Effect of Macrofibers on Behavior and Performance of Concrete Slabs and Overlays

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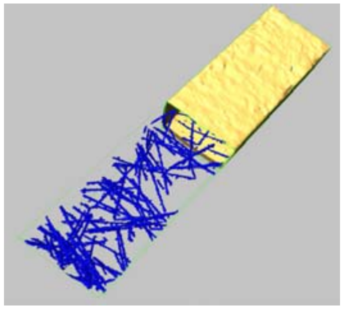
November 7, 2018
TTCC/Fiber Reinforced Concrete Project
National Concrete Consortium
Webinar 2 of 3



Acknowledgements

- 2nd of THREE webinars on FRC overlays
- Presentation and audio will be recorded and posted afterwards
- Webinar information presented can also be found in the upcoming Technical Report and Technical Brief on “Fiber Reinforced Concrete for Pavement Overlays”

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  - TTCC/Fiber-Reinforced Concrete Project
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  - *Drs. Amanda Bordelon, Armen Amirkhanian, Alex Brand*

NATIONAL CONCRETE CONSORTIUM

FRC Overlay Project - Webinars

1. Fiber Reinforced Concrete Overview for Concrete Pavement and Overlays

October 24, 2018 9:00-10:00 a.m CST

This webinar will give a general overview of fibers used for concrete pavements with an emphasis on macrofibers and their effect on concrete properties and pavement construction.

2. Effect of Macrofibers on Behavior and Performance of Concrete Slabs and Overlays

November 7, 2018 9:00-10:00 a.m CST

This webinar will review the significant findings of macrofiber addition to concrete slabs on grade, which include the increase in plain concrete slab capacity, reduction in crack widths, and increase in pavement performance.

3. Overview of Macrofiber Software and Guidelines for Concrete Overlay Design

December 5, 2018 9:00-10:00 a.m CST

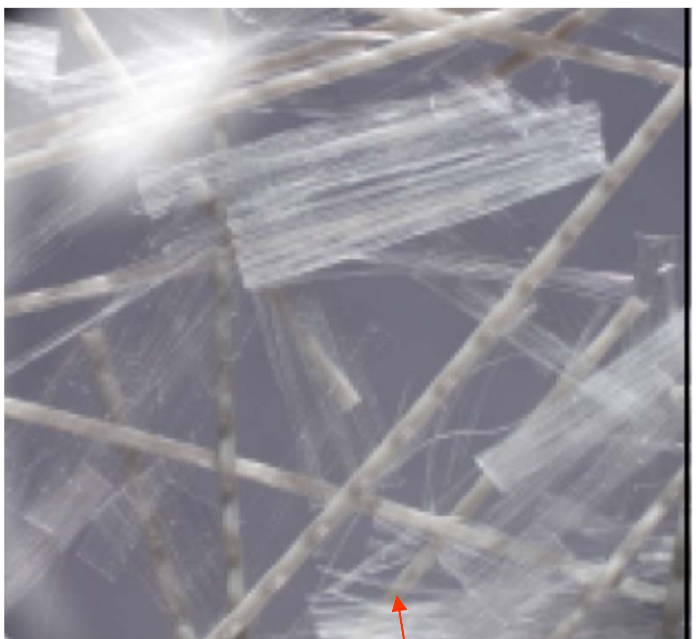
This webinar will provide an overview of the macrofiber software for determining the recommended fiber reinforced concrete residual strength values for application to concrete overlay design.

Webinar Objectives

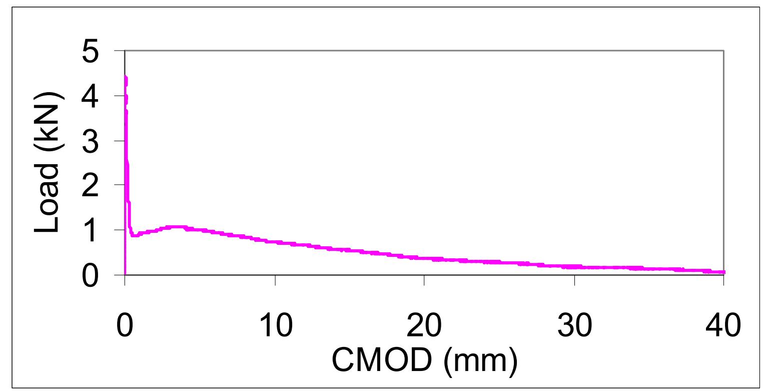
- Review of macrofibers for concrete pavements and overlays
- Overview of concrete slab on grade testing w/ macrofibers
- Full-scale testing of pavements w/ macrofibers
- Macrofibers in concrete overlay projects
- Testing of FRC residual strength

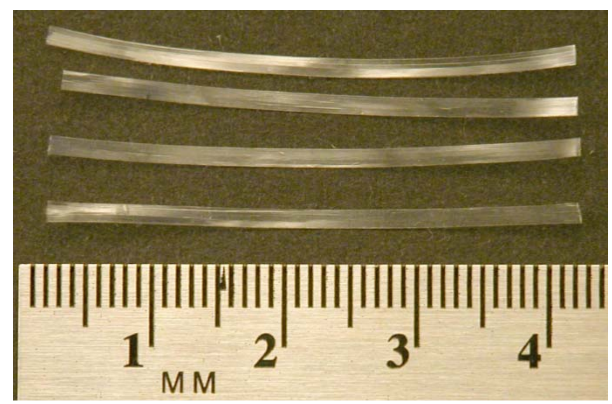
Fiber Type Comparison

- *Structural* (macro-fibers) versus *non-structural* (micro-fibers)



Macro-
Fibers





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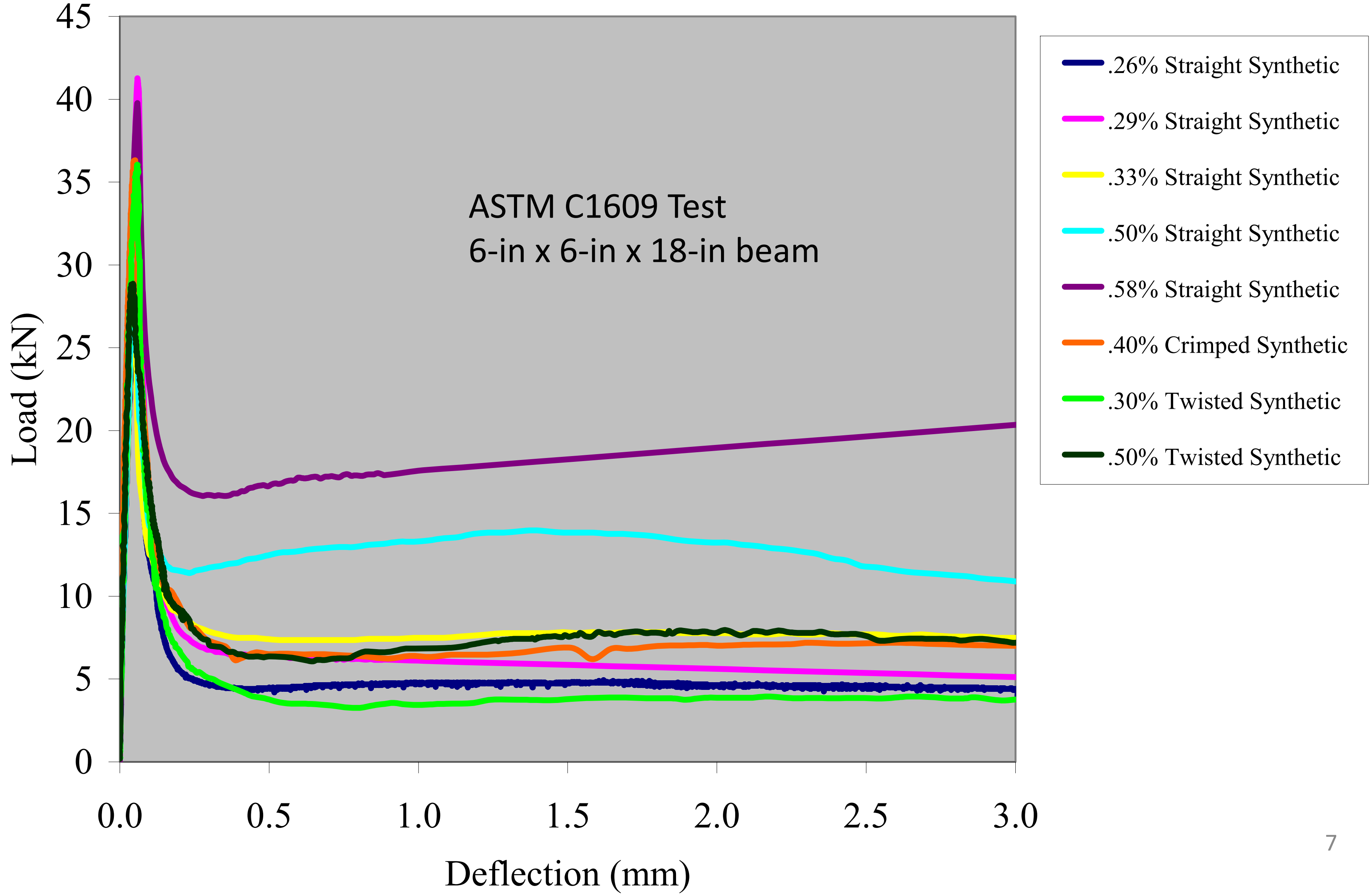
Micro-Fibers – plastic shrinkage (non-structural)

PP – 6.7 lb/yd^3 or 0.44% V_f
Residual strength (e.g., f_{150} = 145 psi)

FRC Beam Toughness or Residual Strength Test (ASTM C1609-12)

6-in x 6-in x 18-in beam

Multiple Synthetic Macro-fibers



MACRO-Fiber Reinforcement Benefits
Concrete Pavements and Overlays

- ***Increase** in structural capacity* of slab
  - reduce required slab thickness (e.g., overlays)
- Maintain crack/joint widths
- Non-uniform support condition
- Tie **longitudinal**/transverse contraction joints
  - *Avoid slab migration*
- Reduce deterioration rates after initial cracking
  - Thin concrete overlays deteriorate more rapidly under traffic

- Should I use fibers on every concrete pavement projects? **NO**

Review of Fiber Reinforced Concrete (Macrofiber) Literature for V_f<1.0%

- FRC *does not* increase tensile or compressive strength of plain concrete
- FRC *does not* increase or *decrease* flexural strength or splitting strength of plain concrete beams
- FRC *does* increase concrete toughness/strain capacity

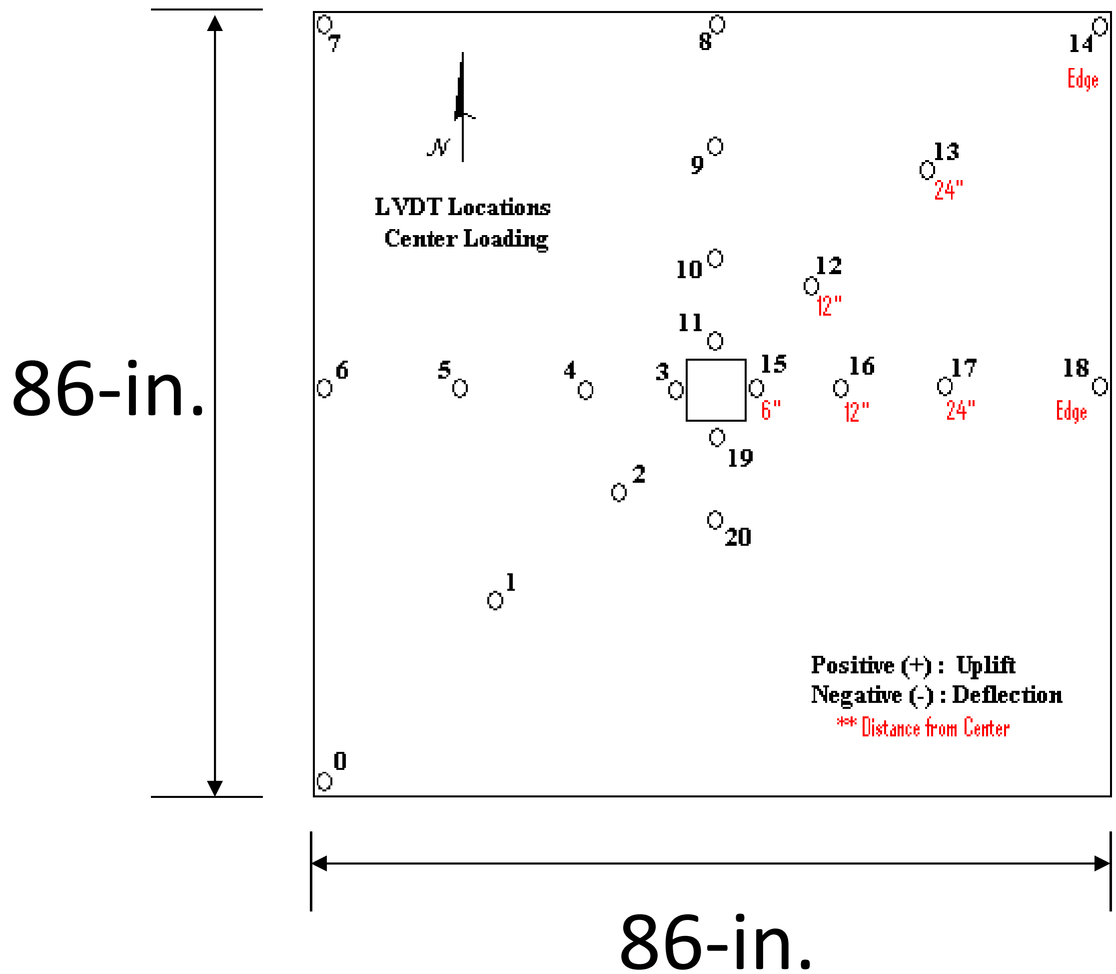
Q1. How do macrofibers affect plain concrete slabs?

Q2. Why use fibers in slabs?

