Effect of Early-Age Concrete Elastic Properties on Fatigue Damage in PCC Pavements With & Without Fibers

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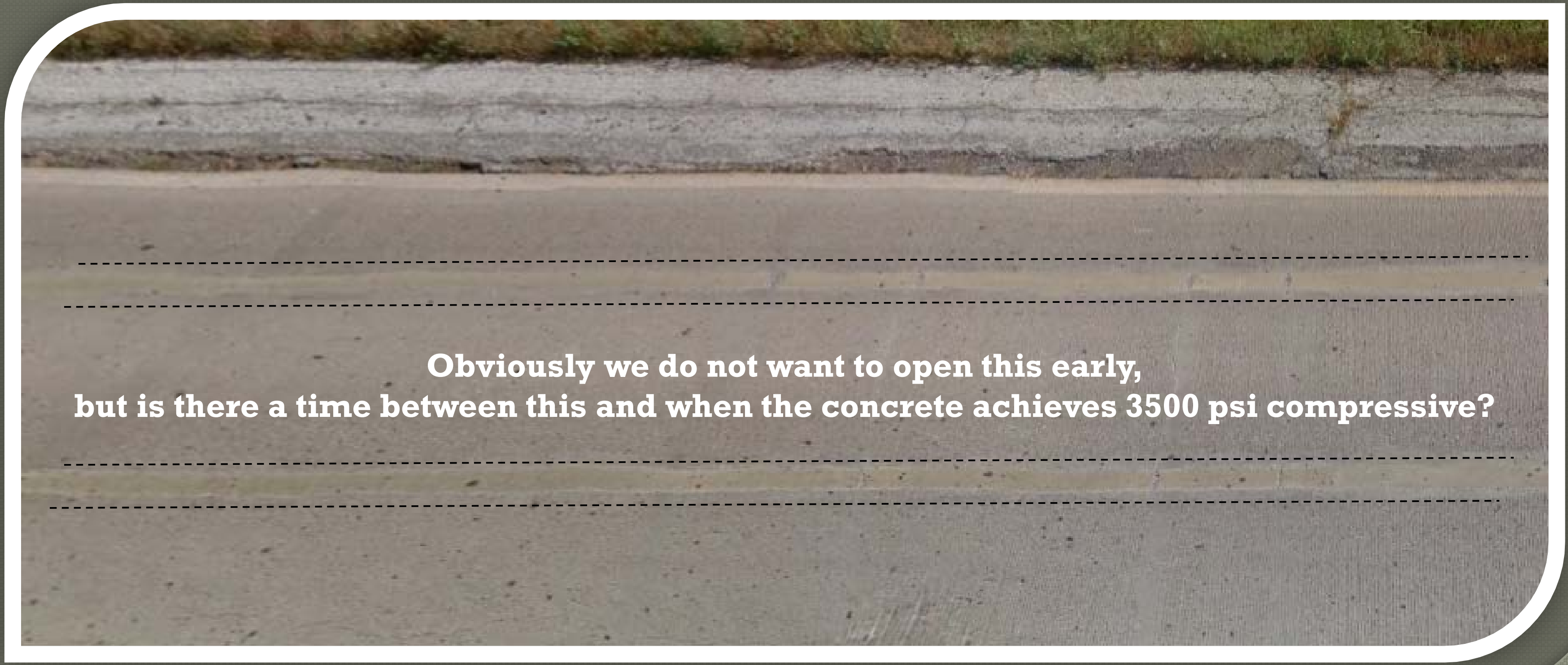
The Research Objective

- **Technically:** To investigate how early-age elastic properties in concrete pavements might resist damage due to early loading fatigue, particularly as it impacts long-term durability.
- **Basically:** Can ordinary PCC pavements or patches be opened earlier than currently specified? Does including fibers help?
- **Why?** May result in decreased time for opening to traffic: potential cost savings through use of shorter periods of traffic control, as well as potential for enhancing highway user satisfaction.

Our Inspiration

- A 20+ yr-old pavement showing no damage associated with it having been driven on when it was ‘green’ enough to leave tire impressions.



