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

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University of Illinois Urbana-Champaign

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”

- Funding and oversight for this research was provided by:
  - TTCC/Fiber-Reinforced Concrete Project
  - National Concrete Consortium
  - National Concrete Pavement Technology Center
  - Snyder and Associates, Inc.
  - “Fiber Reinforced Concrete for Pavement Overlays” Technical Advisory Committee
  - Drs. Amanda Bordelon, Armen Amirkhanian, Alex Brand
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)

Micro-Fibers – plastic shrinkage (non-structural)

PP – 6.7 lb/yd³ 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

ASTM C1609 Test
6-in x 6-in x 18-in beam

Load (kN)

Deflection (mm)

- .26% Straight Synthetic
- .29% Straight Synthetic
- .33% Straight Synthetic
- .50% Straight Synthetic
- .58% Straight Synthetic
- .40% Crimped Synthetic
- .30% Twisted Synthetic
- .50% Twisted Synthetic
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)

Test Slab Dimensions

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

\(v_f = \text{volume fraction}\)

*designed to achieve similar concrete toughness values

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 ($A_s=0.058\text{in.}^2/\text{ft}$)
• 1/3 depth from surface (target)
Concrete Mix Design (kg/m³)

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

Average Results

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)

- Plain
- 0.48% Synthetic Macro Fiber
- 0.32% Synthetic Macro Fiber
Slab Load Capacity

Maximum Surface Deflection at the Slab’s Center (mm)

- Plain
- 0.48% Synthetic Fiber
- 0.32% Synthetic Fiber
- 0.35% Hooked End Steel Fiber
- 0.50% Crimped Steel Fiber
- WWR

Peak Load – Plain Concrete
# Failure Load Summary (kN)

**Roesler et al. (2004)**

<table>
<thead>
<tr>
<th>Slab Type</th>
<th>Tensile</th>
<th>Flexural</th>
<th>Ultimate</th>
<th>Slab/Beam Flex. Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plain</td>
<td>75</td>
<td>108</td>
<td>135</td>
<td>1.39</td>
</tr>
<tr>
<td>Synthetic (0.48%)</td>
<td>70</td>
<td>143</td>
<td>195</td>
<td>2.09</td>
</tr>
<tr>
<td>Synthetic (0.32%)</td>
<td>75</td>
<td>135</td>
<td>174</td>
<td>1.82</td>
</tr>
<tr>
<td>Hooked Steel (0.35%)</td>
<td>70</td>
<td>141</td>
<td>228</td>
<td>2.01</td>
</tr>
<tr>
<td>Crimped Steel (0.50%)</td>
<td>90</td>
<td>167</td>
<td>220</td>
<td>2.22</td>
</tr>
<tr>
<td>WWR</td>
<td>65</td>
<td>122</td>
<td>201</td>
<td>1.53&lt;sup&gt;20&lt;/sup&gt;</td>
</tr>
</tbody>
</table>
Effect of Macrofibers on Concrete Slab Flexural Capacity

• Fibers improve flexural cracking load over plain concrete

**Increase over Plain**

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

*higher concrete strength
Effect of Macrofibers on Concrete Slab Ultimate Capacity

• Fibers improve ultimate cracking load over plain concrete

  Increase over Plain

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

*higher concrete strength
Deflection Profile

Plain Concrete Slab

Distance from Center (mm)

Deflection (mm)

-1200 -1000 -800 -600 -400 -200 0 200 400 600 800 1000 1200

Pre 1st Flex. Crack (108kN)
Post 1st Flex. Crack (80kN)
Pre 2nd Flex. Crack (145kN)
Post 2nd Flex. Crack (100kN)
(135kN)
Deflection Profile

Synthetic 0.48% - Concrete Slab

Distance from Center (mm)

Deflection (mm)

-1200 -1000 -800 -600 -400 -200 0 200 400 600 800 1000 1200

Pre 1st Flex. Crack (143 kN)
Post 1st Flex (135 kN)
Pre 2nd Flex. Crack (161 kN)
Post 2nd Flex (155 kN)
Ultimate Load (195 kN)
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