Past Concrete Slab Tests (abridged)

1. Barros, J. & Figueiras, J. 1998. Experimental Behaviour of Fibre Concrete Slabs on Soil. *Mechanics of Cohesive-Frictional Materials* 3: 277-290.
2. Beckett, D. 1990. Comparative Tests on Plain, Fabric Reinforced and Steel Fibre Reinforced Concrete Ground Slabs. *Concrete* 24(3): 43-45.
3. Beckett, D. 1995. Thickness Design of Concrete Industrial Ground Floors. *Concrete* 29(4): 21-23.
4. Beckett, D. 1998. Thickness Design Methods for Concrete Industrial Ground Floors. *Concrete* 32(6): 12-16.
5. Beckett, D., & Humphreys, J. 1989. *Comparative Tests on Plain, Fabric Reinforced and Steel Fibre Reinforced Concrete Ground Slabs*. Thames Polytechnic School of Civil Engineering, Report No. TP/B/1, Dartford.
6. Beckett, D., Van De Woestyne, T & Callens, S. 1999. Corner and Edge Loading on Ground Floors Reinforced with Steel Fibers. *Concrete* 33(3): 22-24.
7. Bischoff, P., Valsangkar, A., & Irving, J. 2003. Use of Fibers and Welded-Wire Reinforcement in Construction of Slab on Ground. *ASCE Practice Periodical on Structural Design and Construction*, 8(1): 41-46.
8. Brand, A., Amirkhanian, A., Roesler, J. (2014), Flexural Capacity of Full-Depth and Two-Lift Concrete Slabs with Recycled Aggregates, Transportation Research Record 2456, pp. 64-72.
9. Falkner, H., Huang, Z., & Teutsch, M. 1995. Comparative Study of Plain and Steel Fibre Reinforced Concrete Ground Slabs. *Concrete International* 17(1): 45-51.
10. Falkner, H. & Teutsch M. 1993. Comparative Investigations of Plain and Steel Fibre Reinforced Industrial Ground Slabs. *Institut für Baustoffe, Massivbau und Brandschutz, Technical University of Brunswick, Germany*, No. 102.
11. Meda, A. 2003. *On the Extension of the Yield-Line Method to the Design of SFRC Slabs on Grade*. Studies and Researches, Vol. 24, Milano, Italy: Politecnico di Milano.
12. Meda, A., Plizzari, G., Sorelli, L., & Rossi, B. 2003. Fracture Mechanics for SFRC Pavement. *Concrete Structures: The Challenge of Creativity*, CEB-FIP.
13. Roesler, J., Altoubat, S., Lange, D., Rieder, K.-A., & Ulreich, G. 2006. Effect of Synthetic Fibers on Structural Behavior of Concrete Slabs on Ground. *ACI Materials Journal* 103(1): 3-10.
14. Roesler, J., Lange, D., Altoubat, S., Rieder, K.-A., & Ulreich, G. 2004. Fracture of Plain and Fiber-Reinforced Concrete Slabs under Monotonic Loading. *ASCE Journal of Materials in Civil Engineering* 16(5): 452-460.
15. Roesler, J.R., Cervantes, V.G, and Amirkhanian, A.N (2012), “Accelerated Performance Testing of Concrete Pavement with Short Slabs”, International Journal of Pavement Engineering, Volume 13, Issue 6, pp. 494-507.
16. Sham, S. & Burgoyne, C. 1986. *Load Tests on Dramix Steel Fibre Reinforced Concrete Slabs.* A Report to Sir Frederick Snow and Partners, Consulting Engineers. Imperial College of Science and Technology, Department of Civil Engineering, Concrete Laboratories.

Test Slab Dimensions



Slab Thickness
5-in

k-value = 370 psi/in

Roesler, Lange, Altoubat, Rieder, Ulreich. (2004), "Fracture of Plain and Fiber-Reinforced Concrete Slabs under Monotonic Loading," *ASCE Jrnl of Matls in Civil Engineering*, Vol. 16, No. 5, pp. 452-60.

Large-Scale Slab Testing Program

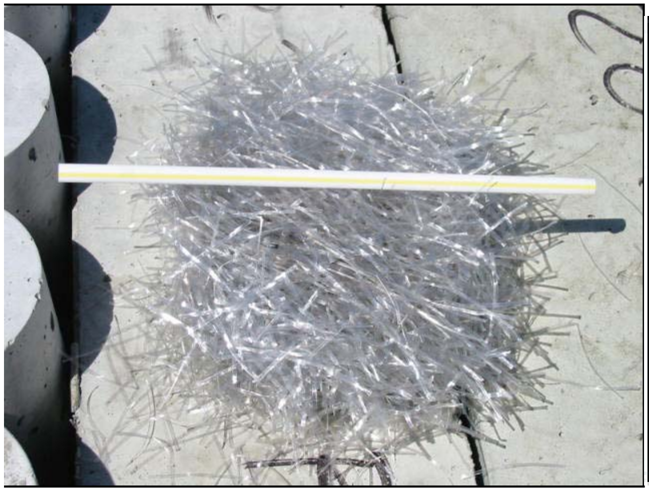
1. Plain Concrete
2. Synthetic Fiber (v_f = 0.48%)*
3. Synthetic Fiber (v_f = 0.32%)
4. Hooked End Fiber (v_f = 0.35%)*
5. Crimped Fiber (v_f = 0.5%)*
6. Welded-Wire Reinforcement
   – 152x152MW19

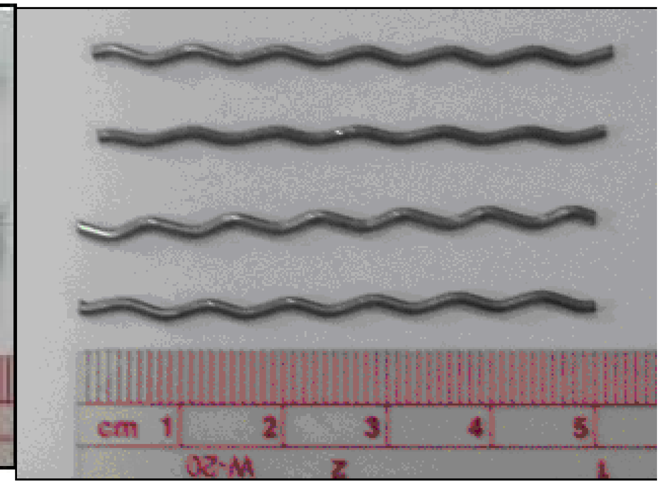
V_f = volume fraction

*designed to achieve similar concrete toughness values

Roesler, Lange, Altoubat, Rieder, Ulreich. (2004), “Fracture of Plain and Fiber-Reinforced Concrete Slabs under Monotonic Loading,” *ASCE Jrnl of Matls in Civil Engineering*, Vol. 16, No. 5, pp. 452-60.

Slab Tests with Macrofiber Types





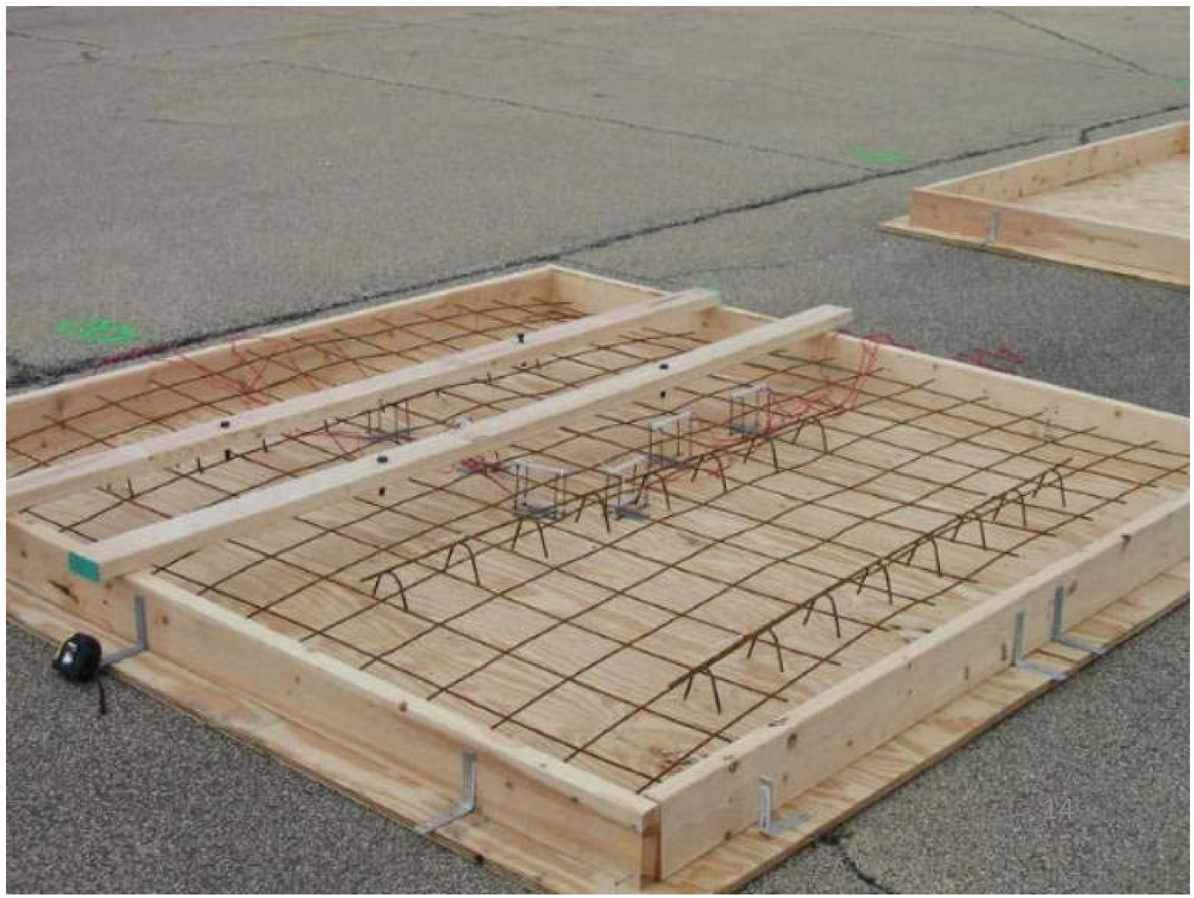
Synthetic Straight
Length = 40mm
Aspect ratio = 90
Tensile Strength = 620 MPa
Elastic Modulus = 9.5 GPa

Steel Hooked End
Length = 60mm
Aspect ratio = 65
Tensile Strength = 1,000 MPa
Elastic Modulus = 180 GPa

Steel Crimped
Diameter = 1.3mm
Aspect ratio = 50
Tensile Strength = 1,000 MPa
Elastic Modulus = 180 GPa

Welded-Wire Reinforcement

- 152 x 152 MW19 (A_s=0.058in.^{2}/ft)
- 1/3 depth from surface (target)



Concrete Mix Design (kg/m^3)

• Coarse Aggregate	976
• Fine Aggregate	807
• Cement Content	360
• Water	183
• Superplasticizer (ml/100kg)	1,117
• W/C Ratio	0.51

