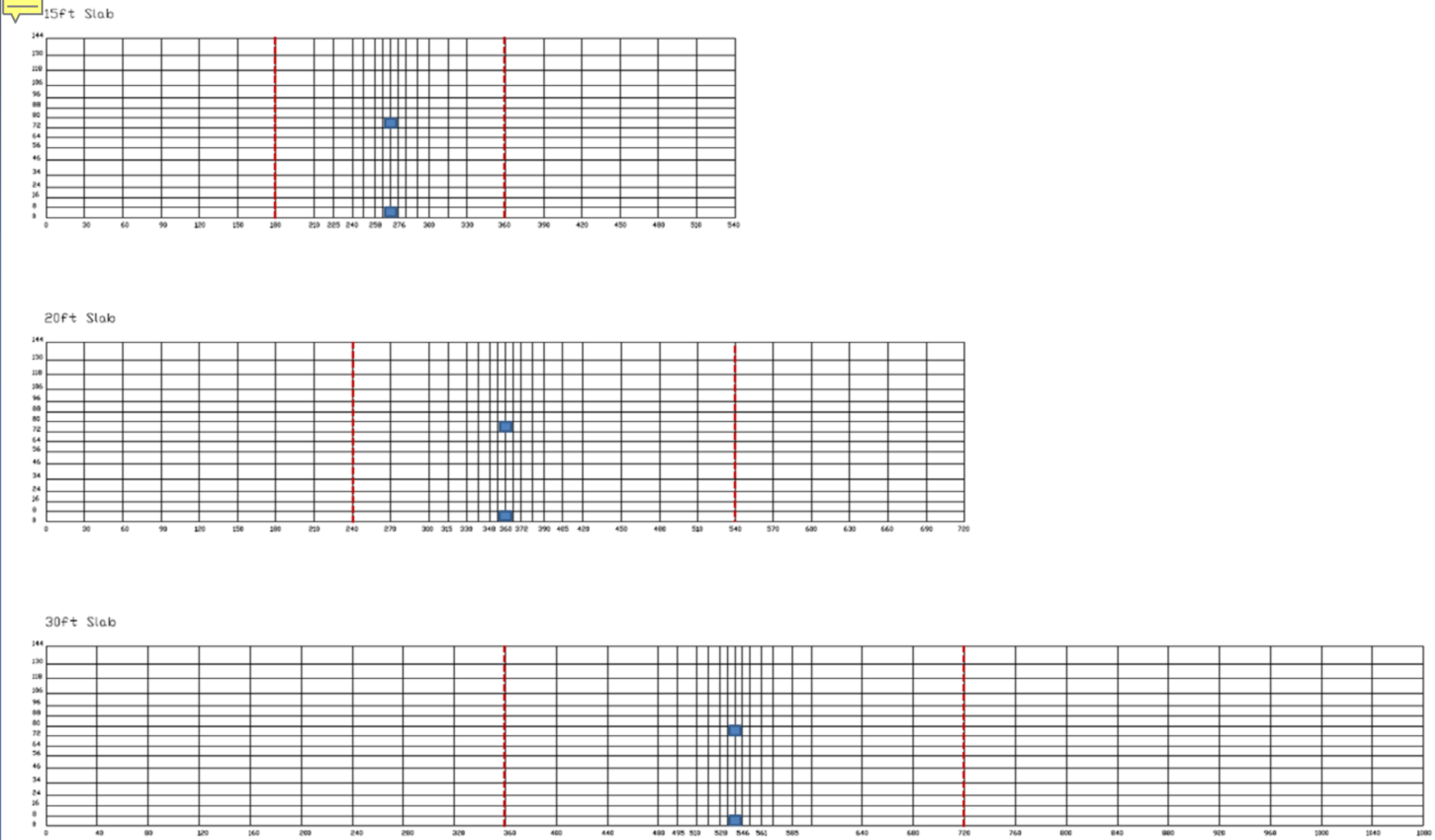
- The Long-Term Pavement Performance (LTPP) database was used to evaluate the effects of various factors on performance of Jointed Plain Concrete Pavements (JPCP) in the U.S. with emphasis on Florida and its neighboring states.
- Critical stress analysis was also performed, using the FEACONS program, on the selected LTPP JPCP sections to determine the maximum stress in the concrete slab under a critical load and temperature condition.
- The maximum computed critical stress for each condition was divided by the modulus of rupture of the concrete to determine the stress-to-strength ratio.



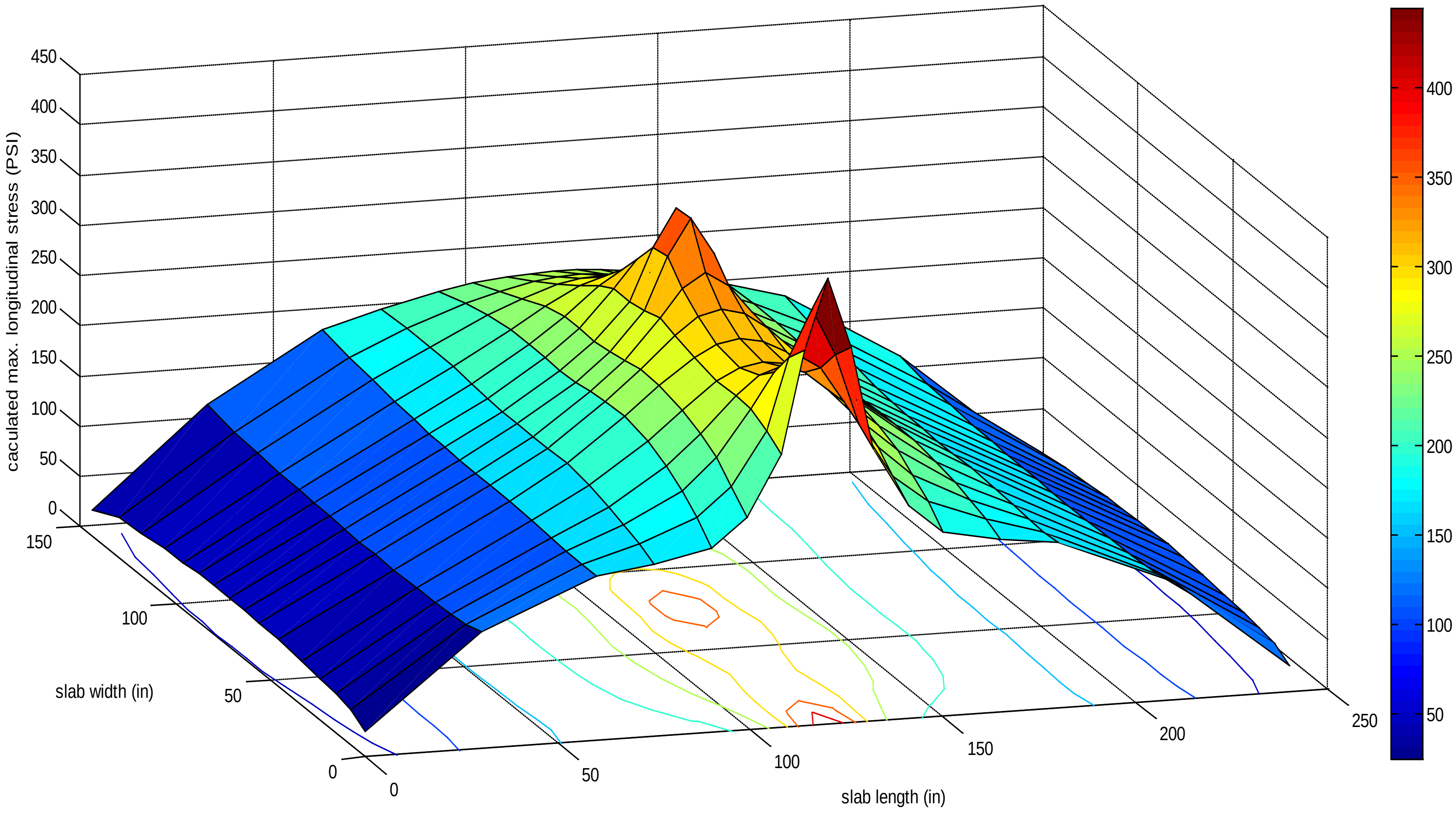
Locations of LTPP JPCP test sections in Wet and No-Freeze Climate Zone used in the analysis

