Early Opening Strength of Fibrous Concrete for Pavement

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104th Annual THE Conference
University of Illinois at Urbana-Champaign
Design, Construction & Environment
Illini Union A

February 27, 2018

INTRODUCTION

Challenges in Portland Cement Concrete (**PCC**) **pavements** at early opening to traffic (**EOT**)

- **Traffic Congestion and Delay**
- **Economy**
- **Fatigue Damage/Stiffness Degradation**
- **Durability Issues: Freeze/thaw, spalling…**

OBJECTIVES

- Assess the effect of concrete pavements **elastic properties** on their **fatigue damage** when opened to **early traffic**
- Correlate mechanical and elastic properties of lab results to field performance using **non-destructive methods (maturity and dynamic modulus tests)**
- Develop relationship between **strength or elastic characteristics** of concrete pavements and **post fatigue damage**

OBJECTIVES (cont'd)

- Perform analytical studies that mimic and enhance the experimental studies using **finite element models**
- Evaluate and revise the current specifications of IDOT on the minimum strength requirements for pavements to be opened to traffic in **Articles 701.17(c)(5)** and **701.17(e)(3)**
- Investigate the possible detrimental effects of **residual strains/stress** induced by loading early-age concrete on **long term-fatigue life** and durability such as **freeze/thaw performance**

IDOT Pavement and Patch Mix Requirements

Class of Concrete	Use	Cement Factor cwt/yd^3		w/cm Ratio	Slump, in	Air Content, %	Min. Compressive Strength (Flexural) (5), psi		Min. Strength required for Opening to Traffic, psi
		Min	Max				Days		
PV	**Pavement**	5.65 (1)	7.05	0.32-0.42	2-4	5.0-8.0	14 Days	28 (6) Days	3500 (650)
		6.05 (2)					3500 (650)	3500 (650)	
PP - Pavement Patching	**PP-1**	6.50	7.50	0.32-0.44	2-4	4.0-7.0	3200 (600)	at 48 hrs	3200 (600)
	PP-2	7.35	7.35	0.32-0.38	2-6	4.0-6.0		at 24 hrs	1600 (250)
	PP-3	7.35 (3)	7.35 (3)	0.32-0.35	2-4	4.0-6.0		at 16 hrs	
	PP-4	6.00 (4)	6.25 (4)	0.32-0.50	2-6	4.0-6.0		at 8 hrs	
	PP-5	6.75 (4)	6.75 (4)	0.32-0.40	2-8	4.0-6.0		at 4 hrs	

(1) Central mixed

(2) Truck mixed or shrink mixed

(3) Use Type III cement. In addition to the cement, 100 lb/yd^3 of slag and 50 lb/yd^3 of silicafume shall be used

(4) The cement shall be a rapid hardening cement from the Department's "Approved list of Packaged, Dry, Rapid Hardening Cementitious Materials for Concrete Repairs" for PP-4 and calcium aluminate cement for PP-5

(5) **Minimum strength requirements in pavements for traffic opening**

(6) **If strength tests are not conducted, the pavement shell be opened to traffic after 28 days when fly ash or GGBF slag are used in the mix**

RESEARCH PLAN

- Task 1. State of the Art Literature Review
- Task 2. Material Selection, Mix Design, and Curing Methods
- Task 3. Laboratory Test Methods for PCC Pavements
- Task 4. Analytical Study and Finite Element Modeling
- Task 5. Jointed slabs under cyclic fatigue
- Task 6. Analysis of Results

Task 2: Material Selection, Mix Design, and Curing Method

Mix Design

Mixture Designation	Cementitious Content, lbs/yd³	w/cm Ratio(2)	Slump (3), in	Air Content, %	Discontinuous Fibers, lbs/yd³
PV-Control	565	**0.42**	2-4	5.0-8.0	0.0
PV-Fiber(1)	565	**0.42**	2-4	5.0-8.0	**4.0 – 8.0**(4)
PP-1-Control	650	**0.42**	2-4	4.0-7.0	0.0
PP-1-Fiber(1)	650	**0.42**	2-4	4.0-7.0	4.0(4)
PP-2-Control	735	**0.36**	2-6	4.0-6.0	0.0
PP-2-Fiber(1)	735	**0.36**	2-6	4.0-6.0	4.0(4)

(1) Trial Mixes using two different types of Fibers will be carried out initially to examine the difference in the PCC performance with the different fibers and select the Fiber with optimum performance for this study

(2) The maximum w/cm ratio was selected to account for worst case scenario

(3) Water Reducing admixtures and superplasticizers will be added as needed

(4) It is recommended to use 4.0 lbs/yd³ of Strux 90/40 for optimum performance. This amount might change depending on the type of fiber used.

Task 2: Material Selection, Mix Design, and Curing Method

Curing Methods for Laboratory Testing

Two curing regimes for laboratory testing:

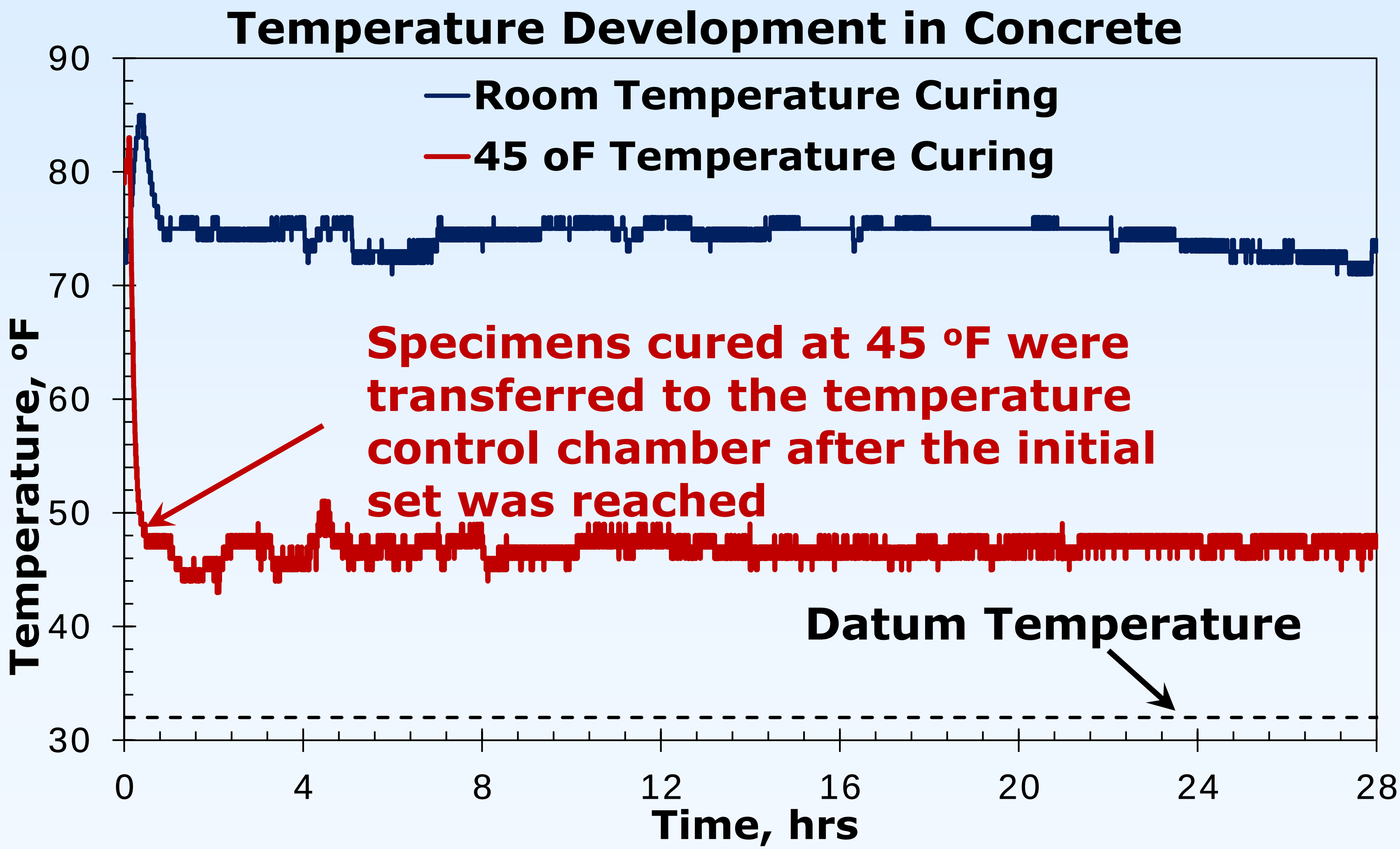
- **Room Temperature curing (RT)** where specimens are placed in a **moisture room or curing tank under a controlled temperature of 23 ^{o}C (73 ^{o}F) and 100% humidity** (according to ASTM C511/AASHTO M 201) until the testing dates.
- **Curing at 40 – 50 ^{o}F (45F)** where specimens are placed inside an **environmental chamber** under a controlled temperature at 40 – 50 ^{o}F until the testing dates.

Task 3: Lab Test Methods for PCC Pavements

Test Method	Description and Testing Times	Test Standard	Sample Size
Compressive strength	Test at 12hrs, 1, 2, 3, 7, 14, & 28 days	ASTM C39	6"x12" cyl. (4"x8" cyl.)
Flexural strength	Test at 12 hrs,1, 2, 3, 7, 14, & 28 days	ASTM C78	6"x6"x21" prism
Flexure toughness of Fibrous Concrete	Test at 12 hrs, 1, 2, 3, 7, 14, & 28 days	ASTM C1609	6"x6"x21" prism
Static Modulus of Elasticity	Test at 12h, 1, 3, 7, 14, & 28 days	ASTM C469	6"x12" cyl.
Linear Drying shrinkage	Start after 1, 3, & 7 days	ASTM C157	3"x3"x11"
Concrete Strength by Maturity	Temperature vs. Time in concrete	ASTM C1074	6"x12" cyl.
Relative Dynamic Modulus (RDM)	Measure before & after fatigue	ASTM C215	
Fracture Mechanic Testing for Notched beams	Test fracture behavior and stiffness degradation at 9 hrs, 12 hrs, 1, 2, 3, 7, 14, and 28 days	Issa 1993 Shah 1990	3"x4"x16" prism
Fatigue Testing for Flexural Beams in Third Point Bending	Test at 12 hrs, 1, 3, & 7 days at different stress levels (0.6, 0.7, 0.8, and 0.90)		6"x6"x21" prism
Fatigue Testing for Jointed Slabs with or without dowel bars	Five slabs tested with different boundary conditions		24"x6-8"x84" slabs
Cyclic Freeze/Thaw tests, RDM and readings every 30 to 36 cycles(1)	Perform Freeze/Thaw test on specimens Fatigued before testing	ASTM C666, Proc. A	3"x4"x16" prisms

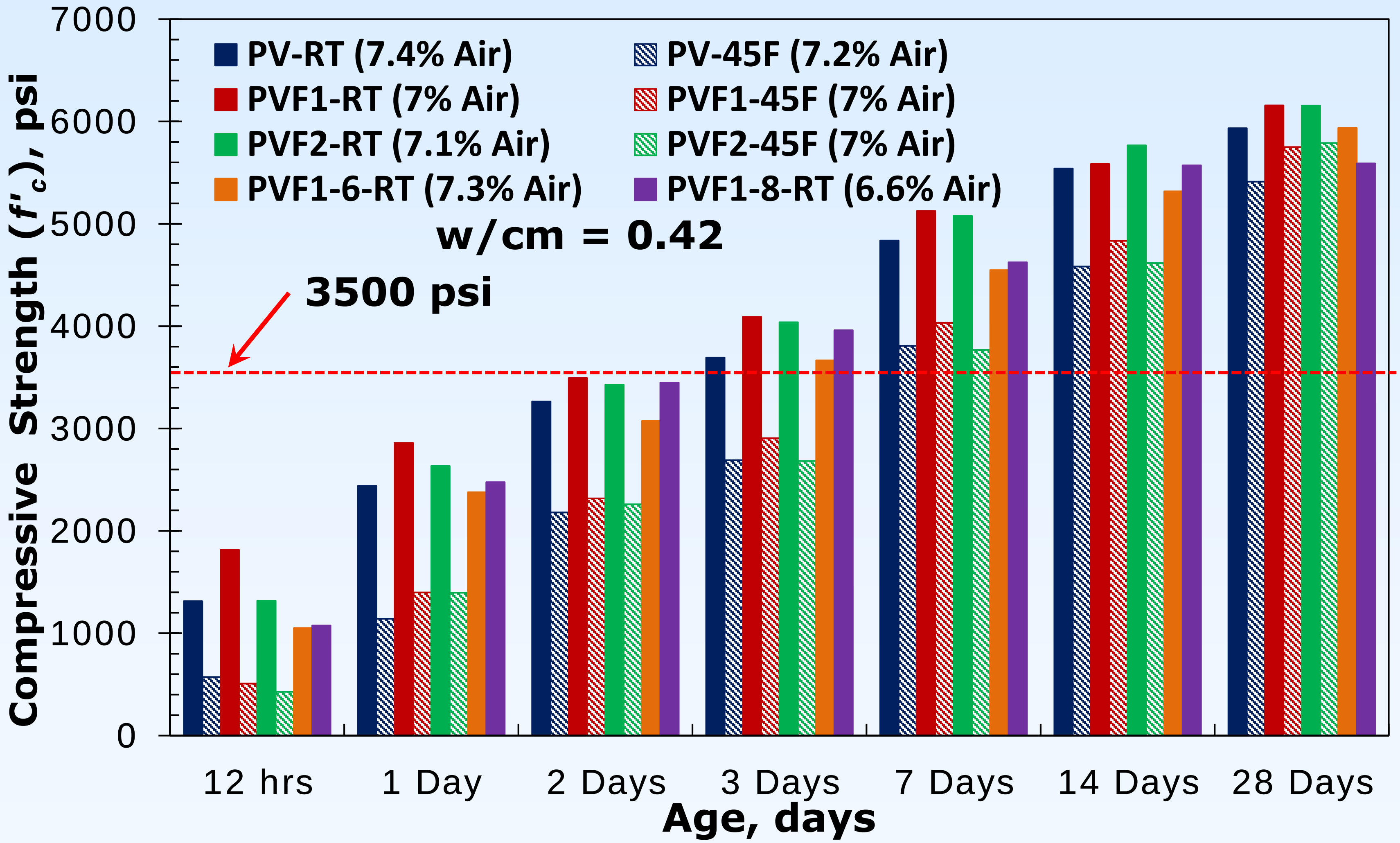
(1) Specimens will be fatigued before testing while other specimens are cured until the day of testing