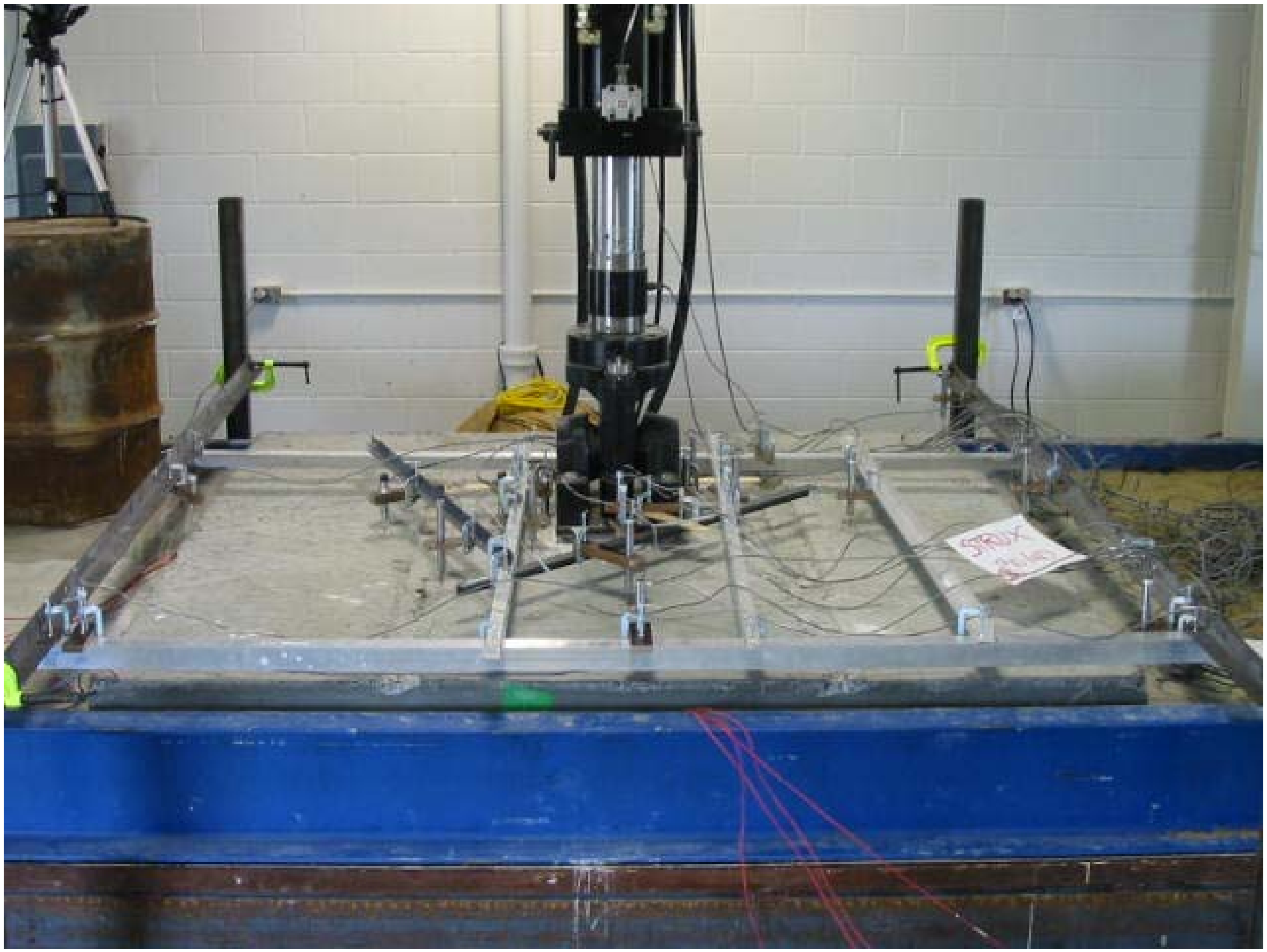
<u>Average Results</u>

Compressive Strength (f’c) = 35 MPa

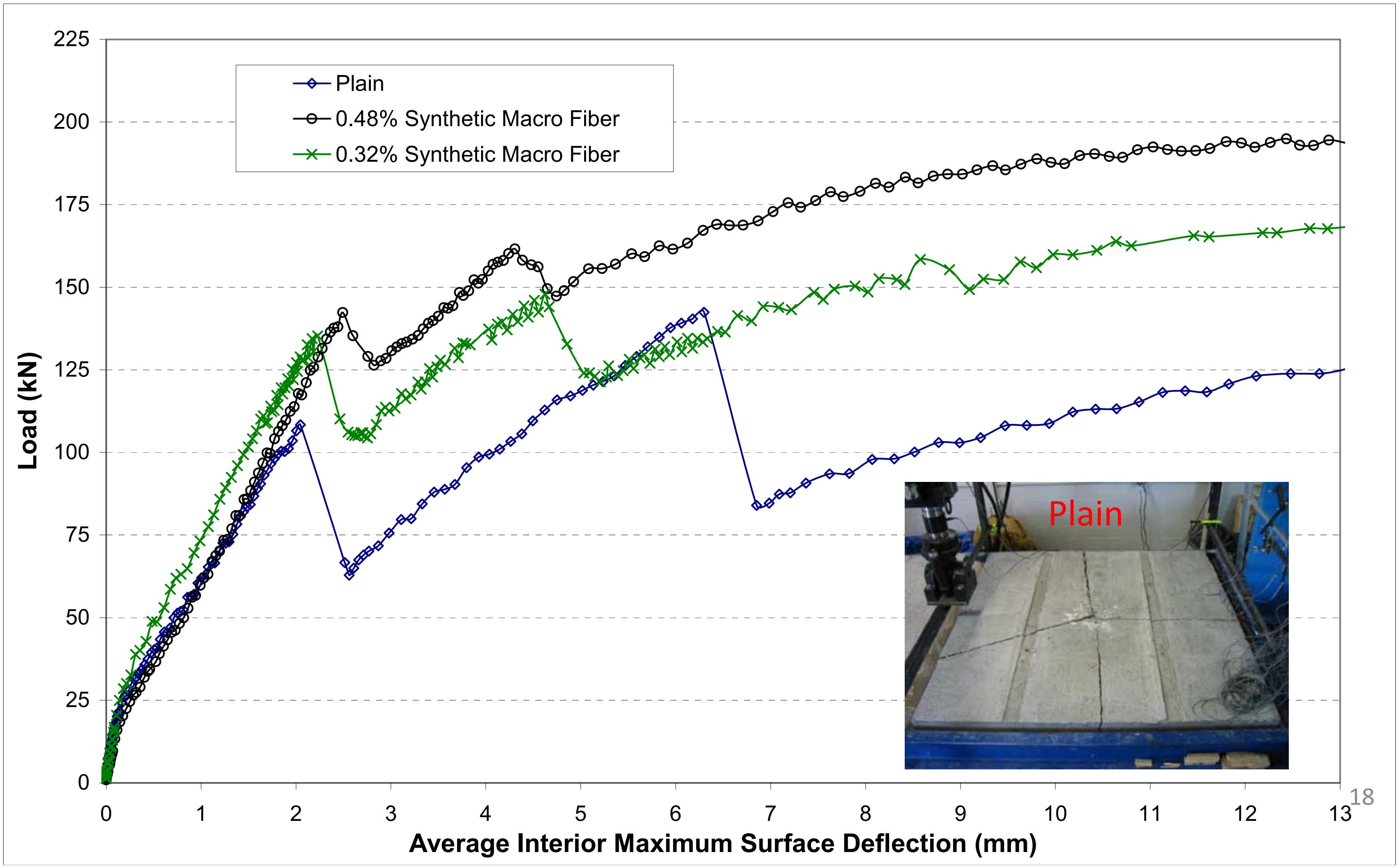
Flexural Strength (MOR) = 5.0 MPa

Concrete Slab Loading Frame

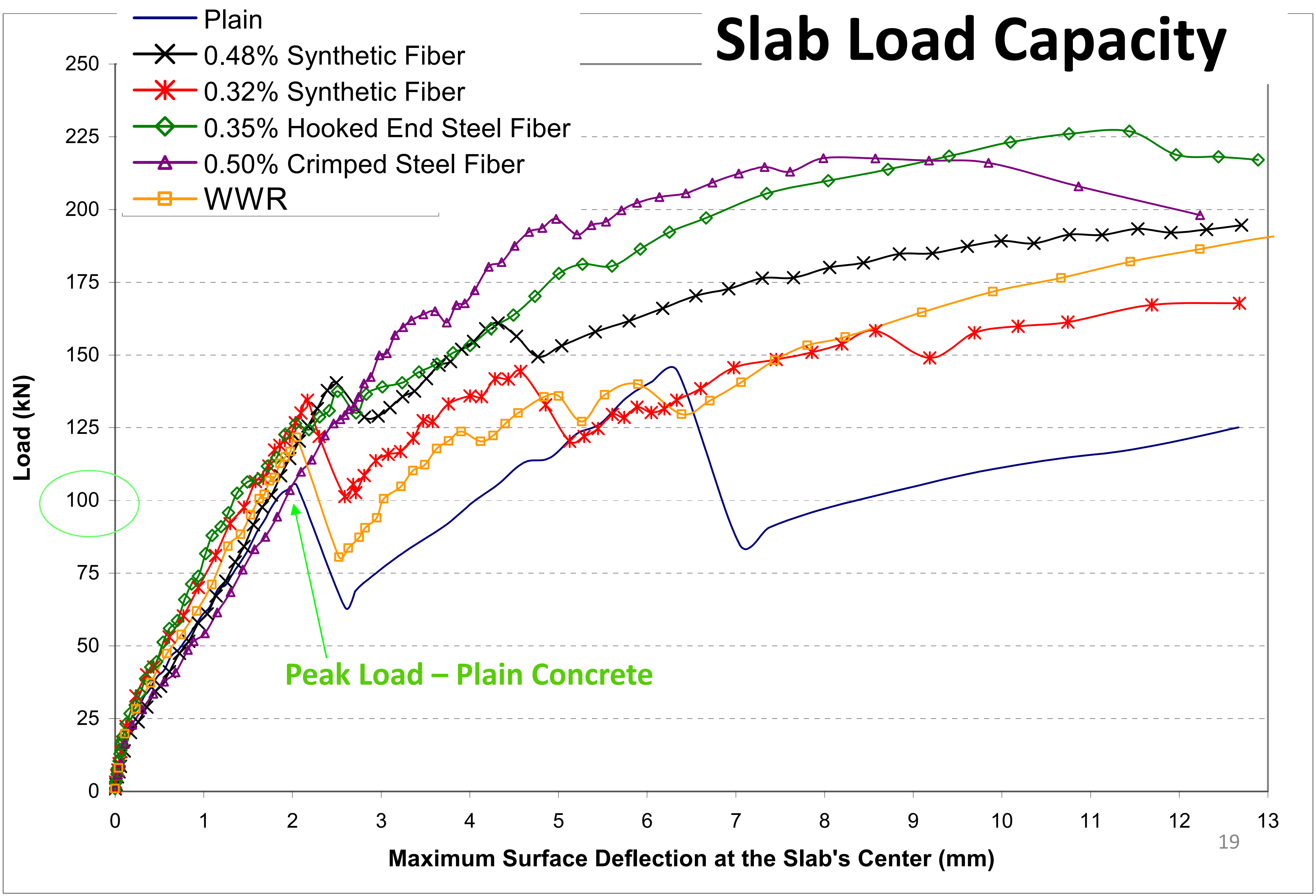
FRC Slab Test Setup – Interior Loading



Monotonic Load-Deflection Plot
Plain/Macrofibers (Synthetic)



Slab Load Capacity



Failure Load Summary (kN)

Roesler et al. (2004)

Slab Type	Tensile	Flexural	Ultimate	Slab/Beam Flex. Strength
Plain	75	108	135	1.39
Synthetic (0.48%)	70	143	195	2.09
Synthetic (0.32%)	75	135	174	1.82
Hooked Steel (0.35%)	70	141	228	2.01
Crimped Steel (0.50%)	90	167	220	2.22
WWR	65	122	201	1.53

Effect of Macrofibers on Concrete Slab Flexural Capacity

- Fibers improve flexural cracking load over plain concrete

Increase over Plain

- Synthetic (0.5%) $\Rightarrow$ 32%
- Synthetic (0.32%) $\Rightarrow$ 25%
- Hooked (0.35%) $\Rightarrow$ 31%
- Crimped (0.5%) $\Rightarrow$ 55%*
- WWR (6x6-W2.9) $\Rightarrow$ 13%

*higher concrete strength

Effect of Macrofibers on Concrete Slab Ultimate Capacity

- Fibers improve ultimate cracking load over plain concrete

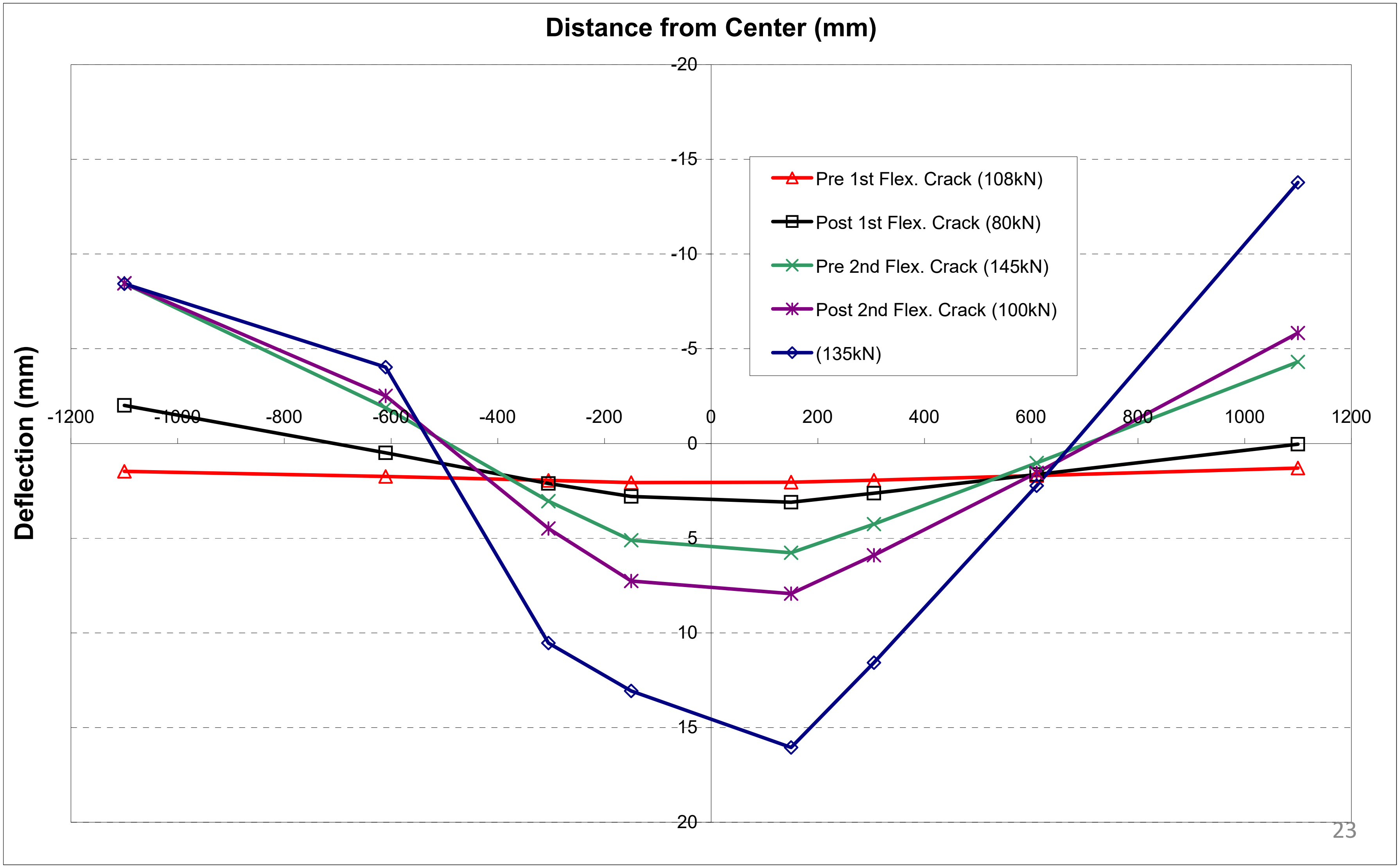
<u>Increase over Plain</u>

- Synthetic (0.5%) $\Rightarrow$ 44%
- Synthetic (0.3%) $\Rightarrow$ 29%
- Hooked (0.35%) $\Rightarrow$ 69%
- Crimped (0.5%) $\Rightarrow$ 63%*
- WWR (6x6-W2.9) $\Rightarrow$ 49%