Critical Stress Analysis

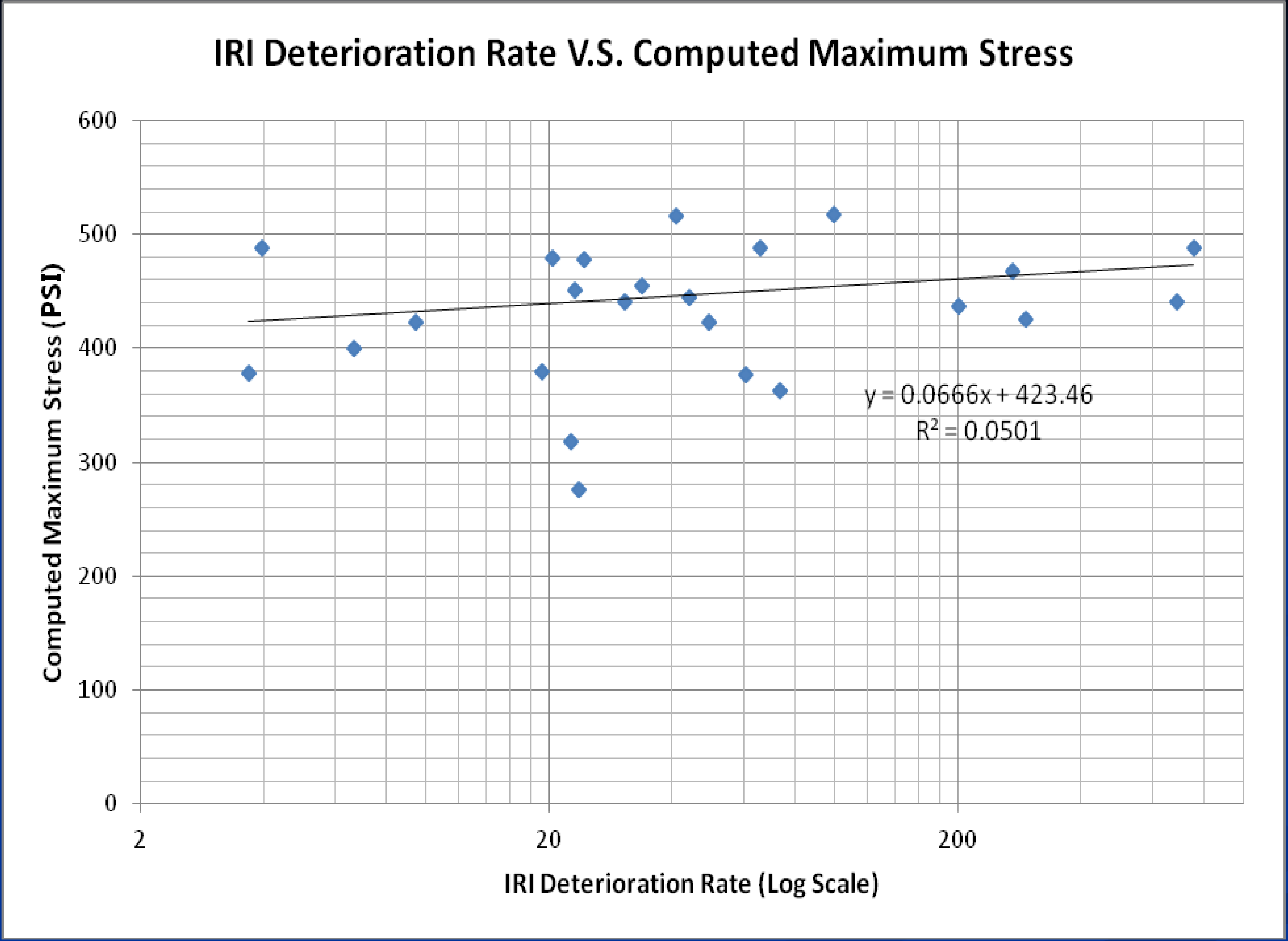
- Using the pavement parameters and material properties for these 24 test sections, maximum stress under a critical load-temperature condition was computed for each test section.
- The maximum stress caused by a 22-kip (98-kN) axial load applied at the middle of the edge of the concrete slab when there was a temperature differential of 20 °F (11.1 °C) between top and bottom of the concrete slab was computed. This represented a critical loading condition as reported by previous studies for FDOT.
- FEACONS computer program was used for the analysis.



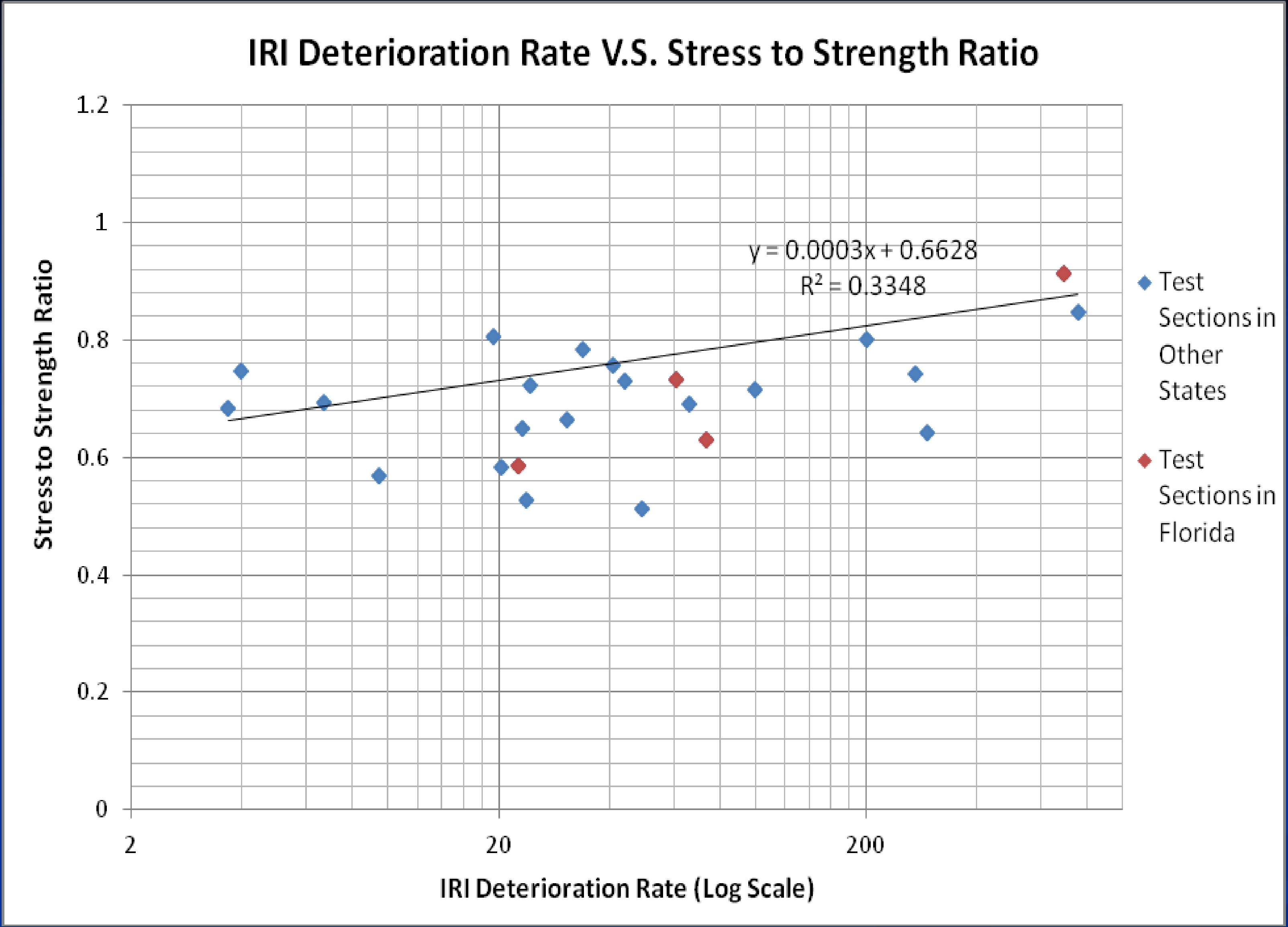
The finite element meshes and locations of applied loads for different slab length