Primary Research Tasks

- Literature Review
- **Stage 1:** Laboratory Characterization of Mixes
  - Conventional paving and patching concrete with & without structural synthetic fibers
- **Stage 2:** Parametric Finite Element Analysis
- **Stage 3:** Laboratory Study of Jointed Slab Sections
- Final Report (September/October 2017)

Stage 1 Testing Highlights:
Nominal Mix Designs

Mixture	Cementitious, pcy	w/cm	Slump, in.	Air, %	Fiber*, pcy
PV	565	0.42	2 - 4	5.0 - 8.0	--
PV-Fiber	565	0.42	2 - 4	5.0 - 8.0	4, 6, & 8
PP-1	650	0.42 - 0.44	2 - 4	4.0 - 7.0	--
PP-1-Fiber	650	0.42 - 0.44	2 - 4	4.0 - 7.0	4
PP-2	735	0.36	2 - 6	4.0 - 6.0	--
PP-2-Fiber	735	0.36	2 - 6	4.0 - 6.0	4
***Two different brands of synthetic fibers were investigated**					

- Type I Portland Cement
- Grade 100 Slag Cement @ 25% replacement
- Natural Sand
- ¾" Crushed Limestone

Stage 1 Testing Highlights:
Mix Characterization

Mechanical Properties

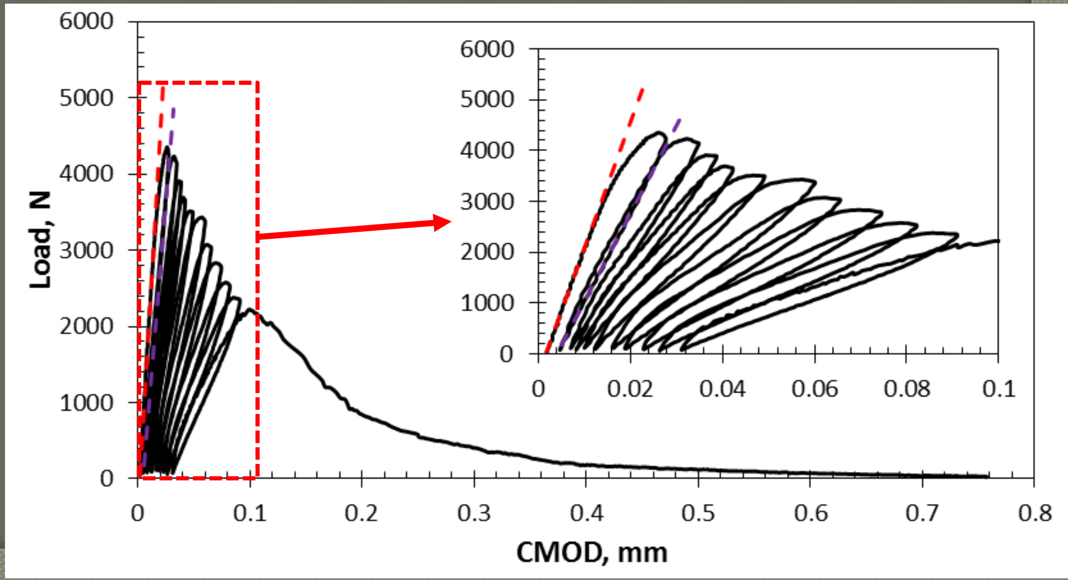
- Compressive Strength
- Flexural Strength (Modulus of Rupture, MOR)
- Flexural Toughness (T_{150}^{D})
- Static Elastic Modulus (E_S)
- Relative Dynamic Modulus (E_D)

All tests performed at the following ages:

- 12, 24, & 72 hrs and
- 7, 14, & 28 days

Stage 1 Testing Highlights: Mix Characterization Cont'd

- Fracture Mechanics
  - 3x4x16-in. notched prism
  - Followed RILEM (Jenq & Shah, 1985) to calculate Critical Stress Intensity Factor (K_{IC}) and Critical Crack Mouth Opening Displacement ($CMOD_C$)
  - For each test, 2 cylinders were tested for RDM and compressive strength



Stage 1 Testing Highlights: Fatigue Testing

- Flexural Fatigue Testing
  - Developed S-N curves for 6x6x21-in. beams tested at 12, 24, & 72 hrs, and 7 days of age
  - Range of applied stresses was determined based on MOR of the mix at each age
    - $\sigma_{i\_max} = S_i \times MOR$
    - $\sigma_{i\_min} = 0.1 \times \sigma_{i\_max}$
  - Stress Levels (S_i) were set to 0.9, 0.8, 0.7, & 0.6