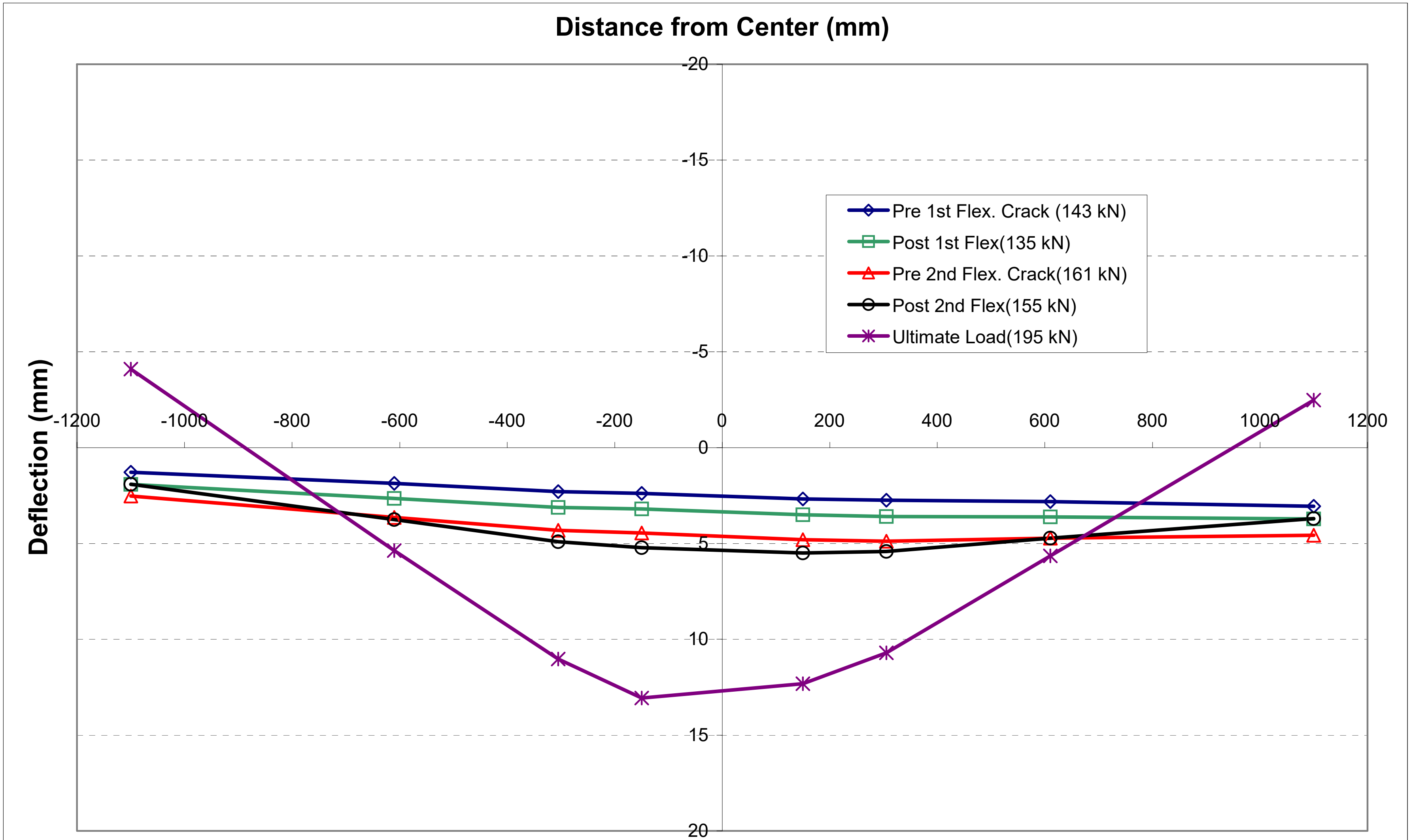
*higher concrete strength

Deflection Profile

Plain Concrete Slab



Deflection Profile
Synthetic 0.48% - Concrete Slab



Slab Cracking Pattern

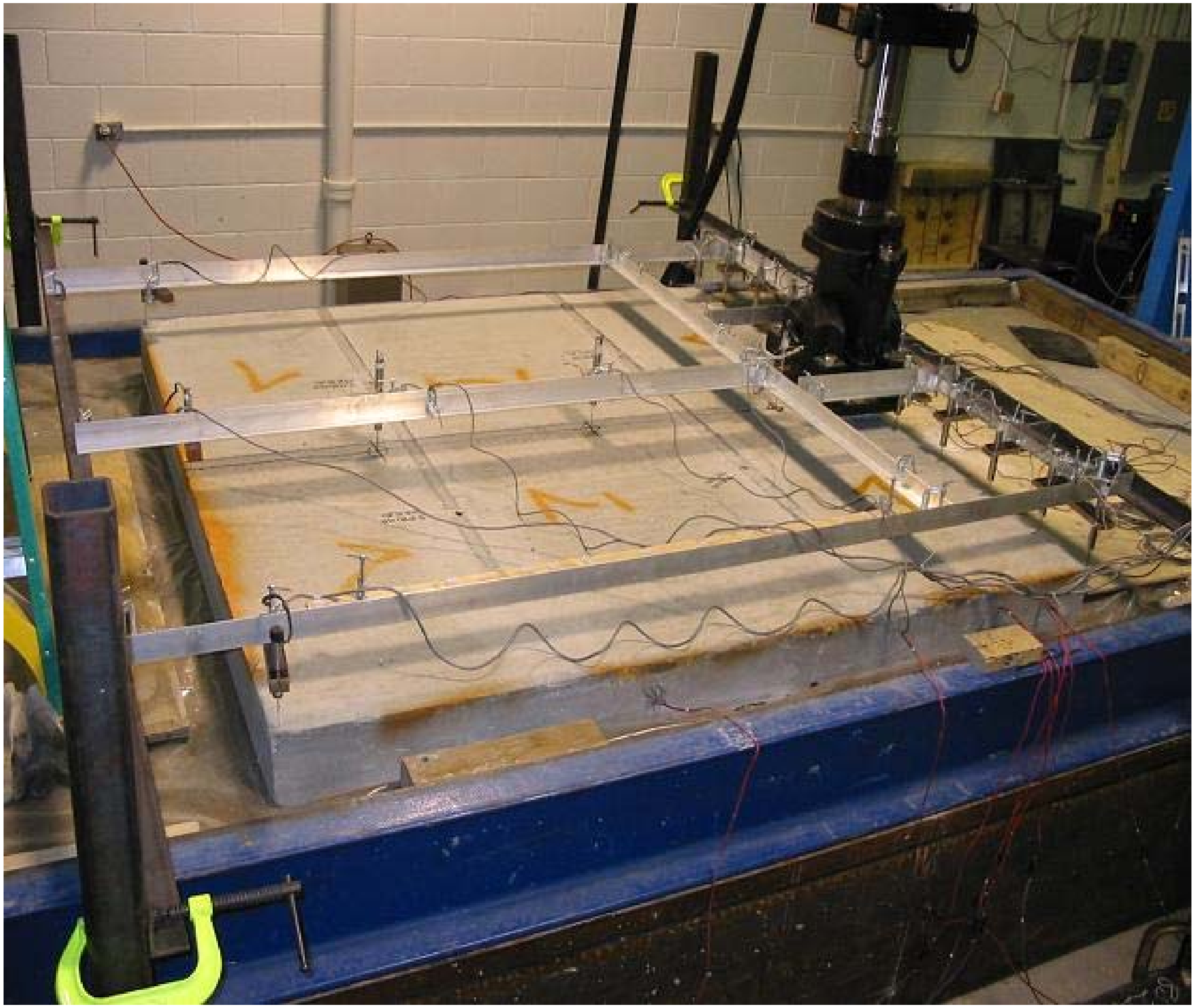
0.32% Synthetic Fibers

Hooked End Steel Fibers

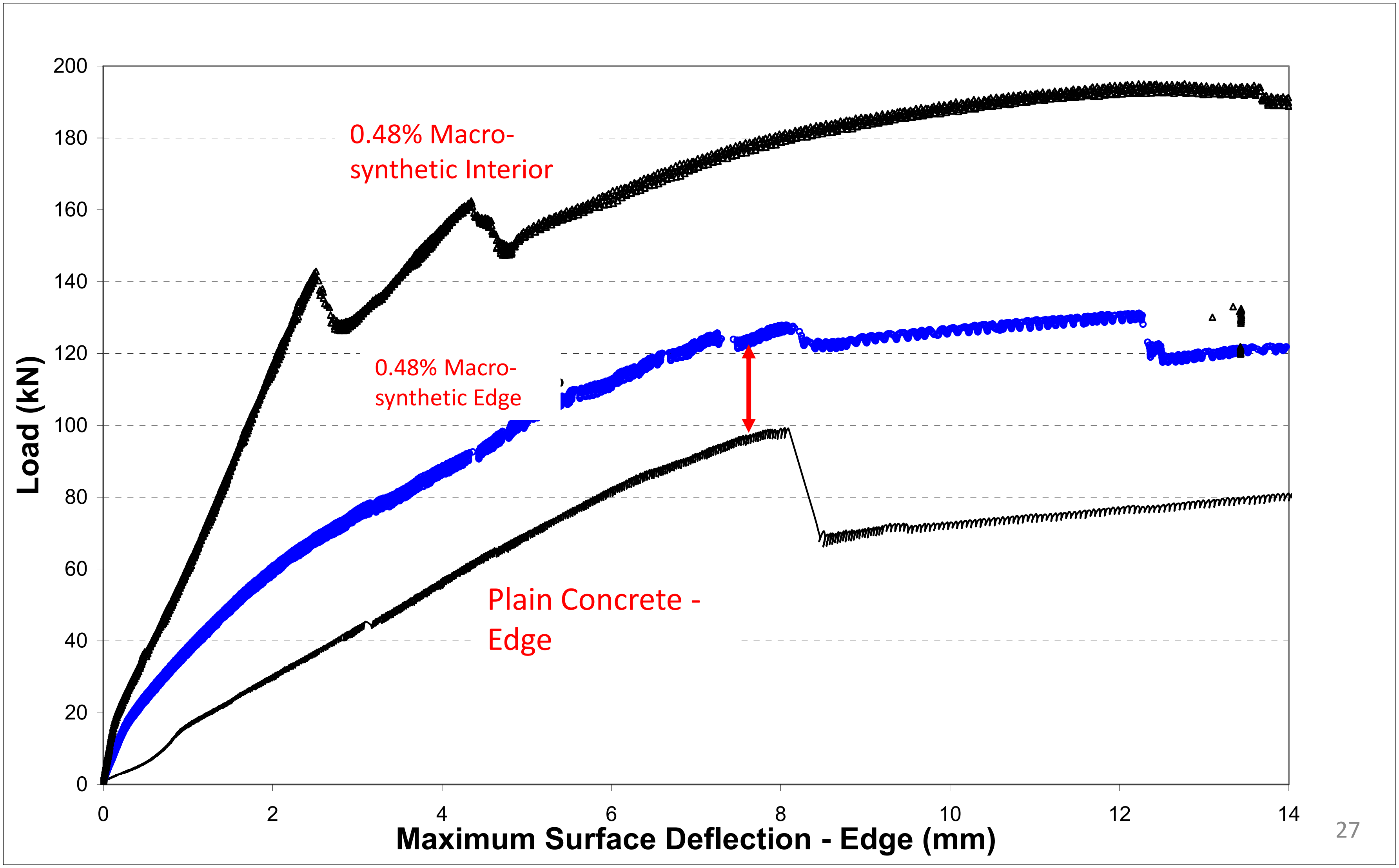
WWR Slab

Plain Concrete Slab

Slab Edge Loading Test



Edge Load-Deflection Plots
Plain vs. 0.48% Macro-synthetic



Edge Loading Results (kN)

Slab Type	Tensile	Flexural	Ultimate
Plain	50	99	96*
Synthetic (0.48%)	55	126	131

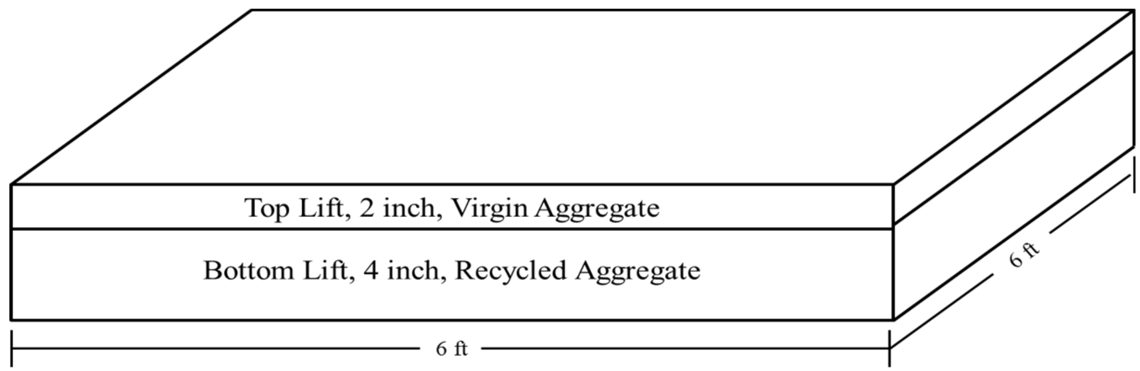
- 27% increase in flexural strength over plain
- 32% increase in ultimate strength over plain