Calculated critical stress for a test section



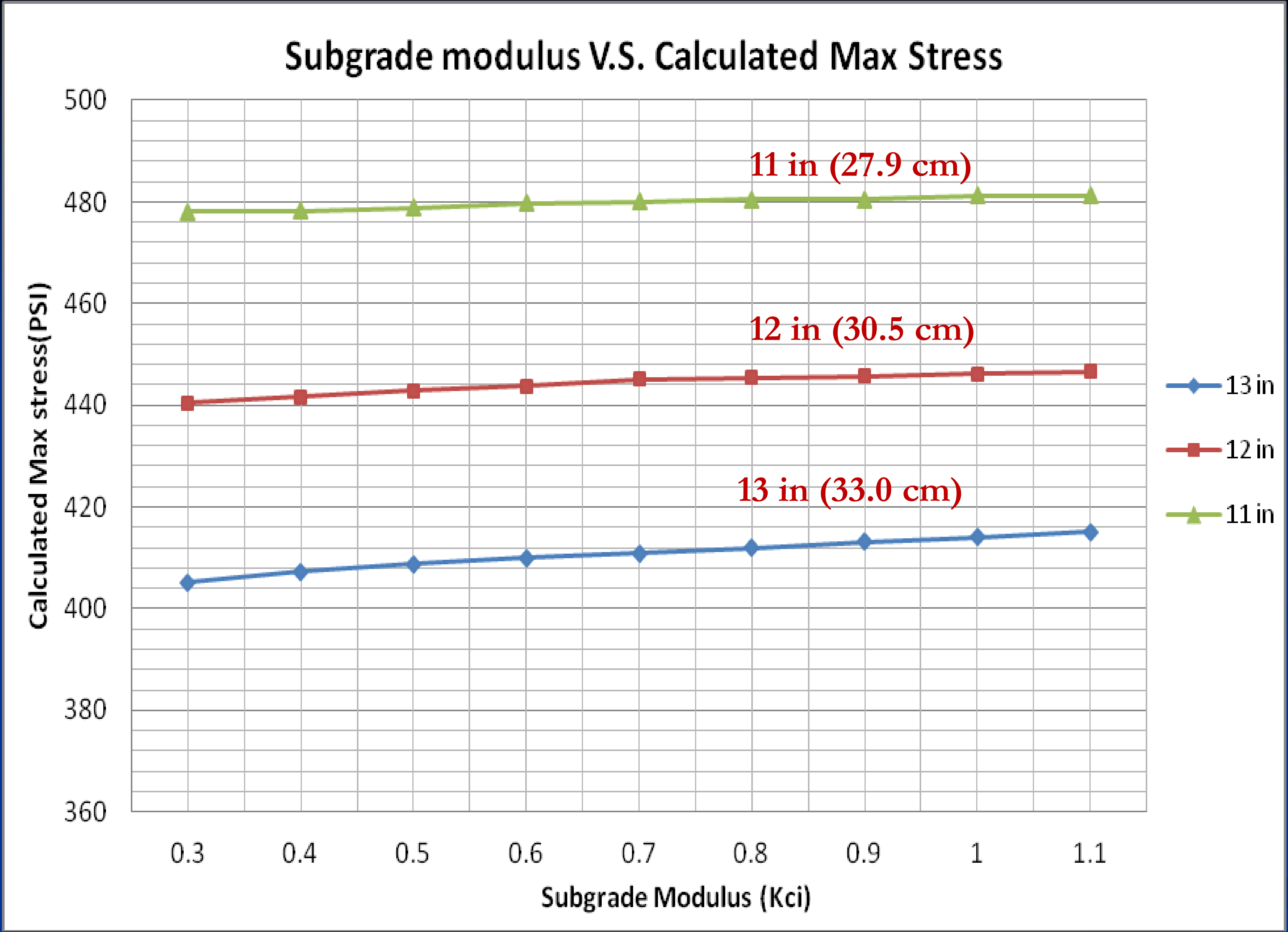
IRI deterioration rate versus maximum computed stress



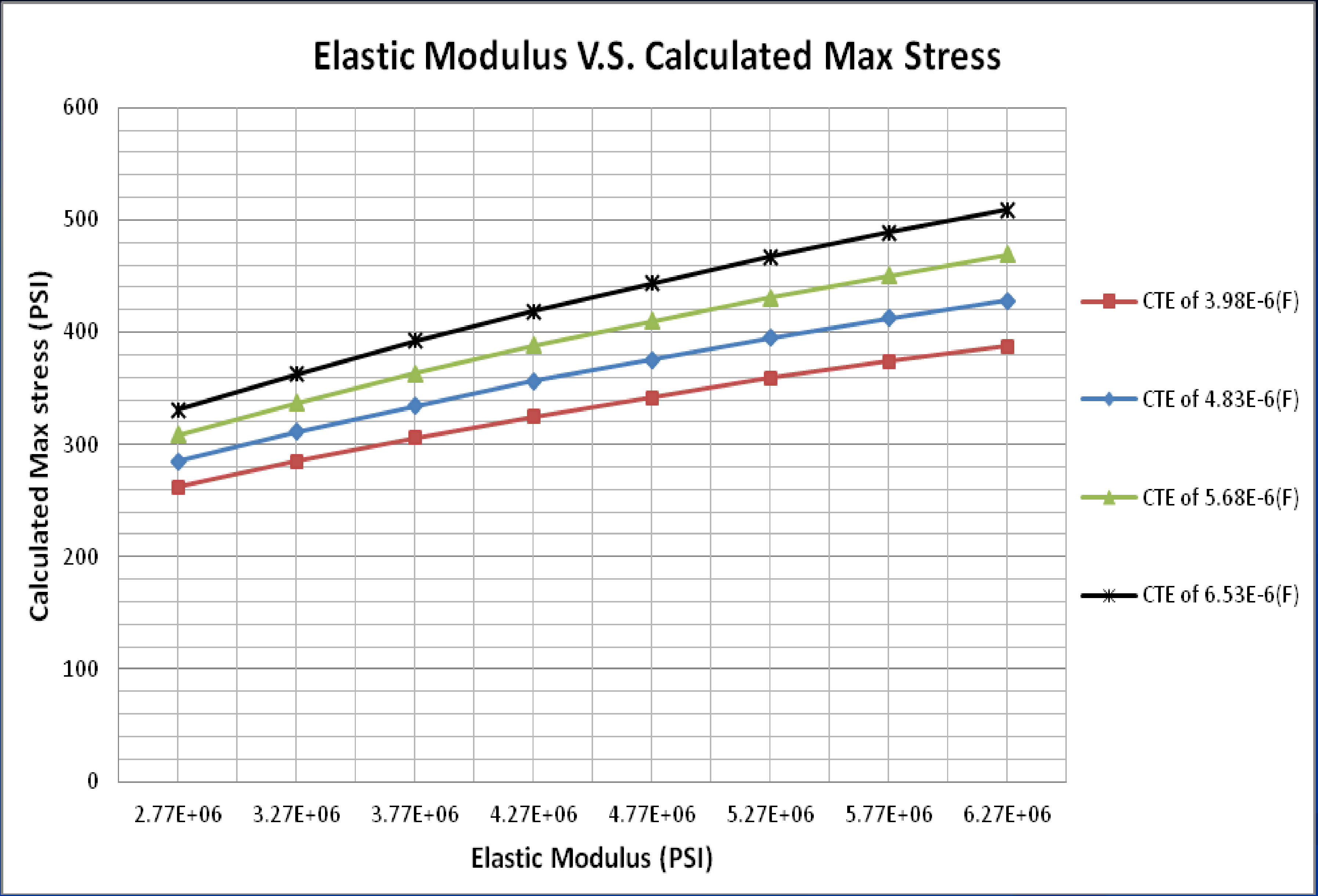
IRI deterioration rate versus stress-to-strength ratio

Findings from critical stress analysis and analysis of LTPP data:

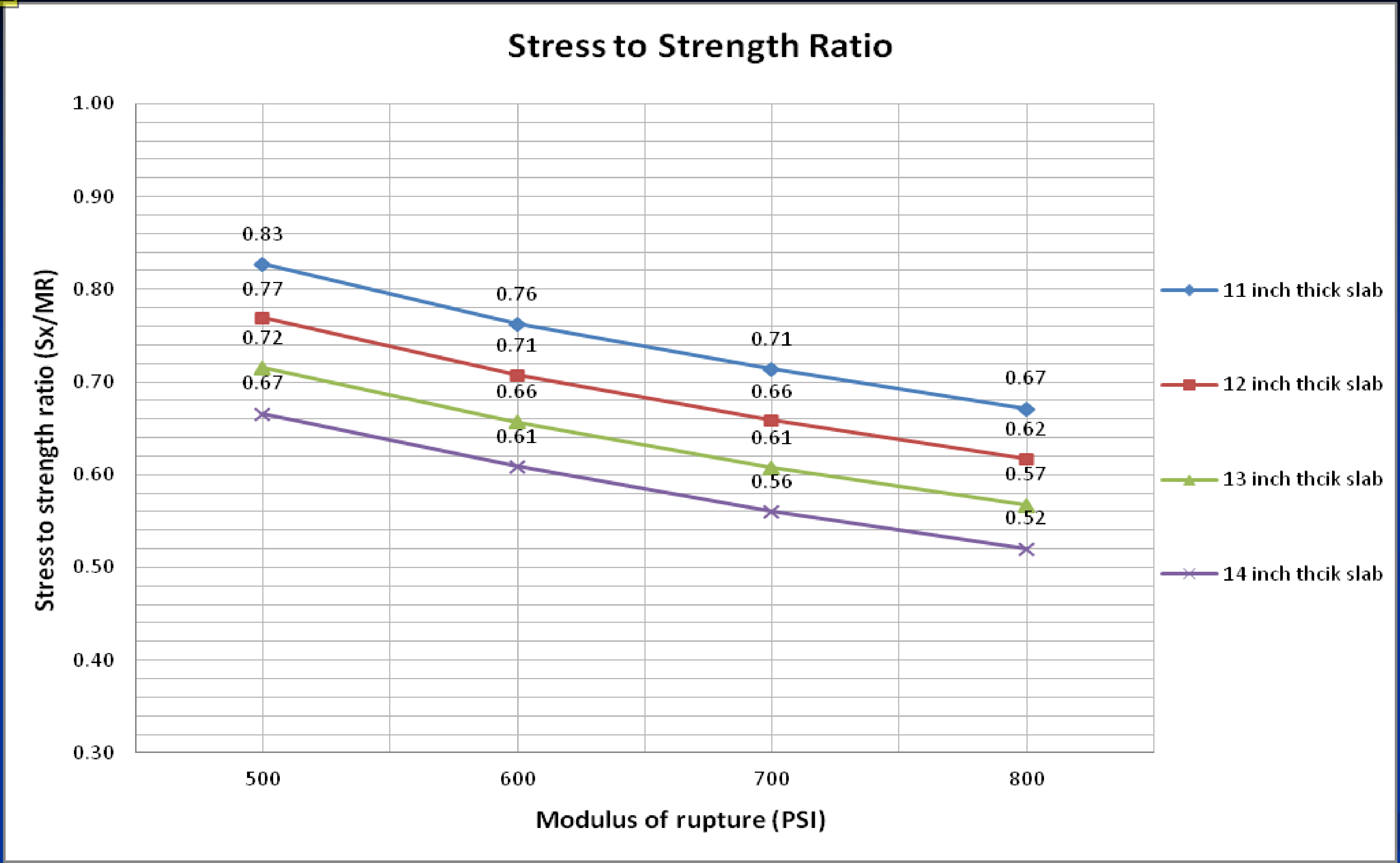
- The computed critical stress to strength ratio was found to be the most significant parameter which can be related to the performance of the LTPP pavements. A lower stress to strength ratio is related to better observed pavement performance.
- The better performing pavements were noted to have a computed stress to strength ratio of less than 0.70.



Calculated maximum stress for different modulus of subgrade reaction and slab thickness



Calculated maximum stresses for different elastic modulus and CTE of concrete



Calculated stress-to-strength ratio with different modulus of rupture and slab thickness

Findings from critical stress analysis:

- The most significant factors affecting the stress-to-strength ratios are the concrete slab thickness and the concrete properties, which include the elastic modulus, modulus of rupture, and coefficient of thermal expansion.
- Variations in the base and subbase properties were found to have minimal effects on the stress-to-strength ratios for concrete slab thickness of 11 inches (27.9 cm) or higher.
- This observed results agree well with the findings from the MEPDG analysis that the most significant factors affecting the performance of the concrete pavement are the concrete slab thickness and the concrete properties.
- Similar to the results from the MEPDG analysis, when the same aggregate is used in the concrete, increasing the flexural strength of the concrete will result in better predicted pavement performance.

4. Examining Life Cycle Cost of Concrete Pavements in Florida

- The cost estimates for Type I-A, Type I-B, and Type II pavements with concrete slab varying from 10 inches (25.4 cm) to 14 inches (35.6 cm) were developed.
- The predicted service lives of these pavements were based on the results of MEPDG analysis using a concrete made with Brooksville aggregate and modulus of rupture of 650 psi (4.48 MPa).

Computed Annual Cost for 10 Miles of 4-Lane Type I-A Pavement

Concrete Slab Thickness (inch)	Total Cost ($)	Expected Life (year)	No Interest	I= 3.5%	I = 5%
			Annual Cost ($)		
10	24,881,600	27	921,541	1,439,461	1,699,211
11	26,594,404	33	805,891	1,371,538	1,661,885
12	28,307,208	42	673,981	1,296,421	1,624,684
13	30,020,012	51	588,628	1,270,494	1,636,951
14	31,732,816	56	566,657	1,300,008	1,697,074

Computed Annual Cost for 10 Miles of 4-Lane Type I-B Pavement

Concrete Slab Thickness (inch)	Total Cost ($)	Expected Life (year)	Annual Cost ($)		
			No Interest	I= 3.5%	I = 5%
10	30,671,446	24	1,277,977	1,909,998	2,222,787
11	32,384,250	30	1,079,475	1,760,775	2,106,642
12	34,097,054	40	852,426	1,596,672	1,987,114
13	35,809,858	50	716,197	1,526,707	1,961,547
14	37,522,662	53	707,975	1,566,233	2,028,976

Computed Annual Cost for 10 Miles of 4-Lane Type II Pavement

Concrete Slab Thickness (inch)	Total Cost ($)	Expected Life (year)	No Interest	I= 3.5%	I = 5%
			Annual Cost ($)		
10	24,362,624	28	870,094	1,378,989	1,635,281
11	26,075,428	36	724,317	1,285,106	1,575,854
12	27,788,232	43	646,238	1,259,512	1,583,744
13	29,501,036	56	526,804	1,208,578	1,577,718
14	31,213,839	60	520,231	1,251,320	1,648,970

Findings from life-cycle cost analysis

- Type II design has the lowest cost estimate, which is slightly less than that for Type I-A design, while Type I-B design has the highest cost estimate.
- When cost of interest was not considered, the most cost-effective slab thickness for all three designs was 14 inches (35.6 cm). With concrete slab thickness of 14 inches (35.6 cm), the expected service for Type I-A, I-B, and II designs are 56, 53, and 60 years, respectively.
- When an interest rate of 3.5% was considered, the most cost-effective slab thickness for all three designs was 13 inches (33 cm). With concrete slab thickness of 13 inches (33 cm), the expected service for Type I-A, I-B, and II designs are 51, 50, and 56 years, respectively.

Recommending Long-Life Concrete Pavement Designs for Florida

- The three typical Florida concrete pavement designs evaluated in this study can be used as long-life pavements if the slab thickness is adequate and the concrete has low elastic modulus, low coefficient of thermal expansion and adequate flexural strength.
- Among the three designs evaluated, Type II pavement has the best predicted performance from the MEPDG analysis and the best drainage characteristics from the results of the drainage evaluation using the steady flow method and the time-to-drain method. Type II pavement also has the lowest cost estimate.

Recommendations (continued)

- Type II design is recommended as the preferred design for use as long-life concrete pavements in Florida. However, if the special select A-3 soil is not available, Type I-A and Type I-B can also be used.
- A concrete slab thickness of 13 or 14 inches (33 or 35.6 cm) is recommended to be used. When 14 inches (35.6 cm) is used, the top 0.5 to 1 inch (1.3 to 2.5 cm) can be considered as sacrificial concrete for future grinding during the life of the pavement to restore ride quality, texture and remediate faulting.

Recommendations (Continued)

- The present FDOT construction specifications for these three types of design are to be followed. In addition to meeting the present FDOT specification requirements for these three designs, the concrete mixture to be used must be designed and evaluated by the following procedure:
    - (1) Design the concrete mix to give a flexural strength of at least 650 psi (4.48 MPa) at 28 days. Use an aggregate which has a past history of producing concrete of low elastic modulus and low coefficient of thermal expansion.
    - (2) Measure the flexural strength, elastic modulus and CTE of the designed concrete mix at 28 days.

Recommendations (Continued)

- (3) Perform MEPDG analysis to evaluate the predicted performance of the designed pavement for a design life of 50 years, using the measured concrete flexural strength, elastic modulus and coefficient of thermal expansion as input properties for the concrete. If the predicted life of the pavement is at least 50 years, the concrete mix would be acceptable for the project. If the predicted life is less than 50 years, a new concrete mix can be designed by either specifying a higher flexural strength or using a different aggregate. Steps 1 through 3 would be repeated until an acceptable concrete mix for the project is obtained.

Use of Reclaimed Asphalt Pavement in Concrete Pavement Slabs

Mang Tia
Nabil Hossiney

Background and Research Needs (1/2)

- More than 100 million tons of reclaimed asphalt pavement (RAP) are generated per year by asphalt pavement rehabilitation and reconstruction in the U.S. Some have been recycled into new asphalt mixtures; some have been used as pavement base materials. However, a large quantity of RAP still remains unutilized and needs to be put to good use.