Stage 1 Testing Highlights: Fatigue Testing

Accounting for early-age strength gain

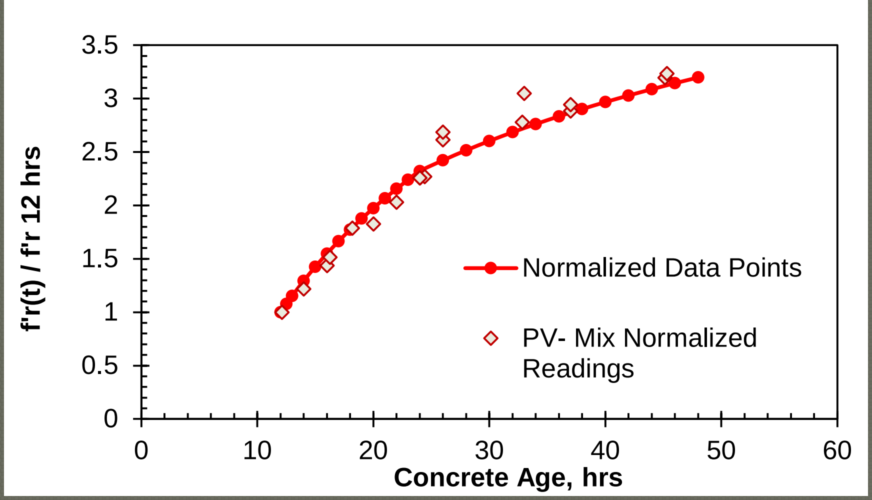
- As the concrete gains strength, the stress level will decrease.
- Thus, it was necessary to increase amplitude and mean load with time to maintain a constant stress level during testing.

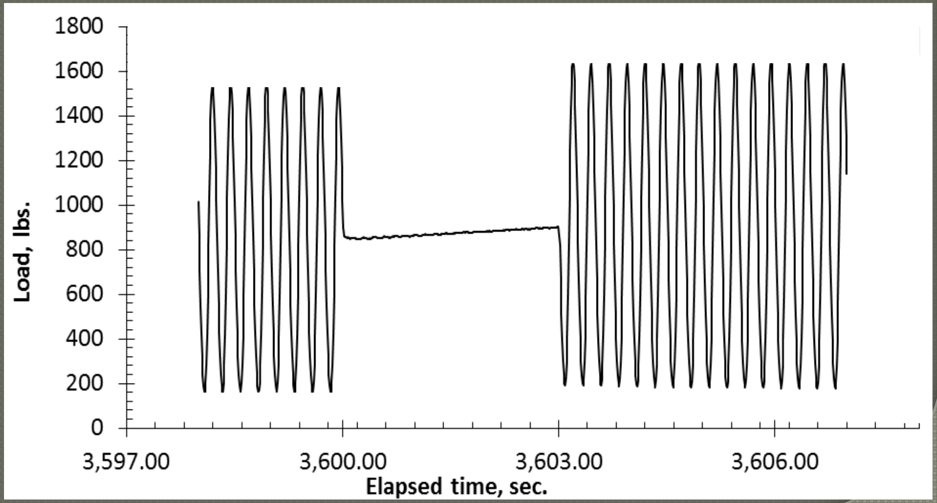
Stage 1 Testing Highlights:

Fatigue Testing – Early Strength Gain

A logarithmic function (normalized with respect to MOR @ 12 hrs) was developed to predict the strength gain over 48 hrs:

$$f'_r(t)/f'_{r\,12\,hrs.} = \begin{cases} \dfrac{-733 + 374\,\text{Log}(t)}{196} & \text{for 12 hrs} \leq t \leq \text{24 hrs} \\ 2.32 \times \dfrac{-302 + 225\,\text{Log}(t)}{413} & \text{for 24 hrs} < t \leq \text{48 hrs} \end{cases}$$