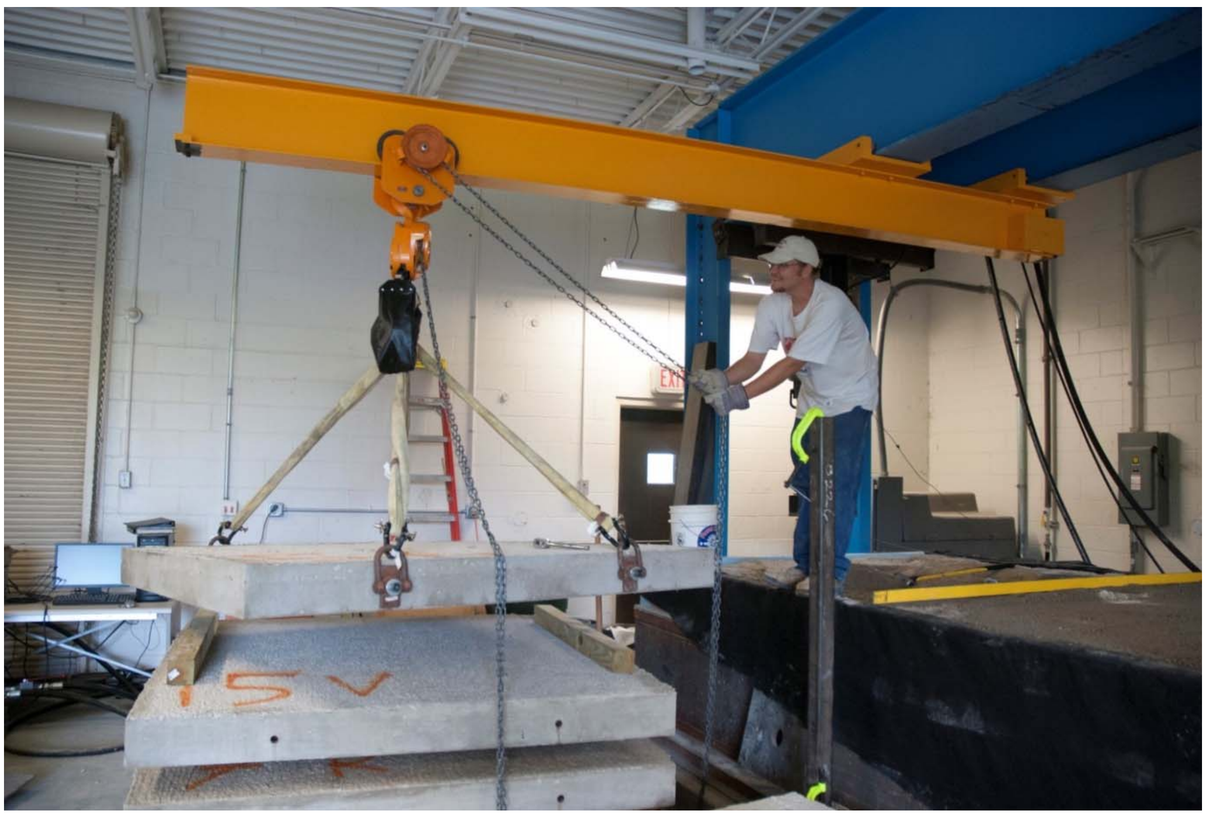
Recycled Materials in Slabs

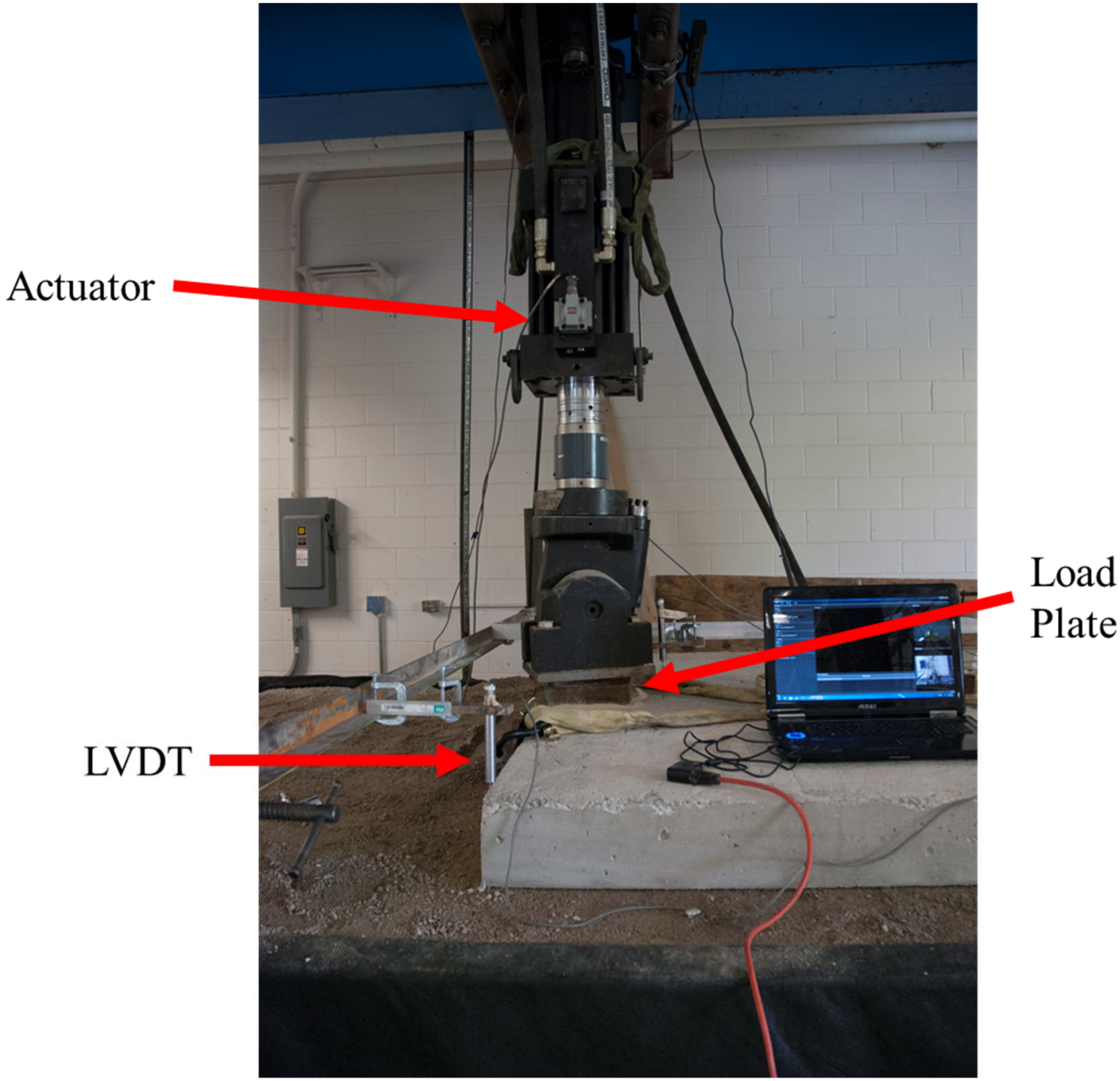
- *Effect of recycled materials on concrete slab capacity and performance*
  - Fractionated Reclaimed Asphalt Pavement (FRAP)
  - Recycled Concrete Aggregate (RCA)
  - Waste cementitious materials (slag, fly ash)

Illinois State Toll Highway Authority

Slab Casting and Testing






Actuator
Load Plate
LVDT

Effect of Concrete Materials on Slab Capacity

Test Configuration	Concrete w/ Virgin Aggregate	Concrete w/ 45% FRAP$	2-Lift w/ 45% FRAP and Fibers$
Beam Flexural Strength (MPa)	5.4	4.0	3.1
Compressive Strength (MPa)	43.0	24.1	17.2
Slab Load Capacity - beam estimate (kN)	61	45	35
Measured Slab Load Capacity* (kN)	**100**	**118**	**109**

**1.8mx1.8m by 15cm slabs on soil foundation (average of 2 tests)*
$8% & 12% air content, respectively
-All tests done at 1-month age

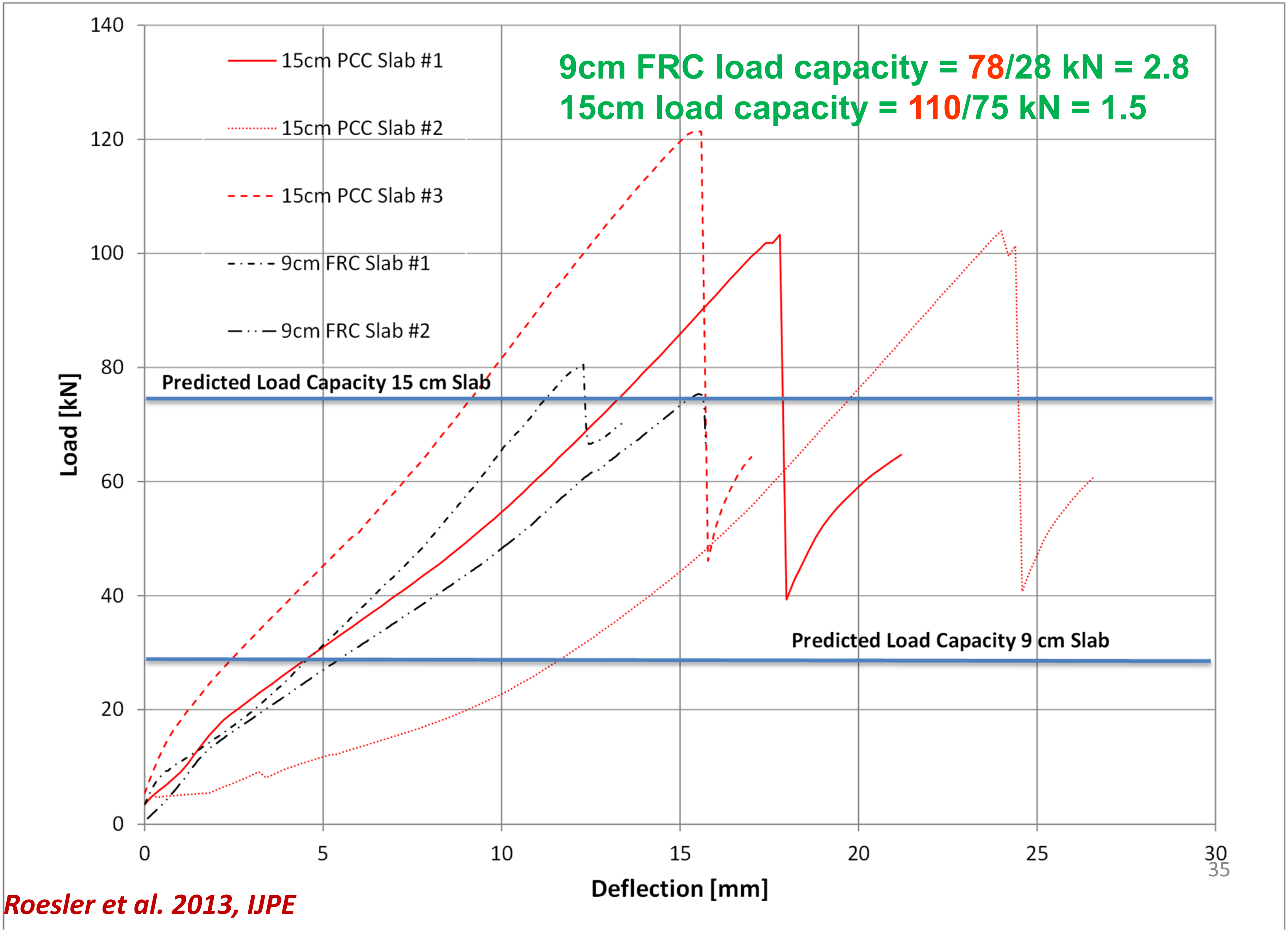
Brand et al. (2014)

FRAP = fractionated reclaimed asphalt pavement

9cm and 15cm Concrete Slab Tests

1.8 x1.8m slab geometry

Actual vs Predicted Slab Capacity



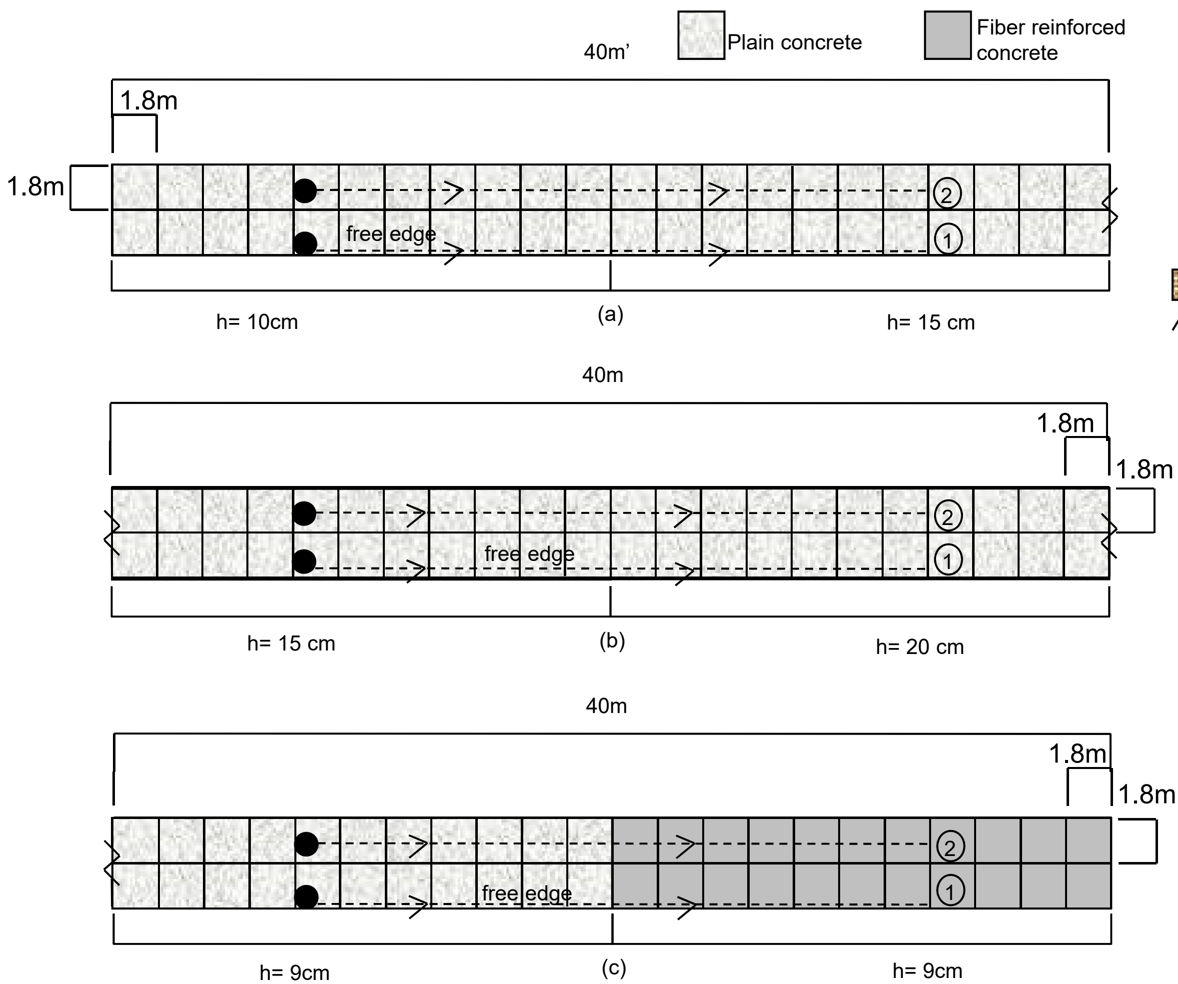
Roesler et al. 2013, IJPE

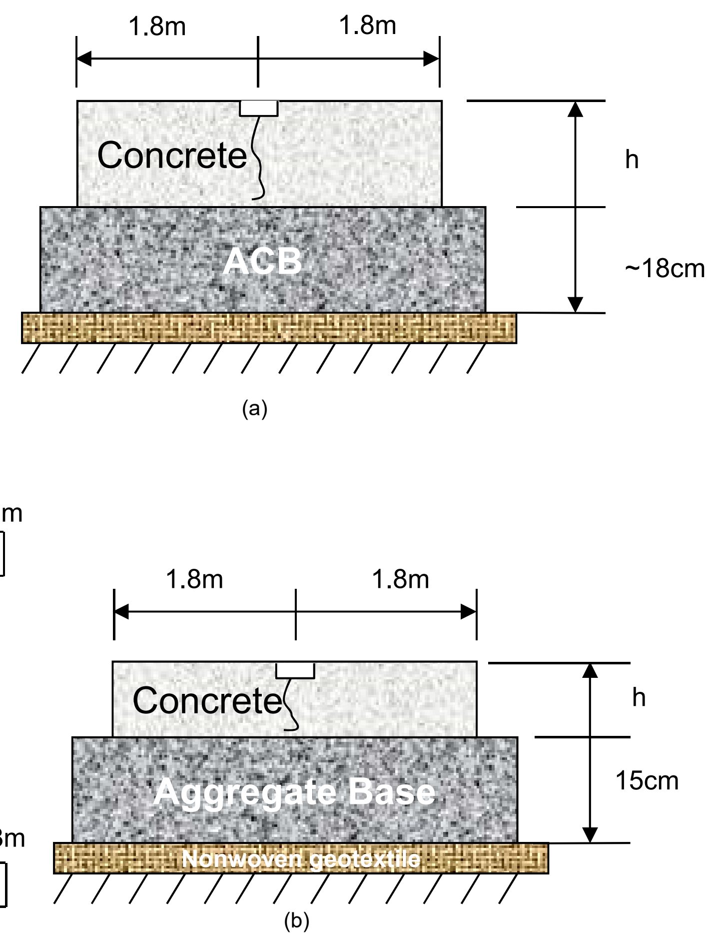
Short Jointed Slab Research- Univ. of IL

- Test Sections (2007-2009)
- 3.5”, 6”, & 8” slab thick.
- Macrofiber vs. no fiber
- Fatigue tests of slabs

Roesler, J.R., Cervantes, V.G, and Amirkhanian, A.N (2012), “Accelerated Performance Testing of Concrete Pavement with Short Slabs,” *International Journal of Pavement Engineering*, Volume 13, Issue 6, pp. 494-507.