Temperature Development in the PV, PP1, and PP2 Mixes



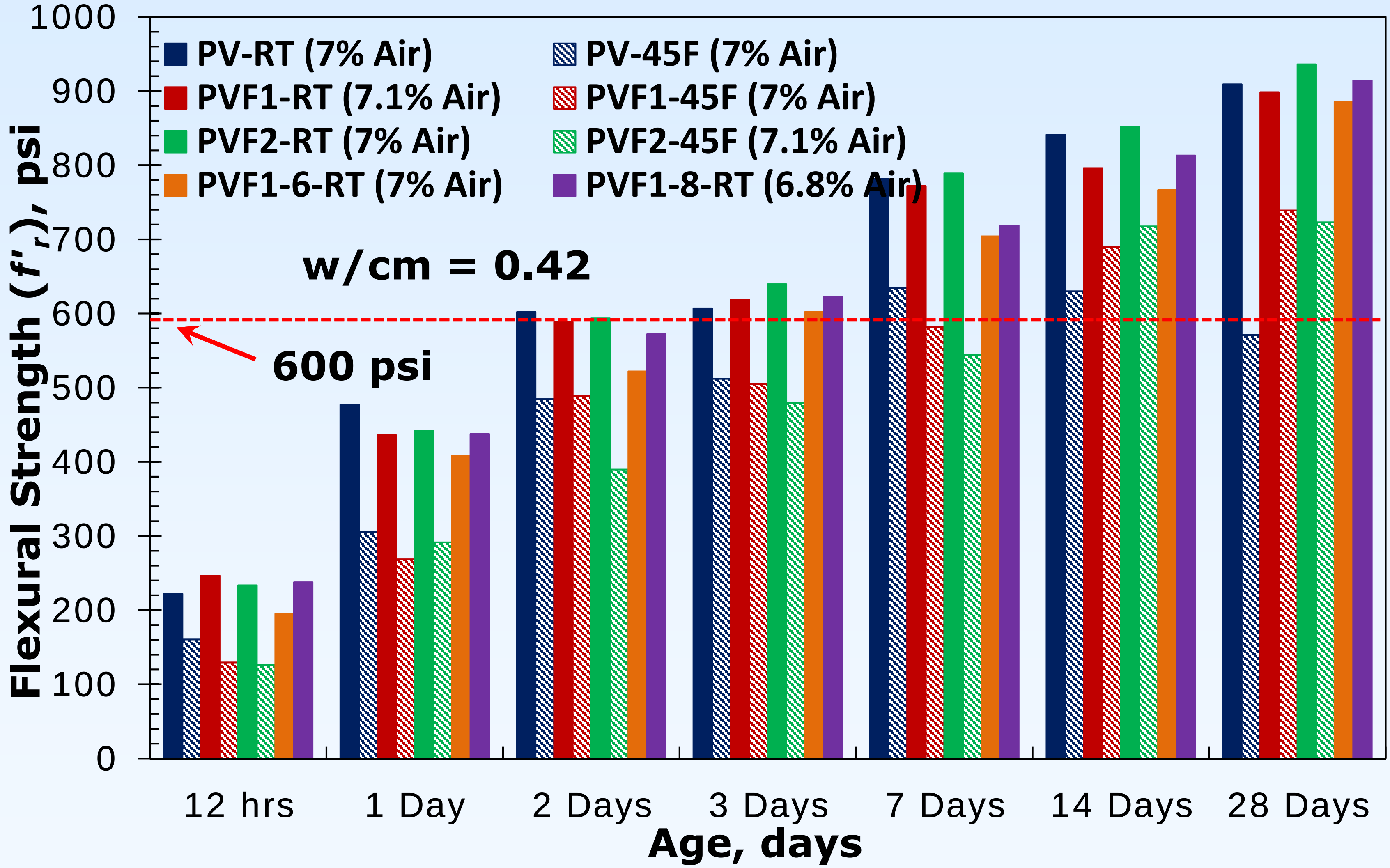
Task 3: Test Results for the PCC Mixes

Compressive Strength in PV Mixes



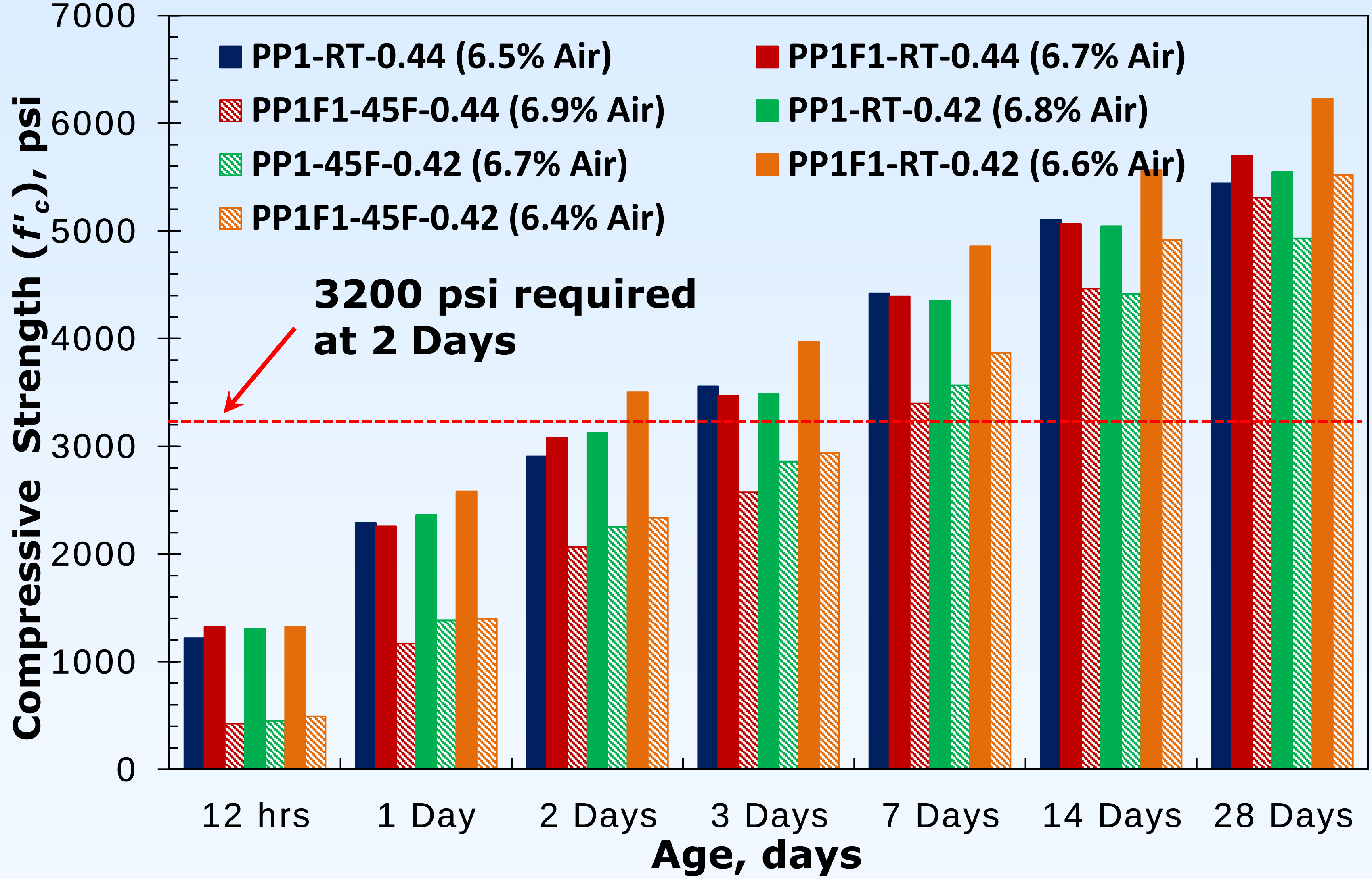
Task 3: Test Results for the PCC Mixes

Flexural Strength in PV Mixes



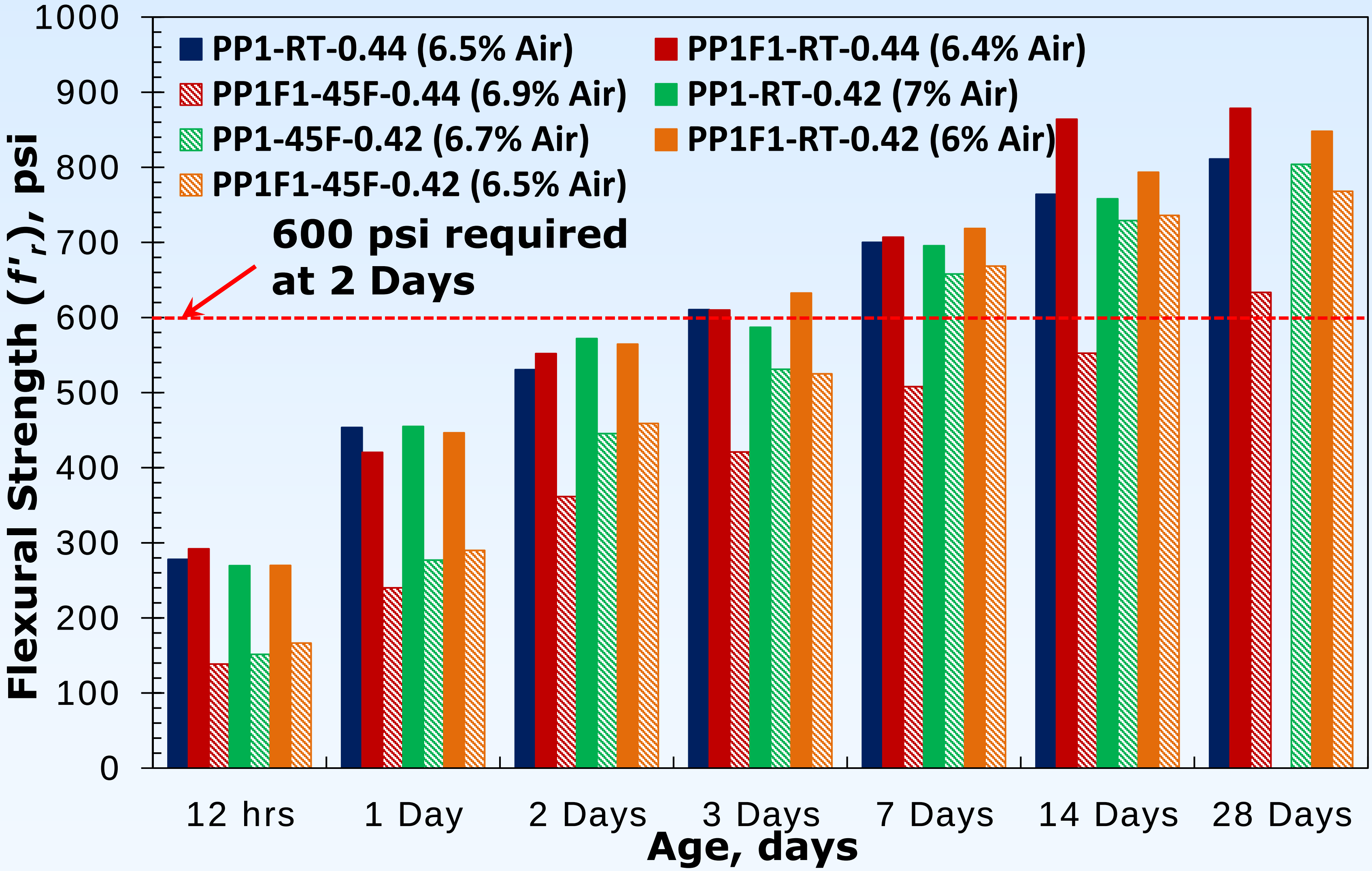
Task 3: Test Results for the PCC Mixes

Compressive Strength in PP1 Mixes



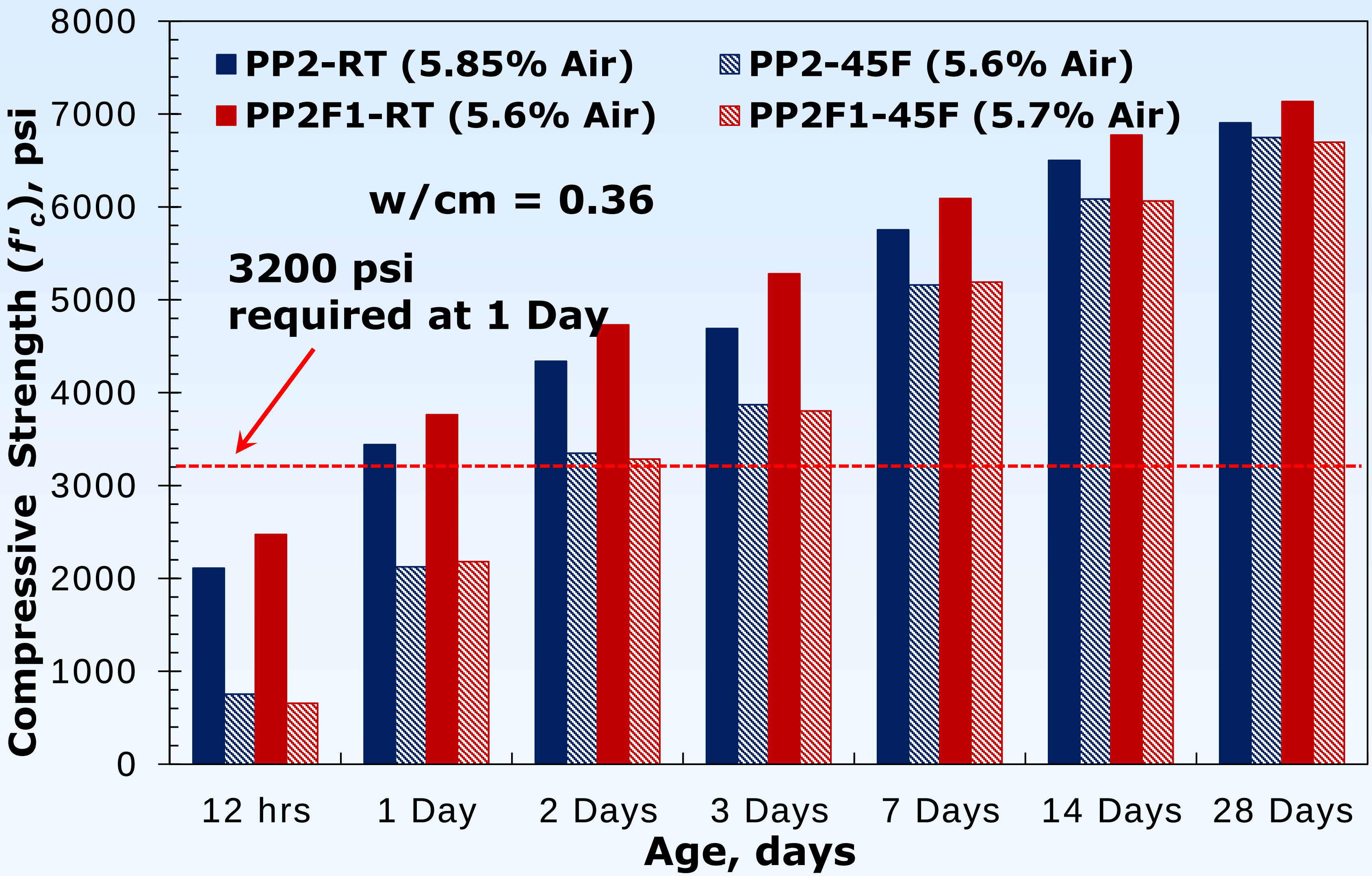
Task 3: Test Results for the PCC Mixes

Flexural Strength in PP1 Mixes



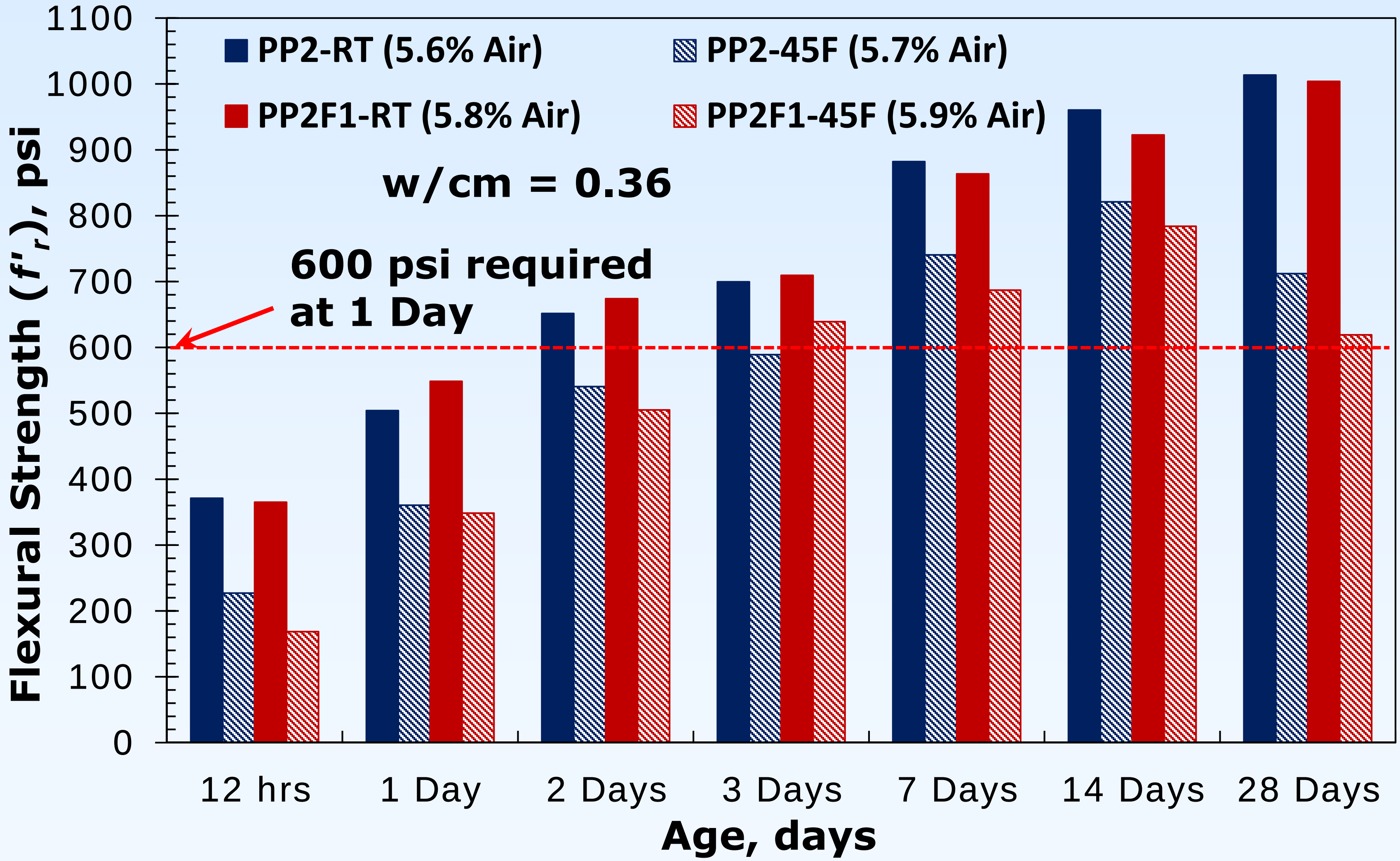
Task 3: Test Results for the PCC Mixes

Compressive Strength in PP2 Mixes



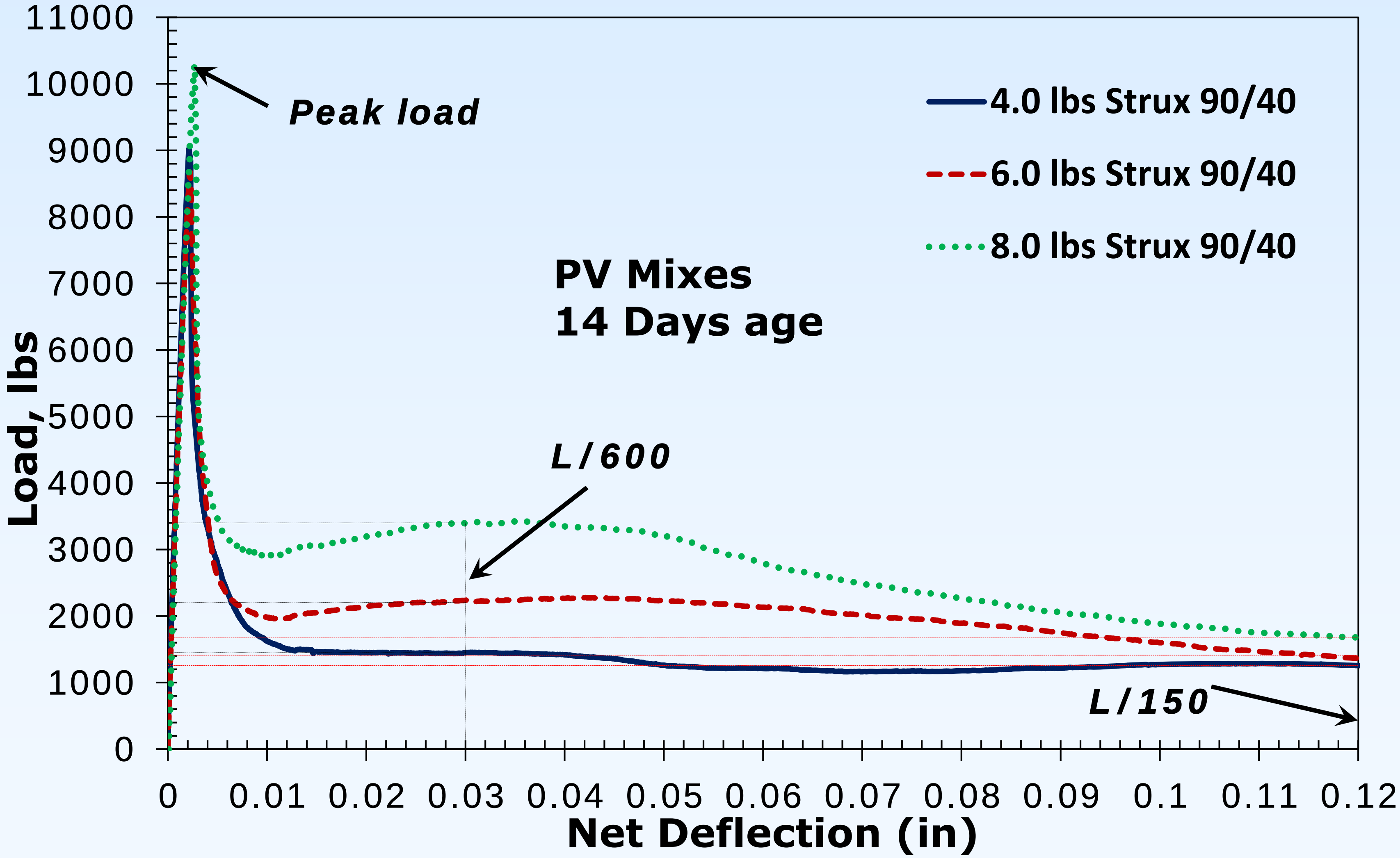
Task 3: Test Results for the PCC Mixes

Flexural Strength in PP2 Mixes



Task 3: Test Results for the PCC Mixes

Effect of Fiber Content on the Flexure Toughness



Task 3: Test Results for the PCC Mixes

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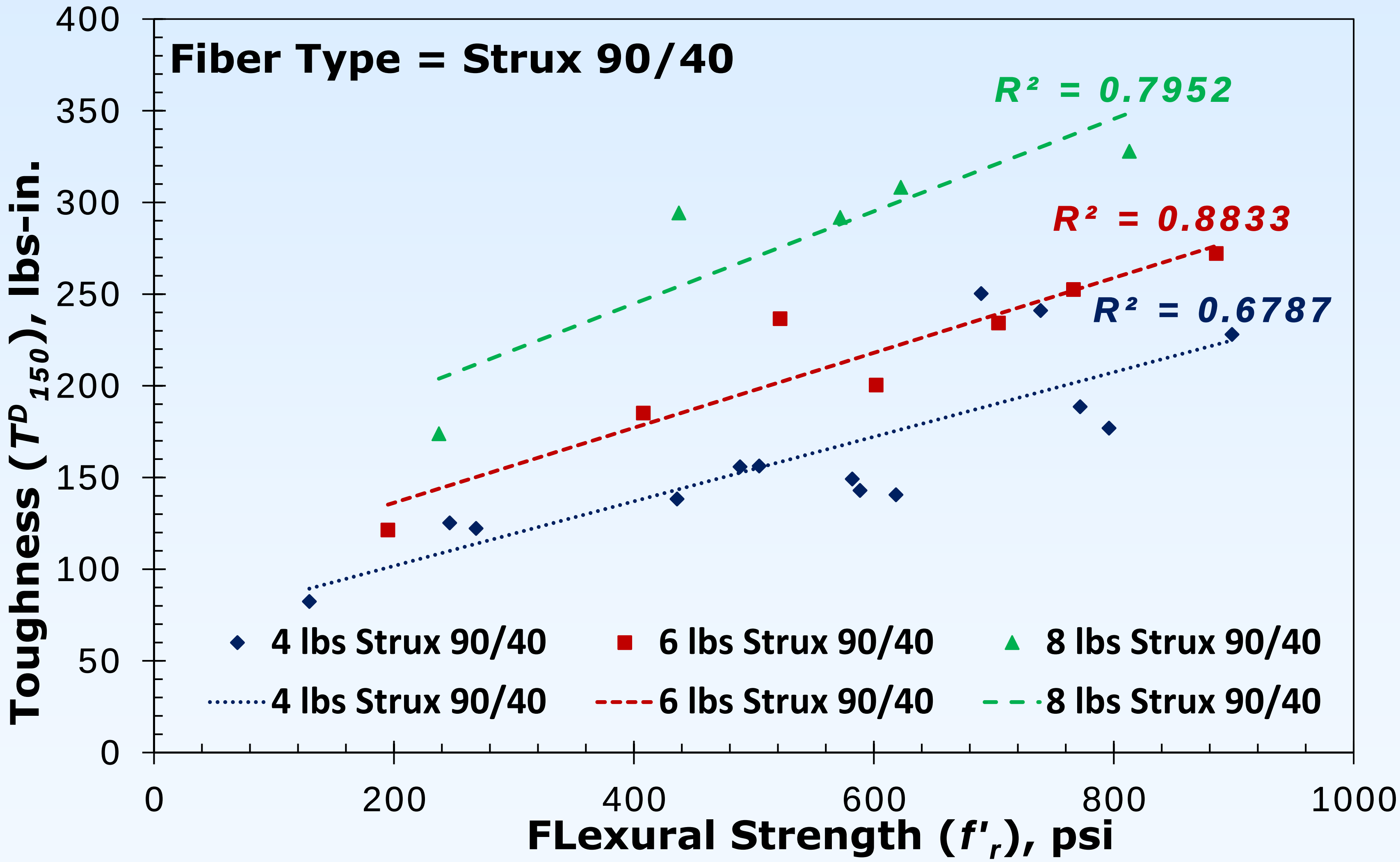
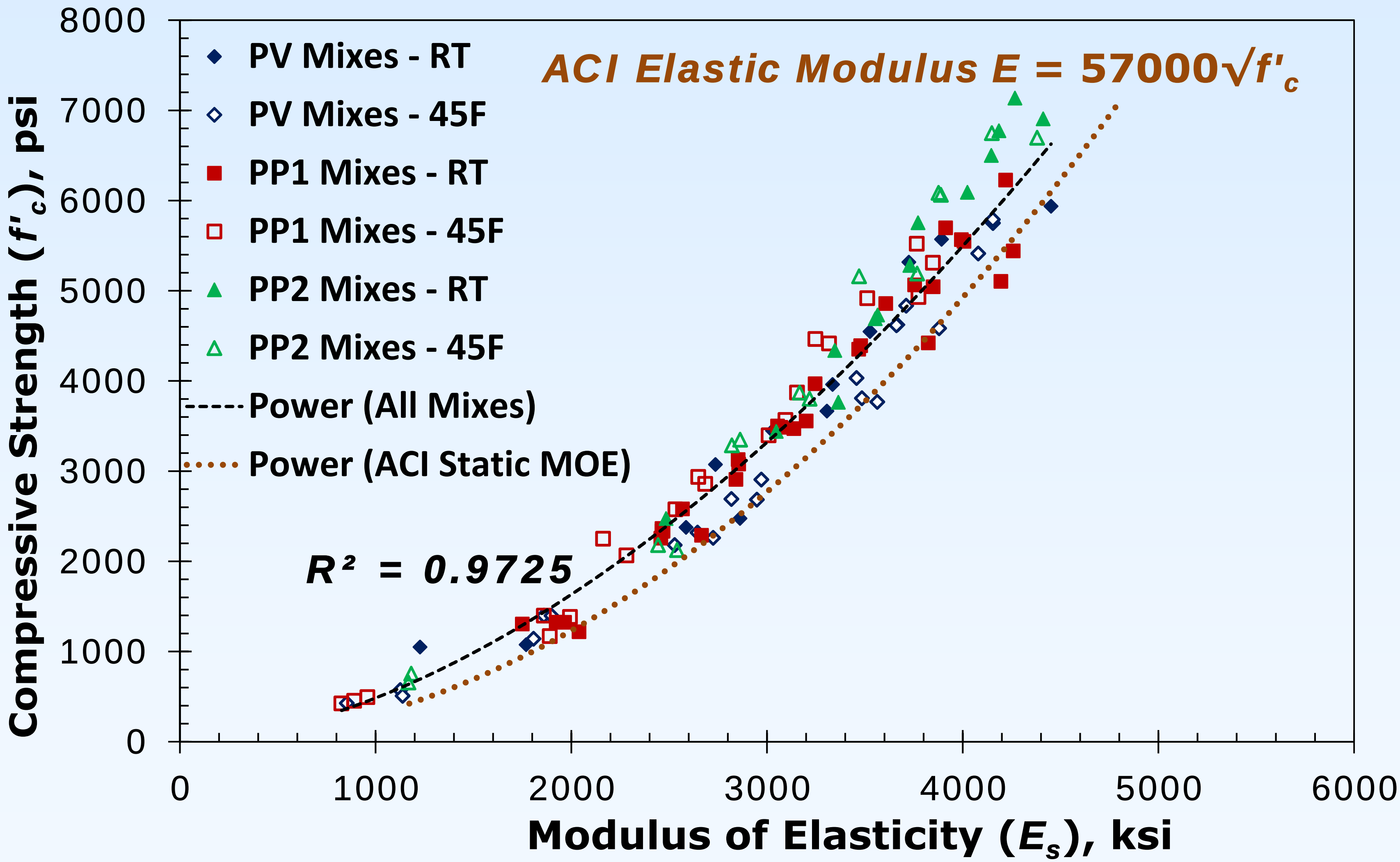


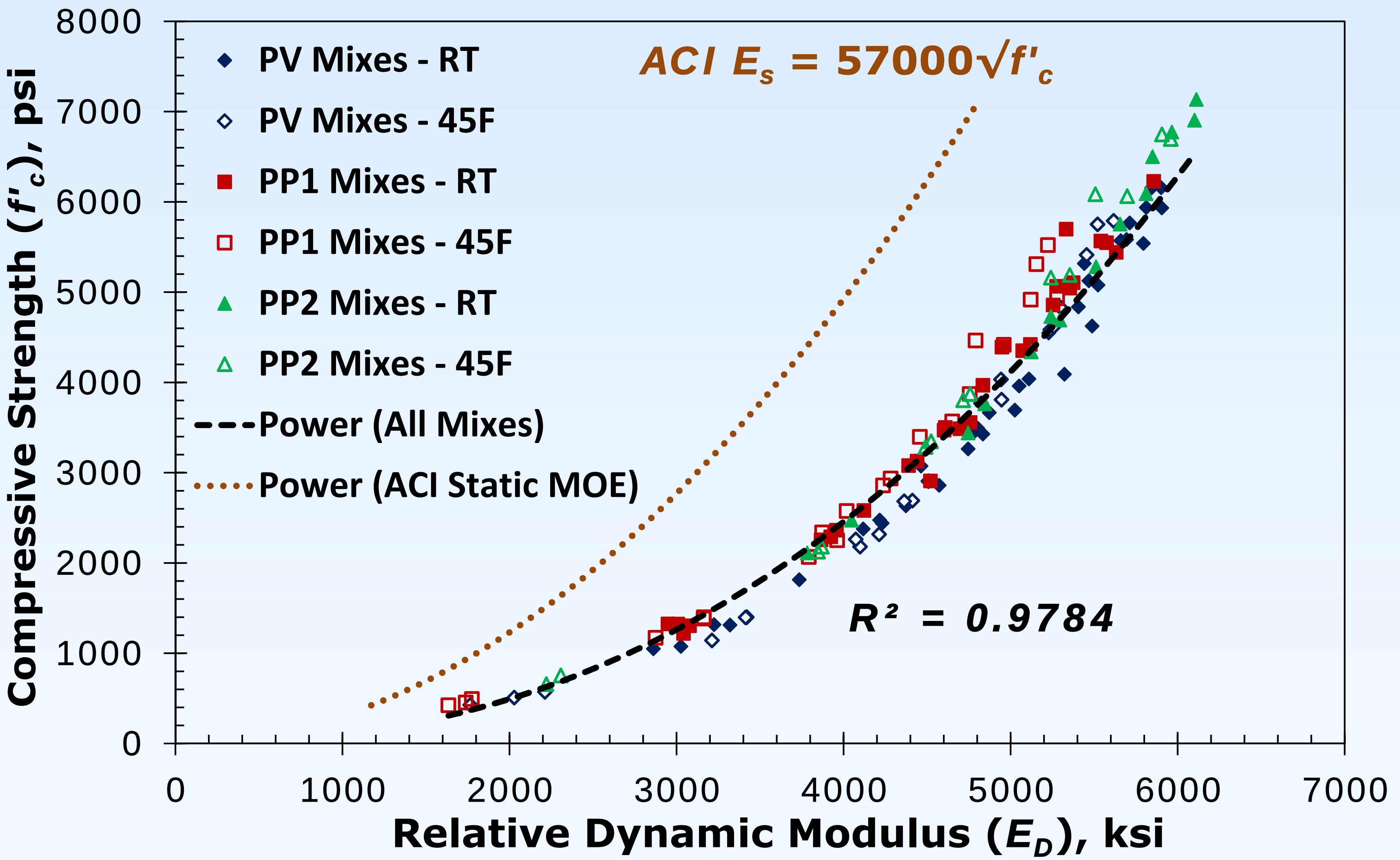
Task 3: Test Results for the PCC Mixes

Compressive Strength vs. Static MOE (E_s)



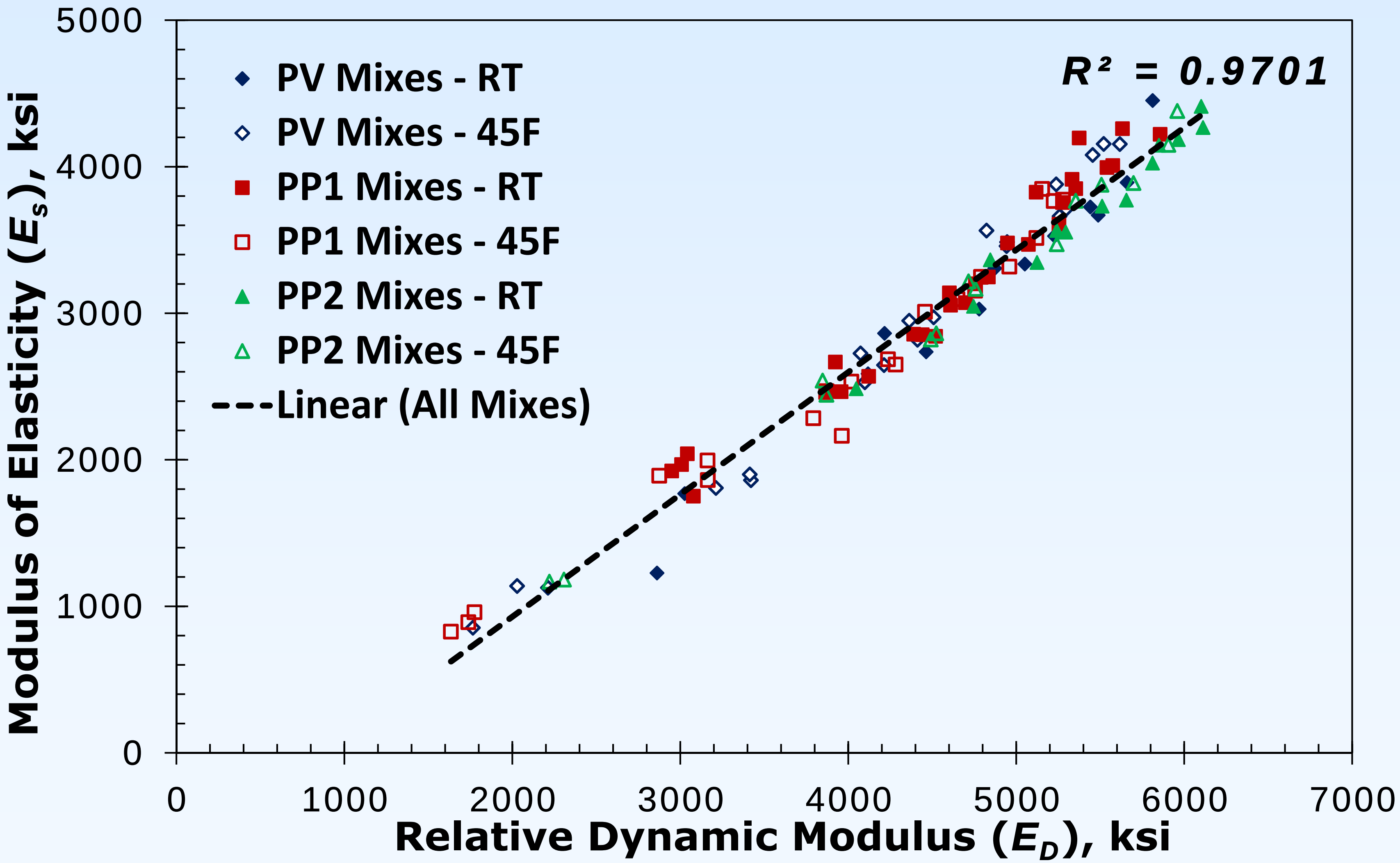
Task 3: Test Results for the PCC Mixes

Compressive Strength vs. Dynamic Modulus (E_D)



Task 3: Test Results for the PCC Mixes

Static Modulus of Elasticity vs. Dynamic Modulus



Task 3: Test Results for the PCC Mixes

Relative Dynamic Modulus (E_D) as a function of Compressive Strength (f'_c): Suggested best fitting Equation

$$E_D = 70,000\sqrt{f'_c} + 500,000\ psi$$

Static Elastic Modulus (E_S) as a function of the Relative Dynamic Modulus (E_D) : Suggested best fitting Equation

$$E_S = 0.79E_D - 500,000\ psi$$

Fatigue Loading

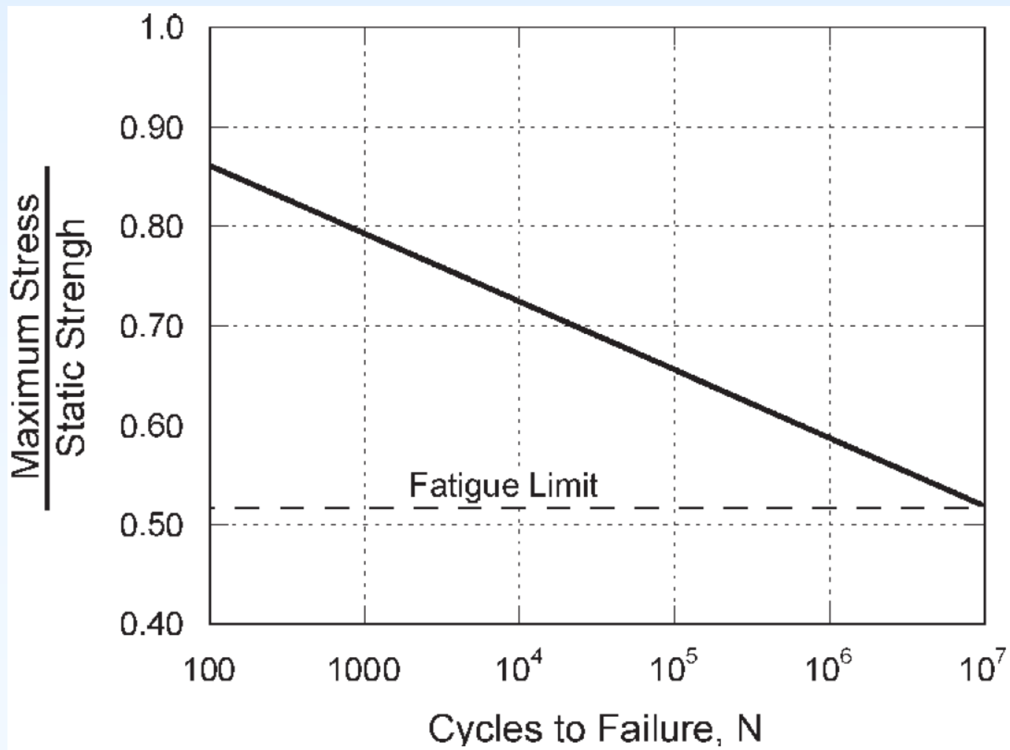
6 x 6 x 21 in. Beam under cyclic fatigue loading

- **Fatigue** is described as a repeated application of a load at a level below the ultimate strength capacity of the concrete
- In PCC pavement, **flexural fatigue** due to repeated loading is one of the major distress mechanisms that leads to **cracking**

Fatigue Load Testing: *S-N Curve*

- Fatigue limit in concrete is defined as the maximum flexural stress to strength ratio at which the failure in concrete occurs after large number of cycles (> 10^7)
- In normal strength concrete, the fatigue limit is defined approximately 55% of the MOR

Typical S-N curve of concrete



Task 3: Lab Test Methods for PCC Pavements

S-N curve for PCC Pavement at EOT

– The proposed loading configuration is characterized by increasing the load applied to the specimen such that the stress level is maintained over time (90%, 80%, 70%, and 60%).

– This enables the loading program to keep a fixed stress level with the increase of the strength.

– The strength gain can be predicted using the MOR-maturity relationship for PV mixes.

Fatigue Load Testing without dowel bars

Batch Mix	Type of Fibers	Amount of Fibers
PV	No Fibers	-
PVF1	Strux® 90/40	4 lbs./yd.^{3}
PVF1-8lbs	Strux® 90/40	8 lbs./yd.^{3}
PVF2	MasterFiber	4 lbs./yd.^{3}

Fatigue Testing Setup

- **PVF1**, **PVF2** and **PVF1-8lbs** were batched to investigate the effect of fiber inclusion on concrete fatigue performance.

Fatigue Load Testing without dowel bars

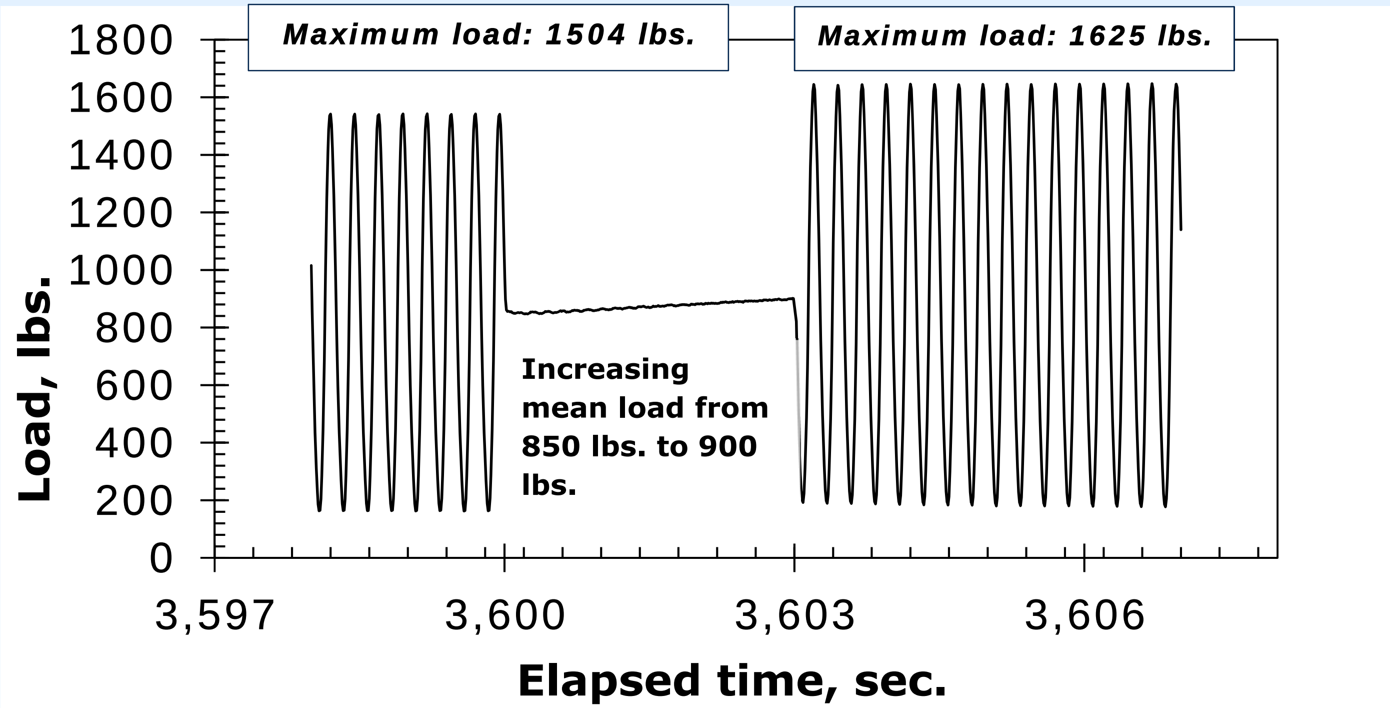
Testing Procedure…

- The stress levels (***S_i***) were set to **0.9, 0.8, 0.7, & 0.6**
- Fatigue tests were performed at a frequency of **4 Hz.**
- **RDM measurements** were taken for each specimen to verify the accuracy of the identified stress level in the beam to be tested for fatigue.
- The number of cycles **(*N_i*)** at failure was recorded.

Task 3: Lab Test Methods for PCC Pavements

Fatigue Load Testing

- The increase in **amplitude** and **mean load** was done at intervals varying from **30 minutes** to **2 hours**.
- The testing machine was programed such that the load is ramped to the new mean and amplitude values at the end of each loading event.

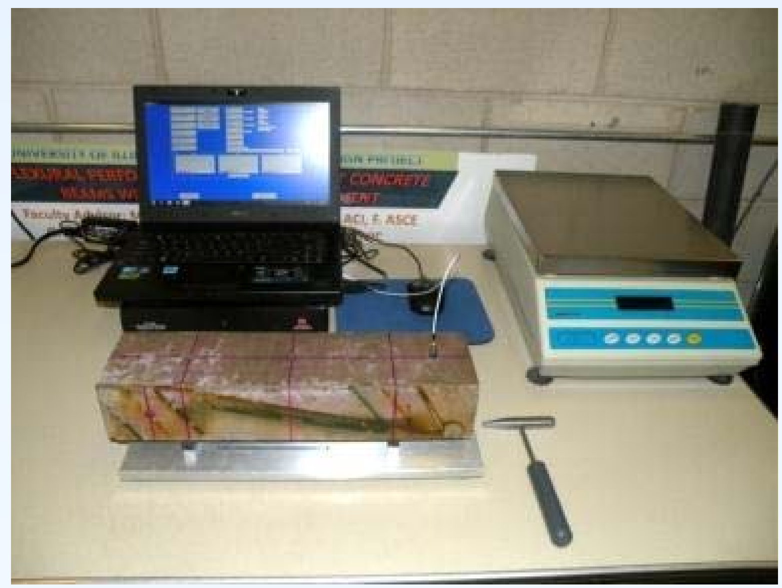


Typical load ramping case taken one hour after test initiation

Task 3: Lab Test Methods for PCC Pavements

Fatigue-Freeze/Thaw Testing

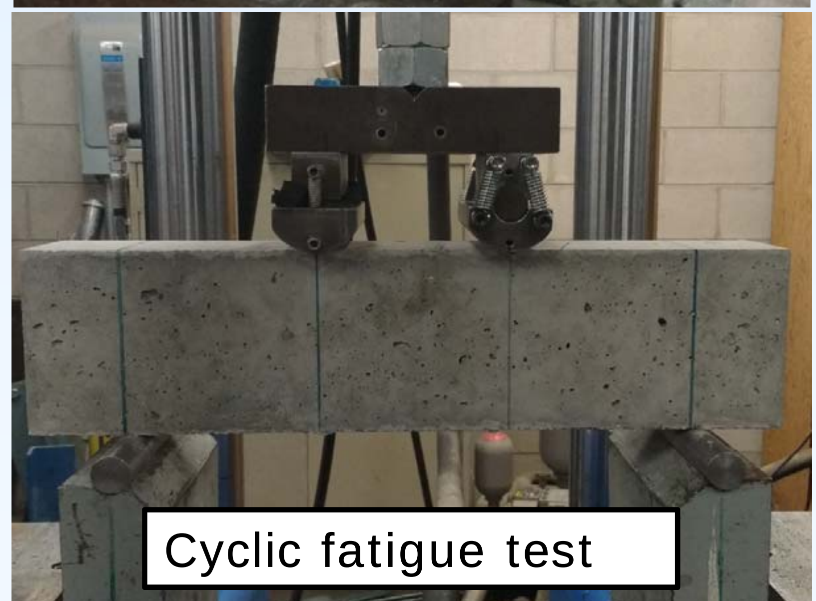
- **Freeze/Thaw** test according to **ASTM C666, Procedure A** was conducted after completing the **fatigue test**
- The purpose is to study the performance of concrete against freeze/thaw that could be aggravated after inducing fatigue stresses at early age
- PCC prisms are **fatigued for limited cycles** before testing them for freeze/thaw
- The damage assessment is quantified by conducting **ASTM C215** to measure the **RDM up to 300 cycles** of **freezing and thawing**.