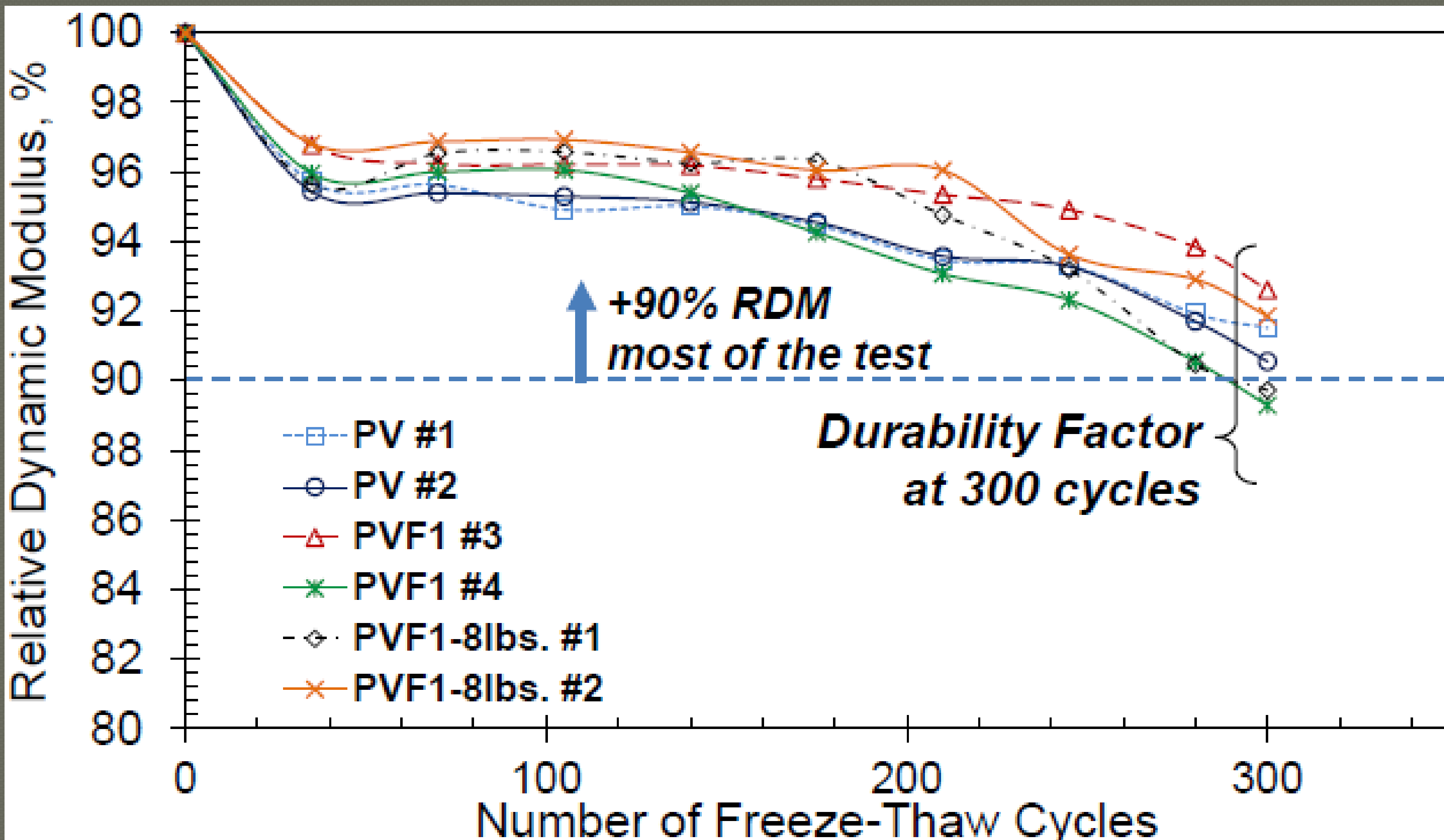




Stage 1 Testing Highlights: Fatigue Testing & Durability

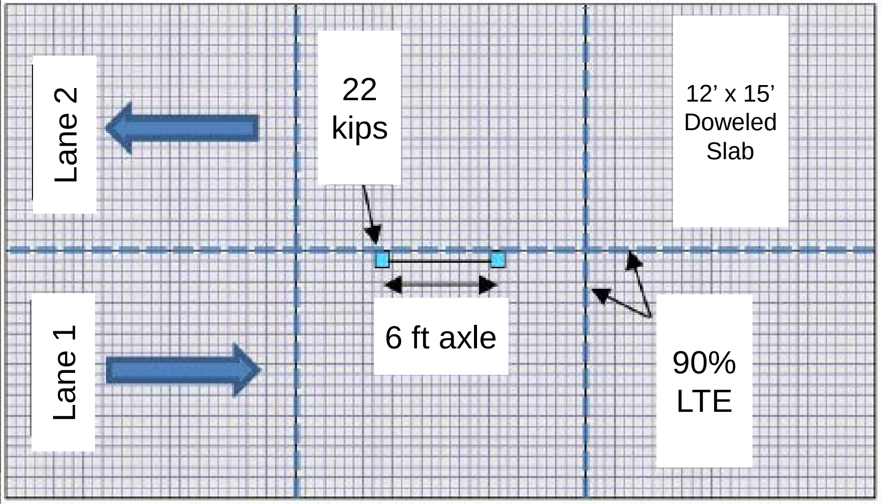
- **Next step:** Can we subject a specimen to fatigue and then assess its long-term durability?
- **What did we try?**
  - First, subject specimen to fatigue cycling at early ages: 12 hrs, 24 hrs, 72 hrs, & 7 days
  - Then, subject specimen to freeze/thaw (ASTM C 666, Procedure A)
  - Assess damage in terms of RDM