Concrete Slab Test Sections (2007)



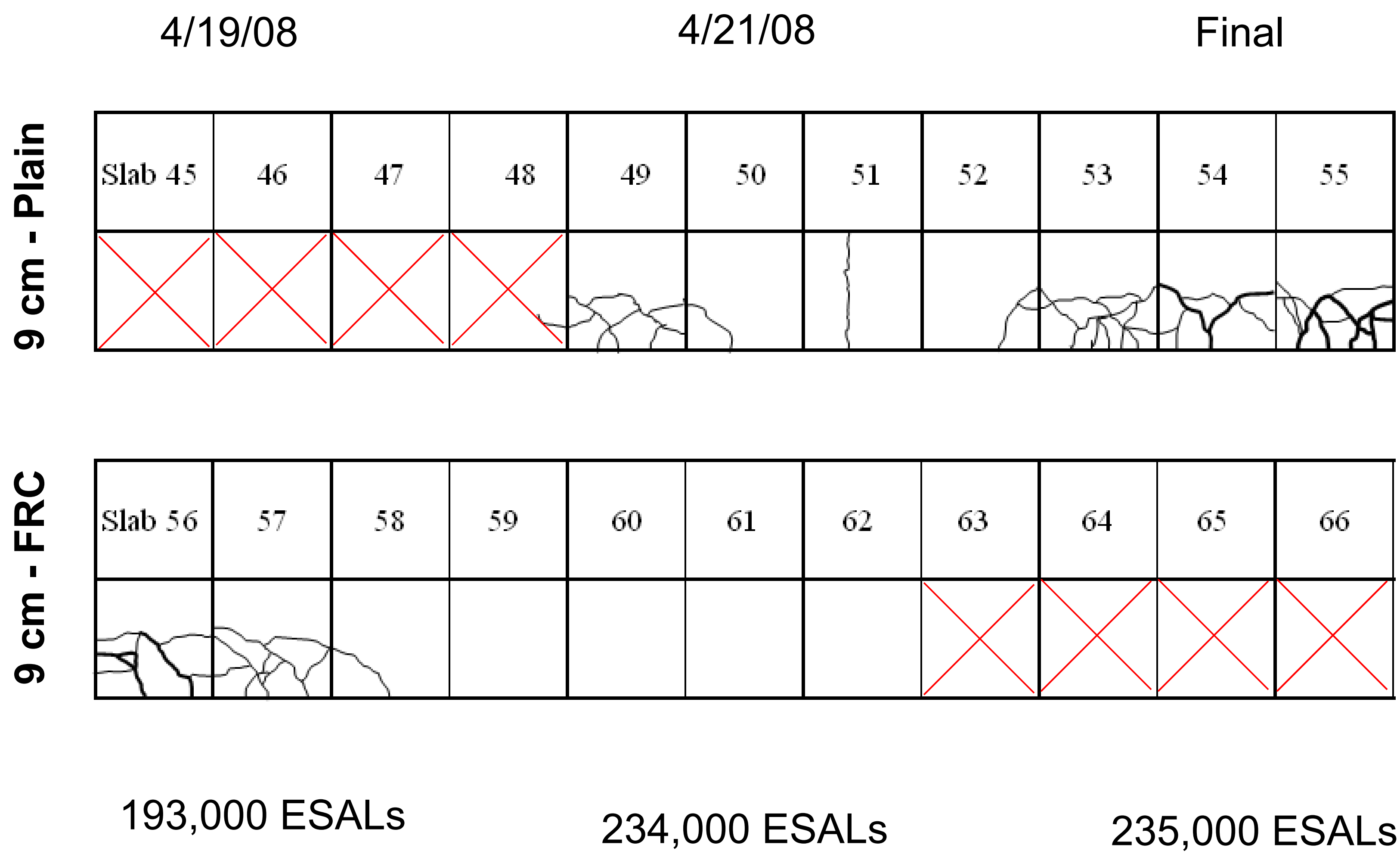


22 slabs per section
Only 14 slabs loaded

April 2008 – Spring-time Loading

- Near edge trafficking
- Soil has low CBR ≤ 4

SECTION 3 (South) – 9 cm CRACK DEVELOPMENT

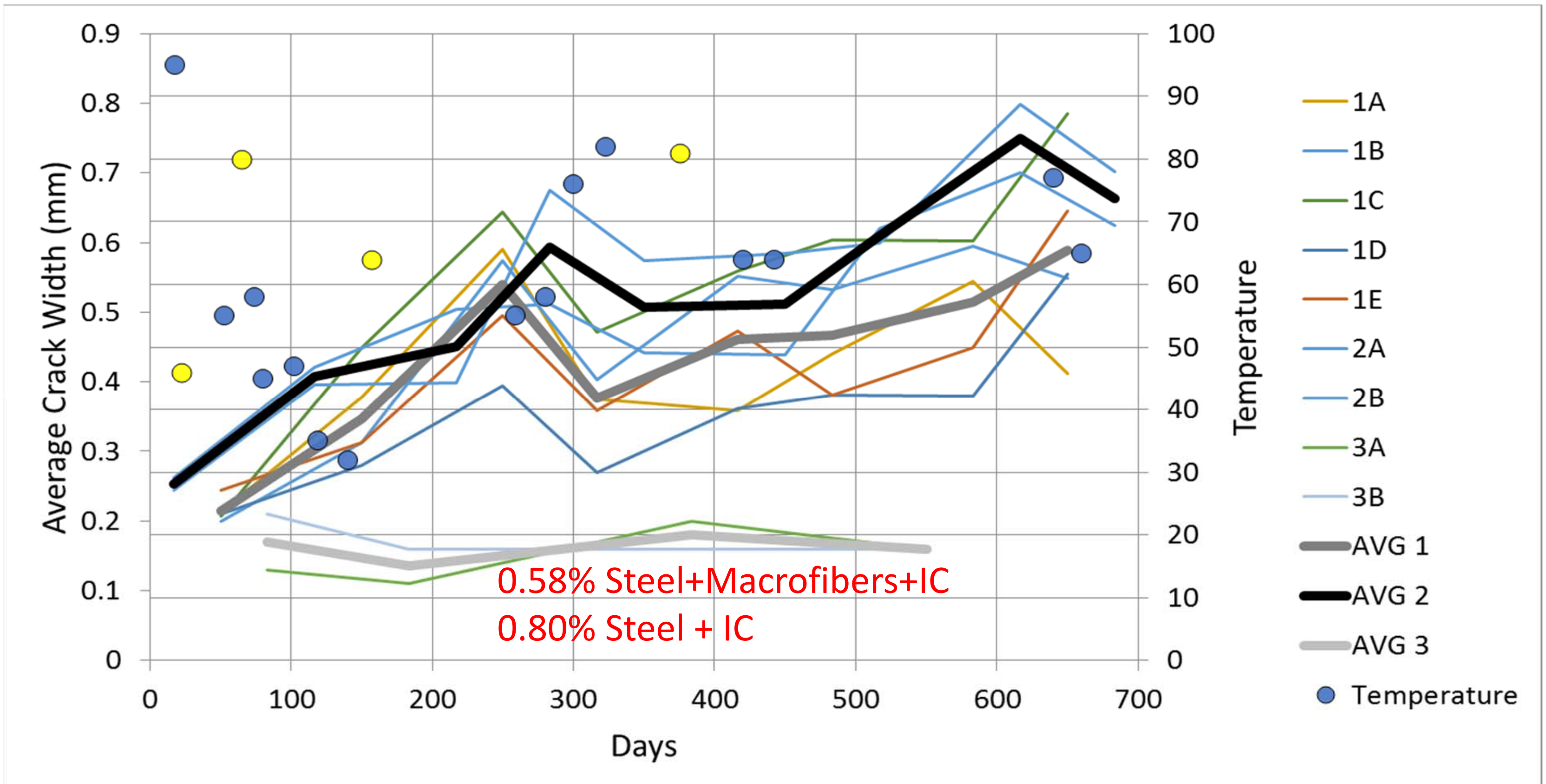


Loading Summary: 3.5 inch Slabs

Load [kN]	Passes	Cumulative ESAL	Percent Slabs Cracked PCC	Percent Slabs Cracked FRC
Section 3 South				
22.2	2,643	4,477	0.0	0.0
22.2	2,778	9,183	0.0	0.0
40.0	3,000	69,183	0.0	0.0
40.0	309	75,363	0.0	0.0
40.0	5,875	192,863	57.1	14.3
40.0	2,053	233,923	57.1	28.6
53.4	10	234,592	100.0	42.9

Cracking on 3.5-in. Section

CRCP Crack Width



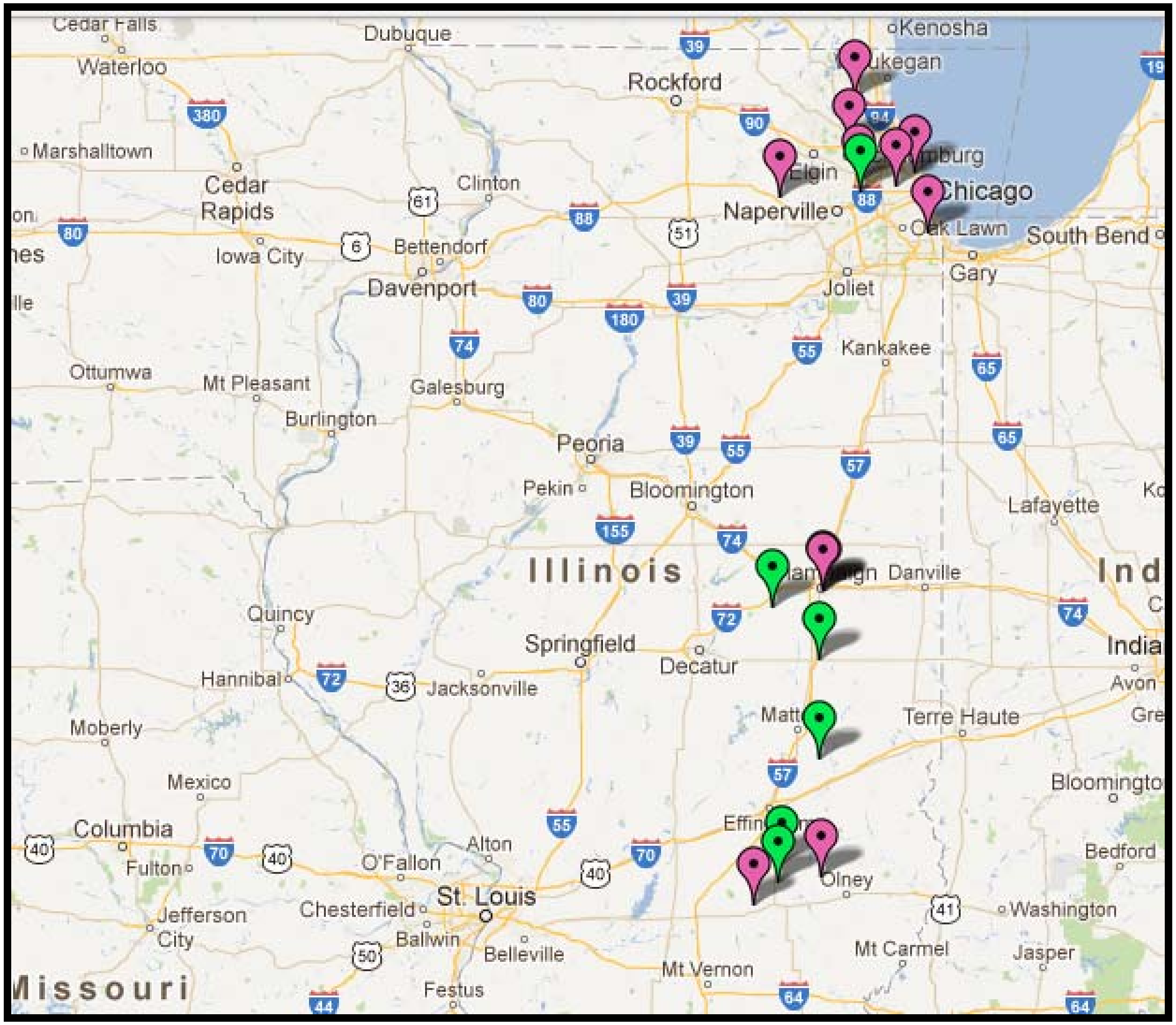
2016-2017 Illinois Tollway E-OWB

Macro-fibers in Concrete Slabs can …

- Reduce slab thickness for same performance
- Increase slab performance for same thickness
- Increase slab size for same performance
- Post-cracking serviceability.