Background and Research Needs (2/2)

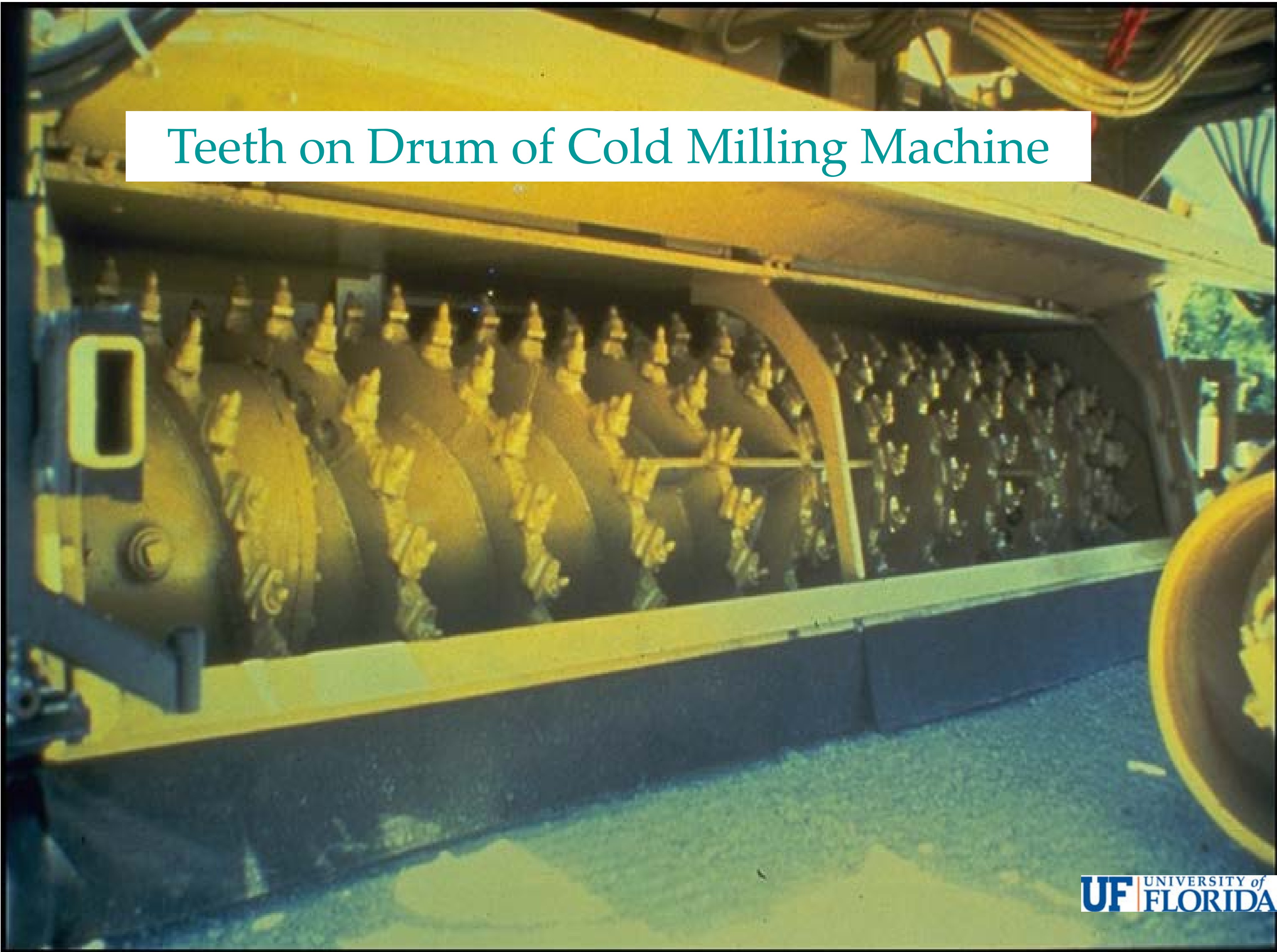
- Using RAP in concrete offers the possibility of producing a low modulus concrete, which could have lower stresses due to the same applied loads in concrete pavements.
- With the increasing volume of waste or by-product materials from industry, domestic, and mining sources, decreasing availability of landfill space for disposal and depletion of virgin aggregates, there is a need to assess the feasibility of using RAP as aggregates in concrete for use in concrete pavements.

Objectives of Study

- To evaluate the potential use of RAP in concrete and their effects on the mechanical and thermal properties of concrete.
- To determine the performance of concretes containing different amounts of RAP when used in a typical concrete pavement in Florida.

RAP removed by Cold Milling Machine

Teeth on Drum of Cold Milling Machine



Laboratory Evaluation of Concrete Containing RAP

- Concrete containing 0, 10, 20, and 40% of RAP were produced in the laboratory, and evaluated for their properties that are relevant to performance of concrete pavements. Two different RAPs were used. W/C ratio was varied from 0.43 to 0.53.

- The properties evaluated were compressive strength, splitting tensile strength, flexural strength, elastic modulus, coefficient of thermal expansion, and drying shrinkage.

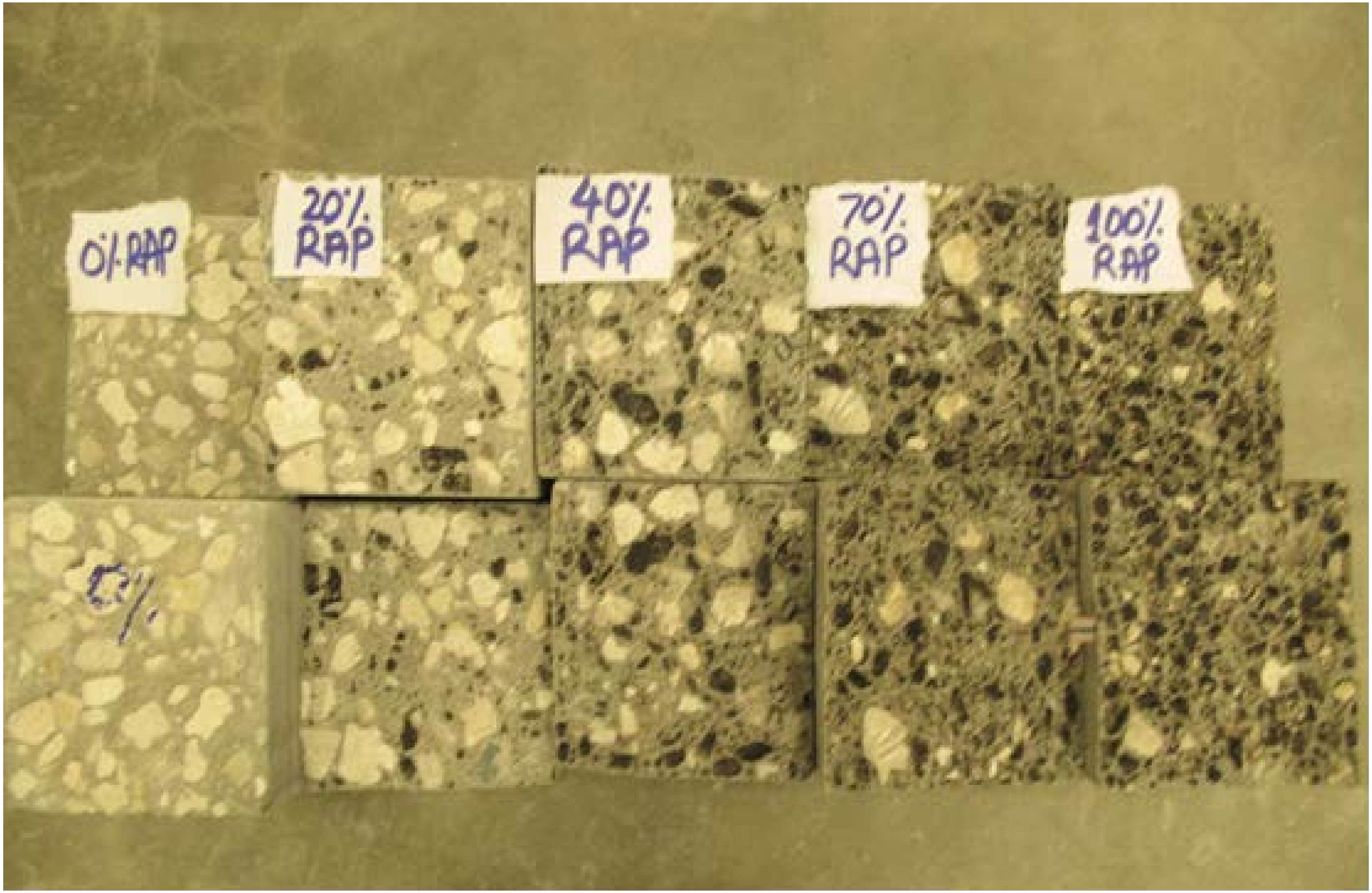
Fine RAP

Coarse RAP

Typical fracture surfaces of a concrete sample containing RAP.