- Plain Concrete - Edge
- 0.48% Macro-synthetic Interior
- 0.48% Macro-synthetic Edge
## Edge Loading Results (kN)

<table>
<thead>
<tr>
<th>Slab Type</th>
<th>Tensile</th>
<th>Flexural</th>
<th>Ultimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plain</td>
<td>50</td>
<td>99</td>
<td>96*</td>
</tr>
<tr>
<td>Synthetic (0.48%)</td>
<td>55</td>
<td>126</td>
<td>131</td>
</tr>
</tbody>
</table>

- 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

- Top Lift, 2 inch, Virgin Aggregate
- Bottom Lift, 4 inch, Recycled Aggregate
## Effect of Concrete Materials on Slab Capacity

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

*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

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*Brand et al. (2014)*  

FRAP = fractionated reclaimed asphalt pavement

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9cm and 15cm Concrete Slab Tests

1.8 x 1.8m slab geometry
Actual vs Predicted Slab Capacity

1.8m x 1.8m slabs on clay soil

9cm FRC load capacity = 78/28 kN = 2.8
15cm load capacity = 110/75 kN = 1.5

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

Concrete Slab Test Sections (2007)

(a) 1.8m x 1.8m x 40m

1. Plain concrete
2. Fiber reinforced concrete

1.8m
1.8m
40m'

(a) Free edge

h = 10 cm
h = 15 cm

(b) Free edge

h = 15 cm
h = 20 cm

(c) Free edge

h = 9 cm
h = 9 cm

ACB

Aggregate Base

Nonwoven geotextile

Concrete

h ~18 cm

1.8m
1.8m

h

22 slabs per section
Only 14 slabs loaded
April 2008 – Spring-time Loading

• Near edge trafficking
• Soil has low CBR $\leq 4$
## SECTION 3 (South) – 9 cm

**CRACK DEVELOPMENT**

<table>
<thead>
<tr>
<th></th>
<th>4/19/08</th>
<th>4/21/08</th>
<th>Final</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>9 cm - Plain</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slab 45</td>
<td>46</td>
<td>47</td>
<td>48</td>
</tr>
<tr>
<td>49</td>
<td>50</td>
<td>51</td>
<td>52</td>
</tr>
<tr>
<td>53</td>
<td>54</td>
<td>55</td>
<td></td>
</tr>
</tbody>
</table>

|        |          |          |       |
| **9 cm - FRC** |          |          |       |
| Slab 56 | 57       | 58       | 59    |
| 60      | 61       | 62       | 63    |
| 64      | 65       | 66       |       |

- 193,000 ESALs
- 234,000 ESALs
- 235,000 ESALs
## Loading Summary: 3.5 inch Slabs

<table>
<thead>
<tr>
<th>Load [kN]</th>
<th>Passes</th>
<th>Cumulative ESAL</th>
<th>Percent Slabs Cracked</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>PCC</td>
</tr>
<tr>
<td><strong>Section 3 South</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22.2</td>
<td>2,643</td>
<td>4,477</td>
<td>0.0</td>
</tr>
<tr>
<td>22.2</td>
<td>2,778</td>
<td>9,183</td>
<td>0.0</td>
</tr>
<tr>
<td>40.0</td>
<td>3,000</td>
<td>69,183</td>
<td>0.0</td>
</tr>
<tr>
<td>40.0</td>
<td>309</td>
<td>75,363</td>
<td>0.0</td>
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<tr>
<td>40.0</td>
<td>5,875</td>
<td>192,863</td>
<td>57.1</td>
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<tr>
<td>40.0</td>
<td>2,053</td>
<td>233,923</td>
<td>57.1</td>
</tr>
<tr>
<td>53.4</td>
<td>10</td>
<td>234,592</td>
<td>100.0</td>
</tr>
</tbody>
</table>
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

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/yd³**
- Considered a **bonded/unbonded hybrid** project, as the conditions of the underlying layer varied project to project
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/yd³ 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)
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)

- UIUC campus FRC UTW Project
  - 2.5-in AC
  - 3.5 in Thick slab
  - 1.2 x 1.2m Joint spacing
  - 3 lb/yd³ or 0.2% Fibers
  - Fly ash