Stage 1 Testing Highlights:
Fatigue Testing & Durability



Stage 2
Analysis and Modeling

- Finite Element Analysis was used to correlate the physical and fatigue testing results to pavement response
- Parametric modeling was used to identify the stress level generated at critical positions due to ESAL loadings,
- For example: Cross-Traffic
  - Critical case for truck loading a slab transversely
  - Higher axle loading, higher tire contact pressure
  - Looking for cases of flexural failure, shear failure, faulting, or corner breaks



Stage 2 Analysis and Modeling: Design Parameters

- Pavement Thickness: 6, 8, 10, 12, 14, and 16 in.
- Modulus of Subgrade Reaction: 50, 100, 200, 300, and 500 psi/in.
- MOE estimated empirically based on test results obtained during mix characterization

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

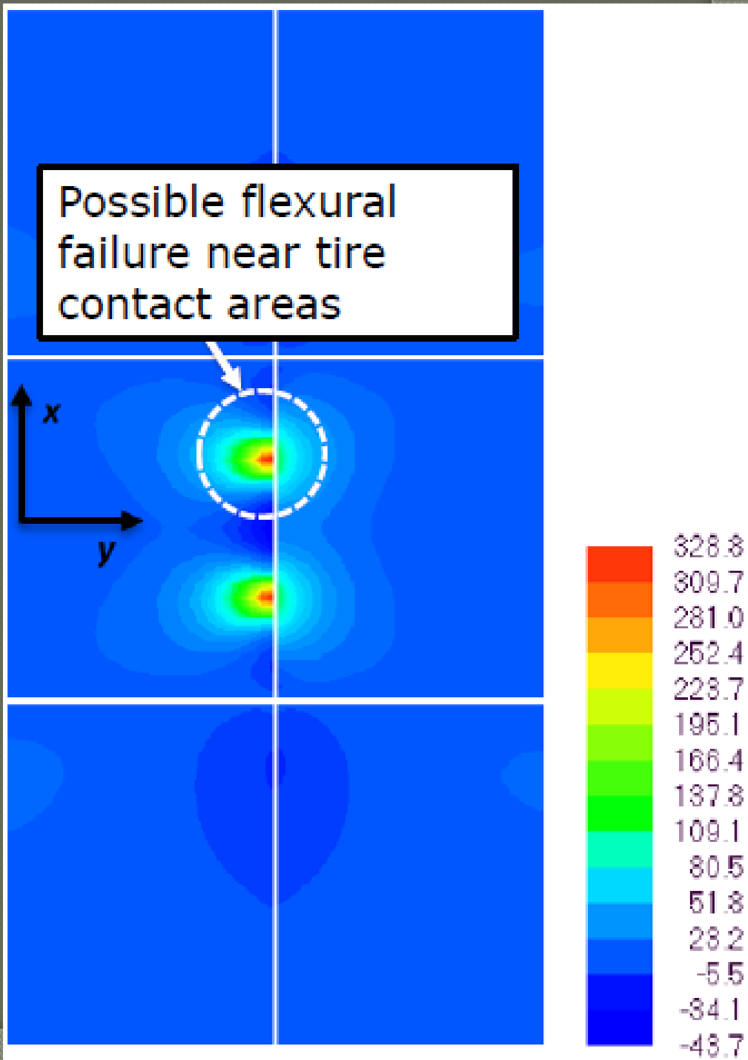
Stage 2 Analysis and Modeling: Design Parameters Cont'd

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)	134 in, 229.2 in.
	Axle load	**22,000 lbs.**
	Contact area of tires	200 in^2
	Tire Pressure	**110 psi**
Joint parameters	**LTE**	**90%**