(The cement paste can be observed to be well bonded to the RAP particles in the concrete sample.)

Fracture Surface of Concrete containing RAP



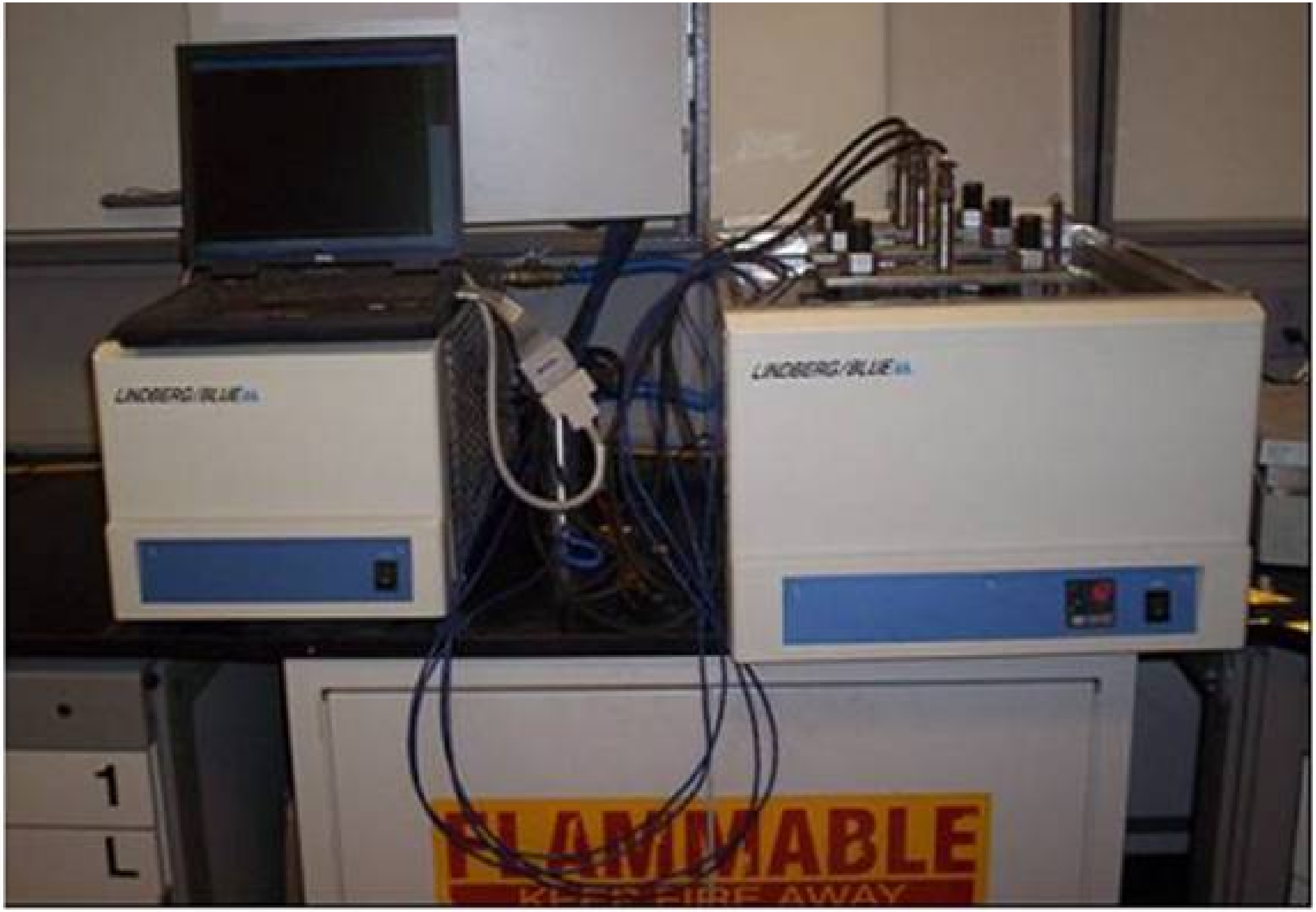
Cement paste bonded well with the RAP particles

Flexural strength test

Compressive strength & elastic modulus test

Splitting tensile strength test

Shrinkage test



Coefficient of thermal expansion test

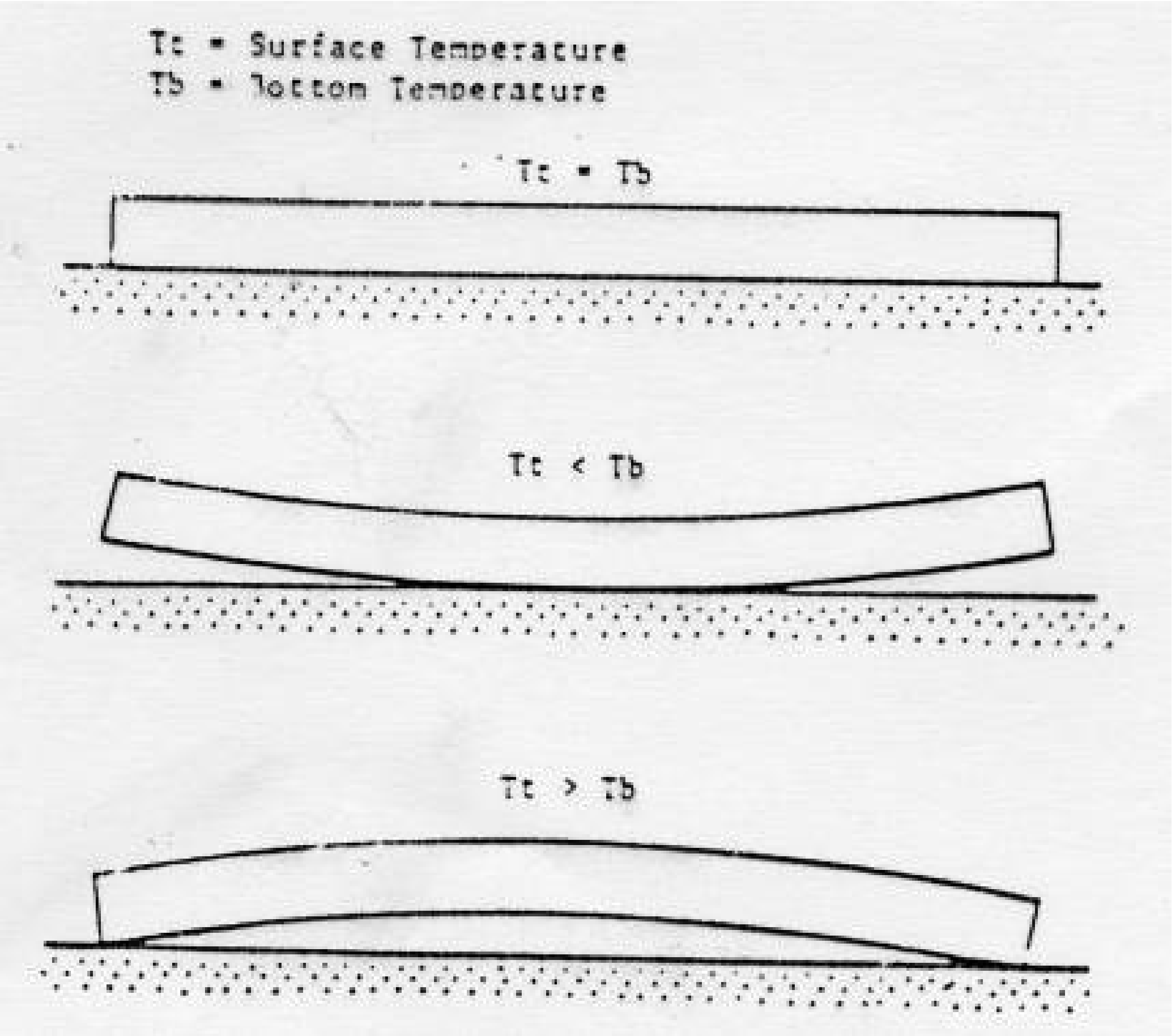
Findings from the Laboratory Evaluation of Concrete Containing RAP

- Compressive strength, splitting tensile strength, flexural strength, and elastic modulus of the concrete decreased as the percentage of RAP increased.
- The coefficient of thermal expansion appeared to increase slightly when the first RAP was incorporated, and to decrease slightly when a second RAP was used.
- The drying shrinkage appeared to increase slightly with the use of RAP in concrete.

Critical Stress Analysis

- Analysis was performed to determine the maximum stresses in a typical 10-inch (25.4 cm) concrete pavement slab in Florida under a critical loading condition, using the concrete properties as measured.
- The ratio of maximum stress to flexural strength of concrete was determined to assess the potential performance of the concrete in service.