<table>
<thead>
<tr>
<th>Material</th>
<th>Amount (lb/yd³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse Agg</td>
<td>1903</td>
</tr>
<tr>
<td>Fine Agg</td>
<td>1214</td>
</tr>
<tr>
<td>Cement</td>
<td>428</td>
</tr>
<tr>
<td>Water</td>
<td>219</td>
</tr>
<tr>
<td>Fly Ash</td>
<td>133</td>
</tr>
<tr>
<td>Strux Fibers</td>
<td>3</td>
</tr>
<tr>
<td>Admixture</td>
<td>Daracem 19</td>
</tr>
</tbody>
</table>

Asphalt Before

During Paving

Sawcutting

Final X-section

- 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)
Richland County, IL: County Highway 9 (2010)

- 5.5-in. PCC overlay of a 7" HMA surface
- 5.5’ x 5.5’ square panels
- 4 lb/yd³ structural synthetic fibers
Hamilton County, IL (Sept. 16, 2014)

FRC UTW (4-in)
Existing Asphalt Concrete (3-in)
Cement Treated Soil (8-in.)
Natural Soil

4 lb/cy of macro-fibers
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
Flexure Test Method
ASTM C1609-12 and JCI-SF4

ASTM C1609-10

\[ \text{MOR} = \frac{P_L}{bd^2} \]

\[ f_{150}^{150} = \frac{P_{150}^{150}L}{bd^2} \]

\[ R_{150}^{150} = \frac{f_{150}^{150}}{\text{MOR}} \times 100\% \text{ or } R_{T,150}^{150} = \frac{150 \cdot T_{150}^{150}}{\text{MOR} \cdot bd^2} \times 100\% \]

JCI-SF4

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

\[ R_{e,3} = \frac{f_{e,3}}{\text{MOR}} \times 100\% \]

Beams: 6 in x 6 in (15x15cm)
Span (L): 18 in (45cm)
L/150 = 0.12 in (3 mm)
Flexural Beam Results
150x150x550mm

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

- Plain Concrete
- 0.32 % Synthetic Macro fibers
- 0.48 % Synthetic Macro fibers
- 0.35 % Hooked End Steel Fibers

Flexural Stress, MPa vs. Beam Deflection (mm)
Flexural Beam Results

100x100x350mm

- Plain Concrete
- 0.32% Synthetic Macro Fibers
- 0.35% Hooked End Steel fibers
- 0.48% Synthetic Macro Fibers
### Flexural and Residual Strength Values*

<table>
<thead>
<tr>
<th></th>
<th>Flexural Strength MOR psi [MPa]</th>
<th>$f_{150}$ psi [MPa]</th>
<th>$R_{150}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plain Concrete</td>
<td>686 [4.73]</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>0.32% Synthetic</td>
<td>680 [4.69]</td>
<td>126 [0.87]</td>
<td>18.0</td>
</tr>
<tr>
<td>0.48% Synthetic</td>
<td>699 [4.82]</td>
<td>225 [1.55]</td>
<td>32.0</td>
</tr>
<tr>
<td>0.35% Hook Steel</td>
<td>679 [4.68]</td>
<td>234 [1.61]</td>
<td>34.5</td>
</tr>
<tr>
<td>0.50% Crimp Steel</td>
<td>766 [5.28]</td>
<td>184 [1.27]</td>
<td>24.0</td>
</tr>
</tbody>
</table>

*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
Modified Strength Equations

• \( \text{MOR}' = (\text{MOR} + f_{150}) \)
  
  – \( \text{MOR} \) = plain concrete flexural strength
  – \( F_{150} \) = residual strength
  – \( \text{MOR}' \) = effective flexural strength of FRC

• \( f_{150} = 150 \text{ psi (for example)} \)
• \( \text{MOR} = 600 \text{ psi} \)

• Stress Ratio (SR) = \( \frac{\text{(Total Stress)}}{f_{150} + \text{MOR}} \)

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

![Graph showing the effect of macro-fibers on slab thickness.](image)

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?

Bordelon (2011)