Modeling Results
Cross-Traffic Construction Traffic

Out of 120 cases

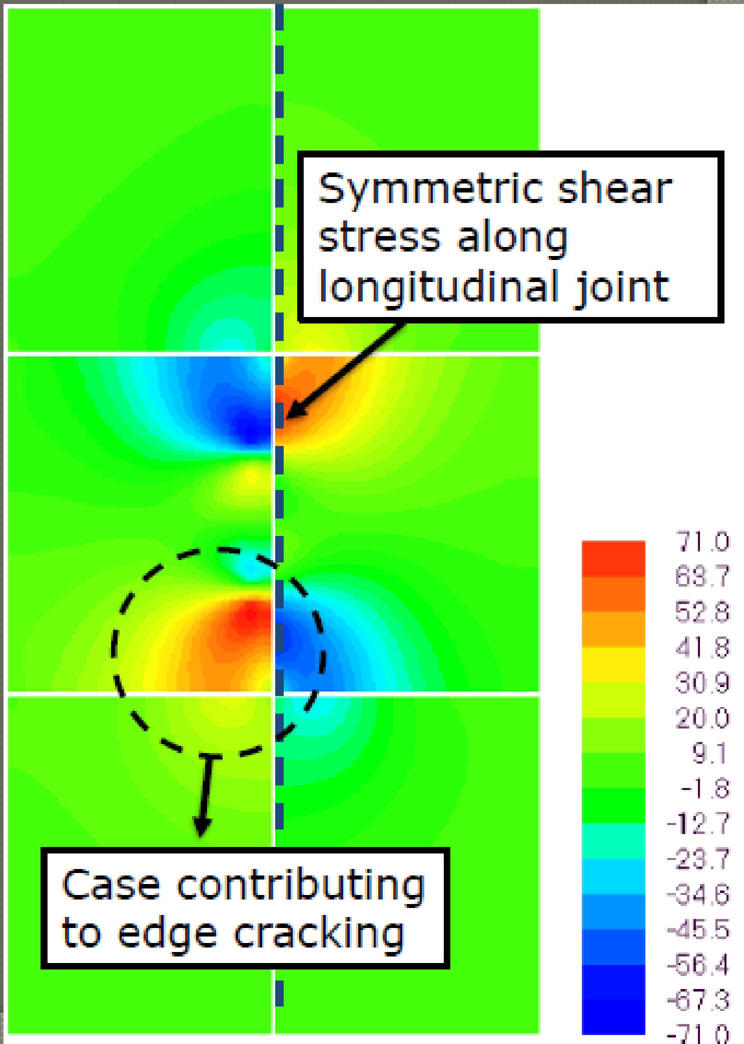
- Possible flexural failure when opening at:
  - 12 hrs: 16 cases when t ≤ 12”
  - 24 hrs: 7 cases when t ≤ 8”
  - 72 hrs: 1 case when t = 6”
  - 7 days: none



Modeling Results

Cross-Traffic Construction Traffic

- Possible shear failure when opening at:
  - 12 hrs: 11 cases when t ≤ 10”
  - 24 hrs: 7 cases when t ≤ 8”
  - 72 hrs: 5 cases when t = 6”
  - 7 days: 4 cases when t = 6”
- Majority of these ‘failing’ cases were for a combination of variables probably unlikely to occur in the field (e.g., very low modulus of subgrade reaction).