Testing Procedure for Fatigue-Freeze/Thaw

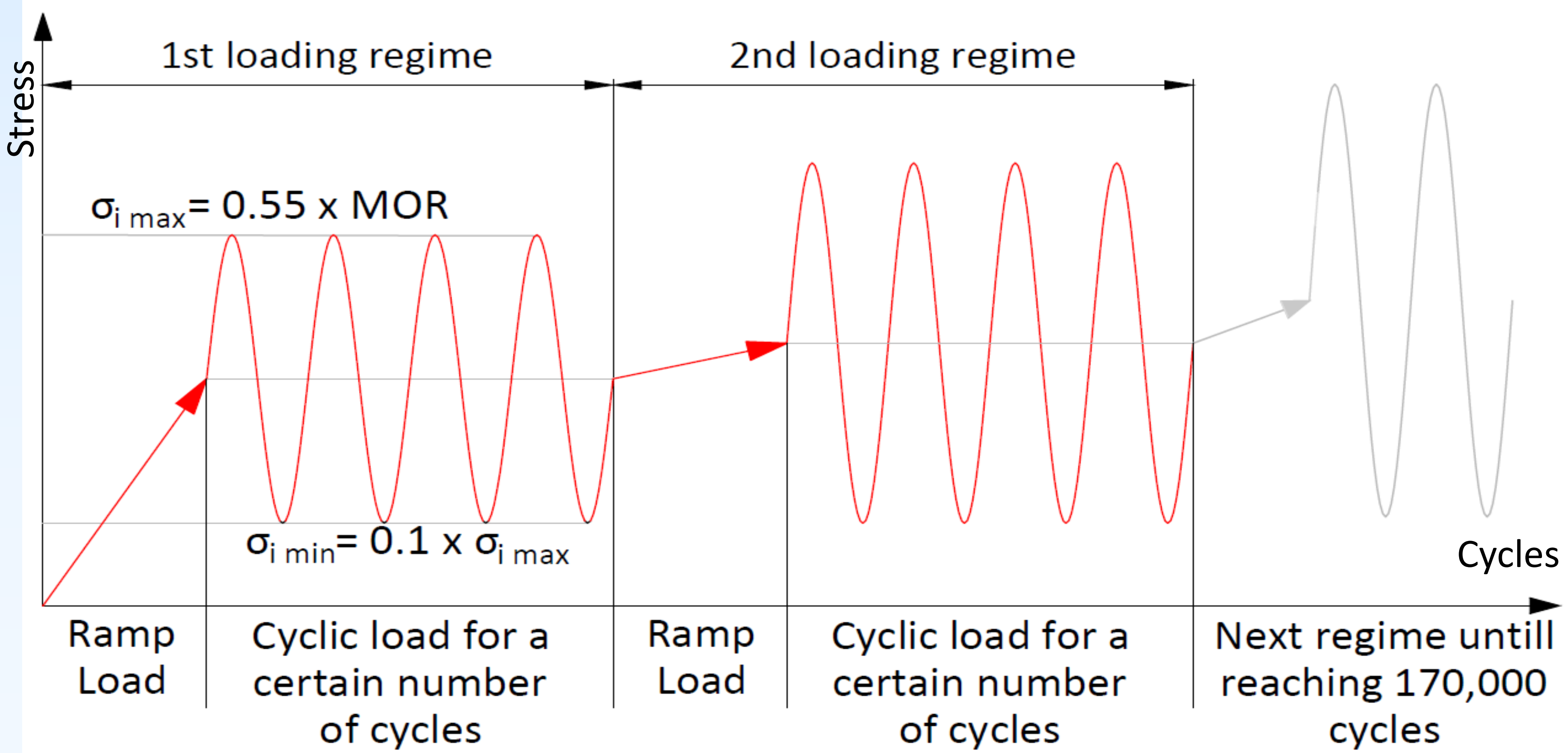
- Prior to each fatigue loading, two beams were tested for static flexural strength in order to determine the **MOR**
- The average of the MOR readings was used to determine the mean and amplitude of the cyclic loading for a **0.55 Stress level** applied for **170,000 cycles**


Static test

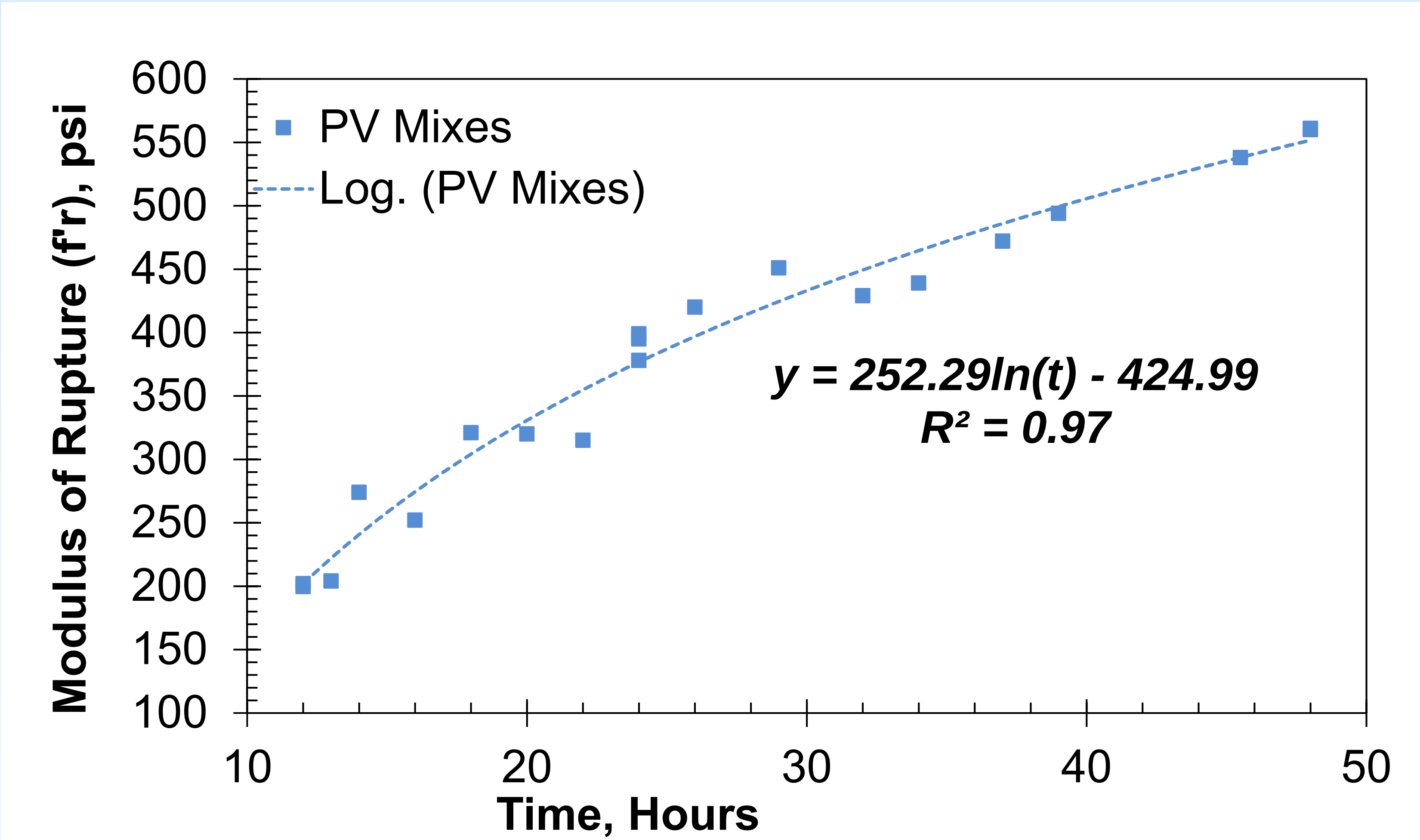

Cyclic fatigue test

Loading Pattern for Fatigue-Freeze/Thaw

The maximum stress applied is the average MOR obtained multiplied by the stress level (i.e. σ_{i_max} **= 0.55 x MOR**). Whereas the minimum load applied is 1/10 of the maximum load (σ_{i_min} **= 0.1 x** σ_{i_max}).



Task 3: Lab Test Methods for PCC Pavements



$$f'_r(t)/f'_{r\;12\;hrs.} = (252.29\,ln(t) + 424.99\ )/203$$

For $12\ \text{hrs.} \leq\ t\ \leq 48\ \text{hrs.}$

Testing Procedure for Freeze/Thaw

- RDM readings were also collected for each specimen to verify the reliability of the average MOR used to determine the fatigue load characteristics
- Fatigued beams were cured for 14 days in the moisture room under a controlled temperature of 73 ^{o}F and 100% relative humidity
- Control samples that are not subjected to fatigue were only tested for freeze/thaw

Freeze-Thaw Testing Results

Concrete durability performance for **PV**, **PV-F1**, **PVF1-8lbs.** mixes against freeze/thaw is evaluated through:

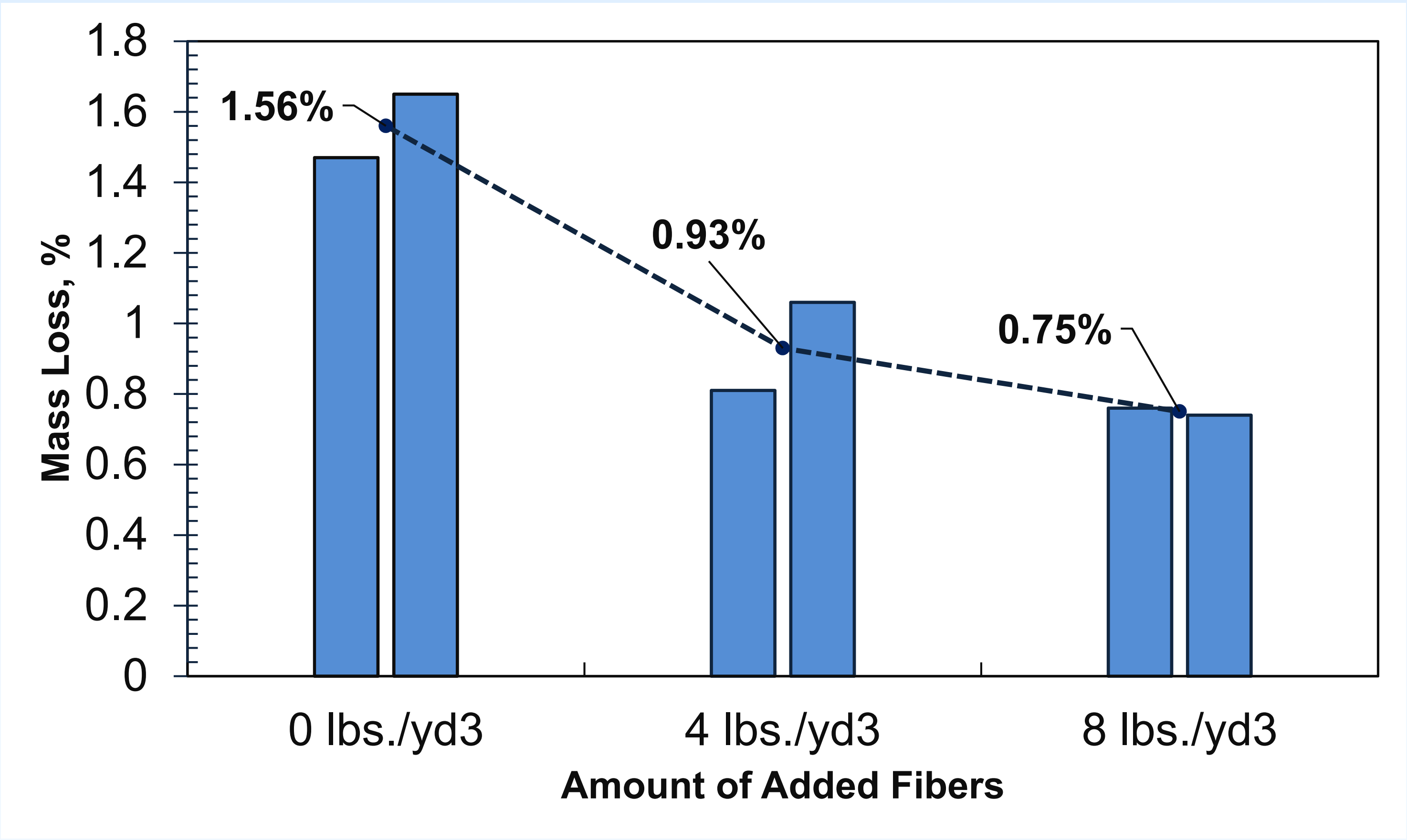
1- The degree of surface scaling which is measured by **mass loss** after freezing and thawing.

2- Interior crack growth which can be tracked using the **decrease in the relative dynamic modulus.**

Task 3: Lab Test Methods for PCC Pavements

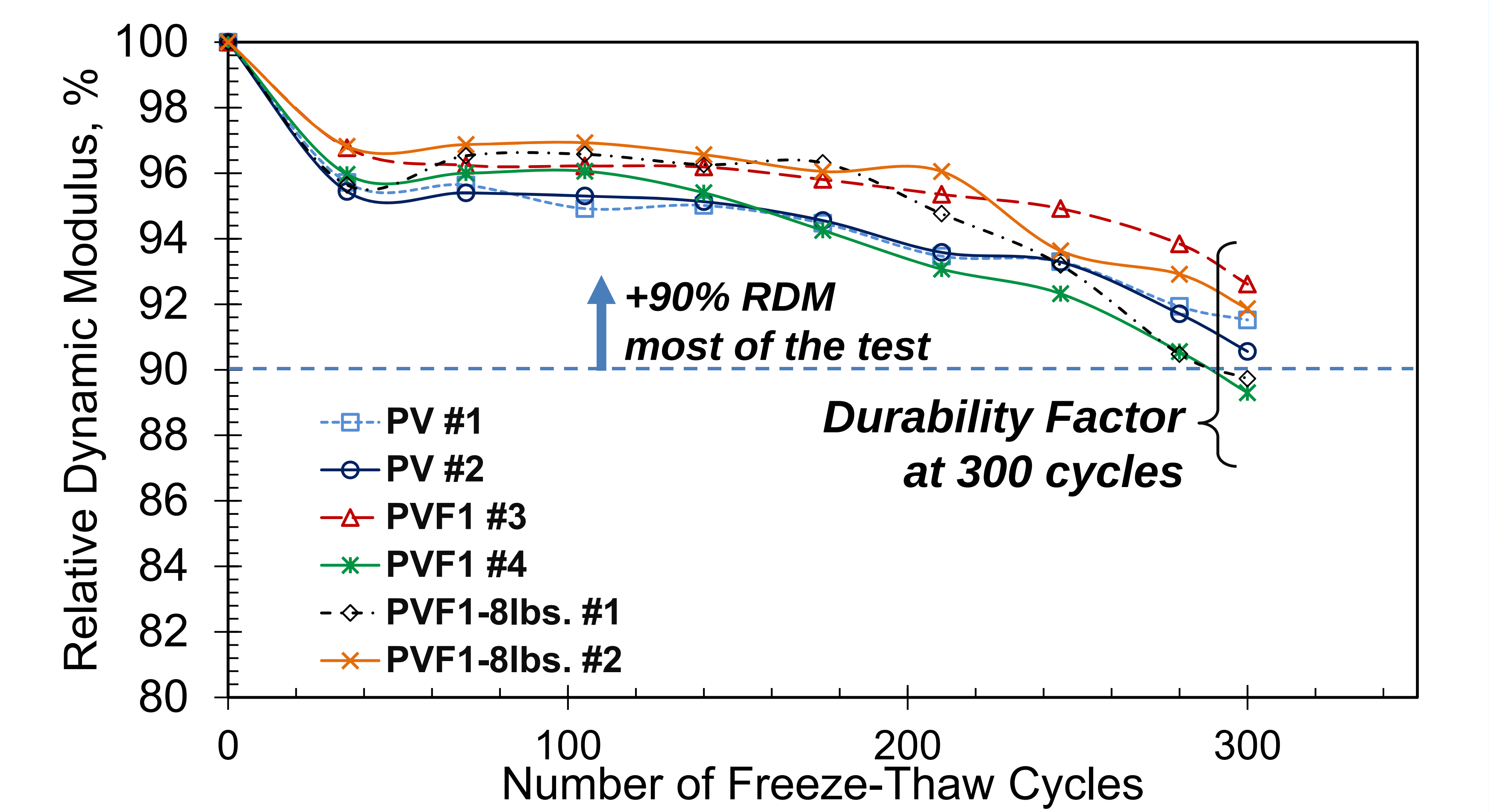
Resistance to surface scaling after 300 freeze-thaw cycles

- Adding 4 lbs./ yd^3 of fibers has reduced scaling by 40%
- Adding 8 lbs./ yd^3 of fibers has reduced scaling by 52 %



Task 3: Lab Test Methods for PCC Pavements

Relative dynamic modulus development



Durability factor values after 300 freeze-thaw cycles

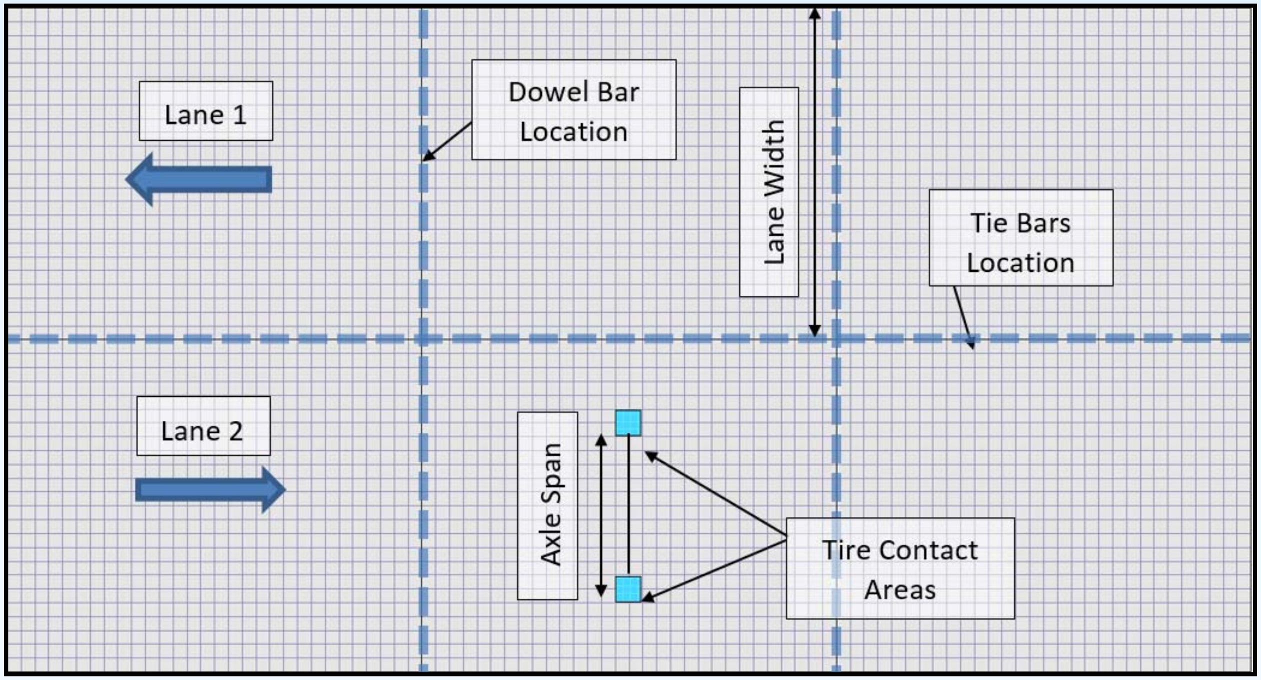
Mix No.	Fresh Air Content, %	Freeze Thaw Performance	
		Average *DF*	No. of Specimens
PV #1	7.2	91.5	6
PV #2	6.9	90.6	5
PVF1 #3	7	92.6	6
PVF1 #4	6.9	89.3	6
PVF1-8lbs. #1	7	89.7	5
PVF1-8lbs. #2	7	91.9	6
Total Number of Specimens			34
Number of Specimens with DF> 90%			25
Number of Specimens with DF> 85%			31

Analytical Study: Software Description

- **ISLAB2000** FEA software designed specifically to analyze rigid and jointed pavements in a practical method.

1. Develop a model for **rigidly connected PCC pavement** in order to evaluate the **fatigue performance** of plain and fiber reinforced concrete.
2. Develop a model for **jointed PCC pavement** in order to identify **critical stress and deflection locations** for later use in real specimens.

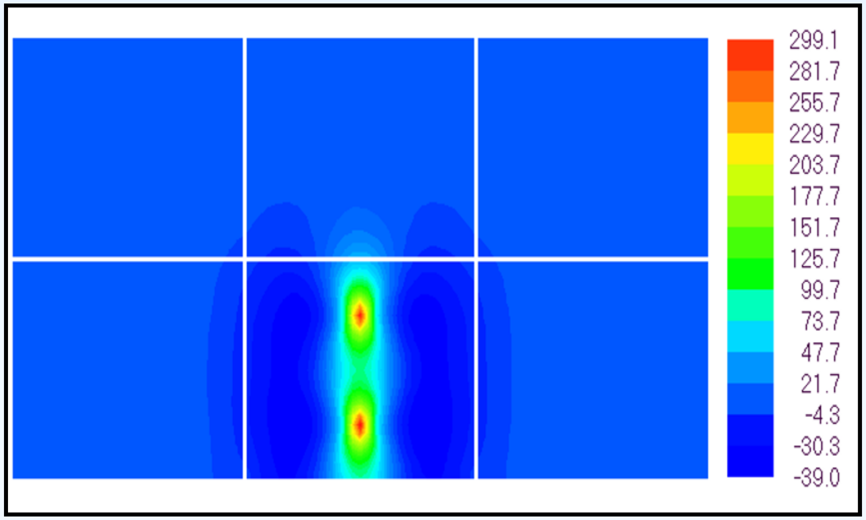
ISLAB 2000
finite element analysis for rigid pavements

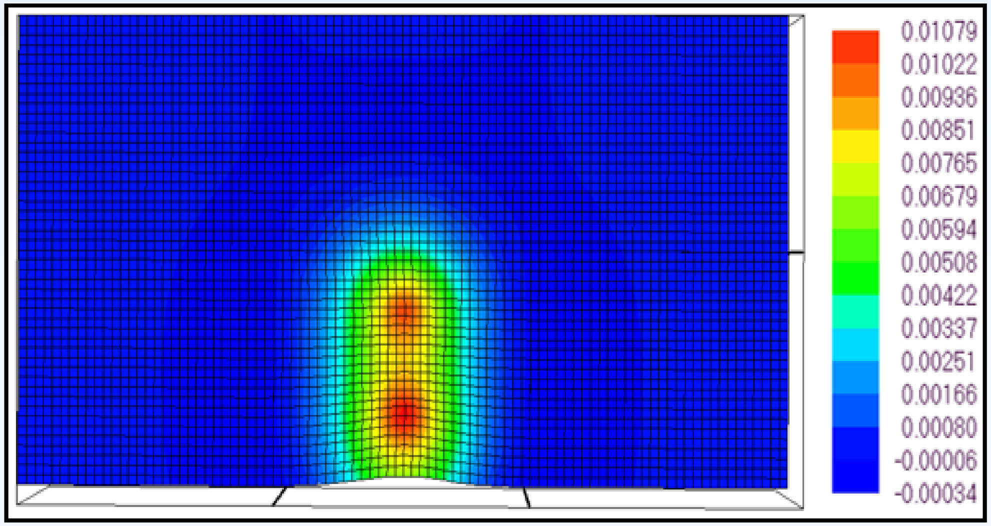


Software Output

The output for stresses and deflections can be obtained at every node from the applied mesh along the x-y grid.

- **Transverse flexural stresses** or **σ_x** (Psi)
- **Longitudinal flexural stresses** or **σ_y** (Psi)
- **Deflections** (in.)

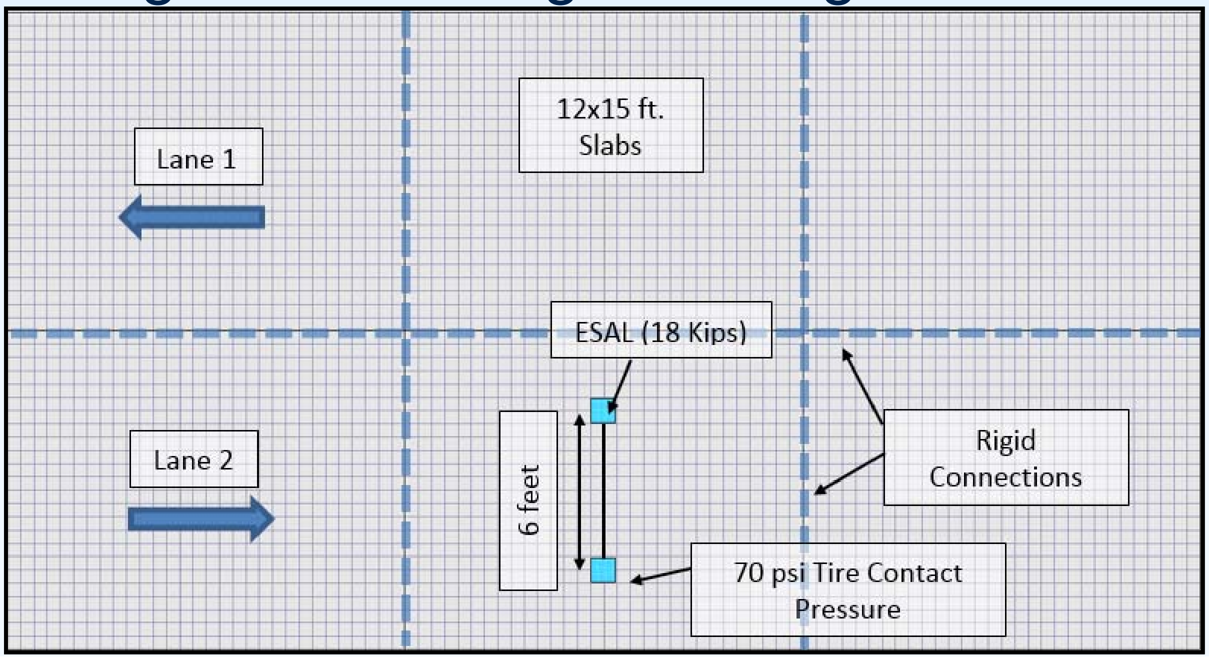




Parametric Study #1 for Rigid Pavements

Objectives :

- Evaluate the **flexural stresses** and **deflections** for varying **slab thicknesses**, **static modulus of elasticity**, and **modulus of subgrade reaction values**.
- Study the cost-effectiveness of using plain concrete for pavements using obtained fatigue testing data.



Input for parametric study #1

The constant input values between each input case

Model parameters	Slab dimensions	12 x 15 ft.
	Number of lanes	2
	Number of slabs per lane	3
	Subgrade Model type	Winkler model
	Mesh size	2 x 2 in^2
Concrete parameters	Unit weight	144 lbs./ft^3
	Poisson's ratio	0.15
Vehicle Load parameters	Axle type	Single Axle/Single Tire
	Aspect ratio of contact area	1
	Axle Span (c-c of contact area)	6 ft.
	Axle position (from bottom left)	264 in, 30 in
	Axle load	18,000 lbs.
	Contact area of tires	257.1 in^2
	Tire Pressure	70 psi

Input for parametric study #1

The **main parameters** of interest that are relevant to the subject of EOT are the following:

- Modulus of elasticity (MOE)
- Modulus of subgrade reaction (K)
- Pavement thickness

A **single axle with single tires** was considered for the applied load for all models.

- 18,000 pounds of applied load (ESAL)
- Two square contact areas equivalent to four circles of 4.51 in radius each
- Tire pressure of 70 psi
- Axle width of 6 feet as for typical truck loading

Effect of static modulus of elasticity

- MOE values represent **12-hour**, **1-day**, **3-day**, and **7-day** concrete age in accordance with the fatigue testing program.
- Estimating the MOE for every case was achieved by using the an **empirical equation** obtained from testing results that correlates static modulus of elasticity values with **average compressive strength** readings.

$$E_S = \frac{1}{0.0027}\,(f_c{}')^{-0.571}$$

E_S = Static modulus of elasticity, Psi.

f'_c = Compressive strength, Psi.

Age	12 Hours	1 Day	3 Days	7 Days
f'_c (psi)	1312.3	2440	3692.5	4836
MOE (psi)	1.767E+06	2.518E+06	3.190E+06	3.722E+06

Task 4: Analytical Study and FEM

Output Results: Fatigue Performance for selected cases

- The maximum longitudinal flexural tensile stresses σ_y was evaluated by the software given the *MOE, K* and slab thickness.
- The stress level *S* is set by dividing σ_y (***numerical***) by *MOR (**experimental**):*

$$S = \frac{\sigma_y}{MOR}$$

- *S-N* linear regression formulas corresponding to the concrete age and type were used and the number of cycles until failure for both plain concrete (PV mixes) and fiber-reinforced concrete, FRC, (PVF1-8lbs mixes) was calculated.