- *Structural enhancements depend on fiber performance in specific concrete!*

Illinois (USA) Concrete Overlay Survey
19 Projects Visited (2012)



King & Roesler (2014)

Decatur, IL: Intersection US 36 and Oakland Avenue (1998)

- 9cm inlay of a milled 15cm HMA surface, 0.9-1.2m wide panels

2012

34% panels cracked
Patching
Rough w/ migration

Chicago, IL: Western Avenue Bus Pads (2003)

- Project consisted of a number of stops along Western Avenue (5 were surveyed) 10ft x 100ft sections, 3.3ft x 4ft joint spacing
- ***4-in thick inlay, high fiber dosage of 7.5 to 8.5 lb/yd^3***
- Considered a **bonded/unbonded hybrid** project, as the conditions of the underlying layer varied project to project

Western Ave. and Iowa

2012

Kane County, IL: North Lorang Road (2004)

- 4.25-4.5" thick concrete overlay of 3-3.5" of HMA over aggregate base
- 4 lb/yd^3 synthetic macro-fibers
- Square 5 ft x 5 ft panels
- Project built to serve a quarry: average of 30 trucks/day (peak of 280/day)

2012

Mundelein, IL: Schank Avenue (2005)

- 4-in. concrete overlay of a composite pavement (2.25 to 6.5-in. HMA over 4.75 to 9.25-in. PCC)
- Square 4ft x 4ft panels
- 4 lb/yd^3 synthetic macro-fibers
- High truck traffic volume (no data available, but comparable to Lorang Road and more general traffic)

2012

E-15 Parking Lot (2006)

- UIUC campus FRC UTW Project
  - 2.5-in AC
  - 3.5 in Thick slab
  - 1.2 x 1.2m Joint spacing
  - 3 lb/yd^3 or 0.2% Fibers
  - Fly ash

Material	Amount (lb/yd^3)
Coarse Agg	1903
Fine Agg	1214
Cement	428
Water	219
Fly Ash	133
Strux Fibers	3
Admixture	Daracem 19

Final X-section

Asphalt Before

During Paving

Sawcutting

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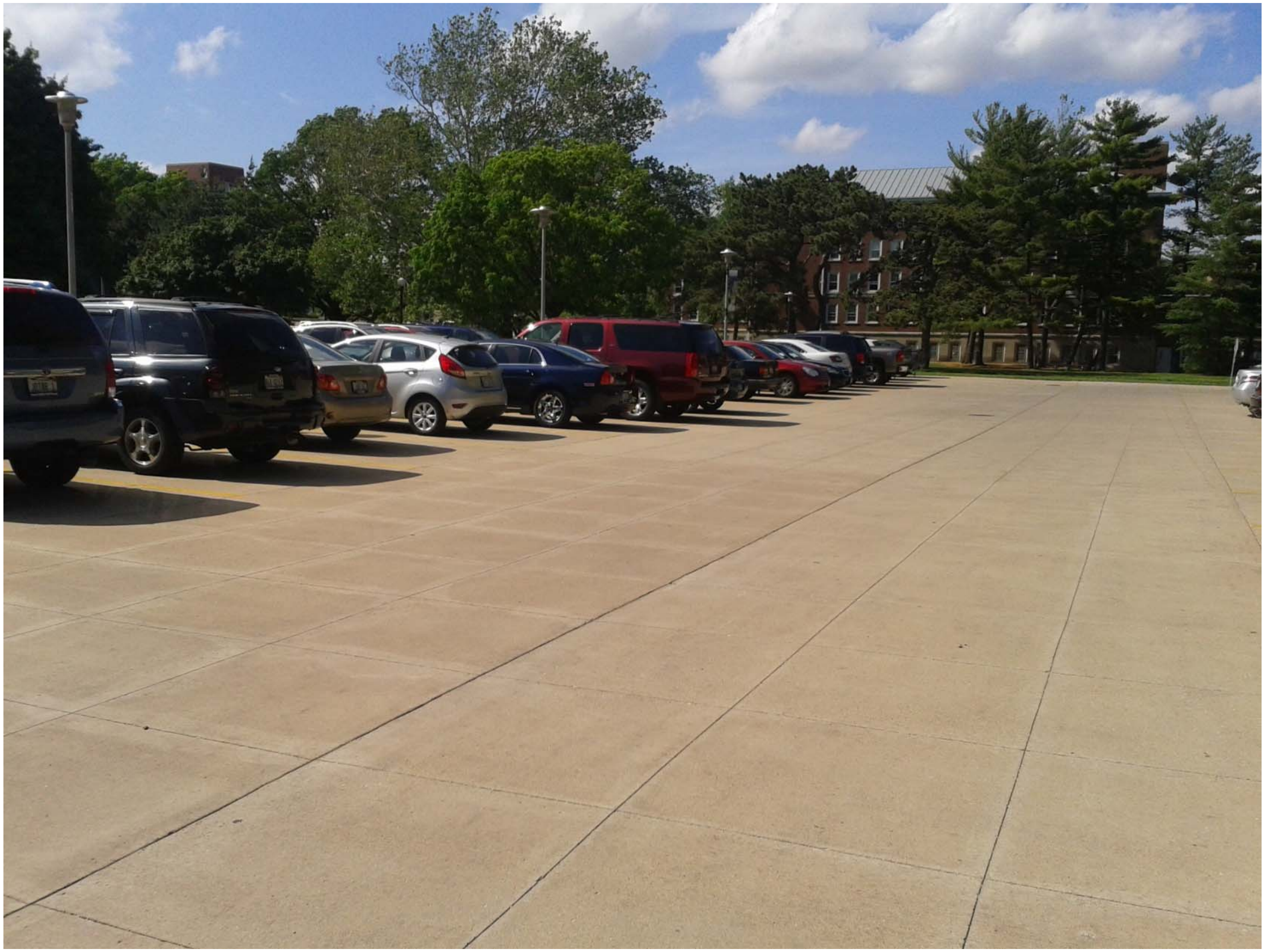
University of Illinois: E-15 Parking Lot (2006)

- 3.5-in. overlay over existing 2.5-in. HMA surface
- 4’ x 4’ panels
- 3 lb/yd^3 synthetic macrofibers

2007 McKinley Parking Lot Project

McKinley Parking Lot (6 years old)



2013

Richland County, IL: County Highway 9 (2010)

- 5.5-in. PCC overlay of a ?” HMA surface
- 5.5’ x 5.5’ square panels
- **4 lb/yd^3 structural synthetic fibers**

2012

Hamilton County, IL (Sept. 16, 2014)

4 lb/cy of macro-fibers

Built in 2013

Bonded Concrete Overlay of Asphalt:
15-year Illinois Experience with Macro-fibers

- Fibers important to good performance
  - Keeping joints tight and reduce risk of faulting/misalignment
  - When distresses occur, fibers help keep the cracks tight, allowing the pavement to remain relatively smooth and serviceable
  - Elimination or reduction in slab migration/movement
- Maintain panel sizes with fibers ≤ 6 ft
- No faulting or cracking on 4ft or 6ft slab sizes with macro-fibers (>2006)
- FRC needs minimum revolutions at high torque in mixer
- If the HMA layer or underlying support have the potential to be major issues (e.g. Schank Ave) and/or heavy truck traffic, ***try higher fiber dosages or fix support layer***

King et al. (2014)

How to specify fibers in concrete?

- Comparison of Flexure Strength Tests
  - ASTM 1018
  - ASTM C1399
  - ASTM C1550
  - **ASTM 1609-10 (2012)**
  - JCI-SF4 (1983)
- **RESIDUAL STRENGTH**

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Flexure Test Method

ASTM C1609-12 and JCI-SF4

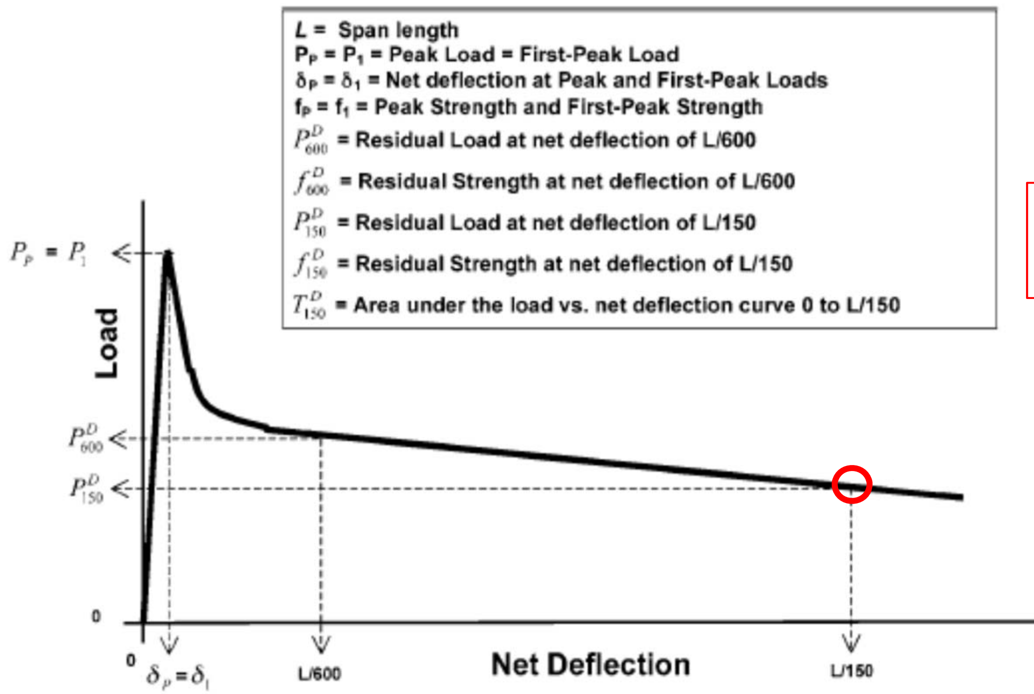


FIG. 3 Example of Parameter Calculations for First-Peak Load Equal to Peak Load (Not to Scale)

ASTM C1609-10

$$MOR = \frac{P_1 L}{bd^2}$$

$$\boxed{f_{150}^{150} = \frac{P_{150}^{150} L}{bd^2}}$$

$$R_{150}^{150} = \frac{f_{150}^{150}}{MOR} * 100\% \quad or$$

$$R_{T,150}^{150} = \frac{150 \cdot T_{150}^{150}}{MOR \cdot bd^2} * 100\%$$

JCI-SF4

$$f_{e,3} = \frac{T_{150,3} S}{bd^2}$$

$$R_{e,3} = \frac{f_{e,3}}{MOR} * 100$$

Beams: 6 in x 6 in (15x15cm)

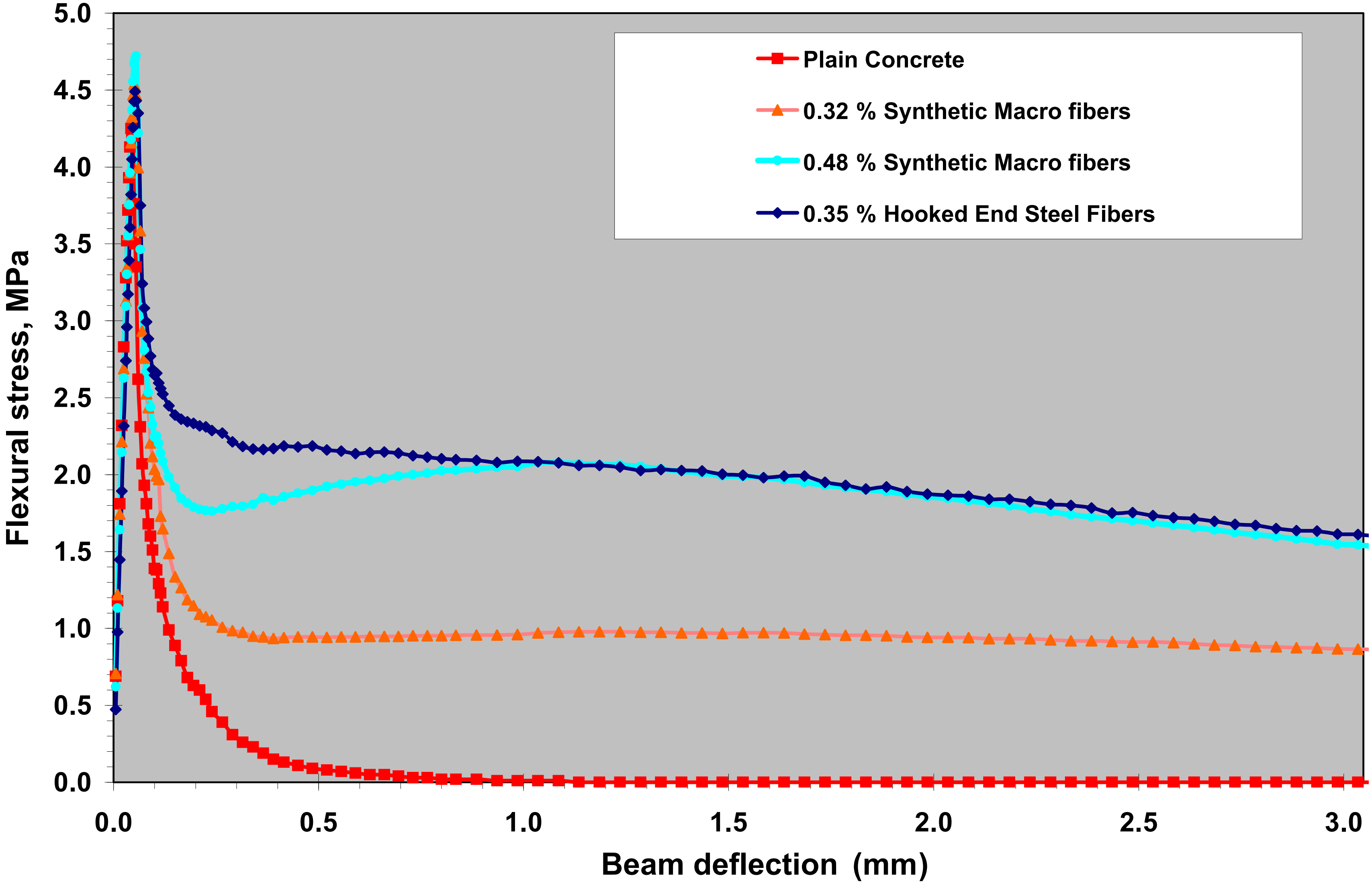
Span (L): 18 in (45cm)