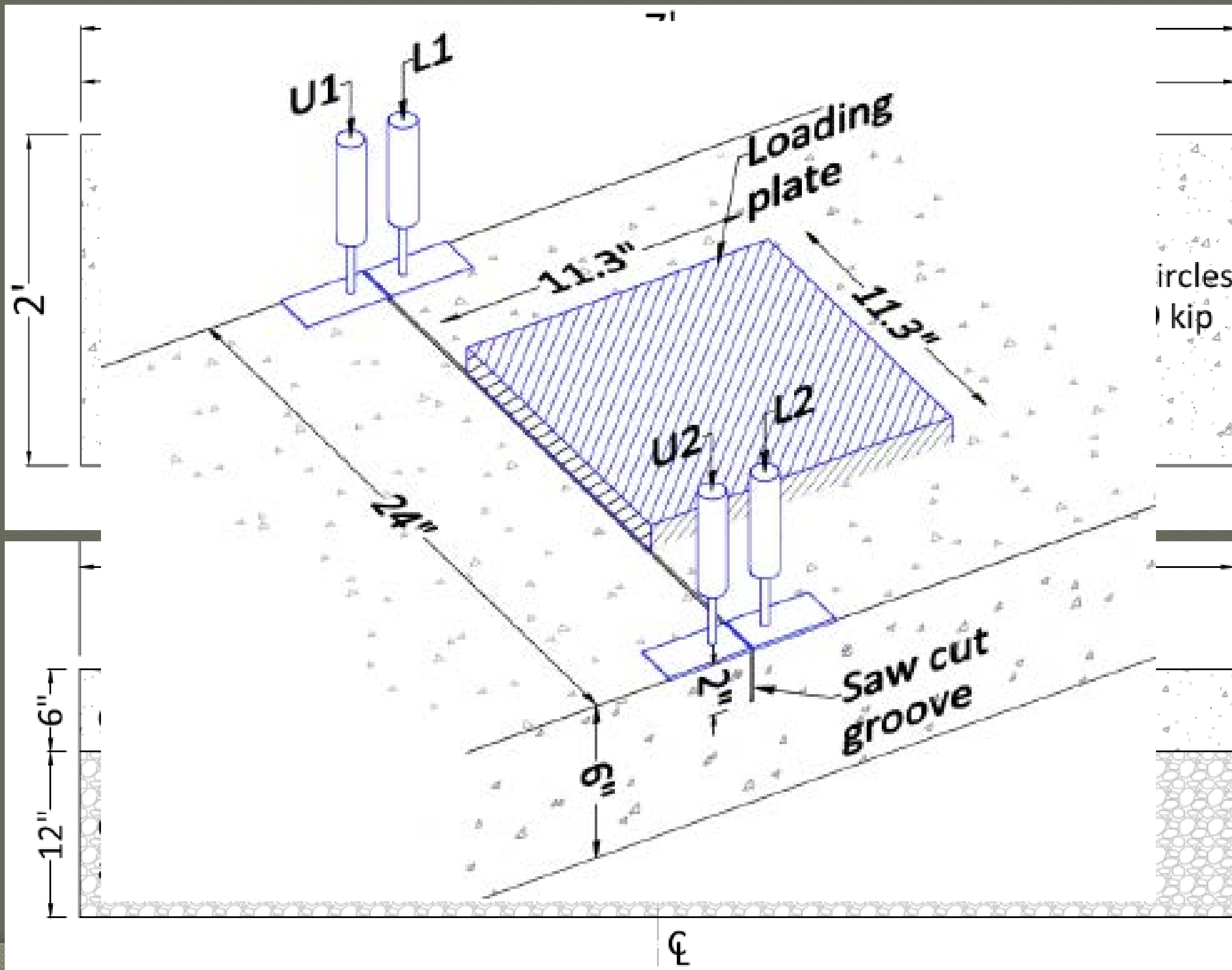
Stage 3 Laboratory Study of JPCP Slabs: Currently In Progress

- **What?** Subjecting early-age fatigue loading to experimental-scale jointed slabs
  - Thicknesses: 6 & 8 in.
  - With & without fibers (4 & 8 pcy)
  - With & without dowels (1 & 1-1/4 in.)
- **Why?** Complements the physical testing and analytical modeling already conducted
  - Also, provides information regarding joint effects: shear, bending, flexural stresses, dowel bar effects

Stage 3 Laboratory Study of JPCP Slabs: Experimental Setup

Top View

Side View



Stage 3 Laboratory Study of JPCP Slabs: Loading Parameters

- Start with static loading to **9 kips** (½ ESAL)
  - Rate of loading **0.02 in/min**
- Measure initial **Load Transfer Efficiency** and **Joint Effectiveness (E)**
- Commence **cyclic fatigue** at 4 Hz
  - Max. applied load: **9 kips**
  - Min. load: 0.1(Max)
- Measure LTE and E @ **10,000**; **100,000**; **300,000**; **700,000;** and **1,000,000** cycles
  - **LTE > 60 % or E > 75%** are considered adequate after **1 million cycles** as recommended by ACPA

Stage 3 Laboratory Study of JPCP Slabs: 1st Slab Tested

- Max. applied load: **9 kips** (initially)
- No. of cyclic loads: **1 million** cycles, then extended to **2.3 million**
- **LTE** and **E** values: **100%**
- Overall deflection: **0.462 in.**
- **Contraction joint crack initiation** started at bottom of slab after 250,000 cycles
- Max. applied load was then increased by 50% to **13.5 kips for 1 million more cycles**
  - **LTE** and **E** remained at **100%**
  - Overall deflection: **0.503 in.**
  - No further crack initiation or propagation