Task 4: Analytical Study and FEM

Output Results: Fatigue Performance for selected cases

- Experimental Flexural strength for concrete PV mixes at all ages

Age	12-Hrs	1-Day	3-Day	7-Day
MOR (psi)	161	306	512	782

- Stress level calculation results from **fatigue testing program for plain concrete and fiber reinforced concrete (FRC)**

Age	Mix type	S-N linear regression relationships
12-Hrs.	Plain	S = -0.030 ln(N) + 1.0090
	FRC	S = -0.028 ln(N) + 1.0257
1-Day	Plain	S = -0.028 ln(N) + 1.0098
	FRC	S = -0.025 ln(N) + 1.0066
3-Day	Plain	S = -0.044 ln(N) + 1.1072
	FRC	S = -0.036 ln(N) + 1.0822
7-Day	Plain	S = -0.041ln(N) + 1.1022
	FRC	S = -0.043 ln(N) + 1.1616

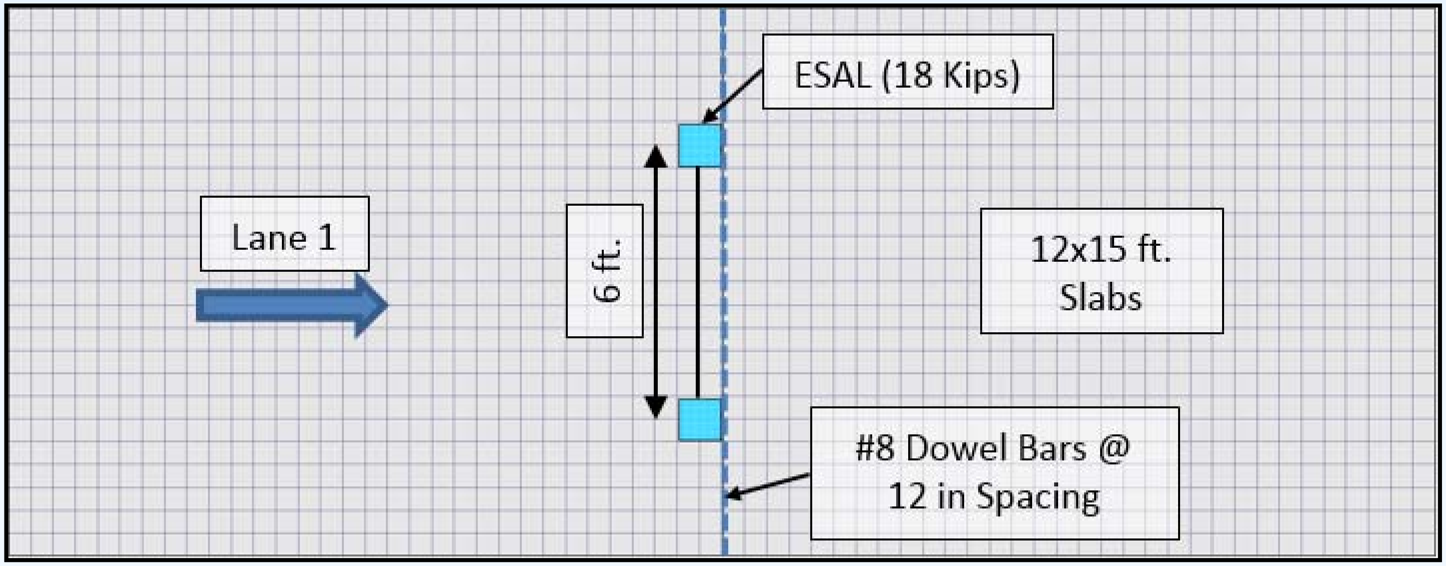
Output Results: Fatigue Performance for 6 in. Slab Thickness

Concrete Age	K (psi/in)	σy (psi)	MOR (psi)	S	N (Plain)	Fatigue Life (Hrs.)	N (FRC)	Fatigue Life (Hrs.)
12 Hrs.	100	296.7	161	***1.84***	-	-	-	-
	300	251.4	161	***1.56***	-	-	-	-
1 Day	100	313.6	306	***1.02***	-	-	-	-
	300	265.1	306	***0.87***	168	0	273	0
3 Day	100	325.8	512	***0.64***	44428	1	239266	17
	300	274.6	512	***0.54***	431214	5	4 10E6	278

Parametric Study #2 for Jointed Pavements

Objectives :

- Evaluate the **flexural stresses** and **deflections** for two jointed slabs.
- Joint parameters including **load transfer efficiency** and **aggregate interlock** provide several loading cases of jointed-plain concrete pavements (JPCP).
- The provided data serves in **determining the structural behavior** of concrete slab specimens that are considered for experimental testing in the next phase of the study.



Input for parametric study #2

Model parameters	Slab dimensions	12 x 15 ft.
	Number of lanes	1
	Number of slabs per lane	2
	Subgrade Model type	Winkler model
	Mesh size	2 x 2 in^2
Concrete parameters	Unit weight	144 $lbs./ft^3$
	Poisson's ratio	0.15
Vehicle Load parameters	Axle type	Single Axle/Single Tire
	Aspect ratio of contact area	1
	Axle Span (c-c of contact area)	6 ft.
	Axle position (from bottom left)	188 in, 30 in.
	Axle load	18,000 lbs.
	Contact area of tires	257.1 in^2
	Tire Pressure	70 psi
Joint parameters	Dowel bar diameter	1 in.
	Dowel Bar length	18 in.
	Dowel bar spacing	12 in.

Effect of Load Transfer Efficiency

- Transverse joint performance is assessed by determining the load transfer efficiency (LTE). LTE represents the ratio of the deflection of a loaded slab over the deflection of an unloaded slab.
- LTE values do not exceed 95%.
- LTE values were investigated for **50%**, **60%**, **70%**, **80%**, **90%**, **91%**, **92%**, **93%**, **94%**, and **95%**.

$$LTE(\%) = \frac{\Delta_a}{\Delta_l} \times 100$$

Where Δ_a= approach slab deflection

Δ_l= leave slab deflection

Task 4: Analytical Study and FEM

Effect of Load Transfer Efficiency

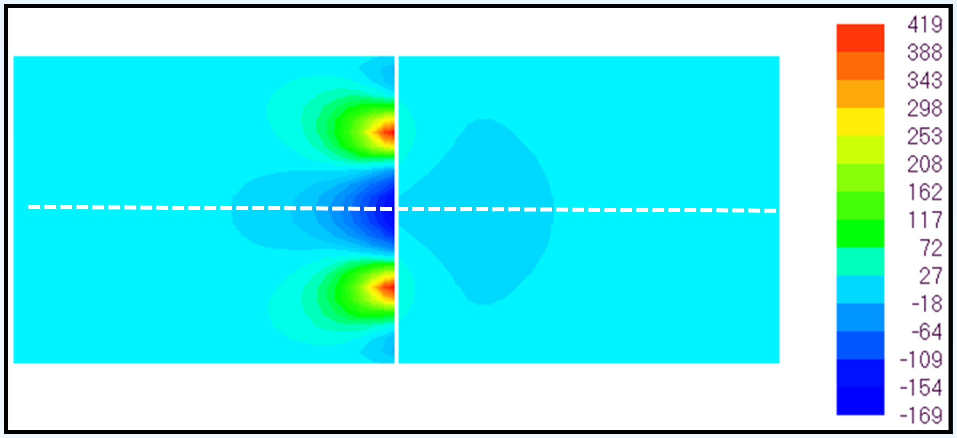
Transverse stresses, longitudinal stresses and deflection results for *LTE*-based cases for K=100 psi/in and t_s=6 in.

LTE (%)	Trans. Stress (psi)	Long. Stress (psi)	Deflection (in)
50	419	112.6	0.0382
60	408	116.8	0.03603
70	393	120.8	0.03429
80	370	124.9	0.03281
90	333	130.2	0.03146
91	328	130.9	0.03133
92	323	131.6	0.03119
93	317	132.4	0.03106
94	310	133.2	0.03093
95	302	134.2	0.03079

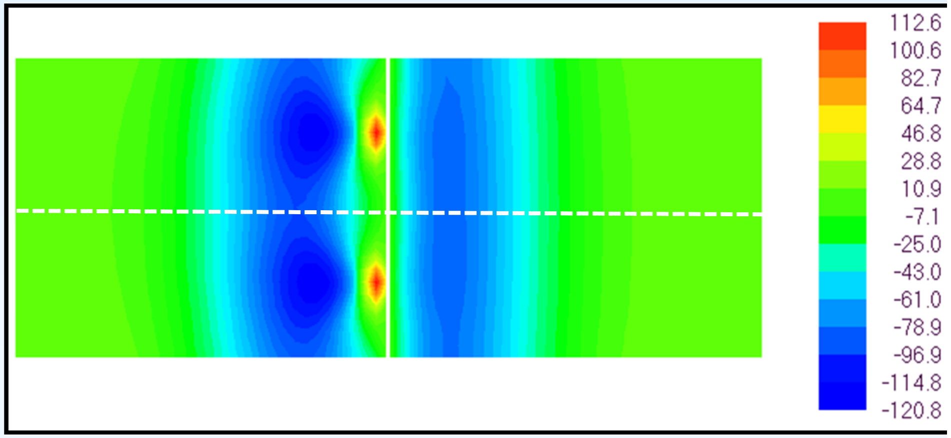
Effect of Load Transfer Efficiency

- For a critical loading case at the face of a contraction joint, tensile stresses in the transverse direction appear to be greater than longitudinal stresses
- Tensile stresses distribution is **symmetric** and **limited to the tire contact areas**

Typical output: Tensile Stresses for LTE of 50%.



Transverse stresses (psi.)



Longitudinal stresses (psi.)

Cyclic fatigue loading of JPCP testing schedule

EXPERIMENTAL TESTING
OF
SLAB PAVEMENTS

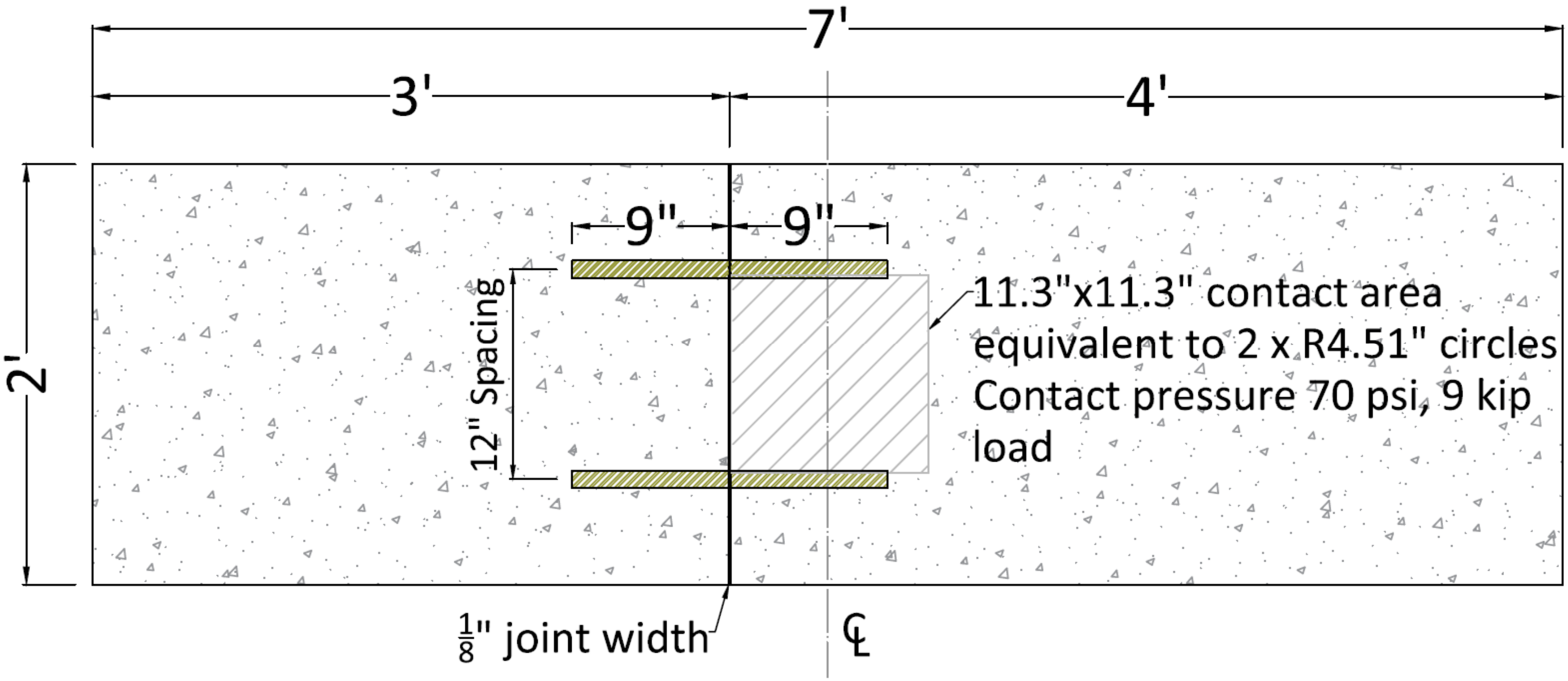
Cyclic fatigue loading of JPCP testing schedule

Specimen characteristics

Specimen #	Pavement Thickness	Joint Type	Dowel Dia.	Fiber Content (lb/yd^3)	Testing Time
1	6 in.	Doweled	1 in	8	1-Day
2	6 in.	Doweled	1 in	-	1-Day
3	6 in.	Non-doweled	-	8	1-Day
4	6 in.	Doweled	1	4	1-Day
5	8 in.	Doweled	1.25 in	8	12-hr

Testing Setup: Concrete Slabs

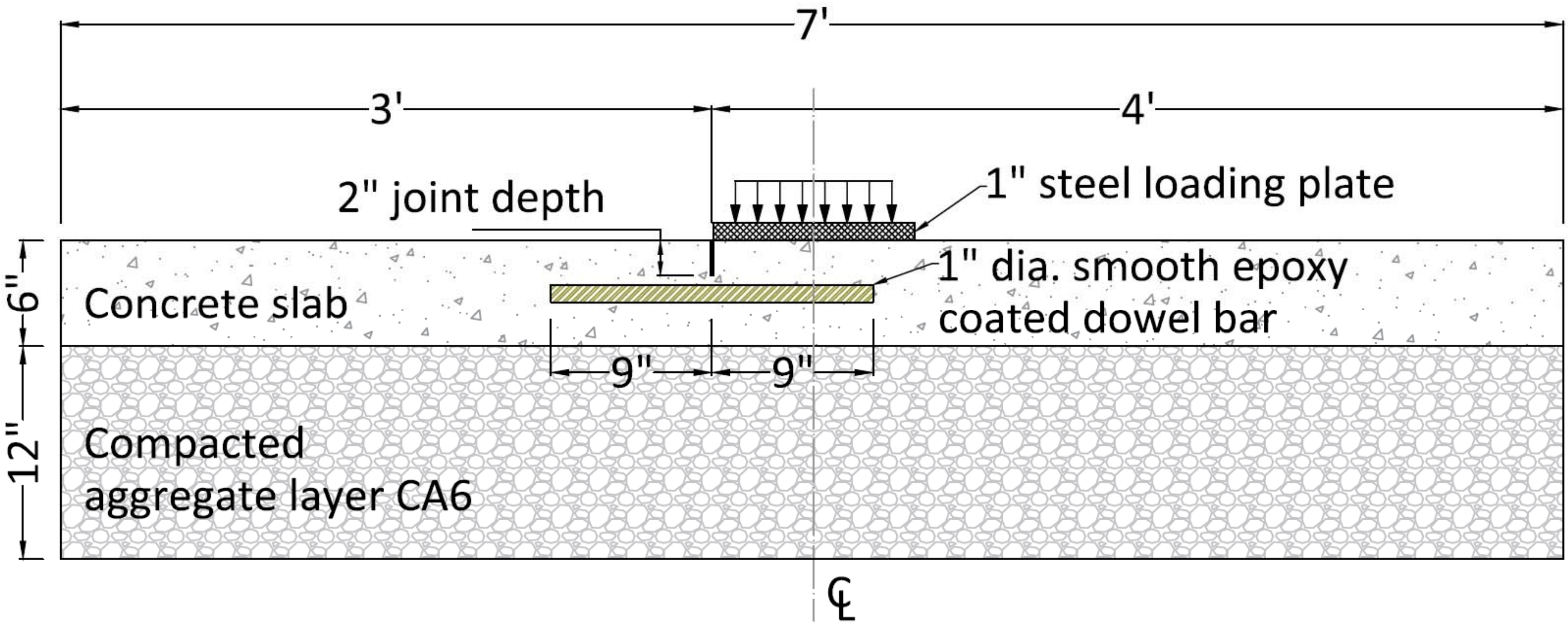
Typical plan view of slab specimen



- Slab Dimensions: 2 ft x 7ft x 6 in or 2 ft x 7ft x 8 in
- Mix Design: PVF1 mixes with 0 to 8 lbs./ yd^3 of STRUX 90/40

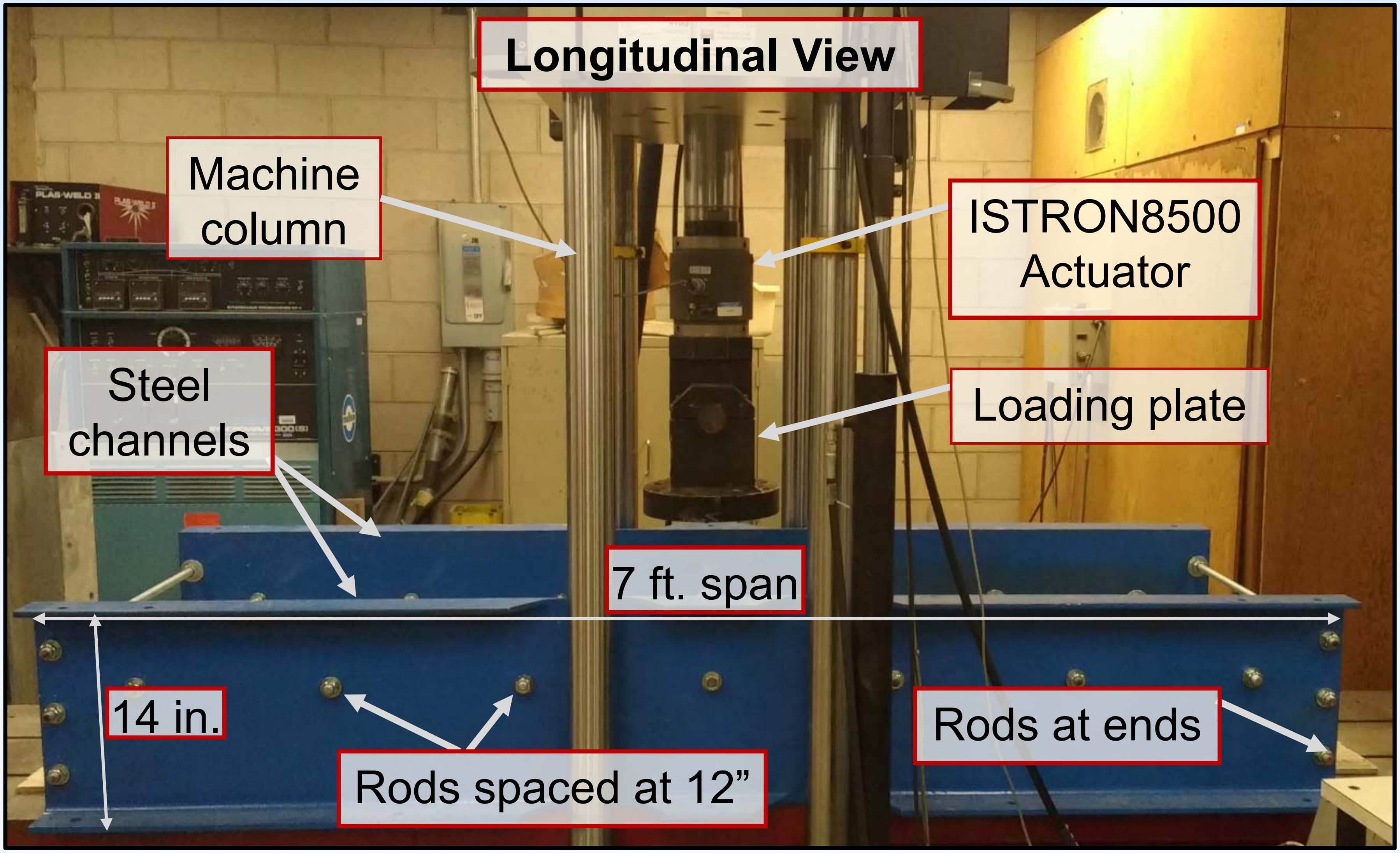
Testing Setup: Concrete Slabs

Typical elevation view of slab specimen

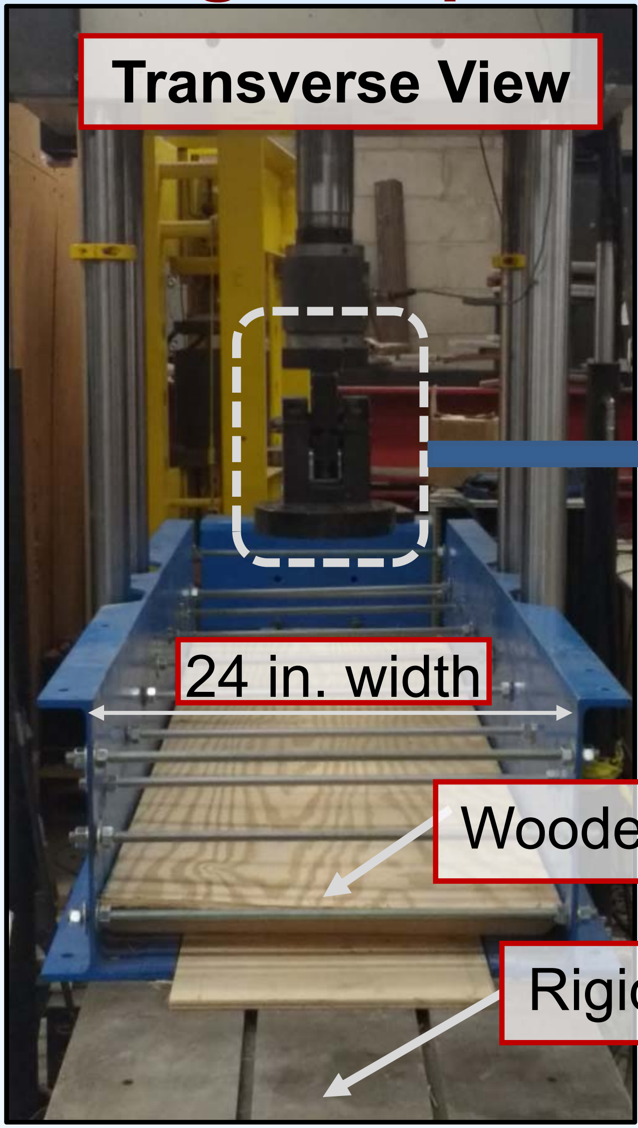


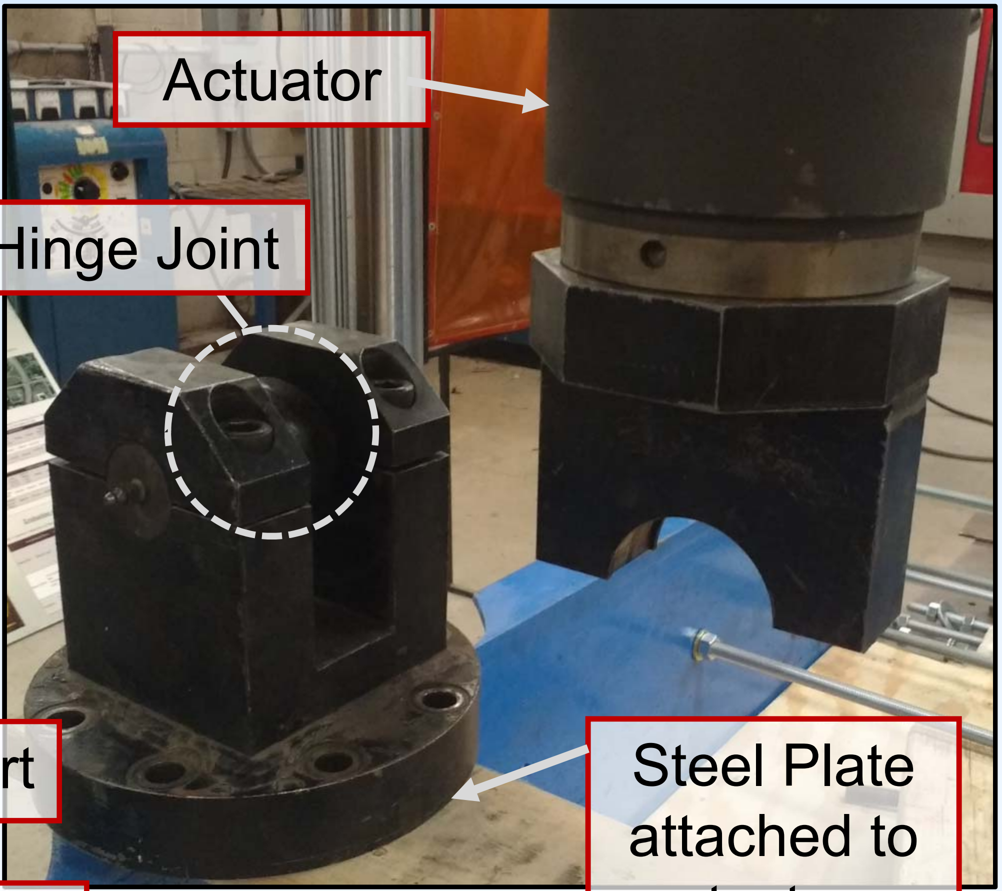
- 1” or 1.25” dia. dowel bars: diameter, round, epoxy coated, and grade 70 steel
- Backfill: 12 inches of compacted CA6 material

Testing Setup: Steel Enclosure and Actuator



Testing Setup: Steel Enclosure and actuator





Testing Setup: Instrumentation and joint efficiency

- Joint efficiency is calculated by measuring the differential deflection between the loaded and unloaded slab
- 4 LVDTs are installed at the corners of the saw-cut joint in order to evaluate the **load transfer efficiency** (LTE) and **joint effectiveness** (E):

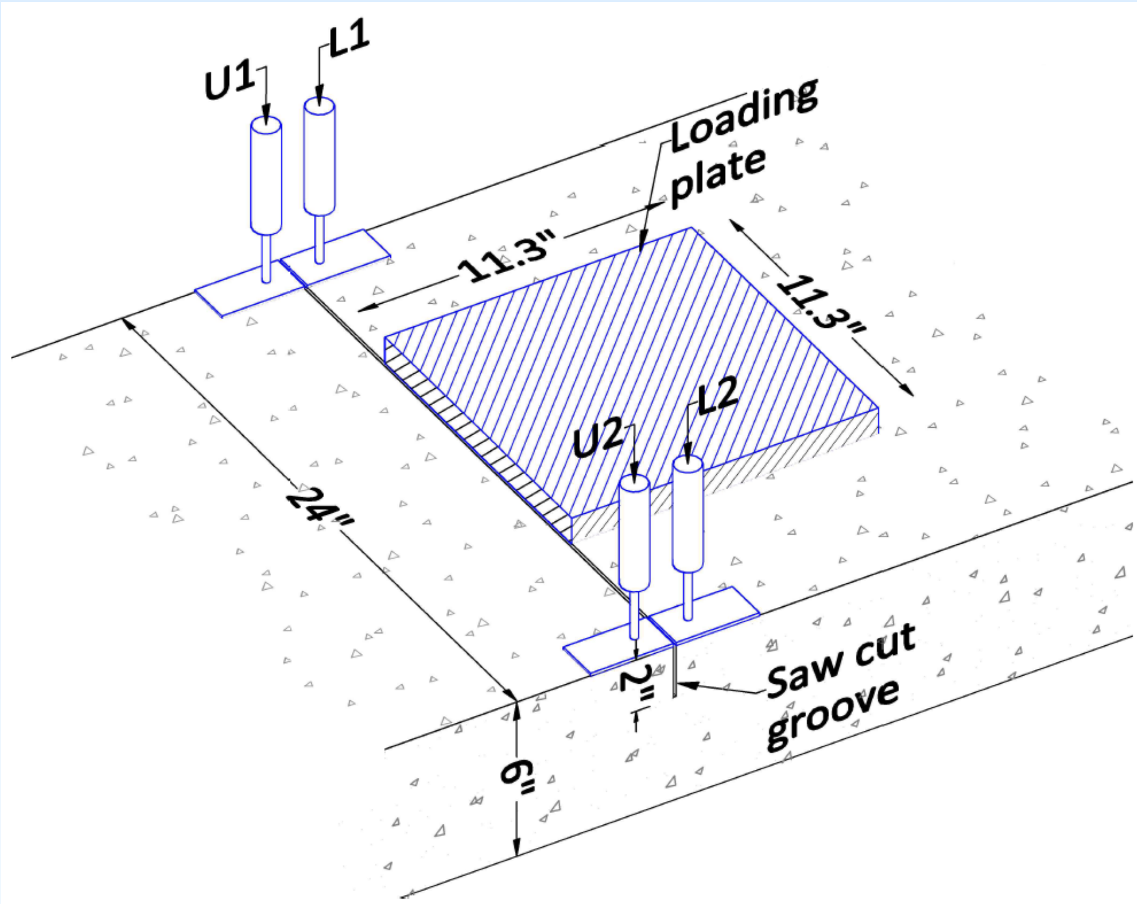
$$LTE = \frac{\delta_u}{\delta_l} \times 100$$

$$E = \frac{2.\delta_u}{(\delta_{l+}\delta_u)} \times 100$$

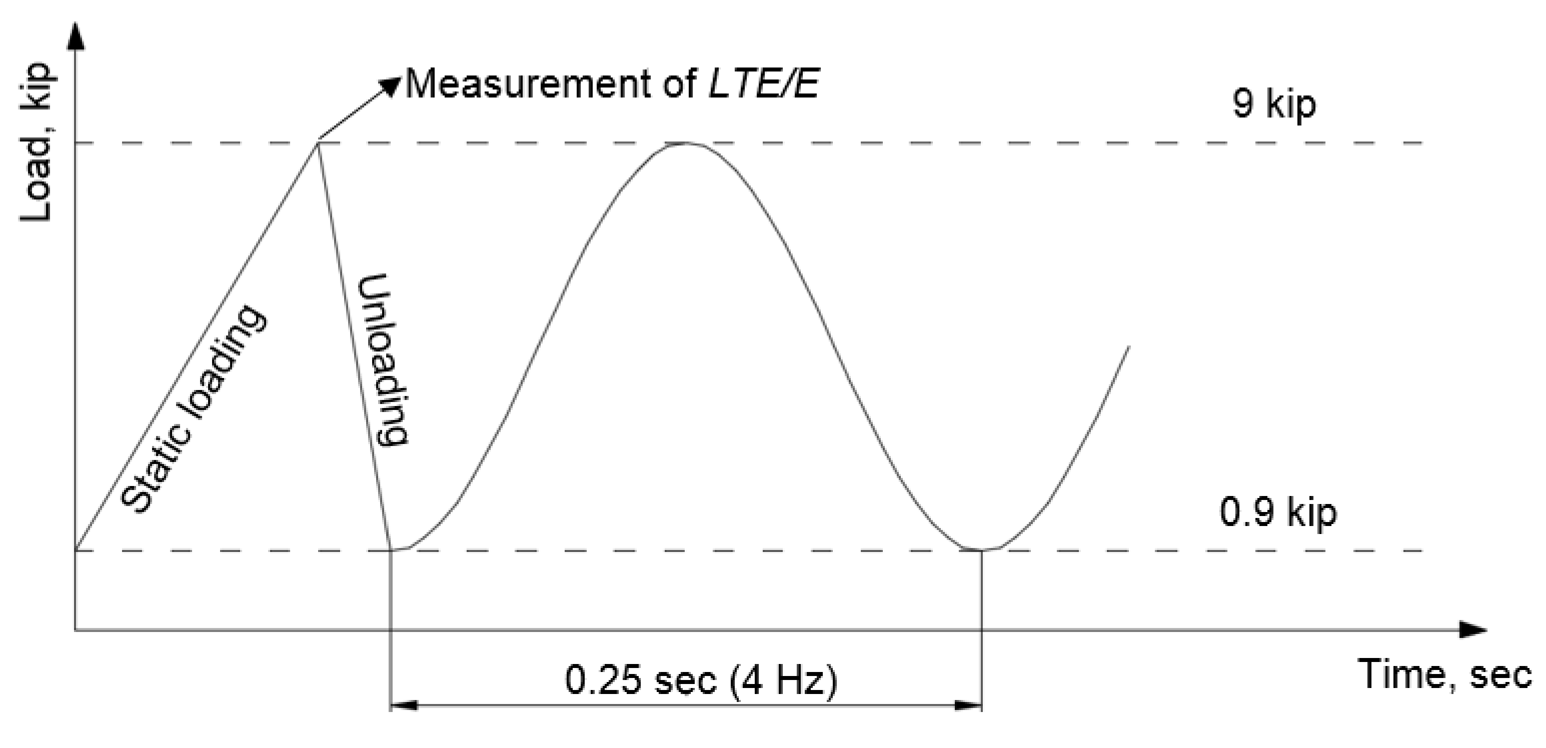
Testing Setup: Instrumentation and joint efficiency

- $\delta_u = \frac{1}{2}(\delta_{U1} + \delta_{U2})$ Average deflection of unloaded slab, in.
- $\delta_L = \frac{1}{2}(\delta_{L1} + \delta_{L2})$ Average deflection of loaded slab, in.
- L1, L2= LVDT position on the loaded slab, in.
- U1, U2= LVDT position on the unloaded slab, in.

