Overview of Macrofiber Software and Guidelines for Concrete Overlay Design

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TTCC/Fiber Reinforced Concrete Project
National Concrete Consortium
Webinar 3 of 3
Acknowledgements

• 3rd 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, and Jeffery Roesler
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 and performance in concrete pavements (slabs)
• Review of ASTM C1609-12 residual strength test (FRC)
• Review FRC pav’t design process
• FRC Overlay Performance Software
  – Demo: inputs and output (residual strength)
• Structural design example (FRC overlay)
• Specification tips
Fiber Type Comparison

- *Structural* (macrofibers) versus *non-structural* (microfibers)

- Micro-Fibers – plastic shrinkage (non-structural)

- **PP** – 6.7 lb/yd³ or 0.44% V_f
  Residual strength (e.g., $f_{150} = 145$ psi)
Review of Fiber Reinforced Concrete Literature
for V_f<1.0% (Macrofibers)

• 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
Monotonic Load-Deflection Plot
Plain/ Synthetic Macrofibers

![Graph showing load vs. deflection for plain and synthetic macrofiber concrete samples.](image-url)

- **Plain**
- **0.48% Synthetic Macro Fiber**
- **0.32% Synthetic Macro Fiber**
Effect of Macrofibers on Concrete Slab Flexural Capacity

• Macrofiber addition improve flexural cracking load over plain concrete slab.

Increase in FRC slab capacity over plain concrete slab

• Synthetic Macrofiber#1 (0.48%) ⇒ 32%
• Synthetic Macrofiber#1 (0.32%) ⇒ 25%
• Hooked Steel Macrofiber (0.35%) ⇒ 31%
• Crimped Steel Macrofiber (0.50%) ⇒ 55%*

*higher concrete strength
How to specify macrofibers in concrete overlays?

- Comparison of Flexure Strength Tests
  - ASTM C1550 (RPT)
  - ASTM C1018 (old)
  - ASTM C1399 (beam)
  - ASTM C1609-12 (beam)
  - JCI-SF4 (1983) - beam

- RESIDUAL STRENGTH
Flexural Performance of FRC

ASTM C1609-12

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

ASTM C1609-12

\[ \text{MOR} = f_1 = \frac{P_1 L}{b \cdot d^2} \]

\[ f_{150} = \frac{P_{150} L}{b \cdot d^2} \]

\[ R_{T,150} = \frac{150 \cdot T_{150}}{f_1 \cdot b \cdot d^2} \]

\( f_{150} \) = residual strength
\( R_{T,150} \) = Equivalent flexural strength ratio
How to specify fibers in concrete?

• Specific FRC mixture must:
  – Be tested according to ASTM C1609-12
  – Achieve a minimum $f_{150}$ residual strength value (design target)
  – Be tested at a certain age (e.g., 7 or 28 days)
  – Be a certain specimen size (e.g., 6”x6” beam)
Flexural Beam Results

150x150x550mm

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

\begin{align*}
\sigma_{150}^f &= \frac{P_{150}^L}{b \cdot d^2} \\
\end{align*}
# Flexural and Residual Strength Values*

<table>
<thead>
<tr>
<th>Material</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)
## Effects of Concrete Mixture Parameters on $f_{150}$ values

<table>
<thead>
<tr>
<th>$f_{150}$ psi [MPa]</th>
<th>Mixture</th>
<th>Fiber type</th>
<th>Age tested days</th>
<th>Fiber volume % of total concrete volume</th>
<th>Fiber dosage amount lb/cy [kg/m$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>90 [0.65]</td>
<td>Mix 1</td>
<td>Synthetic Fiber #1</td>
<td>14</td>
<td>0.27%</td>
<td>4.09 [ 2.42]</td>
</tr>
<tr>
<td>155 [1.05]</td>
<td>Mix 1</td>
<td>Synthetic Fiber #1</td>
<td>28</td>
<td>0.38%</td>
<td>5.76 [ 3.42]</td>
</tr>
<tr>
<td>160 [1.10]</td>
<td>Mix 1</td>
<td>Synthetic Fiber #2</td>
<td>28</td>
<td>0.27%</td>
<td>4.14 [ 2.45]</td>
</tr>
<tr>
<td>160 [1.10]</td>
<td>Mix 2</td>
<td>Synthetic Fiber #3</td>
<td>28</td>
<td>0.50%</td>
<td>7.58 [ 4.50]</td>
</tr>
<tr>
<td>175 [1.21]</td>
<td>Mix 2</td>
<td>Steel Fiber</td>
<td>28</td>
<td>0.19%</td>
<td>25.13 [14.91]</td>
</tr>
<tr>
<td>225 [1.10]</td>
<td>Mix 1</td>
<td>Synthetic Fiber #2</td>
<td>28</td>
<td>0.38%</td>
<td>5.83 [ 3.46]</td>
</tr>
</tbody>
</table>
Effective Flexural Strength Equation

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

  $f_{150} = 125$ psi (FRC mix for example)
  $MOR = 625$ psi (ASTM C78 at 28 days)
  $MOR' = 625$ psi $+ 125$ psi $= 750$ psi