L/150 = 0.12 in (3 mm)

Flexural Beam Results

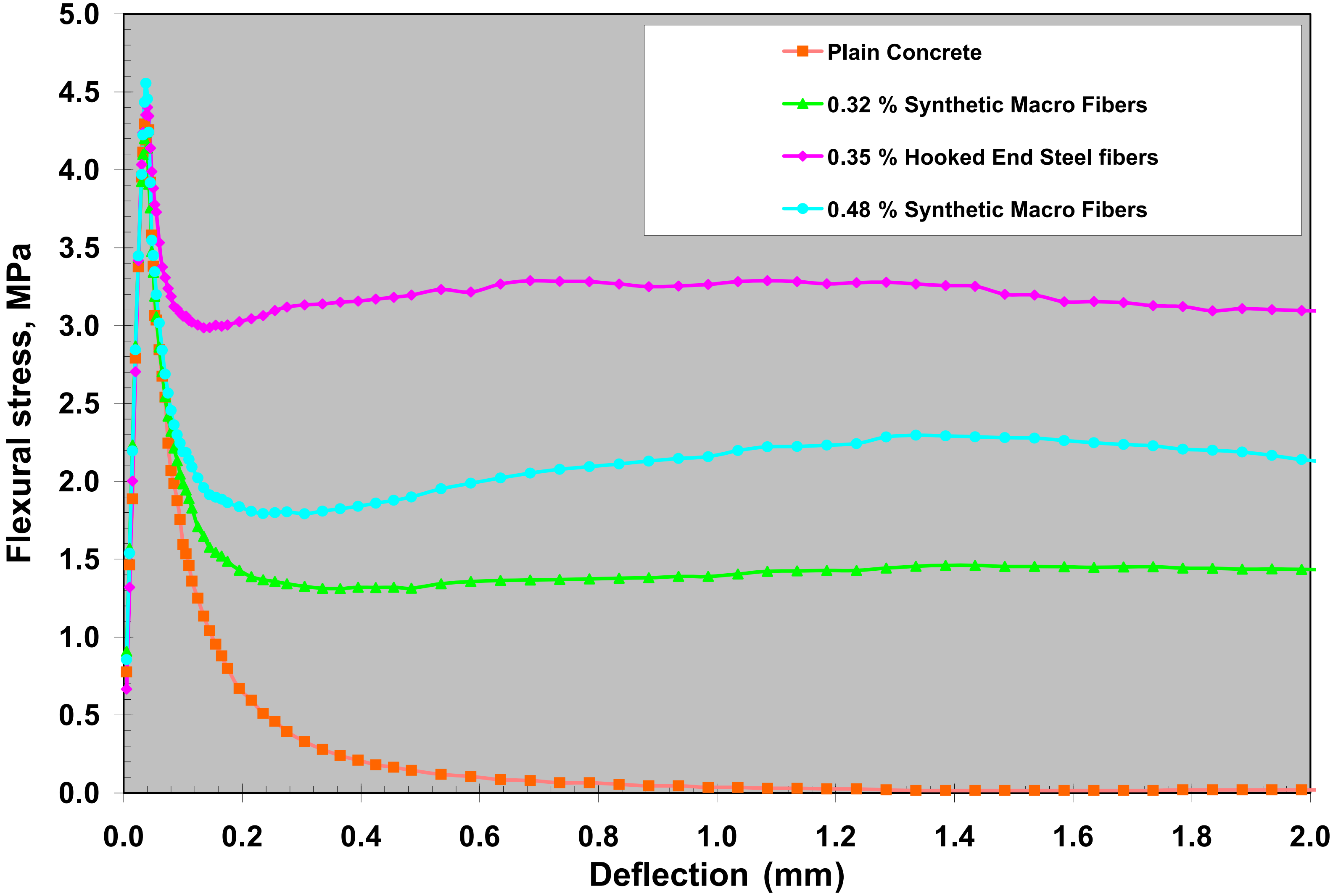
150x150x550mm

$$MOR = \frac{PL}{bd^2}$$



Flexural Beam Results

100x100x350mm



Flexural and Residual Strength Values*

	Flexural Strength MOR psi [MPa]	f_{150} psi [MPa]	R_{150} (%)
Plain Concrete	686 [4.73]	0	0.0
0.32% Synthetic	680 [4.69]	126 [0.87]	18.0
0.48% Synthetic	699 [4.82]	225 [1.55]	32.0
0.35% Hook Steel	679 [4.68]	234 [1.61]	34.5
0. 50% Crimp Steel	766 [5.28]	184 [1.27]	24.0

*Actual values measuring according to ASTM C1609-07 (different roller assembly)

Fiber-Reinforced Concrete Pavement Design

- Use existing concrete pavement design thickness methods *(AASHTO, PCA, FAA, MEPDG, AASHTO Pavement ME)*
  - MOR = plain concrete flexural strength
- Modified flexural strength (MOR’)
  - include benefit of fibers (f_{150}) = residual strength
- Input MOR’ for concrete strength

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Modified Strength Equations

- MOR’ = (MOR + f_{150})

  - MOR = plain concrete flexural strength
  - F_{150} = residual strength
  - MOR’ = effective flexural strength of FRC

- f_{150} = 150 psi (for example)
- MOR = 600 psi

- Stress Ratio (SR) = $\dfrac{\text{(Total Stress)}}{(f_{150} + \text{MOR})}$

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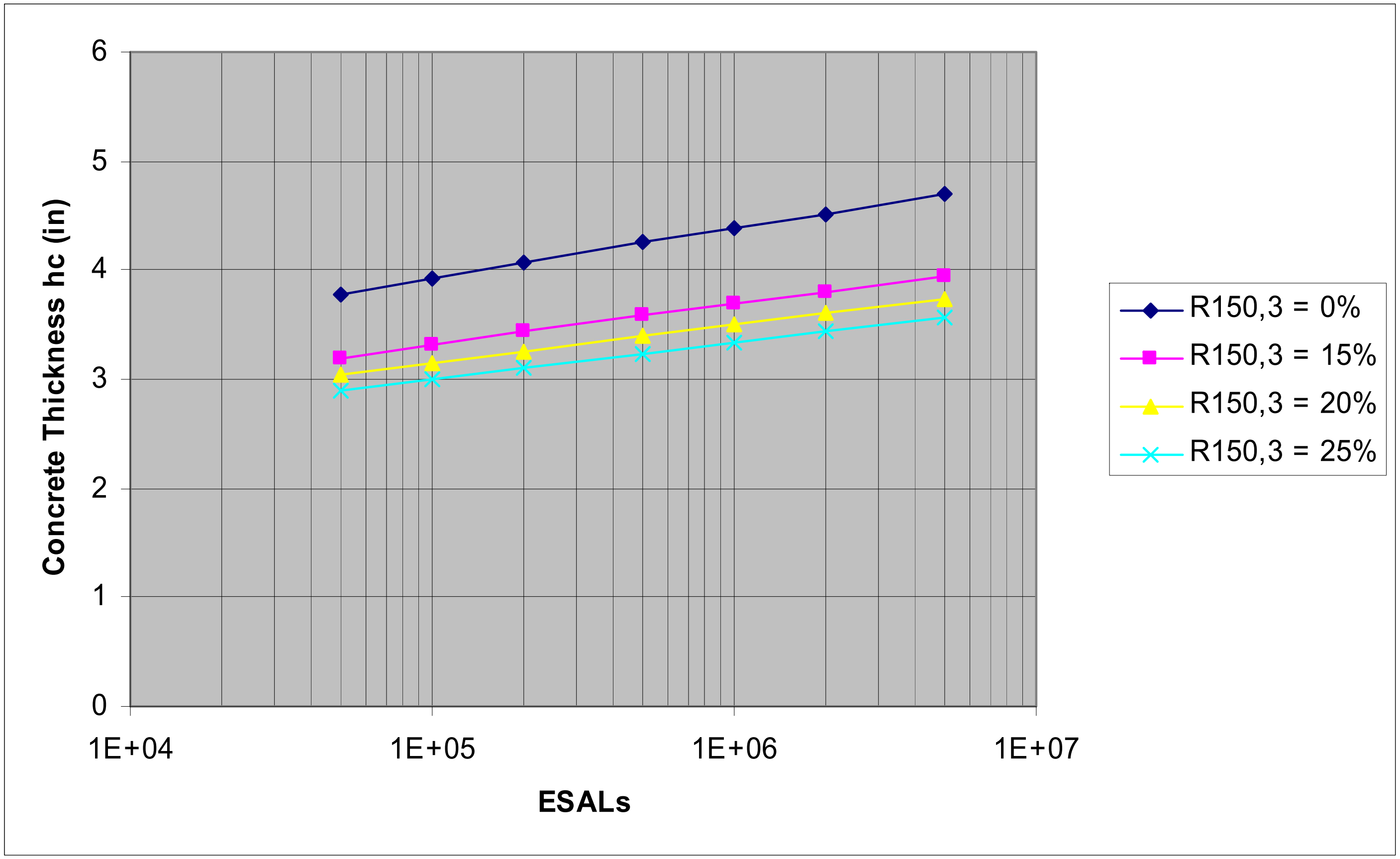
Altoubat et al. (2007)
Bordelon and Roesler(2012)

Illinois Structural Design of Bonded Concrete Overlay of Asphalt (2007-09)

Effect of Macro-fibers on Slab Thickness



Bordelon et al. (2008)

MACRO-Fiber Reinforcement Benefits for Concrete Pavements

- ***Increase*** *in structural capacity* of slab
  - Can reduce required slab thickness for overlays
- Maintain crack/joint widths
- Non-uniform support condition
- Tie **longitudinal**/transverse contraction joints
  - *Avoid slab migration*
- Reduce deterioration rates after initial cracking
  - slab deflect ↑ and displace more easily
  - Thin concrete overlays deteriorate more rapidly under traffic

- Should I use fibers on every concrete pavement projects? **NO**

Questions & Further Information

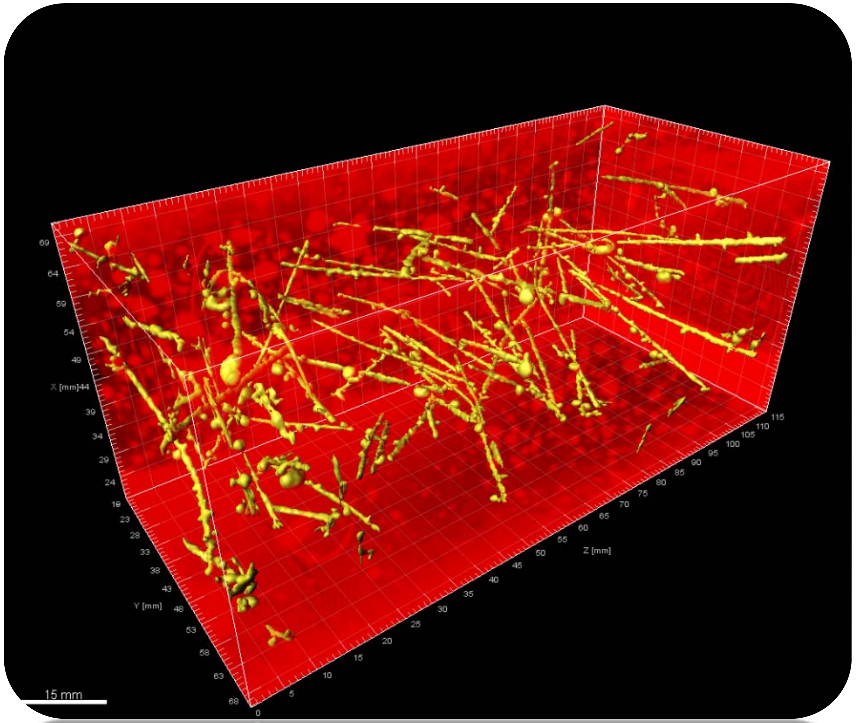
- Contact Speaker:
  - Jeffery Roesler, Ph.D., P.E., University of Illinois Urbana Champaign

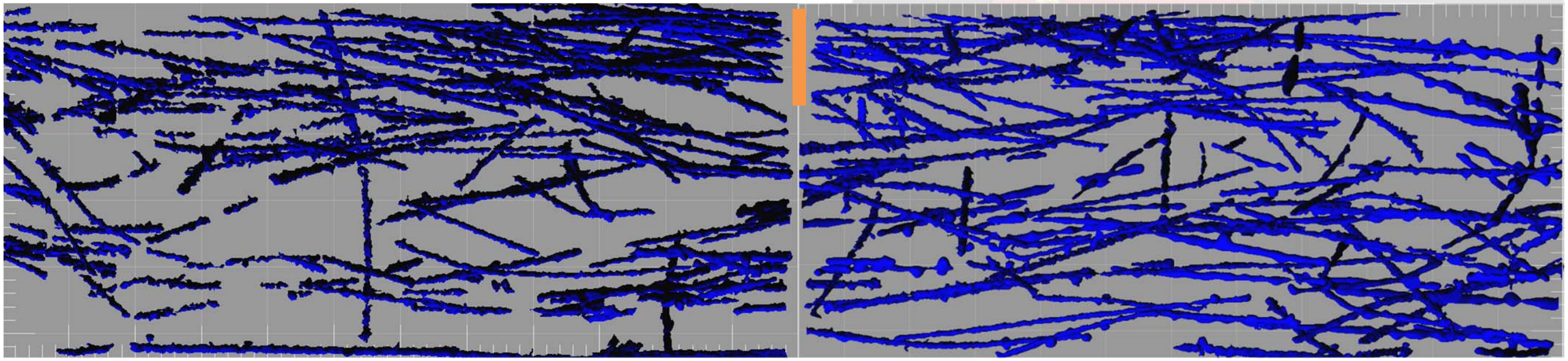
    jroesler@Illinois.edu

- Future Webinars:
  - Overview of new software to select fiber amount: Wed. Dec 5th, 9-10am

    https://register.gotowebinar.com/register/2109690528809036035

Questions?





141 fibers

131 fibers

Bordelon (2011)