LVDT Placement



Testing Setup: Loading pattern

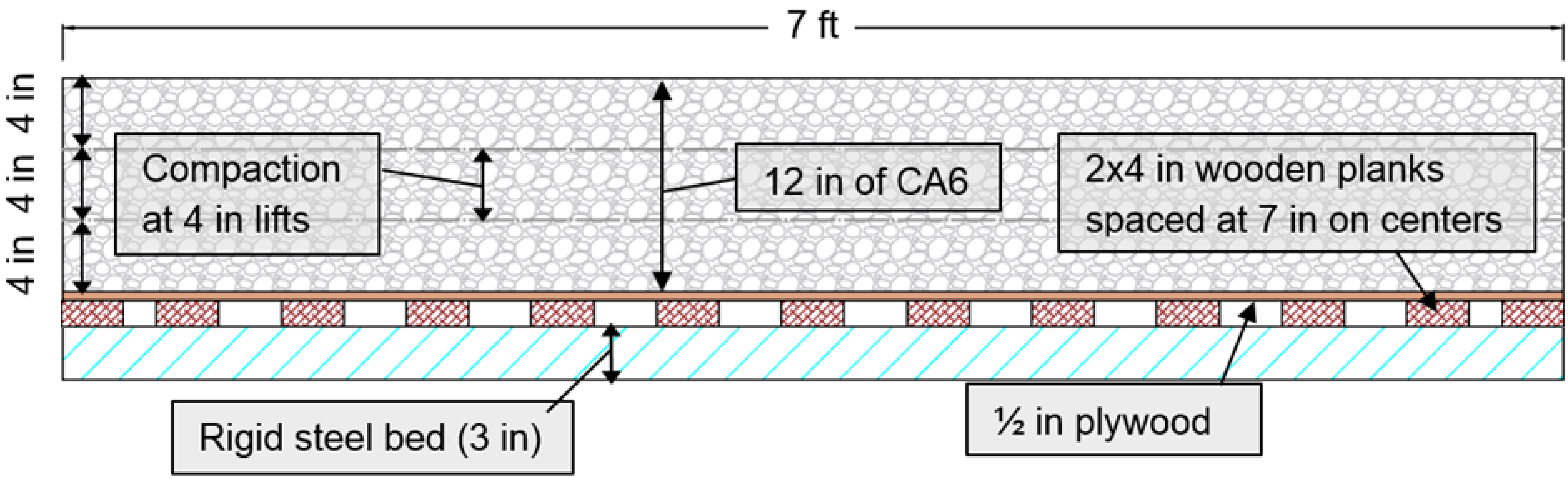


- Static load testing is conducted at rate of **0.02 in/min**
- The pattern seen above is repeated at **10,000**; **100,000**; **300,000**; **700,000** and **1,000,000** cycles
- Cyclic fatigue is paused at these intervals in order to measure **LTE** and **E** values by applying static tests.

Testing Setup: Evaluation of testing results

- For every tested specimens, **LTE** and **E** values are monitored with respect to cycle progression
- Readings of the overall **slab deflection** with respect to cyclic loads will be presented for every tested slab specimen
- Slabs with **LTE > 60 % or E > 75%** are considered adequate after **1 million cycles** as recommended by ACPA

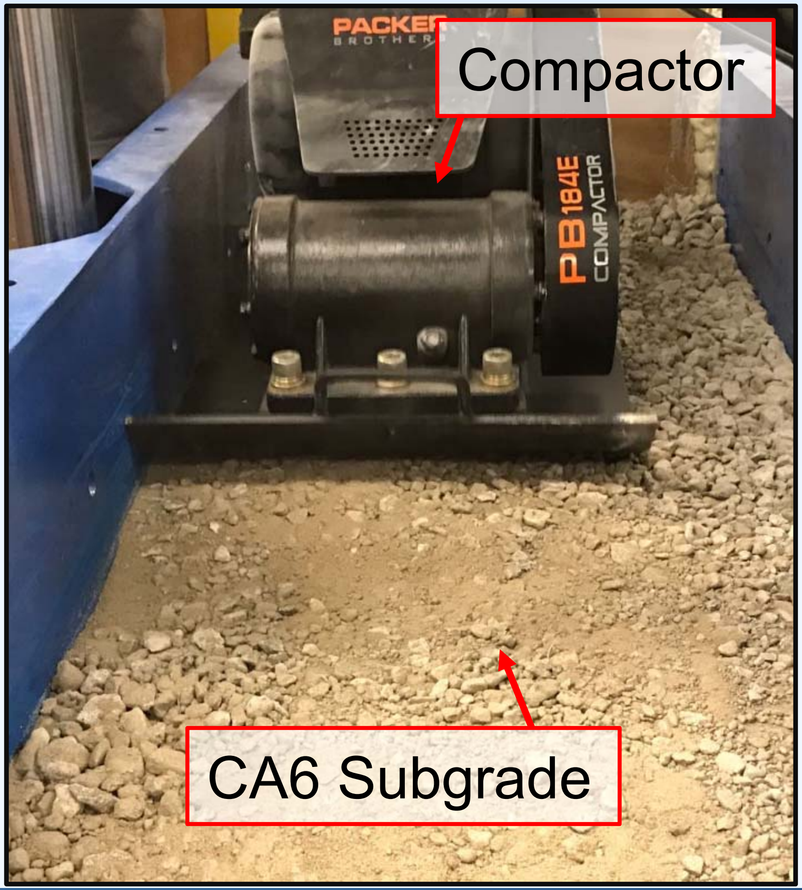
Testing Setup: Subgrade Layer

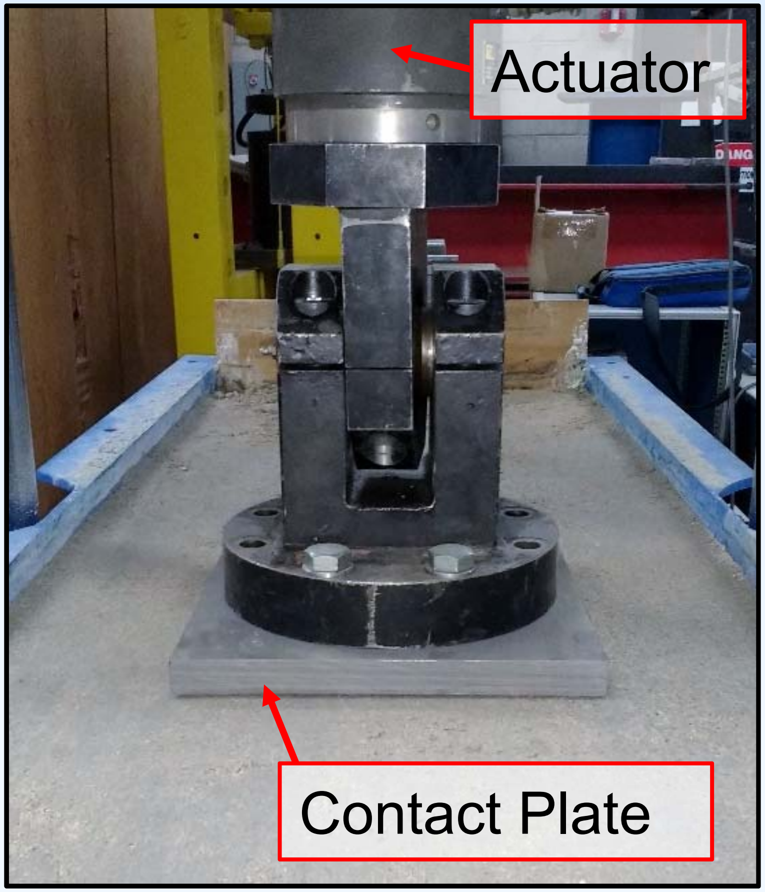


- Direct contact with rigid steel bed was avoided using wooden forms
- Compaction in 4 in. lifts (12 in. total)

Testing Setup: Subgrade Layer

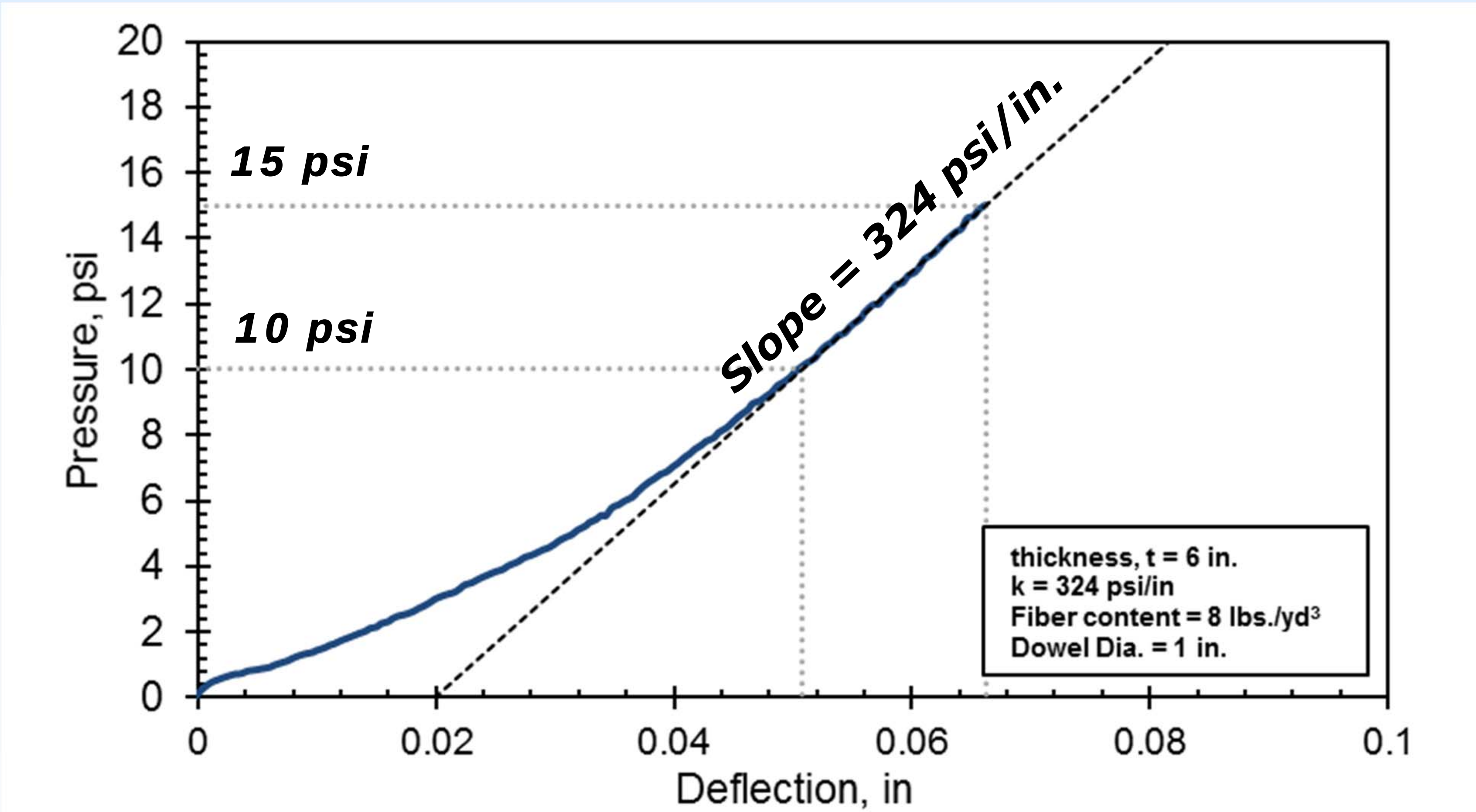
- Compaction was achieved using **vibratory plate compactor**
- **Subgrade modulus reaction** test was conducted after preparing the subgrade layer





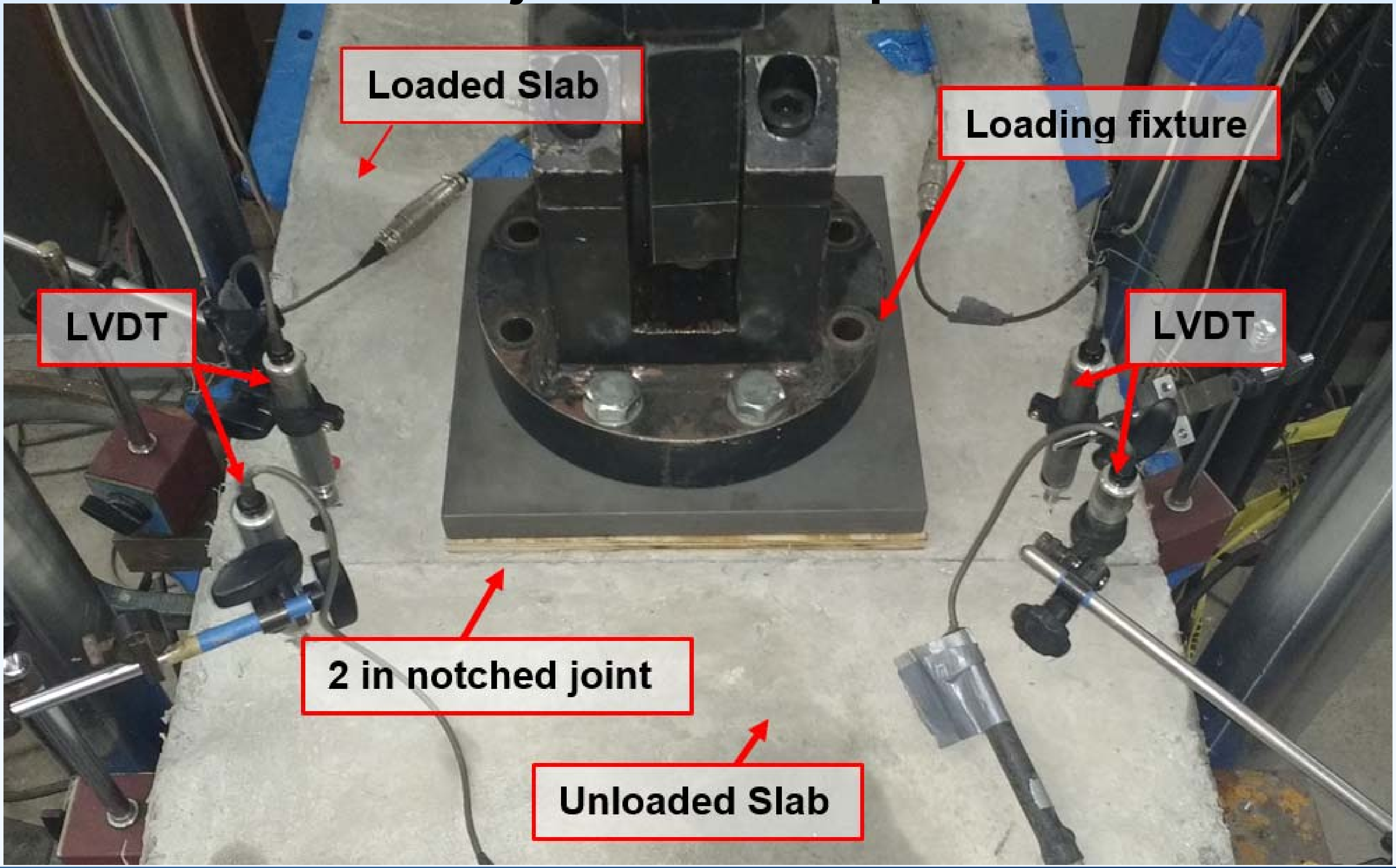
Testing Setup: Subgrade Layer

Plate contact pressure versus deflection for the compacted CA6 layer (**Specimen #1**)

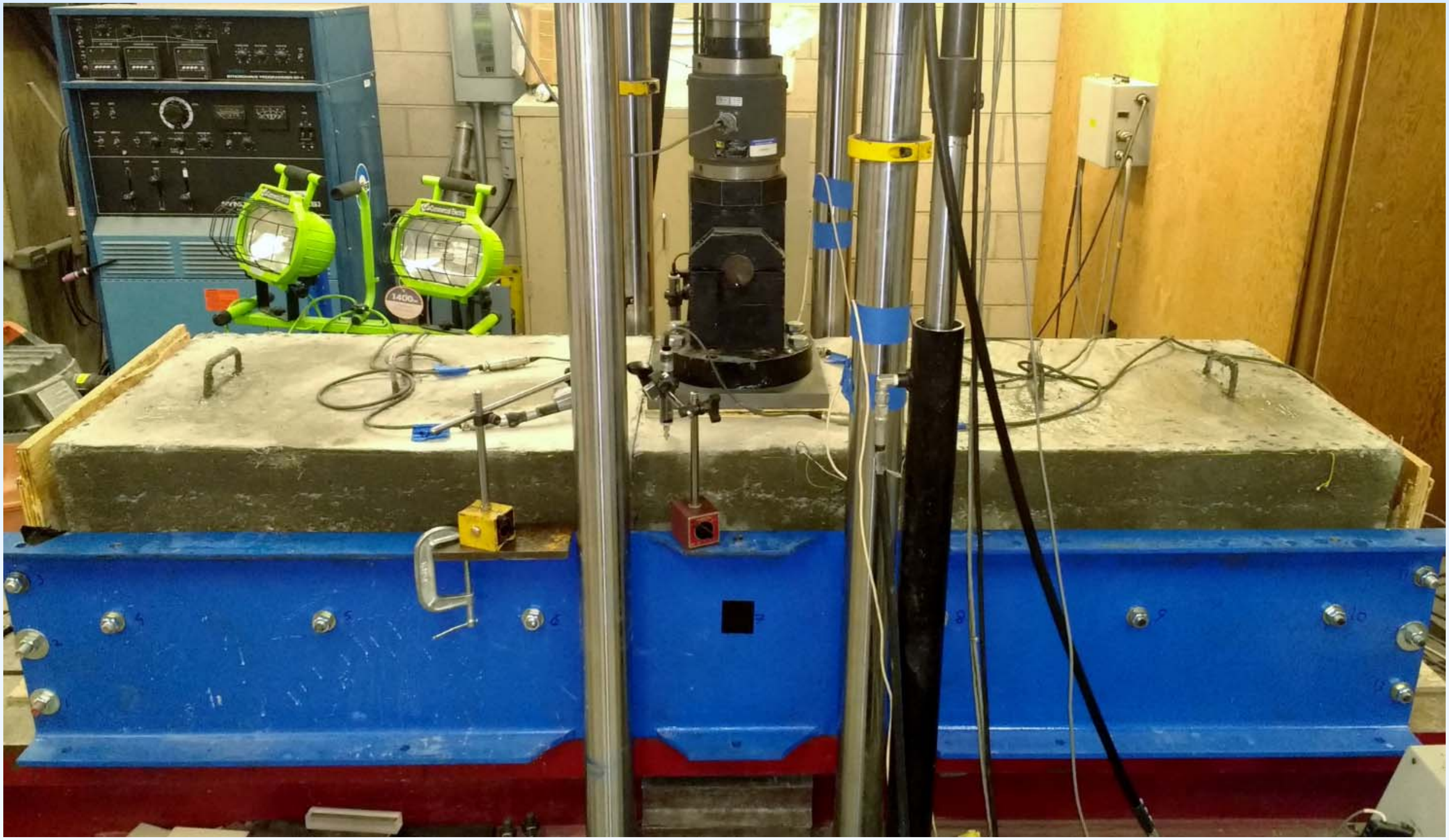


Testing Setup: Instrumentation and joint efficiency

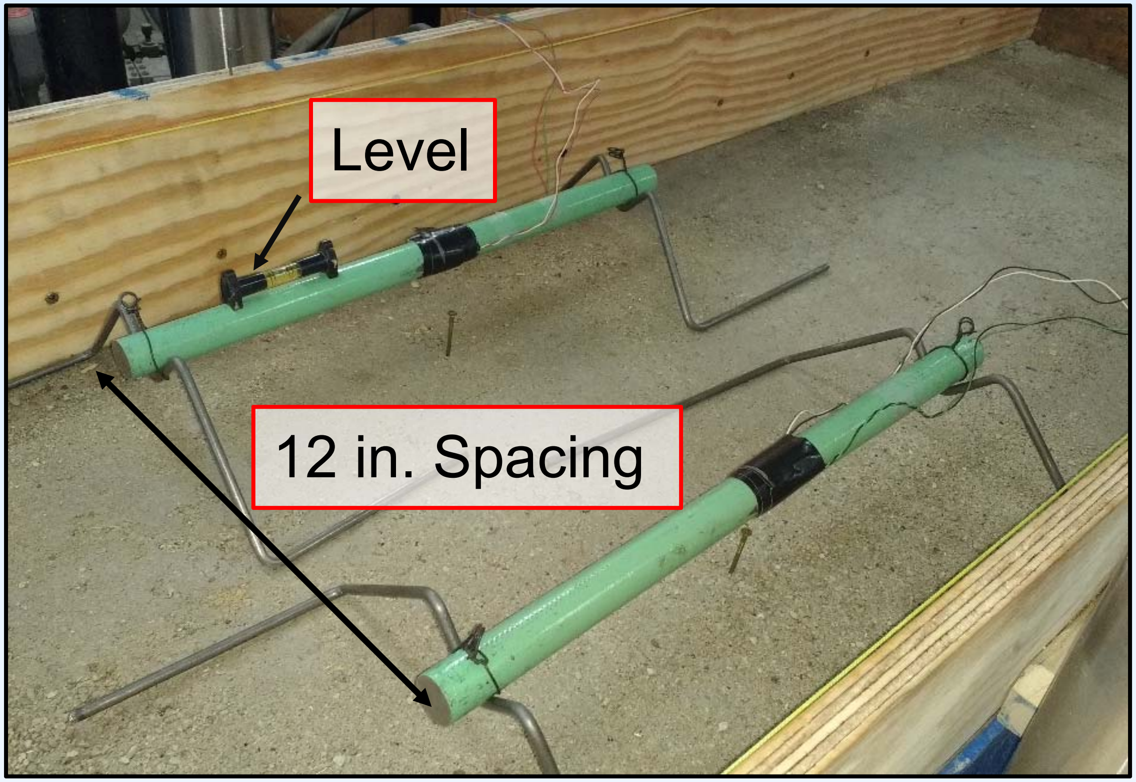
Instrumentation setup during static testing for the jointed slab specimen



First Tested Slab Specimen at 1-Day Concrete Age

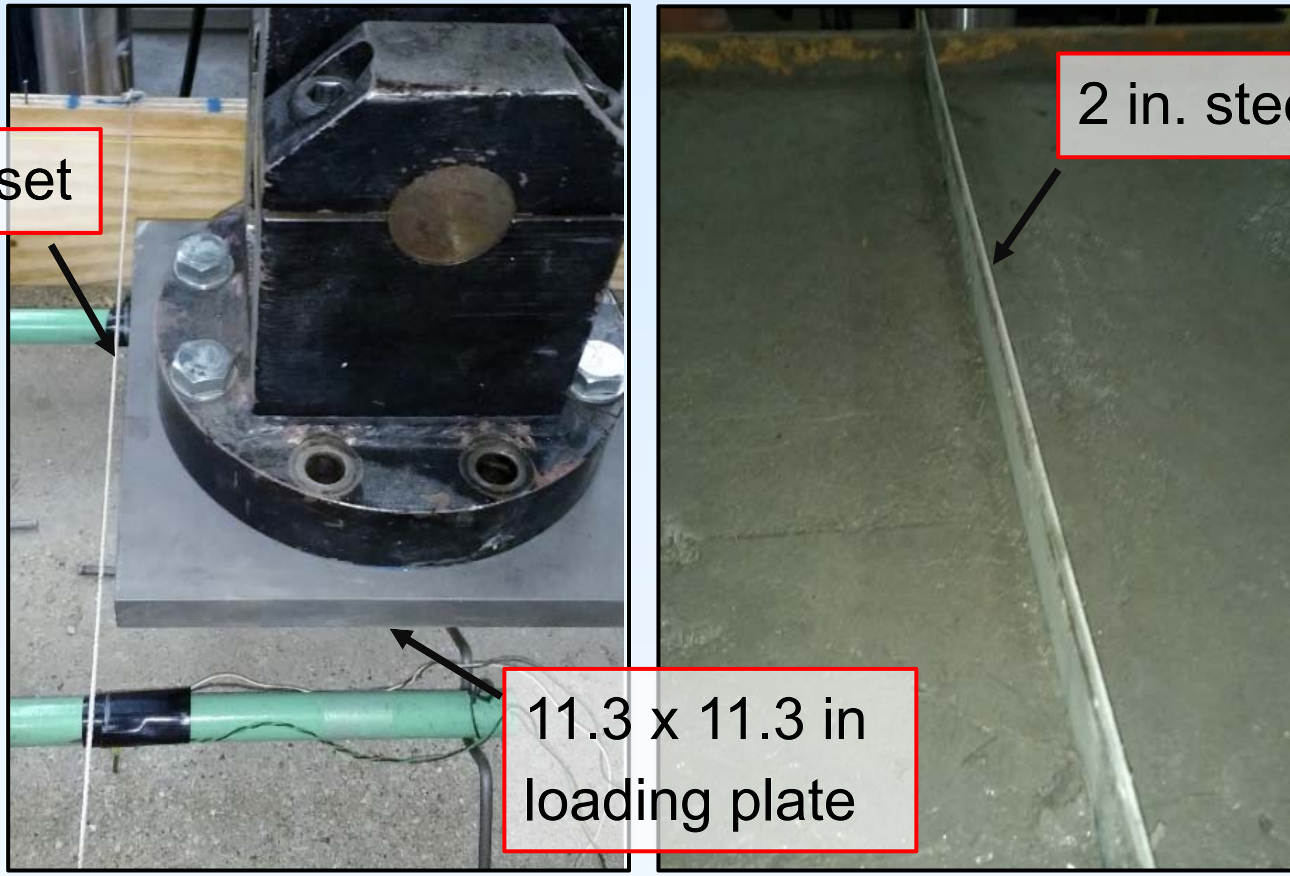


First Tested Slab Specimen: Forming and Dowel Placement



- The specimen included a contraction joint with two, smooth, epoxy coated, and lubricated dowel bars
- Dowel bars have a **1 in. diameter** and are placed at the mid-height of the slab (3 in.)

First Tested Slab Specimen: Groove Placement



- The joint was created using a steel groove embedded **2 in.** the slab
- An offset of **¼ in.** between the plate and the joint was maintained

First Tested Slab Specimen Description

- Slab Thickness was set at the least value for rigid pavement (**6 in.**)
- Concrete **PV** mix with **8 lbs. per cubic yard** of STRUX 90/40
- Contraction joint with two, smooth, epoxy coated, lubricated **dowel bars (1 in. dia.)**
- Contact plate of **11.3 x 11.3 in.** which corresponds to **70 psi** plate pressure at **½ ESAL (9 kip)**

First Tested Slab Specimen Description

- Loading started at **1-Day concrete age**
- Beams and cylinders were casted with the slab specimen and were tested for **flexural** strength, **compressive** strength, and **dynamic modulus.**
- Tested or predicted strength readings were correlated with the loading sequence at which cracking/ loss of transfer occurs

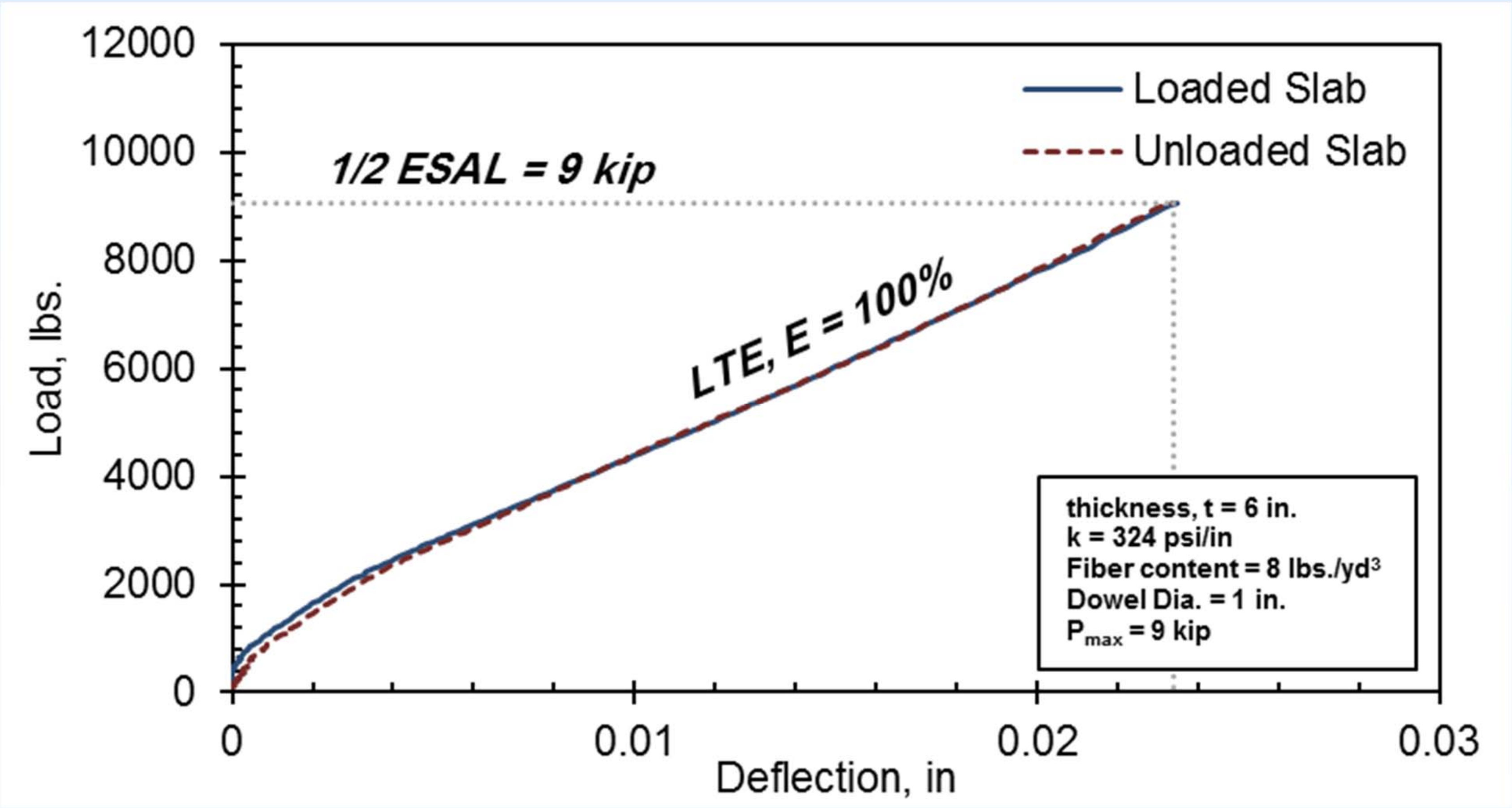
First Tested Slab Specimen: Loading Segments

Testing Segment	Frequency, Hz.	Maximum Applied Load	Number of Cycles, Millions	Start Date	End Date
1	4	9 kip	2.3	2/11/2017	2/18/2017
2	4	13.5 Kip	1	2/18/2017	2/21/2017
3*	Low cycle*	28 - 40 kip	-	2/21/2017	2/21/2017
4	4	30 kip	1	2/21/2017	2/25/2017
5	4	36 kip	1	2/25/2017	2/28/2017

* Testing segment 3 included six cycles that were applied at a stroke rate of 0.02 in./min. in order to initiate cracking