Effects of Temperature Differential:

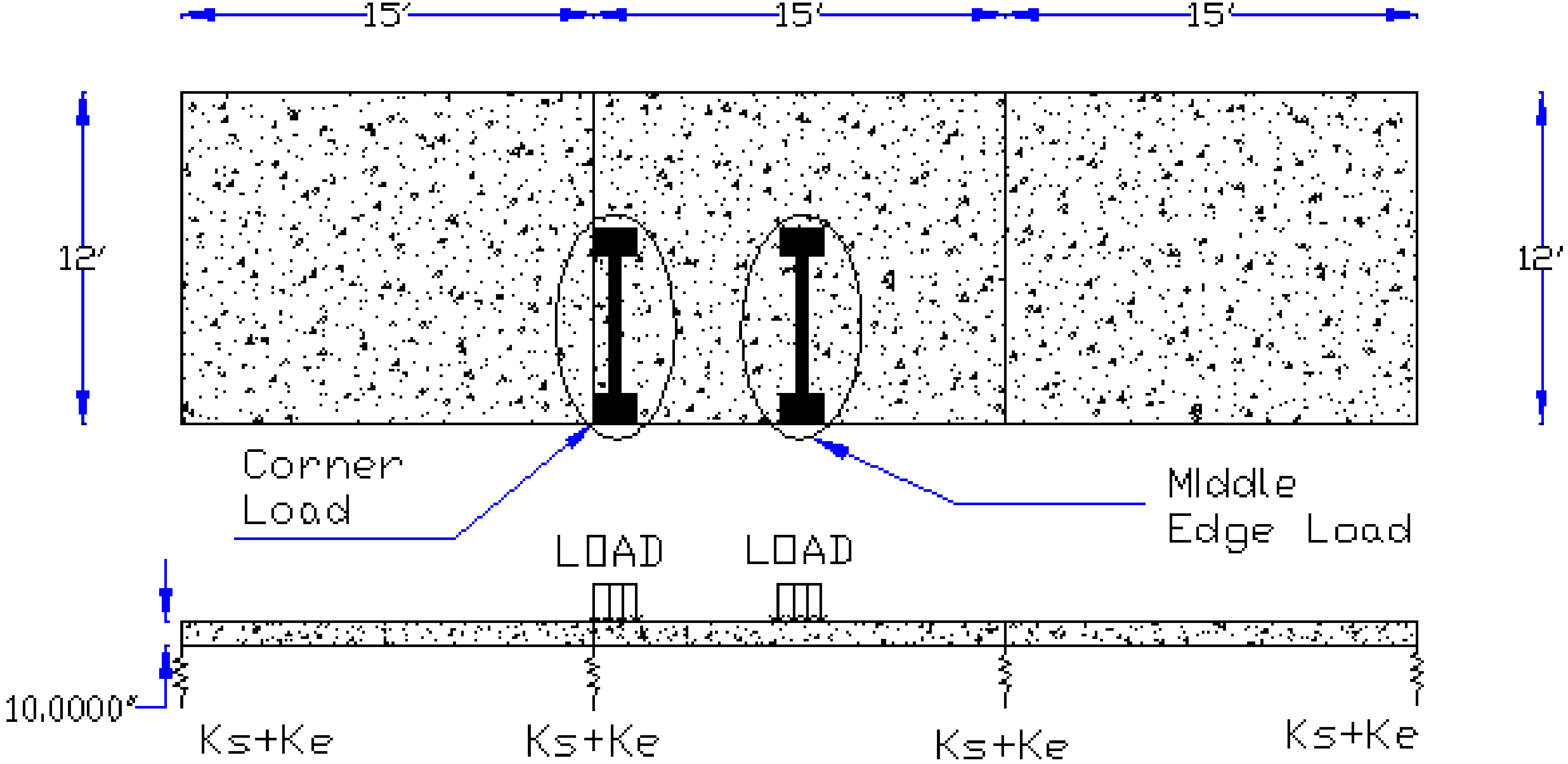


No Temperature Differential

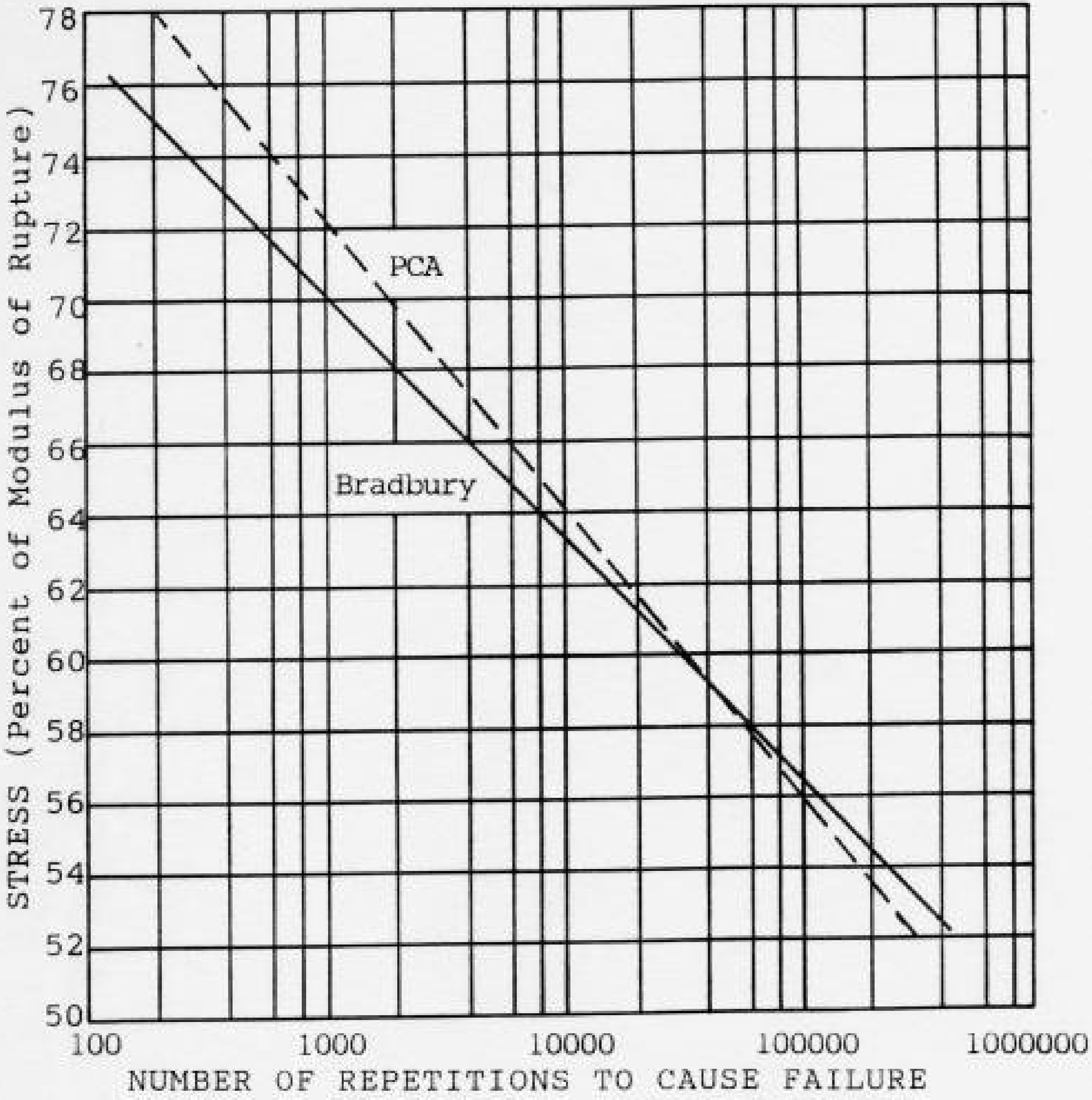
Night time

Day time

Critical Loading Condition

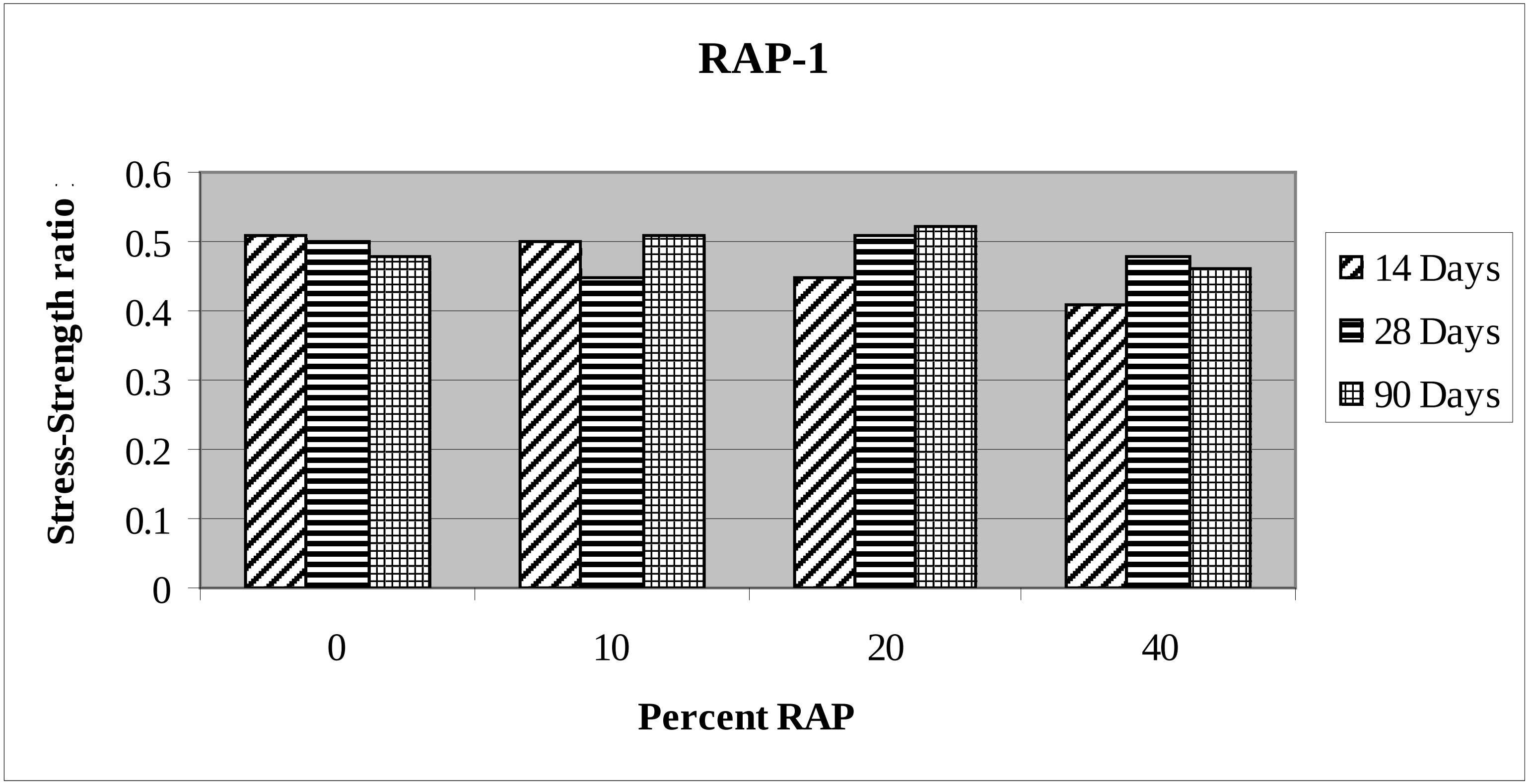


- **22-kip (98 kN) wheel load at slab's middle edge**
- **Temperature differentials of +20 (+11.1 ˚C) in slab**

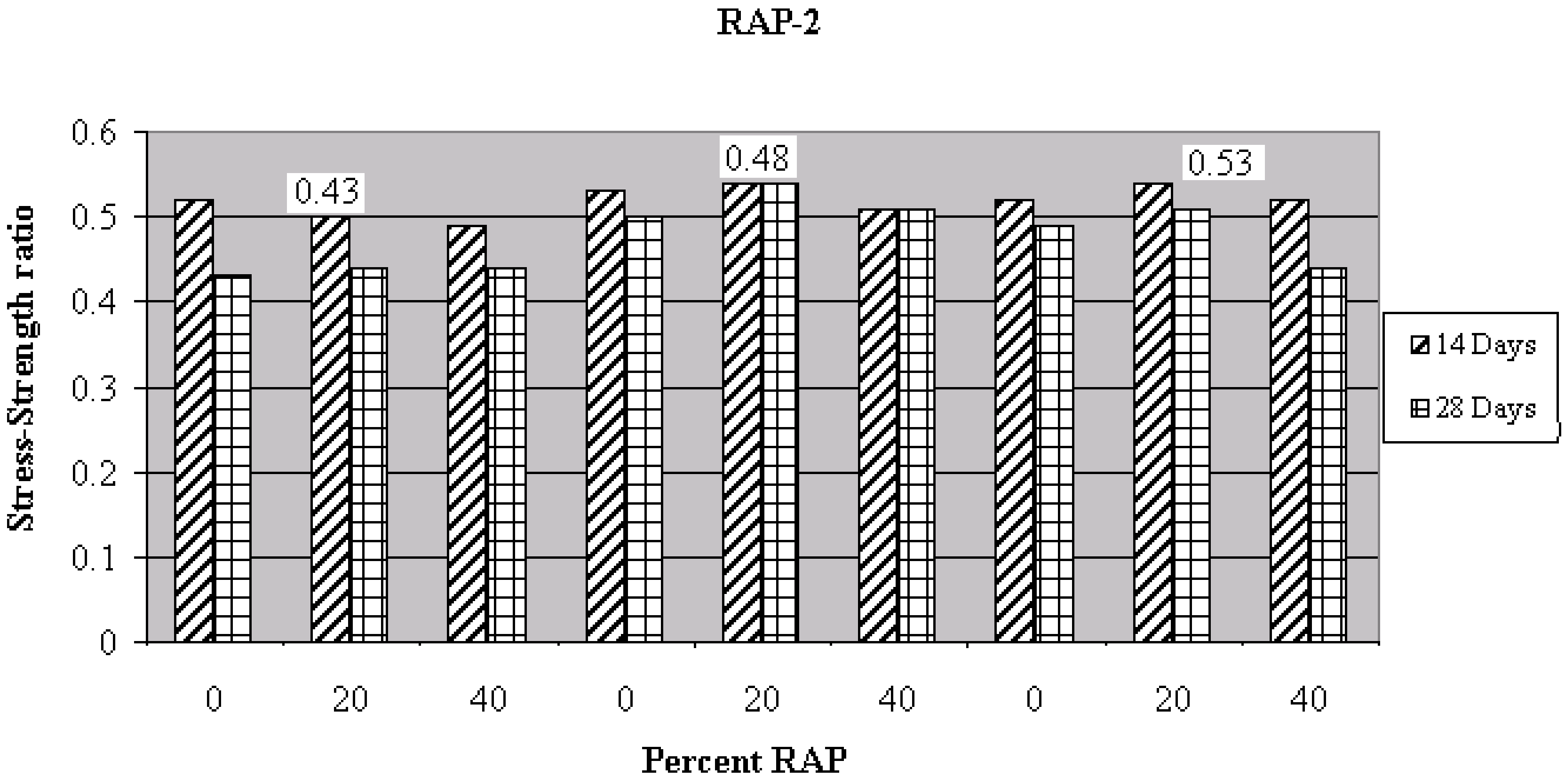


Fatigue curves for plain concrete

Stress-Strength ratio of concrete containing RAP at the middle edge of the pavement with +20 °F temperature differential



Stress-Strength ratio of concrete containing RAP at the middle edge of the pavement with +20 °F temperature differential



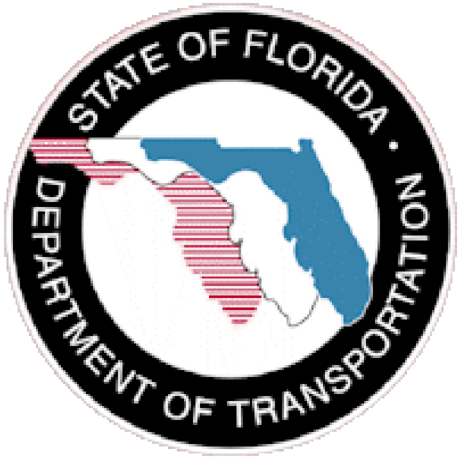
Results of Critical Stress Analysis for Concrete Containing RAP

- The maximum stresses in the pavement were found to decrease as the RAP content of the concrete increased, due to a decrease in the elastic modulus of the concrete.

- Though the flexural strength of the concrete decreased as RAP was incorporated in the concrete, the resulting maximum stress to flexural strength ratio for the concrete was reduced as compared with that of a reference concrete with no RAP.

- This indicates that using a concrete containing RAP could possibly result in improvement in the performance of concrete pavements.

State Materials Office



US 301 Concrete Test Road

Third most populous state in the US
Population: 20 million

Location of Test Road

Obrigado!

Any Questions?