What's Next?
Currently In Progress

- Developing a **practical procedure** for determining time to opening based on fatigue testing results, MOR/Dynamic Modulus, and Finite Element Analysis

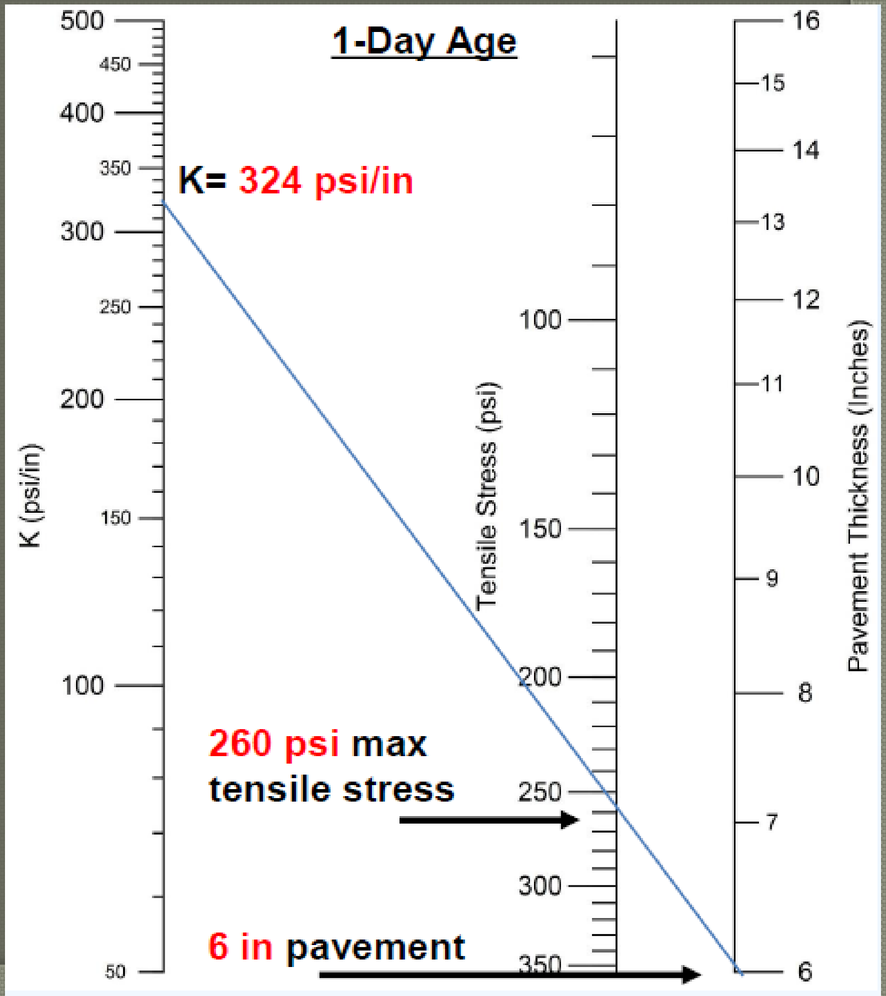
- **What is this looking like so far?**
  - **Nomographs** correlating subgrade modulus, pavement thickness, and max. stress
  - **Fatigue Life formulae** developed for concrete ages: 12, 24, & 72 hrs, and 7 days

Draft Procedure for Early Opening

Example of Nomograph

- Concrete @ 24 hrs
- Modulus of Subgrade Reaction, k (psi/in)
- Pavement Thickness (in.)

Estimates maximum tensile stress to develop at the bottom of the slab under 1 ESAL



Draft Procedure for Early Opening
Example of Fatigue Life Formula

- Concrete @ 24 hrs
  - $S_{24} = \frac{\sigma_{max}}{MOR_{24}}$
  - $N_{24} = e^{-\left(\frac{S_{24} - 1.0066}{0.025}\right)}$
  - $Fatigue\ Life = \frac{N_{24}}{4\ Hz}$
  - Where: σ_{max} = Max. tensile stress developed due to 1 ESAL (from nomograph)

    MOR_{24} = Modulus of Rupture at 24 hrs*

    S_{24} = Stress level at 24 hrs

    N_{24} = No. of cycles until failure

* Can be measured or estimated from correlation to Dynamic Modulus

Question?