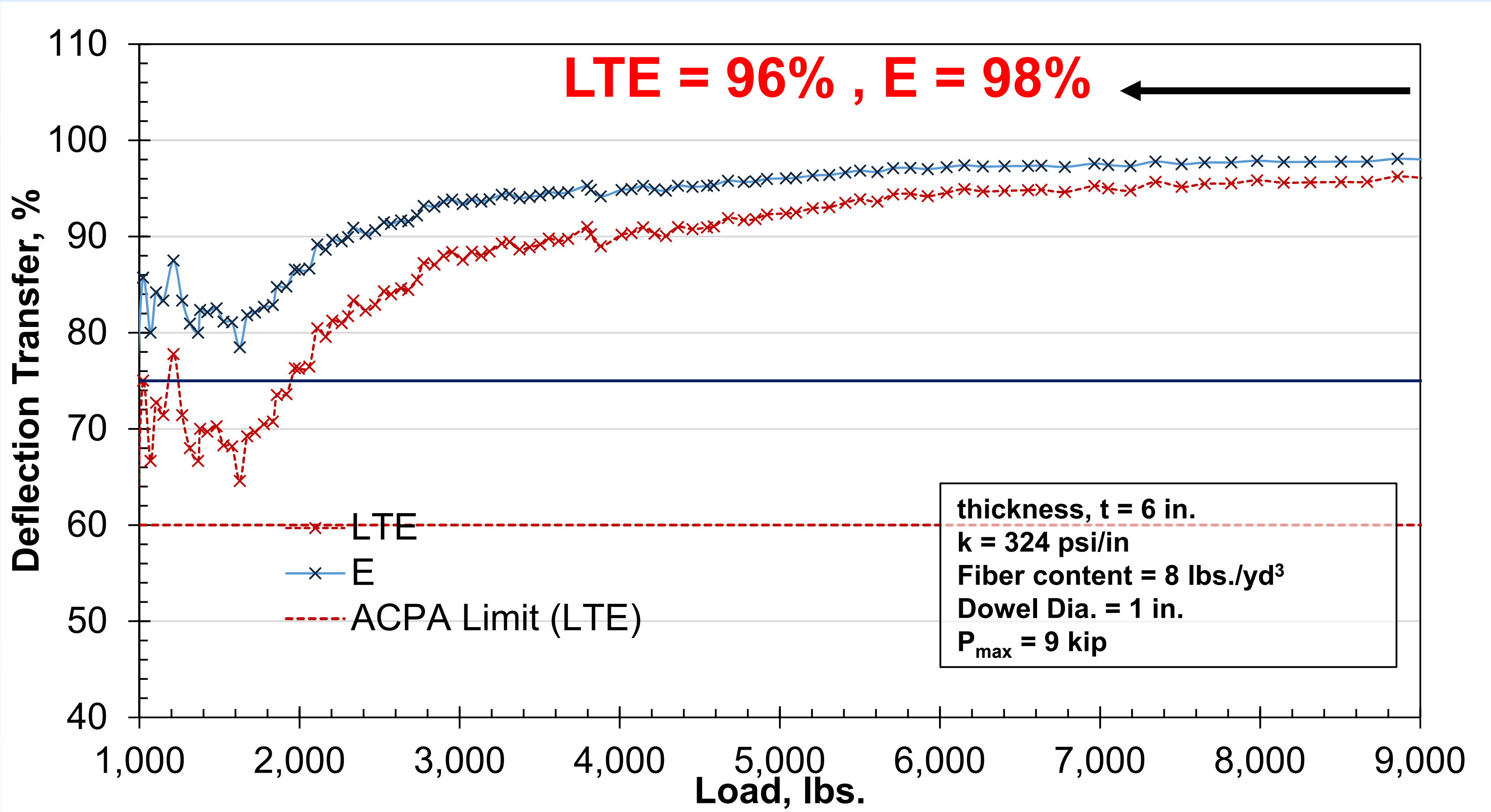
Specimen 1 : Segment 1

Load versus deflection for the first static loading



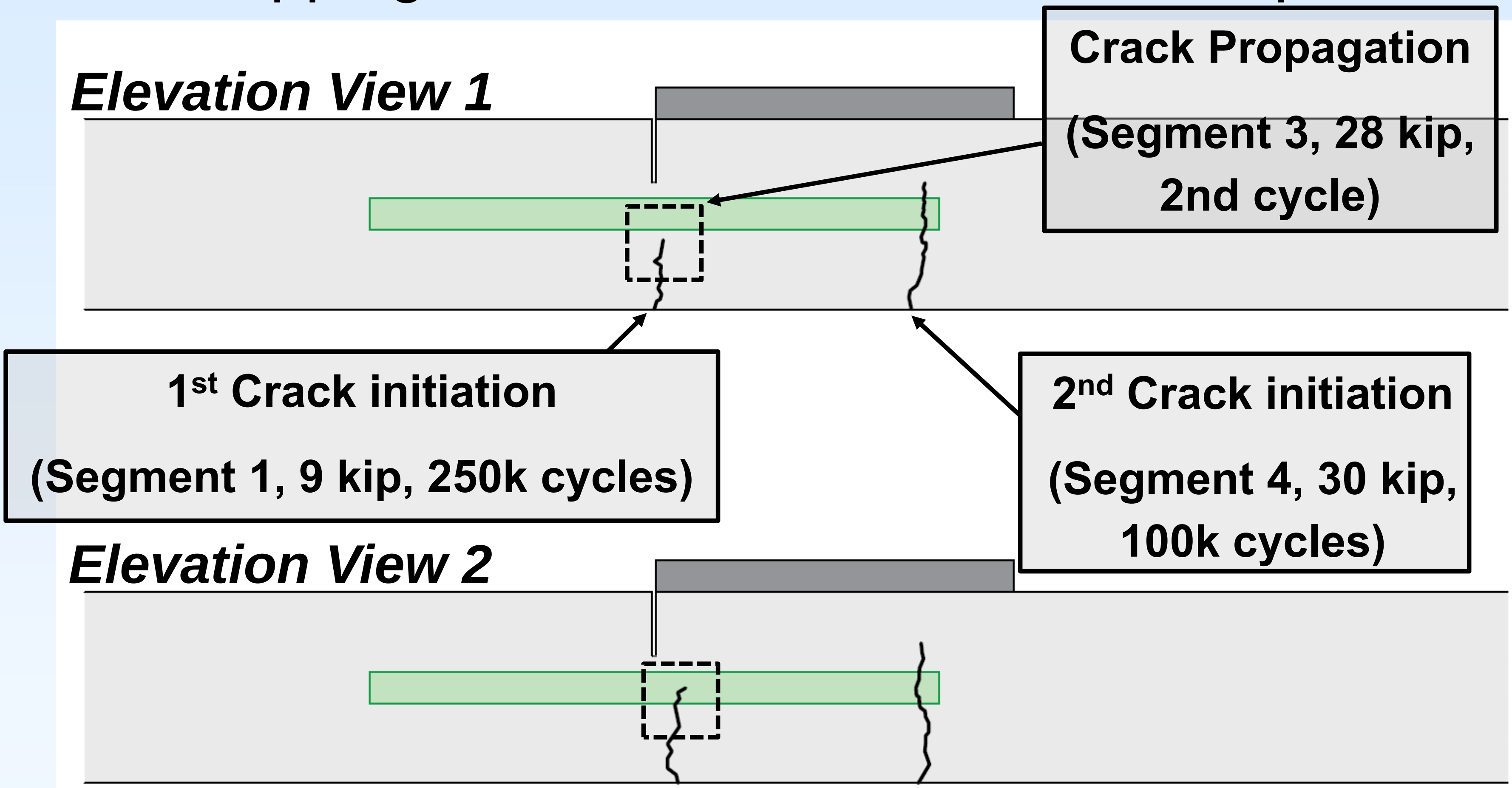
Specimen 1: Joint performance after 1 million ½ ESALs (9 kip)

LTE and E vs. Load development

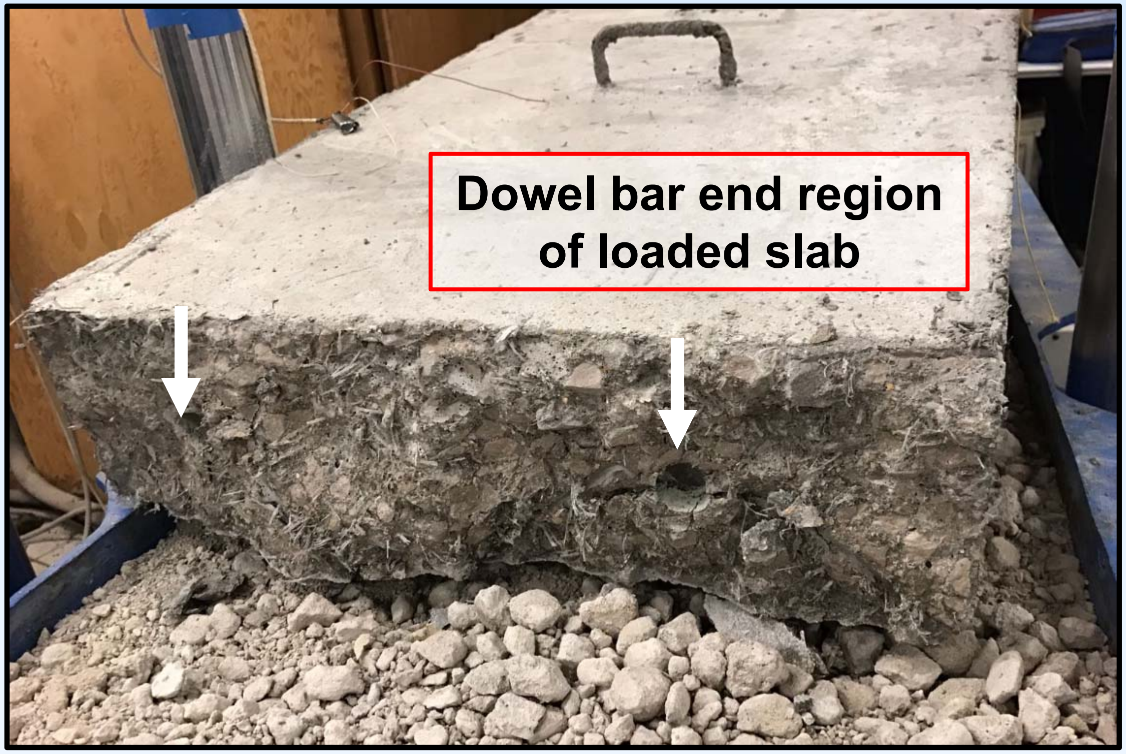


Specimen 1 : Crack Pattern

Crack mapping in the elevation views of the specimen



Specimen 1 : Cracking pattern



Specimen cracking showing crack arresting mechanism due to the presence of 8 lbs. per cubic yard of macro synthetic fibers

Specimen 1: Summary and Conclusions

- Early age loading at **1-Day concrete age** yielded no loss of transfer after applying one million cycles with a maximum load of **½ ESAL (9 kip)**.
- Joint deterioration was observed only after gradually increasing the maximum applied cyclic load from **9 kips to 36 kips** over a span of **5.3 million cycles**

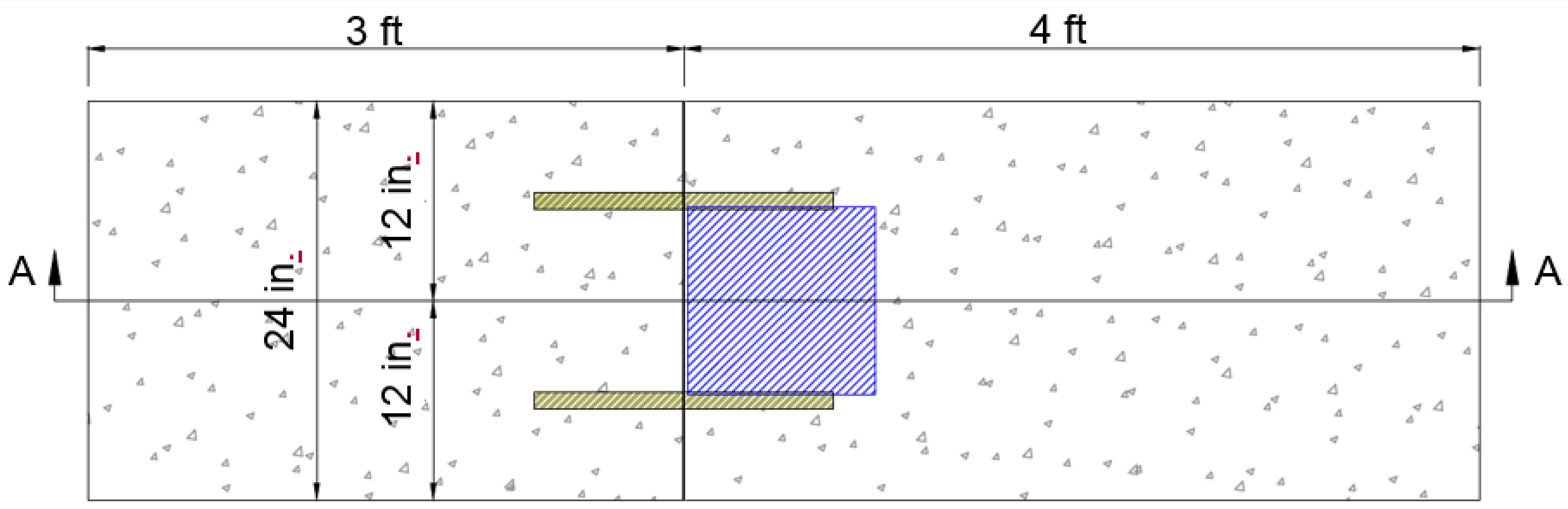
Cyclic fatigue loading of JPCP testing schedule

Specimen characteristics

Specimen #	Pavement Thickness	Joint Type	Dowel Dia.	Fiber Content (lb/yd^3)	Testing Time
1	6 in.	Doweled	1 in	8	1-Day
2	***6 in.***	***Doweled***	***1 in***	***-***	***1-Day***
3	6 in.	Non-doweled	-	8	1-Day
4	6 in.	Doweled	1	4	1-Day
5	8 in.	Doweled	1.25 in	8	12-hr

Specimen 2: Description

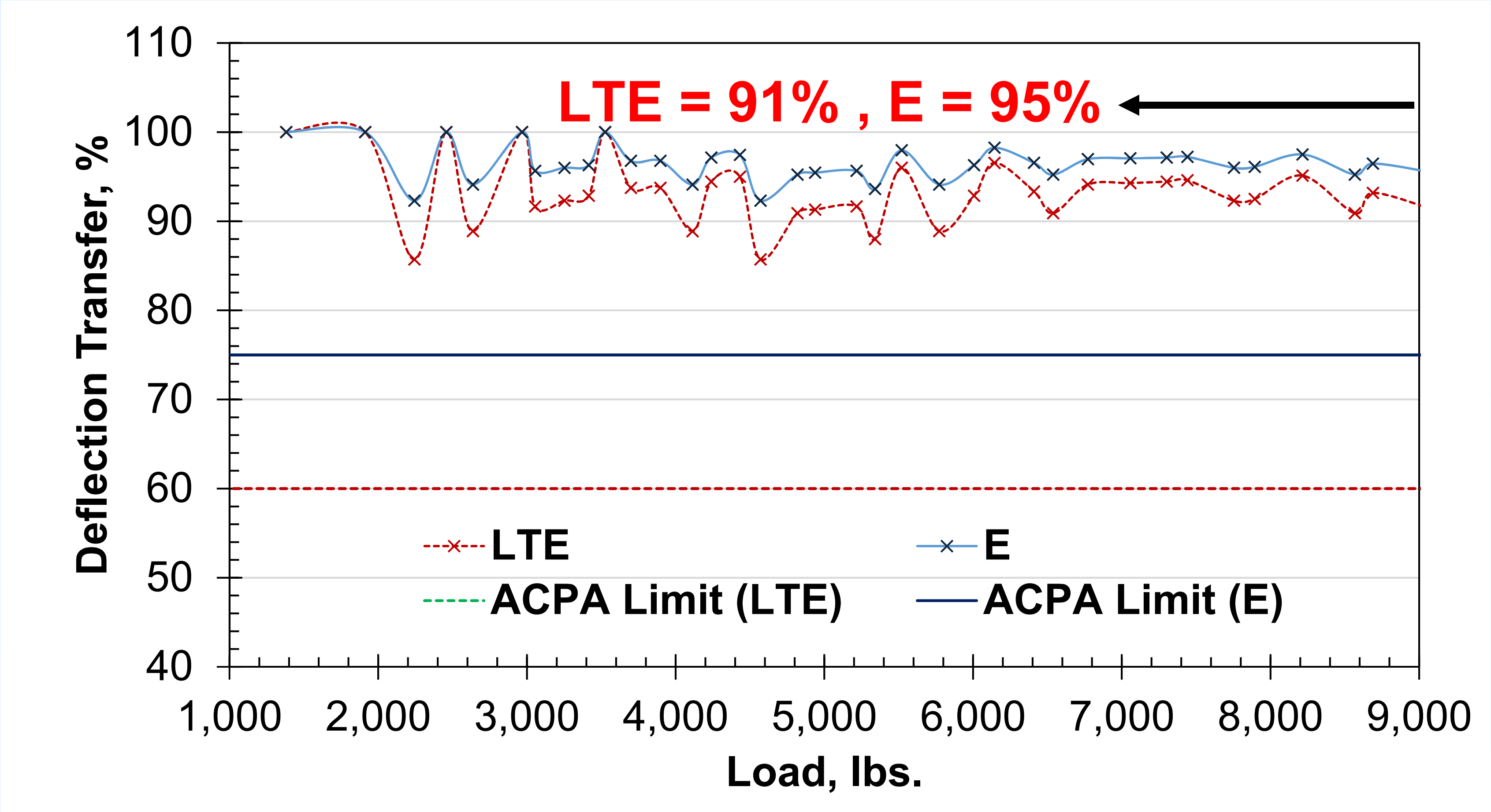
Specimen 2 testing schematic (Plan view)



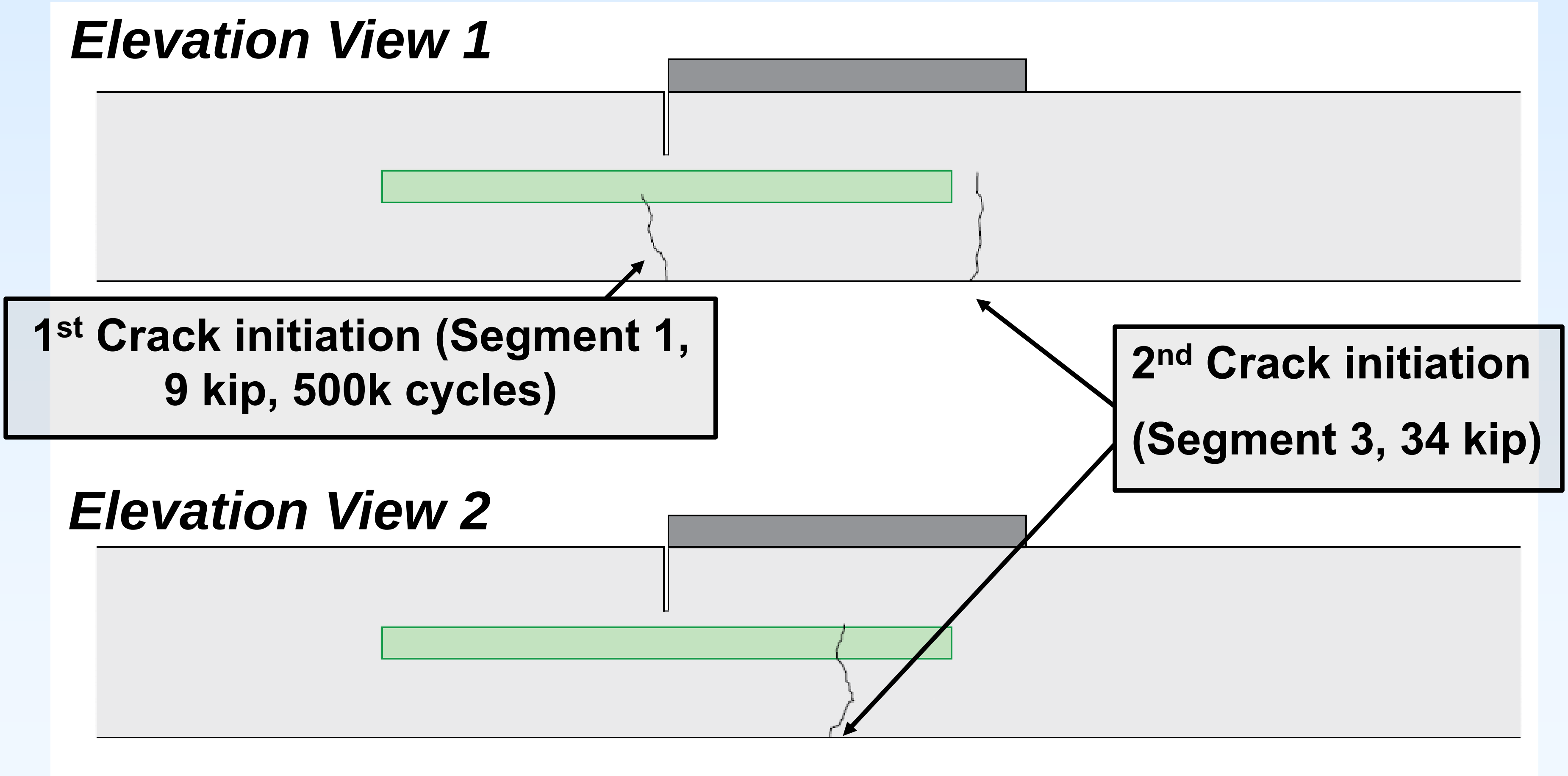
(a) Plan view

Specimen 2: Joint performance after 1 million ½ ESALs (9 kip)

LTE and E vs. Load development



Specimen 2: Crack Pattern after cyclic load completion



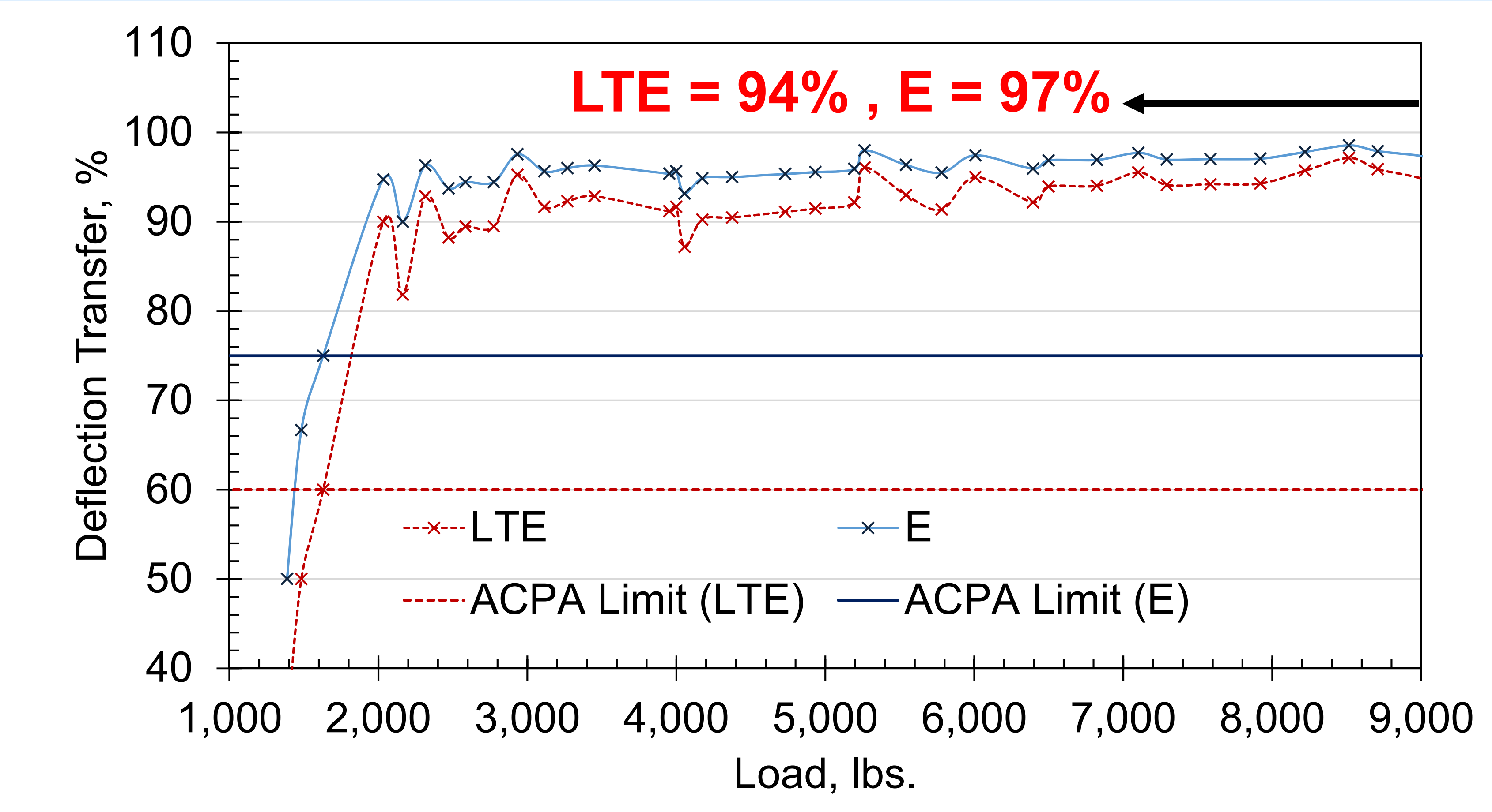
Cyclic fatigue loading of JPCP testing schedule

Specimen characteristics

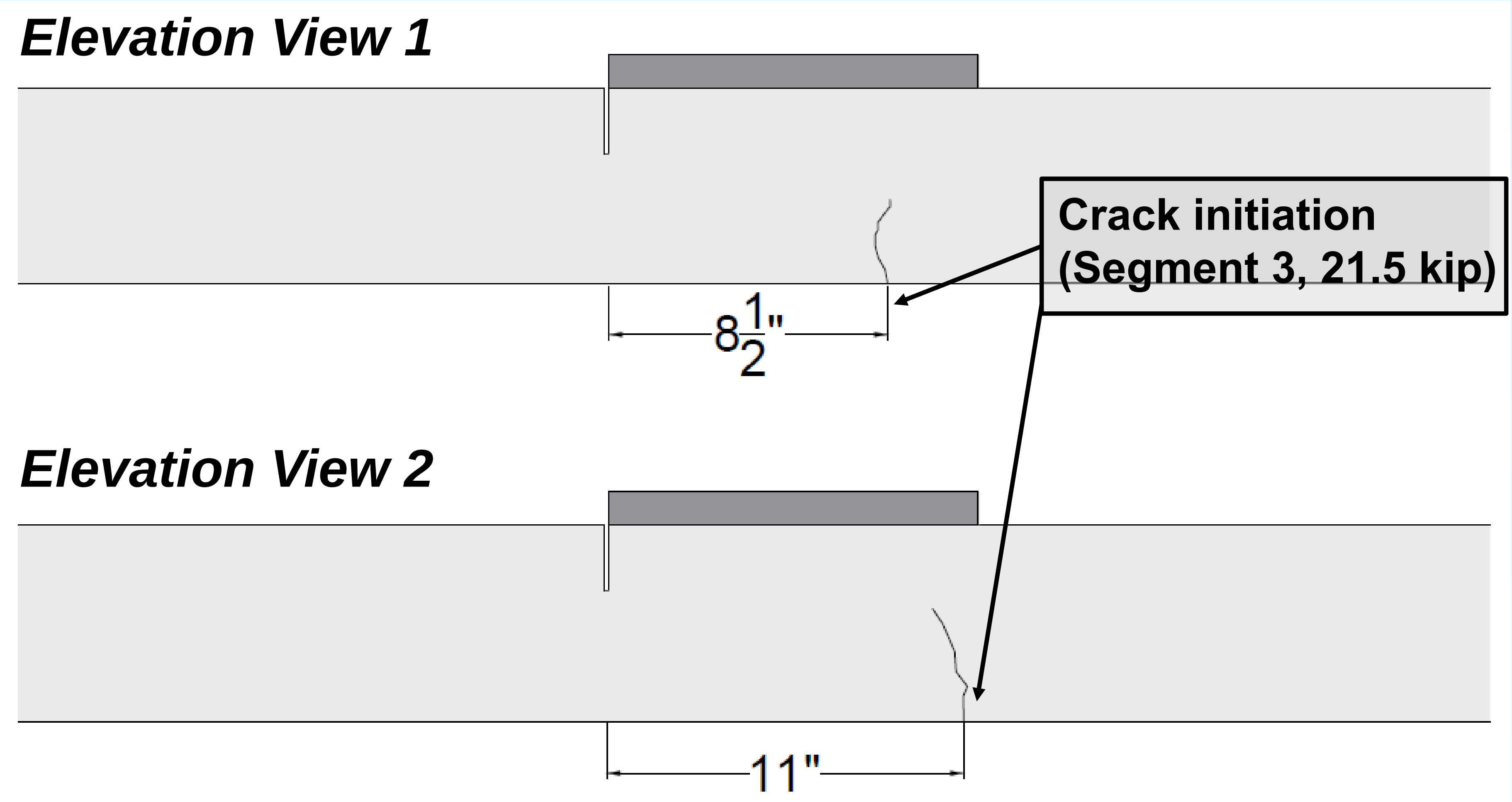
Specimen #	Pavement Thickness	Joint Type	Dowel Dia.	Fiber Content (lb/yd^3)	Testing Time
1	6 in.	Doweled	1 in	8	1-Day
2	6 in.	Doweled	1 in	-	1-Day
3	***6 in.***	***Non-doweled***	***-***	***8***	***1-Day***
4	6 in.	Doweled	1	4	1-Day
5	8 in.	Doweled	1.25 in	8	12-hr

Specimen 3: Joint performance after 1 million ½ ESALs (9 kip)

LTE and E vs. Load development



Specimen 3: Crack Pattern after cyclic load completion

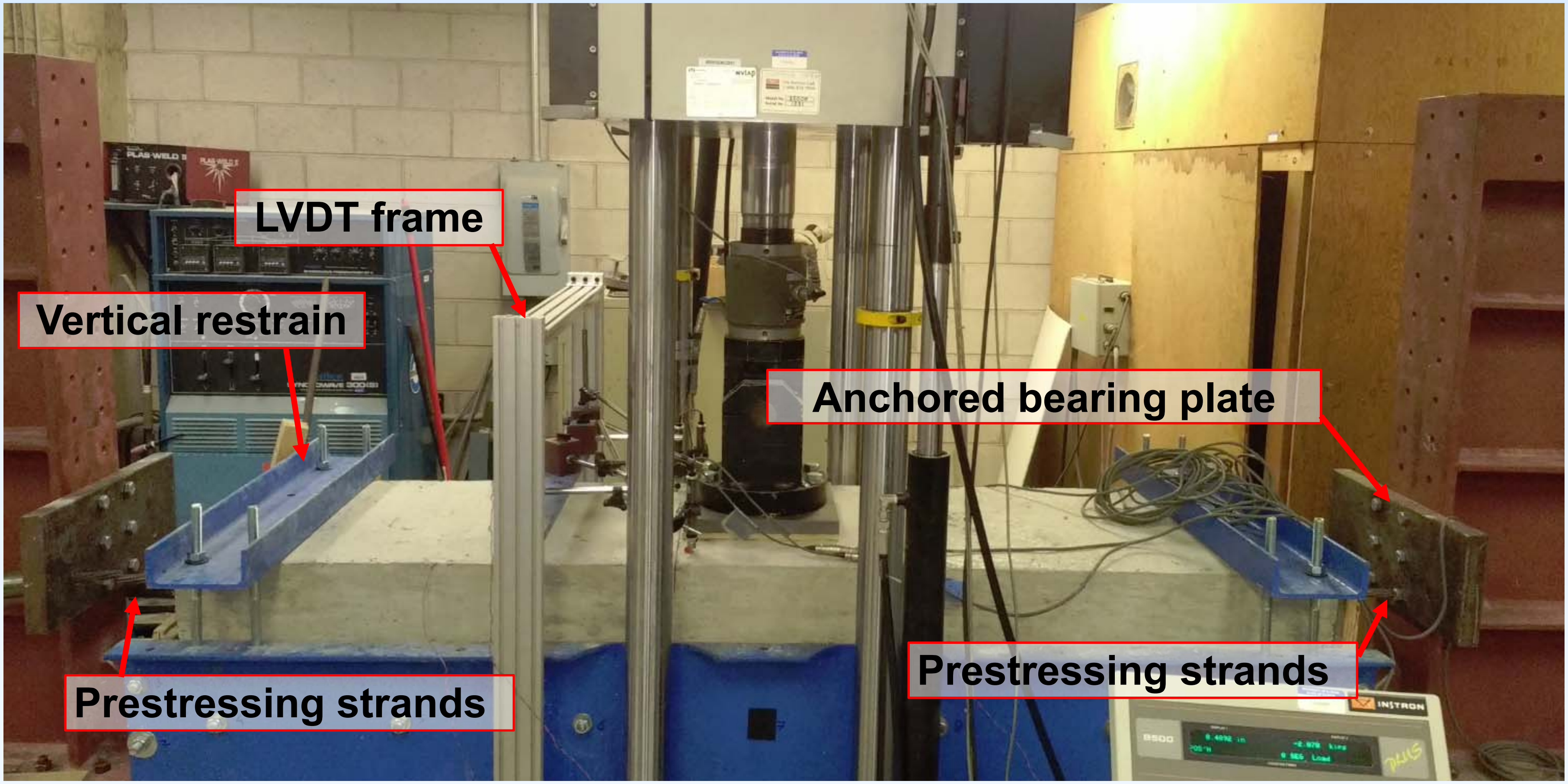


Cyclic fatigue loading of JPCP testing schedule

Specimen characteristics

Specimen #	Pavement Thickness	Joint Type	Dowel Dia.	Fiber Content (lb/yd^3)	Testing Time
1	6 in.	Doweled	1 in	8	1-Day
2	6 in.	Doweled	1 in	-	1-Day
3	6 in.	Non-doweled	-	8	1-Day
4	***6 in.***	***Doweled***	***1***	***4***	***1-Day***
5	8 in.	Doweled	1.25 in	8	12-hr

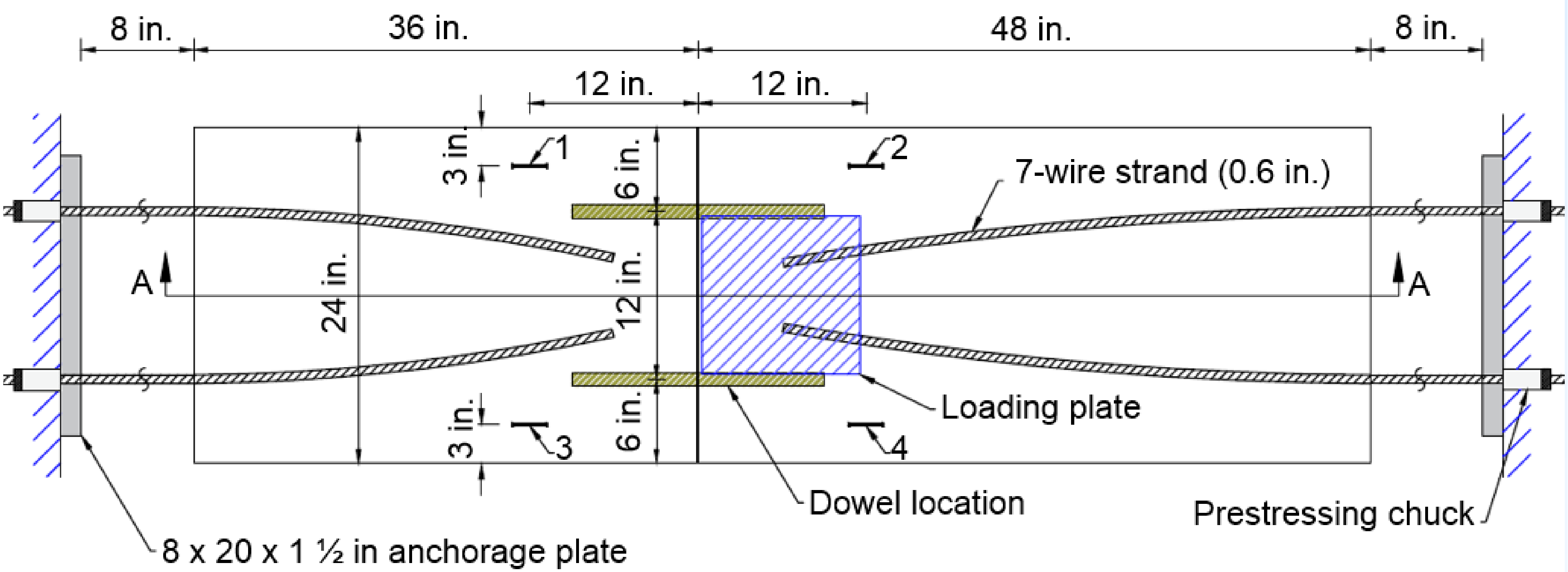
Specimen 4 tested at 1-Day concrete strength



Specimen 4: Description (Boundary Conditions)

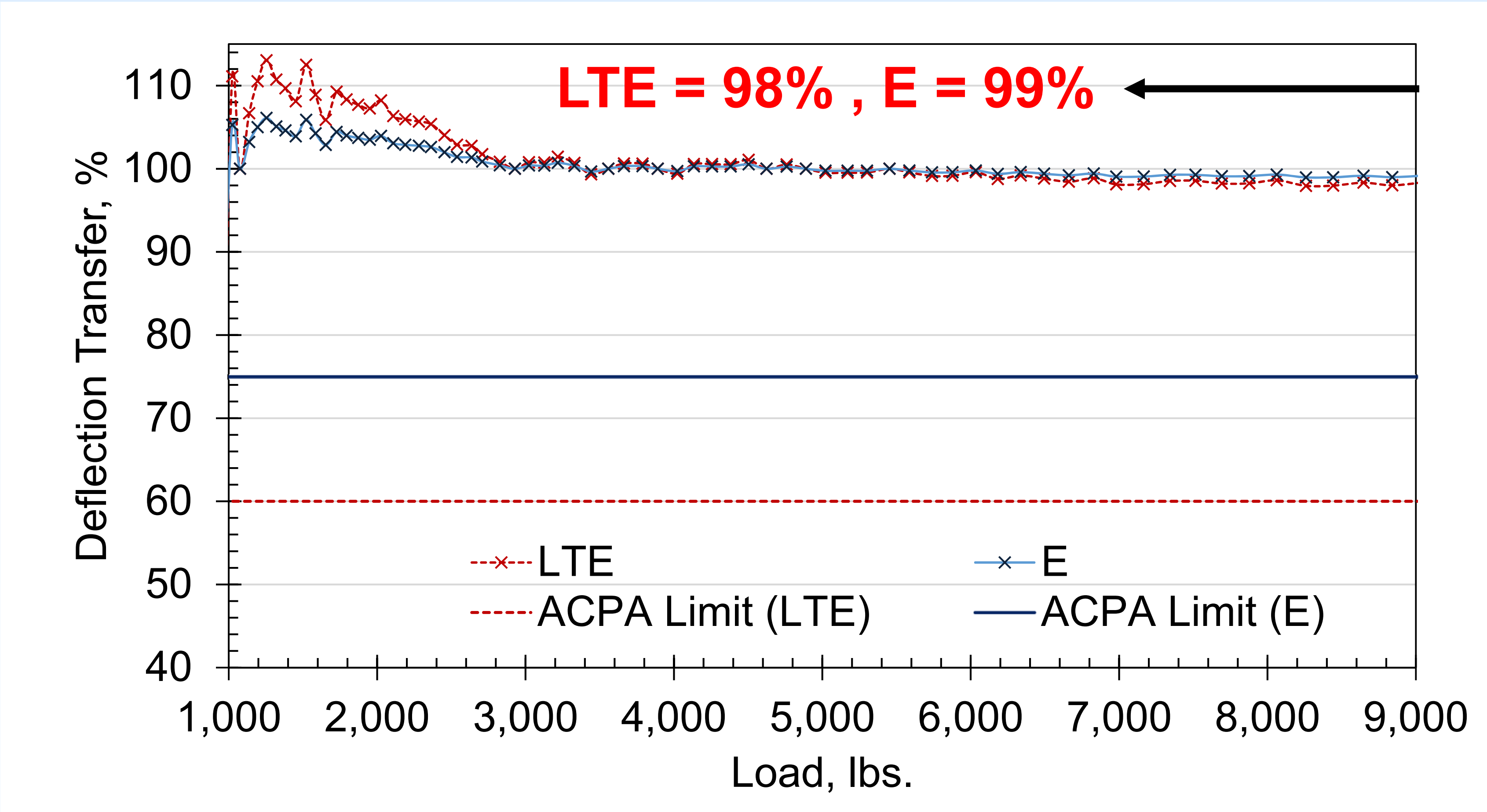
Specimen 4 testing schematic plan view

Anchorage system and instrumentation

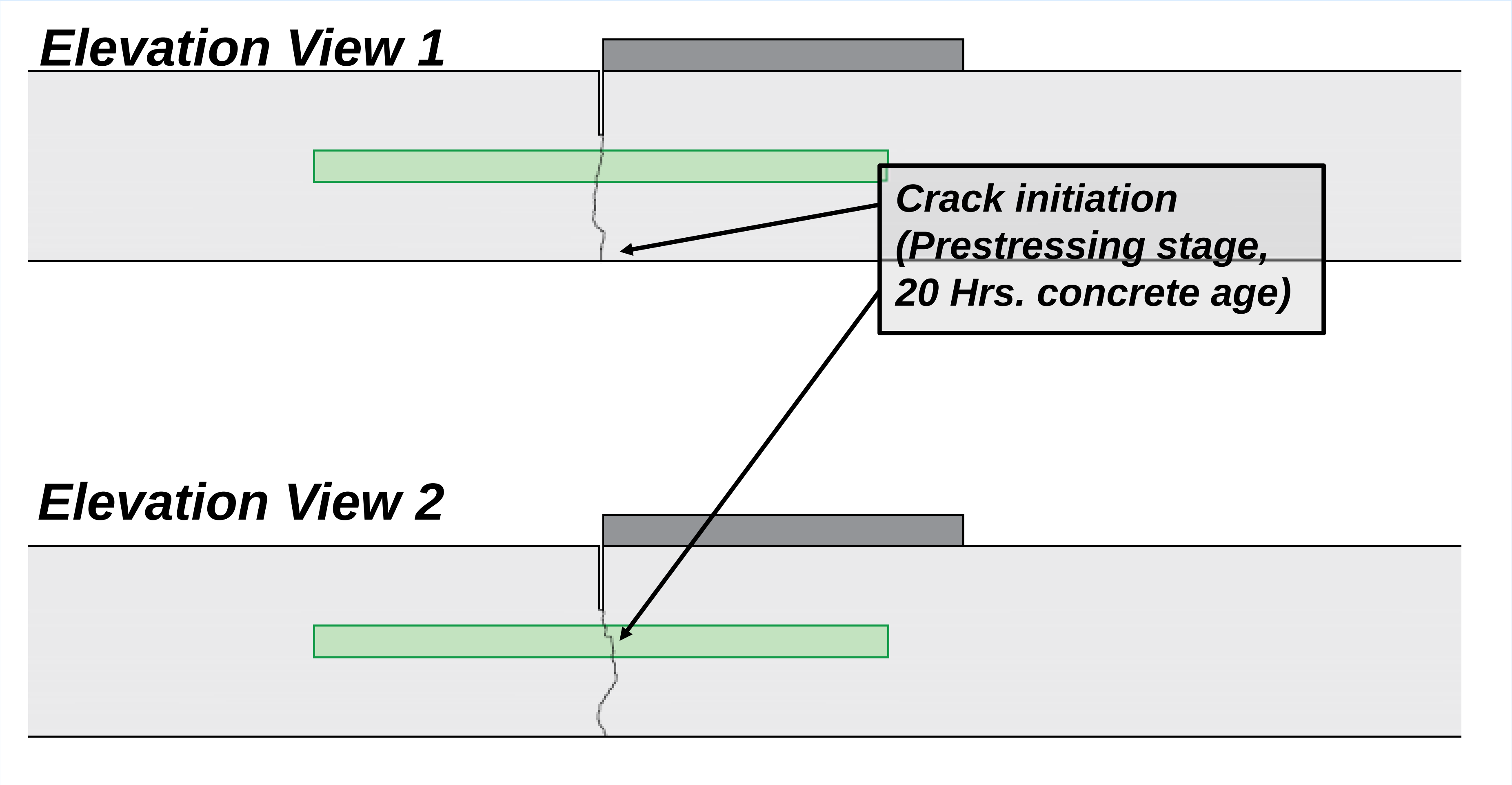


Specimen 4: Joint performance after 1 million ½ ESALs (9 kip)

LTE and E vs. Load development



Specimen 4: Crack Pattern after cyclic load completion

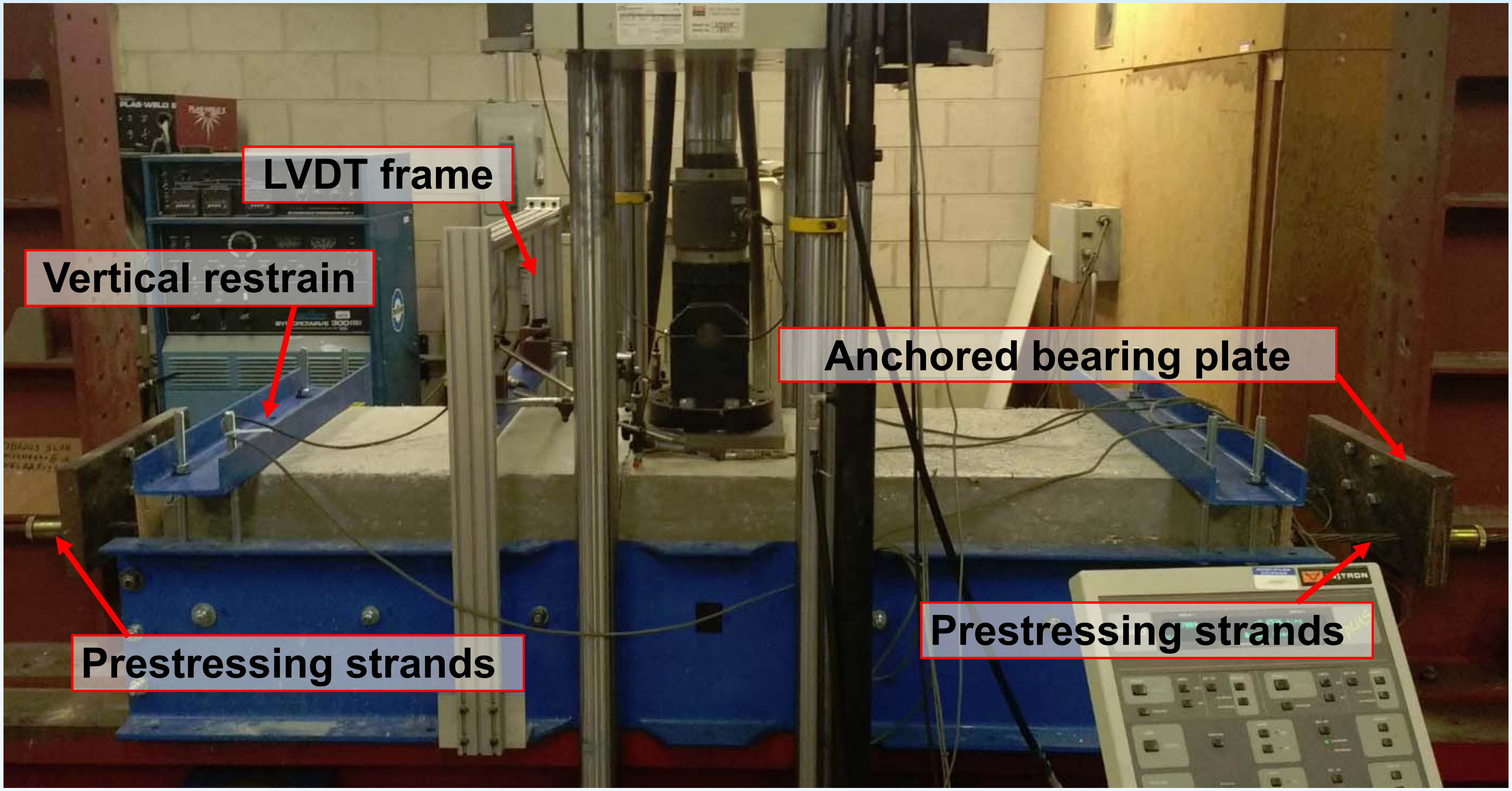


Cyclic fatigue loading of JPCP testing schedule

Specimen characteristics

Specimen #	Pavement Thickness	Joint Type	Dowel Dia.	Fiber Content (lb/yd^3)	Testing Time
1	6 in.	Doweled	1 in	8	1-Day
2	6 in.	Doweled	1 in	-	1-Day
3	6 in.	Non-doweled	-	8	1-Day
4	6 in.	Doweled	1	4	1-Day
5	***8 in.***	***Doweled***	***1.25 in***	***8***	***12-hr***

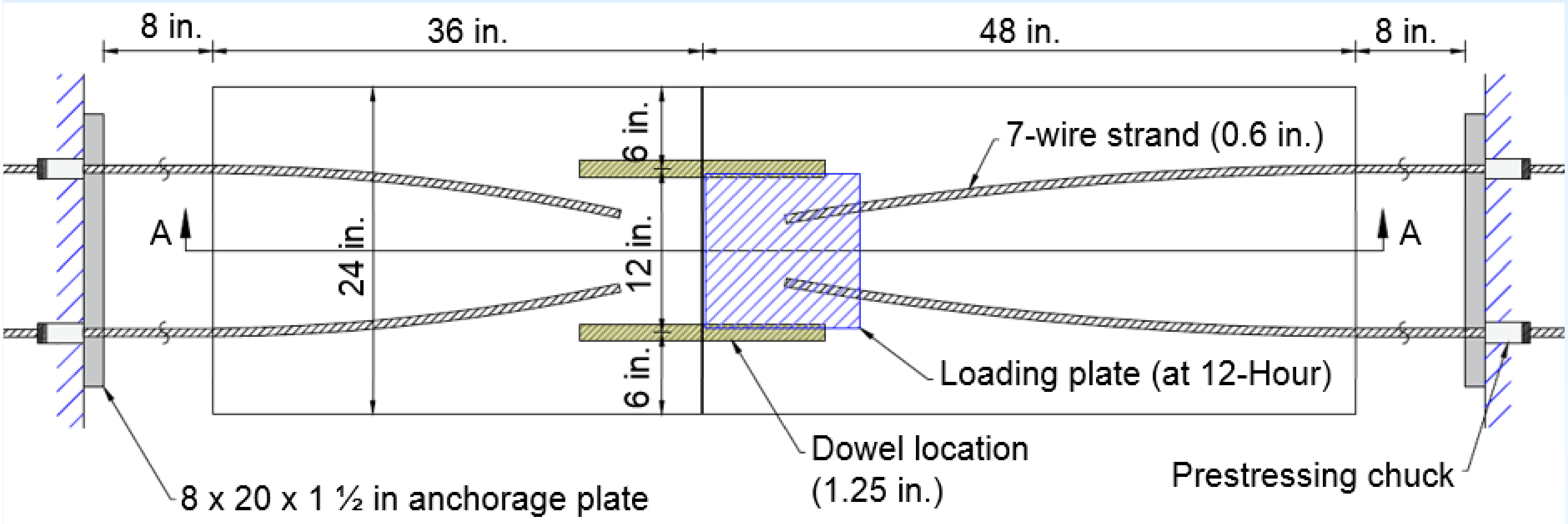
Specimen 5 tested at 12-Hour concrete age



Specimen 5: Description (Boundary Conditions)

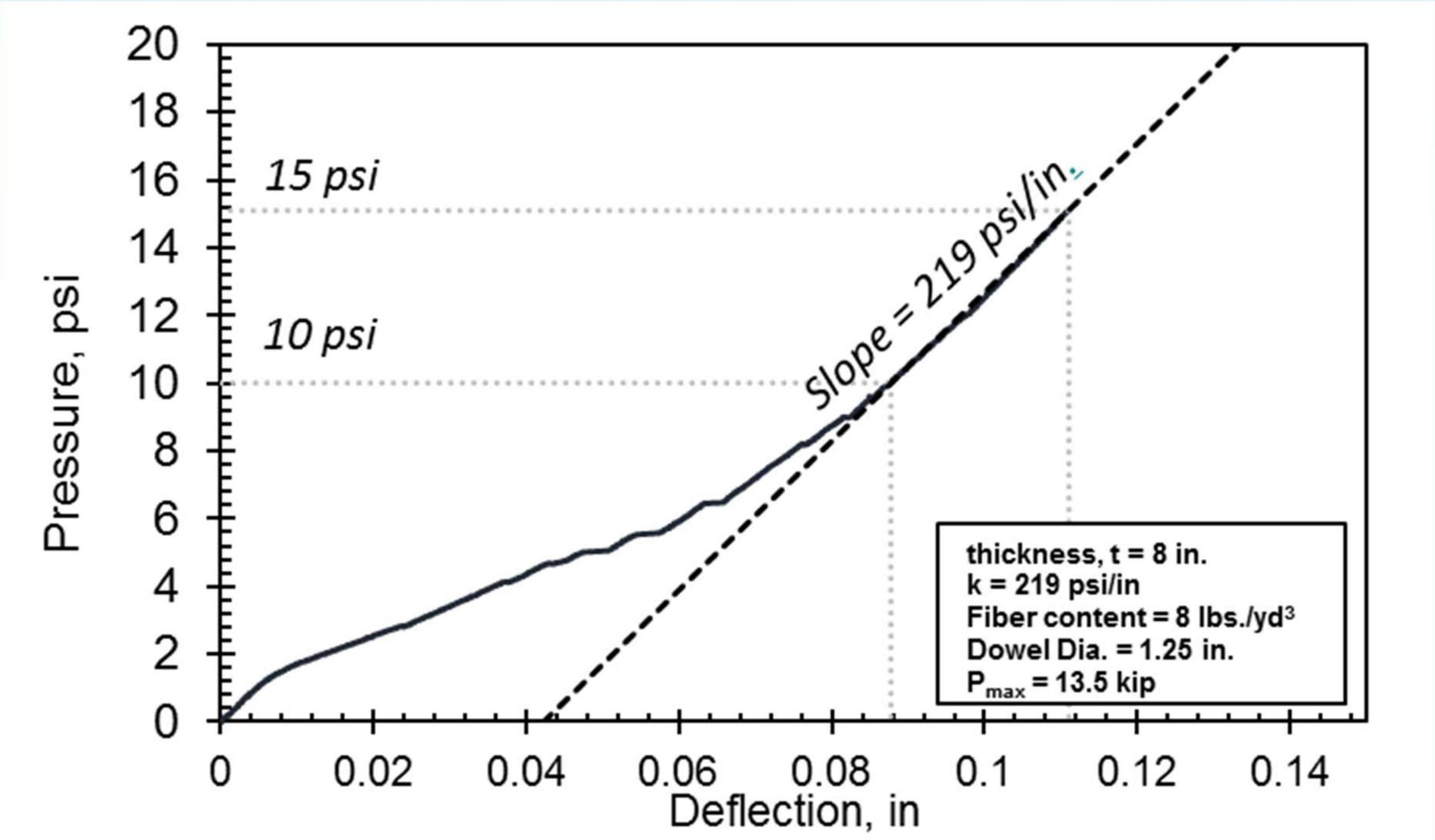
Specimen 5 testing schematic plan view

Anchorage system



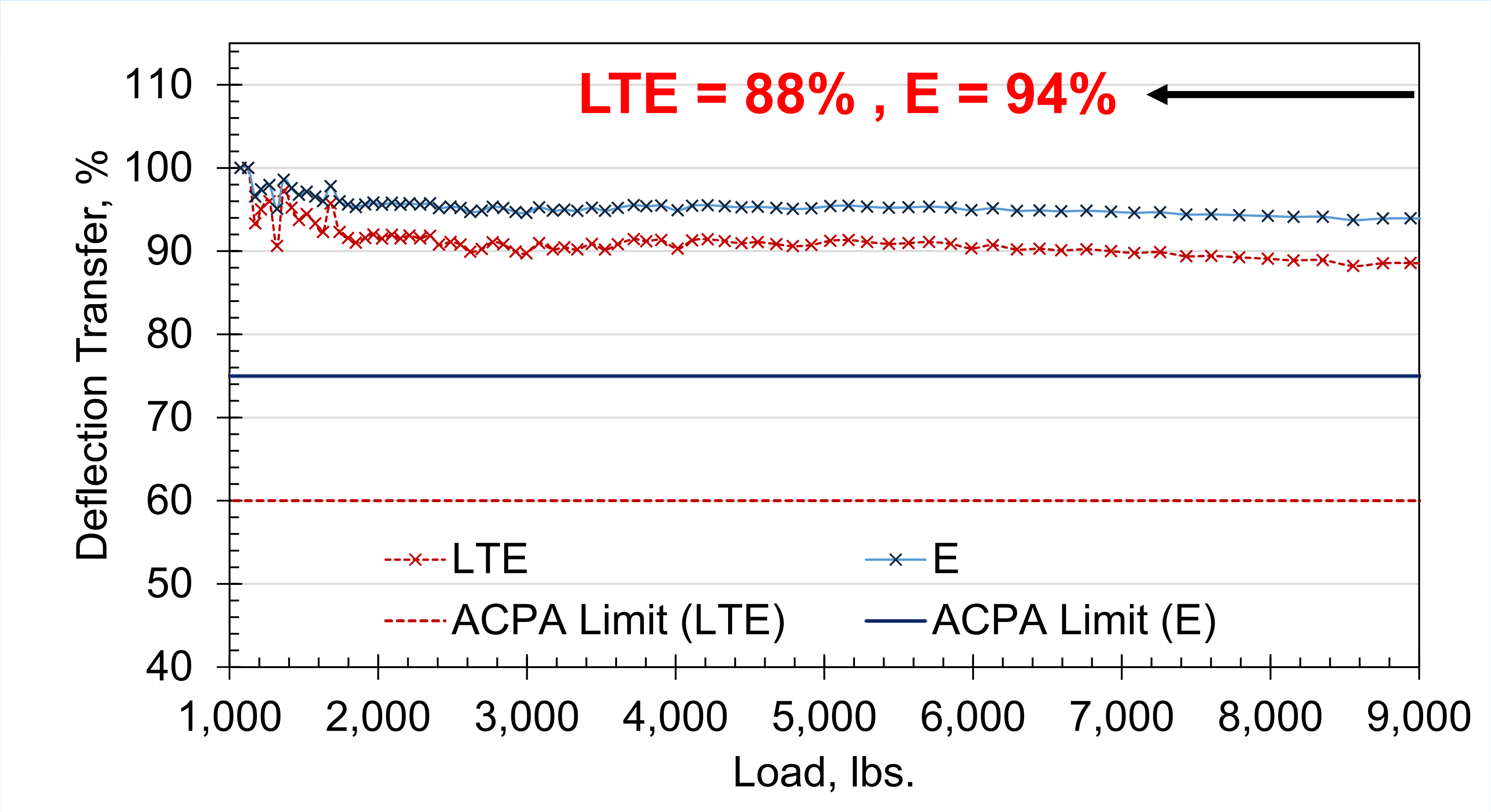
Specimen 5: Subgrade Layer

Plate contact pressure versus deflection for the compacted CA6 layer

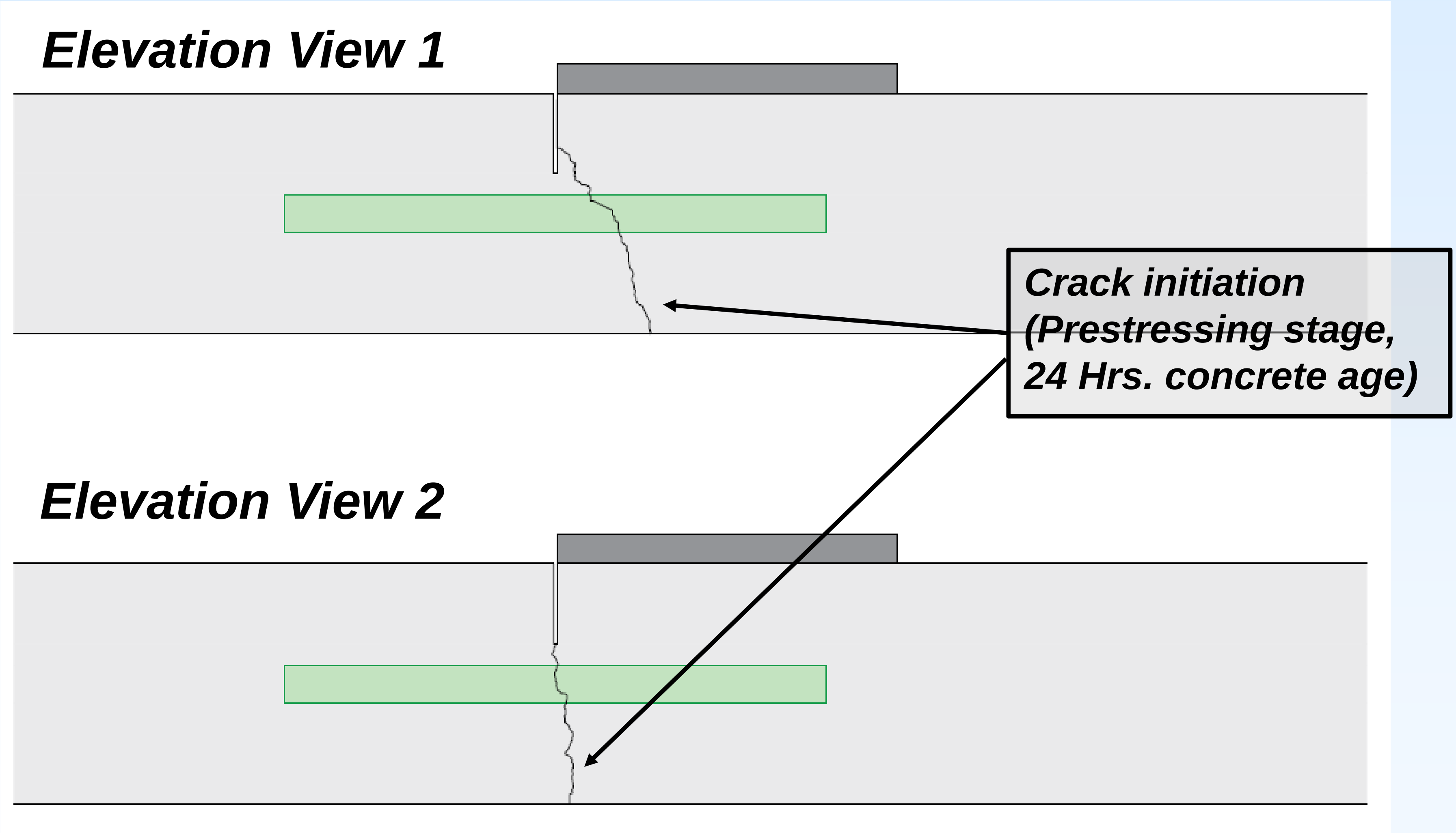


Specimen 5: Joint performance after 1 million ½ ESALs (9 kip)

LTE and E vs. Load development



Specimen 5: Crack Pattern after cyclic load completion



Summary of Task 5: Joint transfer performance

Specimen #	LTE (%)	E (%)	Joint Faulting (in.)	Joint Opening (in.)
	≥ 60 (ACPA)	≥ 75 (ACPA)	≤ 0.2 (IDOT)	Low/Mid/High (IDOT)
1	96	98	5.90E-04	Low
2	91	95	3.15E-04	Low
3	94	97	NA	NA
4	98	99	1.97E-04	Low
5	88	94	1.61E-03	Low

- IDOT standards for joint faulting were met for all tested specimens: Relative deflection values ranged from **3.15×10^{-4}** to **1.61×10^{-3} in**, well within the allowed limit (0.2 in).

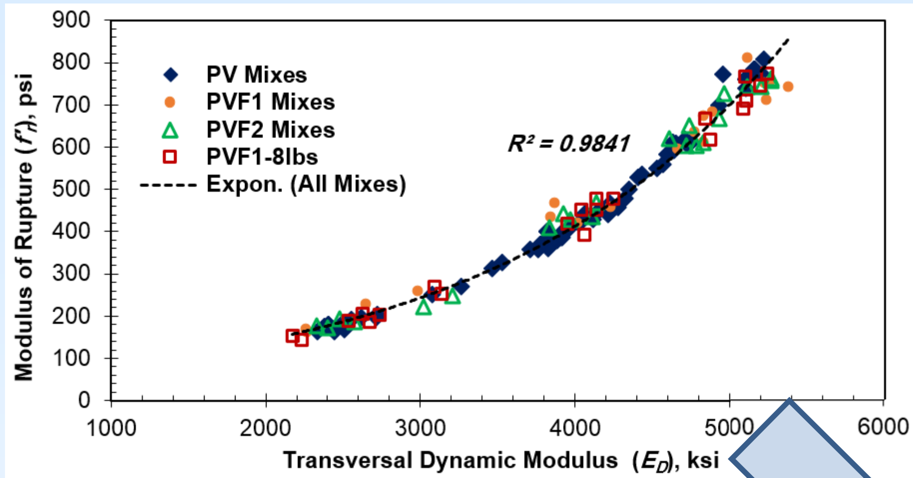
Summary of Task 5: Outcome of the experimental study

- Opening newly paved PCC sections to high traffic volumes at early concrete age is shown to be plausible. The jointed slab specimens remained rigidly connected with adequate joint transfer performance: **LTE ranged from 88 to 98%** while **E ranged from 94 to 99%** which met the ACPA (1991) requirements (LTE= 60%, E= 75%).

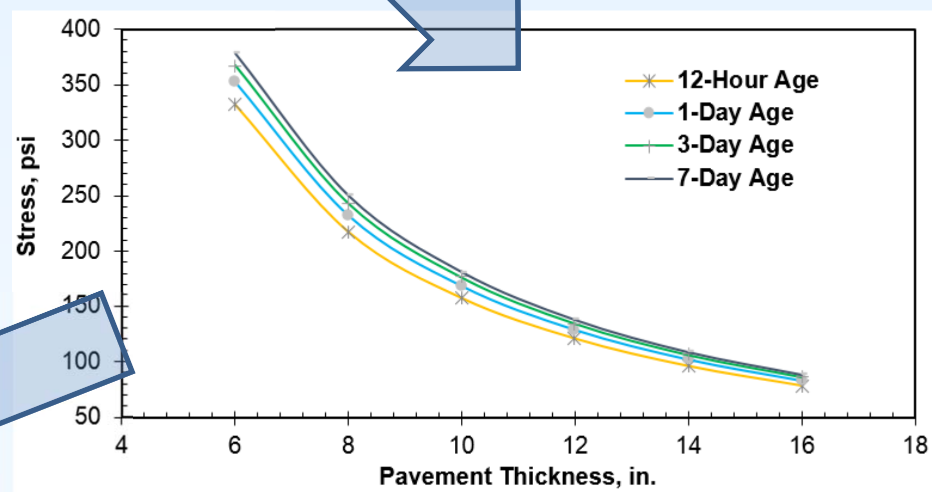
Task 6: Analysis of Results

Incorporating Experimental Results + Numerical Results

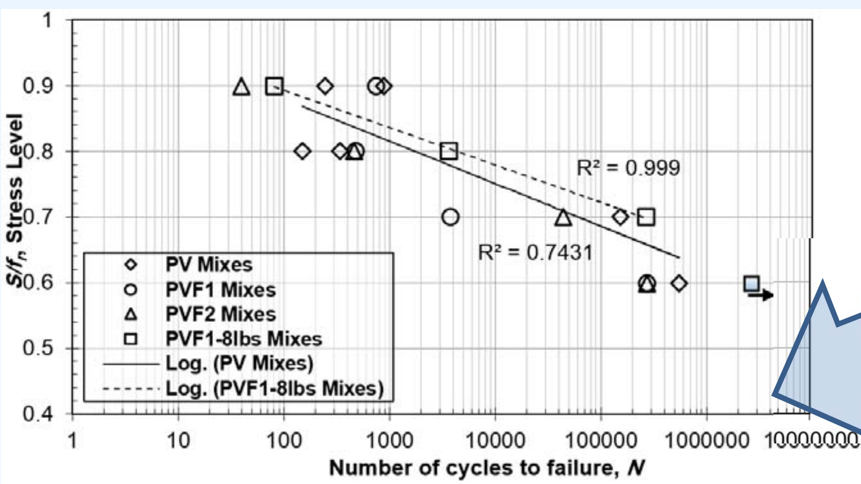
(1) *MOR- E_D*



(2) Numerical Results



(3) Fatigue Performance



Design Aids for Early Opening to Traffic

- The following steps are presented in a simplified manner to fit the general formatting layout of the Illinois *Bureau Design and Environment Manual (BDE Manual)*.

- Experimental and numerical data can be implemented in future design aids currently under development by IDOT.

Design Aids for Early Opening to Traffic

Step 1: Determine dynamic modulus

$$E_D = C\,M\,n^2$$

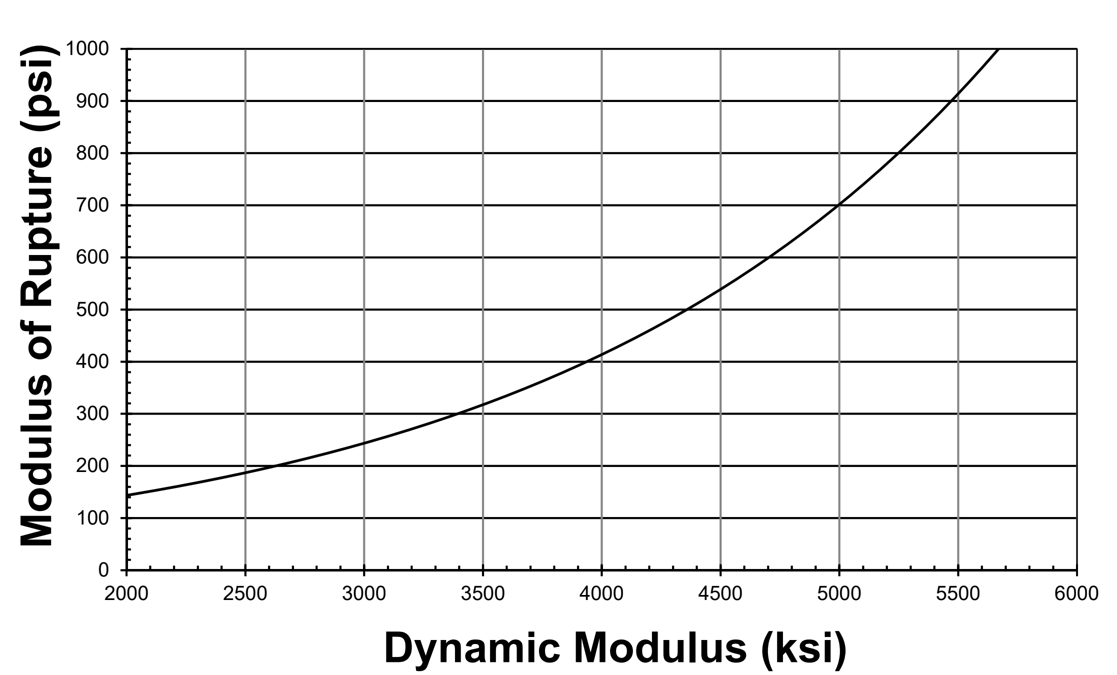
E_D	=	*dynamic modulus in Pascal, converted to ksi for Step 2*
M	=	*mass of beam specimen, kg*
n	=	*transverse resonant frequency, Hz*
C	=	*0.9464 (L3T/bt3)*
T	=	*correction factor (t/3.464)*
L	=	*length of specimen (0.53 m)*
t	=	*depth of specimen (0.15 m)*
b	=	*width of specimen (0.15 m)*

Design Aids for Early Opening to Traffic
Step 2: Determine modulus of rupture

$$MOR = 49.86\, e^{49.86\; 10^{-4} E_D}$$

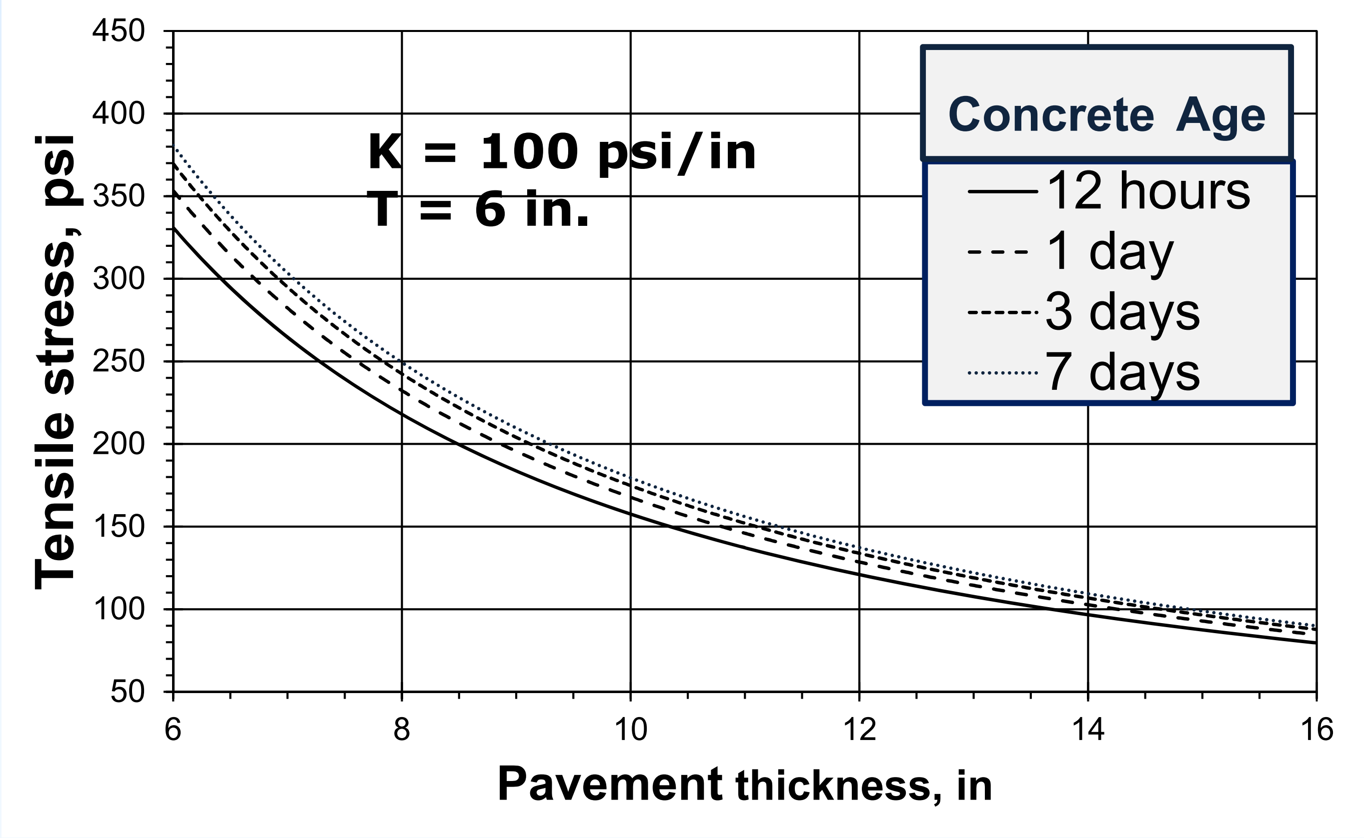
MOR	=	*modulus of rupture, psi*
ED	=	*dynamic modulus of elasticity Step 1, ksi*

- The modulus of rupture can be alternatively obtained



Design Aids for Early Opening to Traffic
Step 3: Determine tensile stress

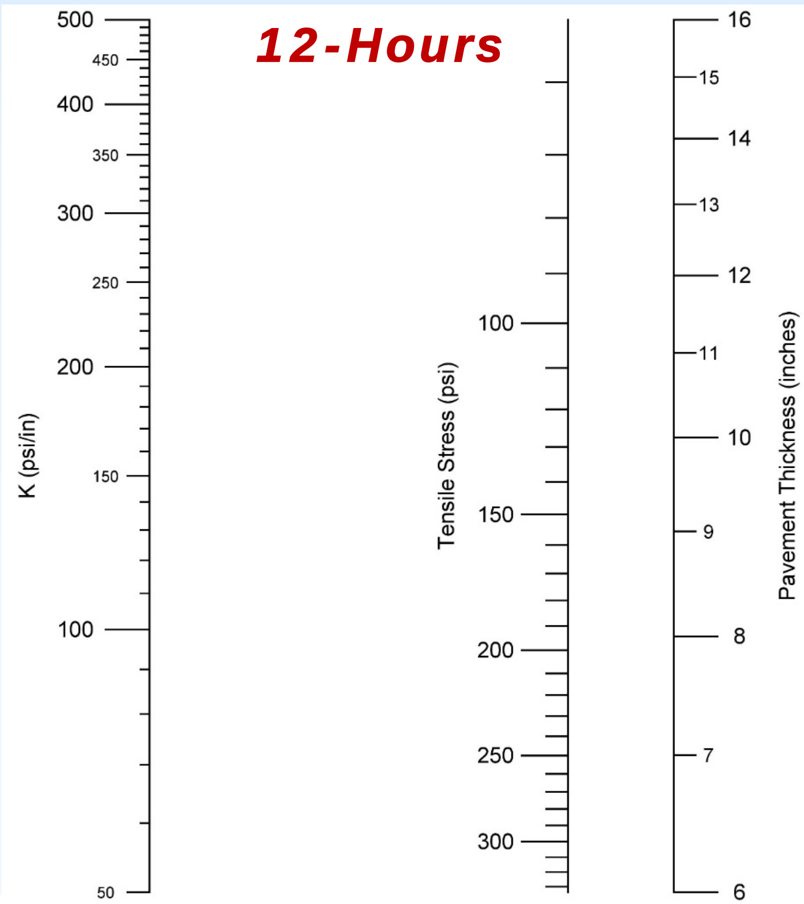
- **Option 1**: Use the charts for a specified ***subgrade modulus reaction value*** (50–500 psi/in.) and ***pavement age***.

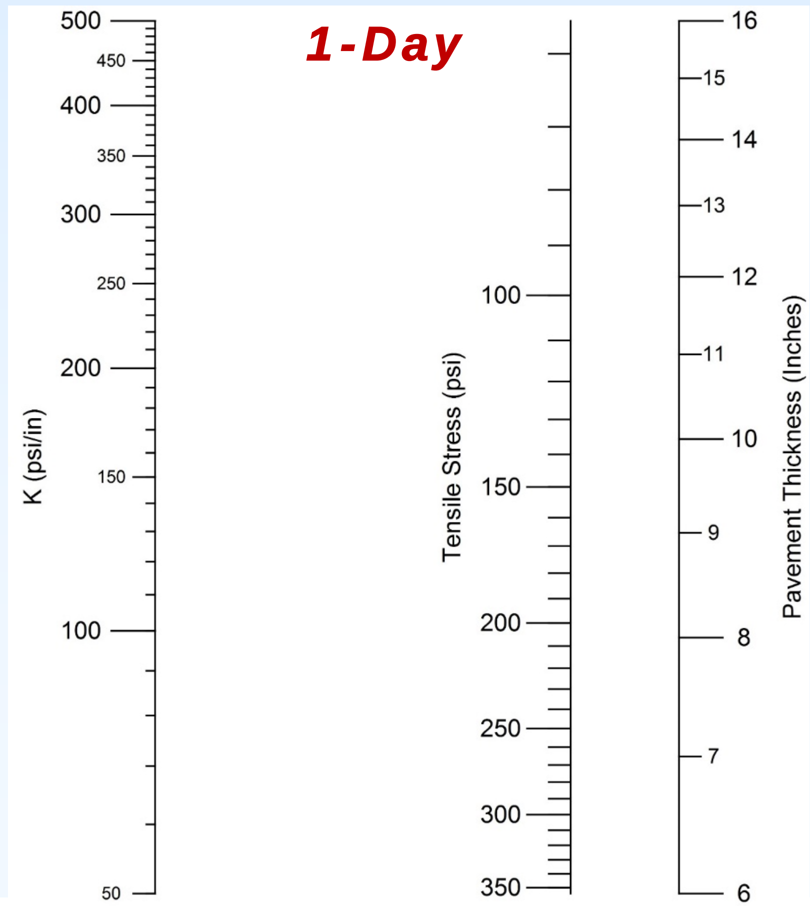


Design Aids for Early Opening to Traffic

Step 3: Determine tensile stress

- **Option 2**: Use nomographs or a specified ***concrete age*** (12-hrs to 7 d).





Design Aids for Early Opening to Traffic

Step 3: Determine tensile stress

$$S = \frac{\sigma}{MOR}$$

S	=	*stress-level ratio*
σ	=	*maximum developed tensile stress, psi*
MOR	=	*modulus of rupture, psi*

Step 4: Determine fatigue life

The number of cyclic loads until failure (**N**) is determined using ***S-N curve relationships*** for **plain** and **fiber-reinforced concrete** pavement mixes.

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Step 4: Determine fatigue life

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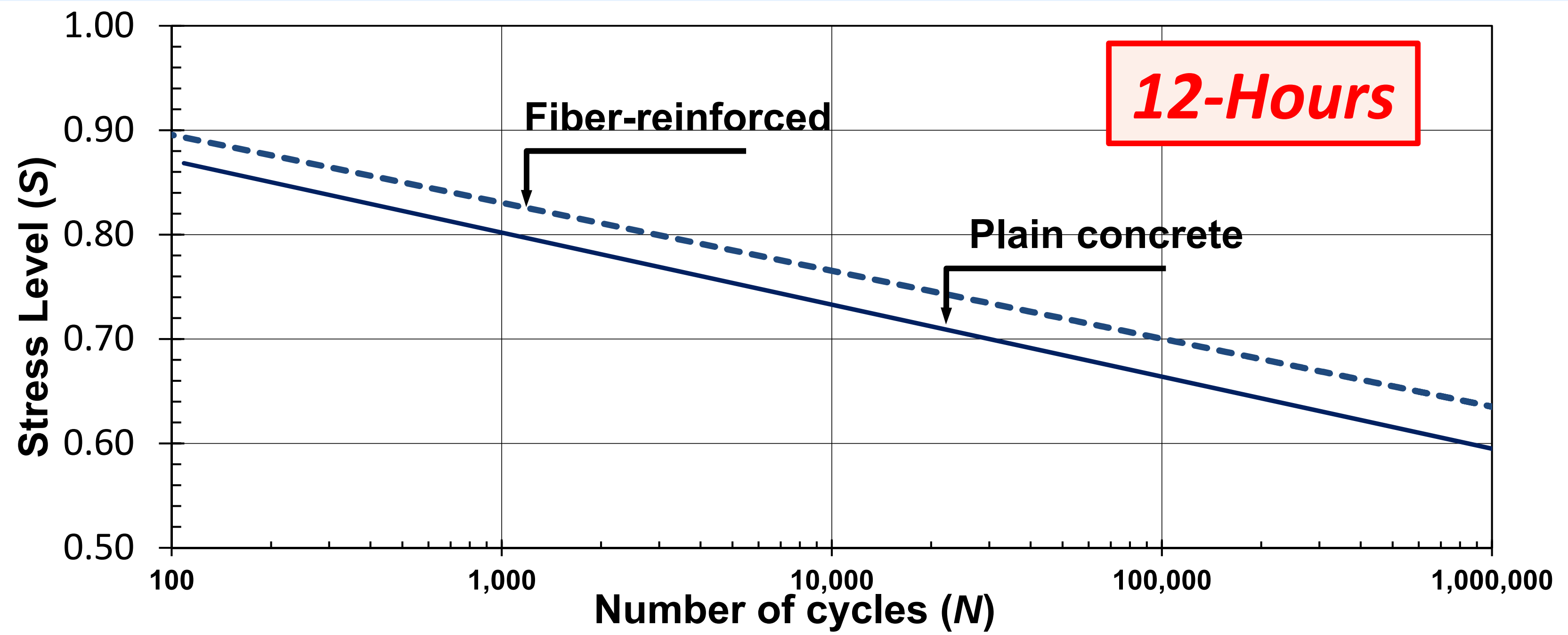
Age	Mix type	S-N linear regression relationships
12 hr	Plain	$N = E^{(1.0090-S)/0.030}$
	FRC	$N = E^{(1.0257-S)/0.028}$



Evaluation of jointed slab fatigue life using implementation procedure

Step I: Estimating flexural strength using non-destructive measures (ASTM C215)

- Dynamic Modulus test at 1-Day concrete age

$$E_{D\ Trans.} = CMn^2$$

$$\boldsymbol{E_{1-Day} = 29381\text{MPa} = 4264.1\ \text{ksi.}}$$

Where C = 0.9464 (L^3T/bt^3) = 396 m^{-1}

M = mass of specimen= 28.2 kg

n = fundamental transverse frequency at 1-Day concrete age= 1621.09 Hz.

Evaluation of jointed slab fatigue life using implementation procedure

Where:

- E_D = Dynamic modulus in Pascals converted to ksi for Step 2.
- M = Mass of beam specimen, Kg.
- n = Transverse resonant frequency, Hz.
- C = 0.9464 (L^3T/bt^3).
- T = correction factor (t/3.464).
- L = Length of specimen (0.53 m).
- t = Depth of specimen (0.15 m).
- b = Width of Specimen (0.15 m).

Step I: Estimating flexural strength using non-destructive measures (ASTM C215)

- Flexural strength calculation:

$$f_{r,\,estimated} = 49.86\, e^{5.29\, 10^{-4} E_D}$$

$$f_{r,\,estimated} = 49.86\, e^{5.29\, 10^{-4}\, 4264.1\ \text{ksi.}} = 476\, psi$$

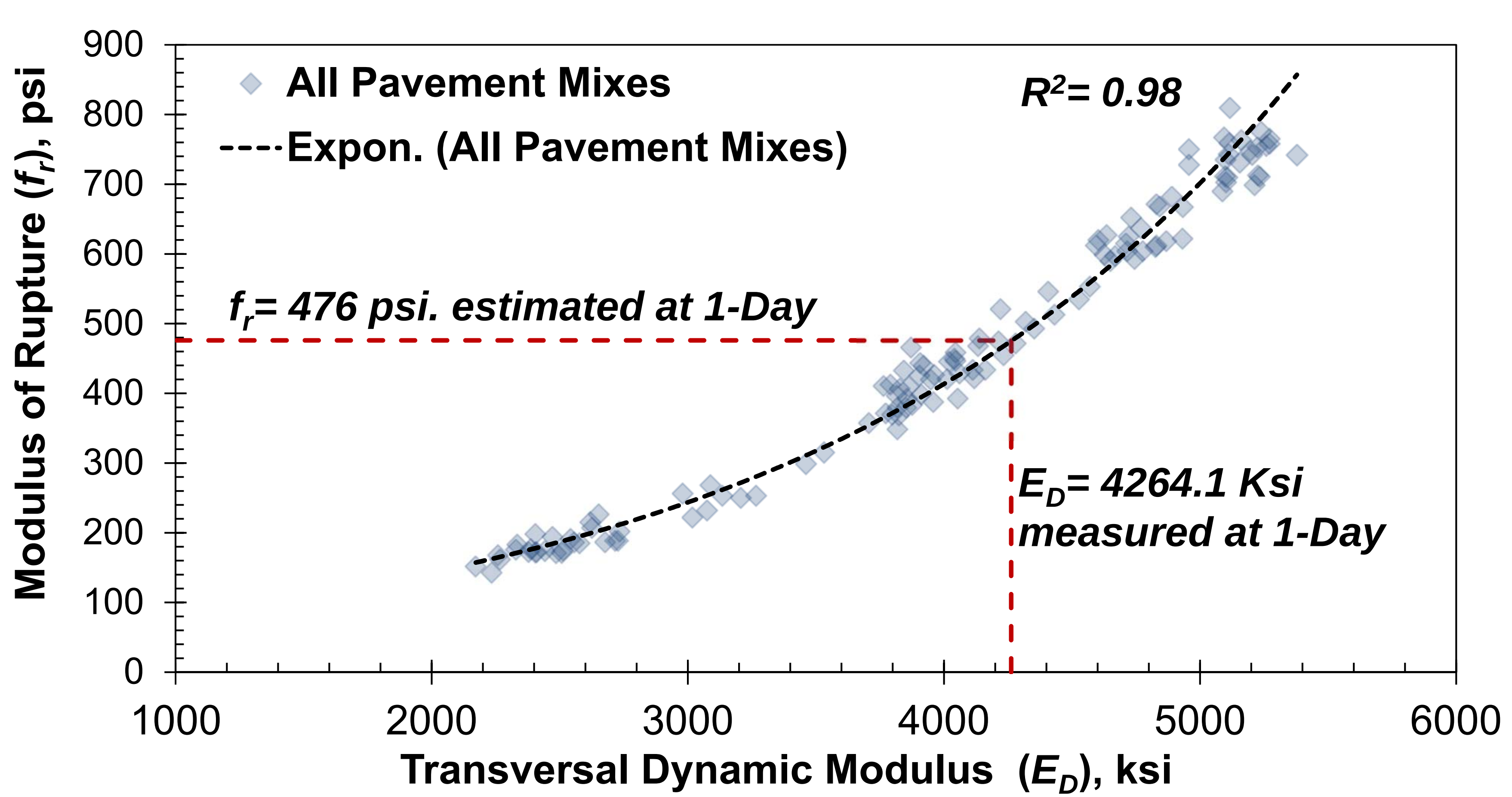
$$f_{r,\,actual} = 465\, psi = \mathbf{97.7\%}\, f_{r.\,estimated}$$

Where f $_{r,\ actual}$ is measured as per ASTM C78

Task 6: Analysis of Results

Step I: Estimating flexural strength using non-destructive measures (ASTM C215)

Modulus of rupture vs. E_D for PV mixes



Step II: Estimation of flexural stresses in concrete pavement using ISLAB2000 analytical model results

Required variables are used to estimate the maximum tensile developed stress at the bottom of the PCC layer:

1- Concrete age: **1-Day**

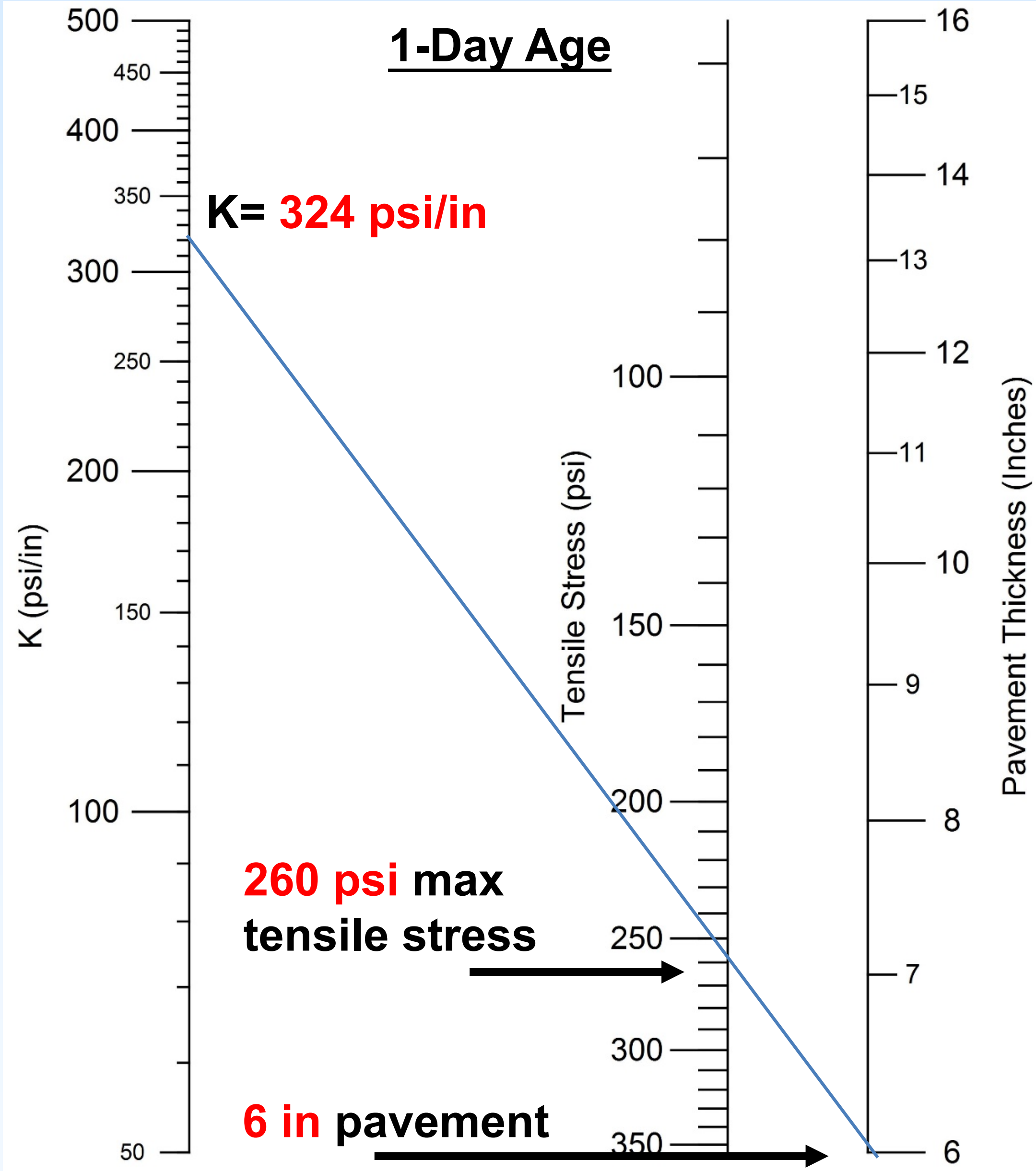
2- Subgrade modulus reaction: Measured at **324 psi/in**

3- Pavement thickness: **6 in**

Task 6: Analysis of Results

Step II: Estimation of flexural stresses in concrete pavement using ISLAB2000 analytical model results

- **Nomographs** correlating subgrade modulus, thickness, and max. stress
- Graphs developed for every concrete testing age: **12-Hour, 1-Day, 3-Day, and 7-Day**



Task 6: Analysis of Results

Step III: Estimation of flexural fatigue life of jointed pavement slab

$$S_{1-Day} = \frac{\sigma_{max}}{f_r} = \frac{260\ psi}{465\ psi} = 0.56$$

$$N_{1-Day} = e^{-\left(\frac{S_{1-Day}-1.0066}{0.025}\right)} = 57.31 \times 10^6\ cycles$$

$$Fatigue\ Life = \frac{N_{1-Day}}{4\ hz} = 14.32 \times 10^6\ seconds = 165\ Days$$

Where $S_{1\text{-}Day}$ = Stress level at 1-Day concrete age

$N_{1\text{-}Day}$ = Number of cycles until failure after 1-Day loading

σ_{max} = Maximum tensile stress developed at the bottom concrete layer due to ESAL. (Step II). = 260 psi.

Task 6: Analysis of Results

Step III: Estimation of flexural fatigue life of jointed pavement slab

S-N Curve at 1-Day concrete age for PV mixes