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

• Fatigue Life: $\log N_f = 17.61 - 17.61 \frac{\sigma}{MOR'}$

Note: $f_{150} = f_{150}^{150}$

Altoubat et al. (2007)
Bordelon and Roesler (2012)
Bonded Concrete Overlay of Asphalt:  
15-year Illinois Experience with Macrofibers

- **Macrofibers** important to good performance
  - Reduce required overlay thickness
  - Keep joints tight and reduce risk of faulting/misalignment
  - When distresses occur, fibers keep cracks tight, allowing pavement to remain relatively smooth and serviceable
  - Reduction to elimination in slab migration/movement

- Maintain panel sizes with fibers ≤ 6 ft
- No faulting or cracking on 4ft or 6ft slab sizes with macrofibers (>2006)
- If the HMA layer or underlying support have the potential to be variable condition (e.g. Schank Ave) and/or heavy truck traffic, *try higher fiber dosages or fix support layer*

*King et al. (2014)*
Pavement Design Methods with FRC input

• Existing design methods / codes
  – British Concrete Society (TR34) – industrial floors
  – Bonded Concrete Overlay of Asphalt (BCOA)
    • IDOT Chapter 53 (2008) BCOA (Bordelon and Roesler 2012)
    • ACPA BCOA calculator (http://apps.acpa.org/applibrary/BCOA/)
  – OptiPave 2.0 (Covarrubias et al. 2011)
    • Short slab technology & unbonded

• New software to select fiber performance* (type/quantity)
  – Provides recommended $f_{150}$ and MOR to be used in design methods
  – Provides estimate on LTE and Reduction of cracking severity after 10 yrs
Illinois Structural Design of BCOA (2007-09)

Effect of Macro-fibers on Slab Thickness

Bordelon et al. (2008)
Fiber-Reinforced Concrete Pavement Design

• Use existing concrete pavement design thickness methods (AASHTO Pavement ME, ACPA Pavement Designer*, FAA, AASHTO 1993)
  – MOR = plain concrete flexural strength

• Effective or modified flexural strength (MOR’)
  – include macrofibers ($f_{150}$) = residual strength

• Input MOR’ for concrete strength instead of MOR

• Warning: Slab size adjustment may be needed!!
New FRC Software for Concrete Overlays

Macro-Fiber Performance Calculator for Concrete Overlays

Instructions: Run an overlay design software to determine the design inputs. Select design choices from the drop-down menus below to narrow down the recommended performance requirement of FRC for the proposed overlay pavement. Determine the estimated effective MOR to input into overlay design software instead of design concrete MOR. Prepare specifications to achieve design residual strength of FRC material.

Design Choices
Type of Overlay Road
- Parking Lot

Millions of ESALS in design life
- < 0.01 million ESALS

Asphalt Pre-Condition*
- Fair

*Refer to Tech Guide to determine asphalt pre-condition

Desired New Concrete Thickness
- 3 to 4.5 inch PCC thickness

Remaining HMA Thickness after Milling
- 4.5 to 6 inches

Overlay Slab Size
- 4 ft

Desired Performance Enhancements
- Basic FRC overlay

Design Suggestions/Warnings:
- 4 ft short slabs are not recommended for unchannelized traffic (ideally for parking lots only)
WHEN to use new FRC Software

• Use existing design procedure for designing overlay or pavement
  – BCOA-ME *(select no fiber)
  – ACPA BCOA app **(put in R_{150})
  – AASHTO Pavement ME
  – Etc.

• Put select inputs from your design into the new FRC selection software

• Software will output recommended f_{150} values

*Warning: some of the existing software that includes “FRC” already changes the MOR internally. Use the MOR’ of this software and un-reinforced (no FRC).
** In software that uses f_{150} or R_{150} AND original MOR, please use these values from the FRC software.
Inputs for FRC Software

- Type of Overlay
- Traffic Amount (ESALs)
- Asphalt Pre-Condition* (FRC software only asks about 1 layer below)
- Desired Concrete Thickness
- Remaining HMA Thickness after Milling
- Slab Size
- Performance Enhancements*
- Plain (or FRC) Concrete MOR
- Tested FRC $f_{150}$ value (optional)

*clarified further in this webinar and in full report
## Asphalt Pre-Condition

- Software accepts Poor, Localized Poor, Fair, and Good
- Different ways to rate the existing condition
- Effects choice of bond vs. unbonded overlay primarily

<table>
<thead>
<tr>
<th></th>
<th>Poor and Localized Poor</th>
<th>Fair</th>
<th>Good +</th>
</tr>
</thead>
<tbody>
<tr>
<td>HMA Structural Number</td>
<td>2</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>HMA Stiffness</td>
<td>100 ksi [0.7 GPa]</td>
<td>350 ksi [2.4 GPa]</td>
<td>600 ksi [4.1 GPa]</td>
</tr>
<tr>
<td>HMA Seasonal Resilient Modulus</td>
<td>430 ksi [3GPa]</td>
<td></td>
<td>580 ksi [4 GPa]</td>
</tr>
<tr>
<td>HMA Distresses</td>
<td>Stripping, delaminations, poor drainage, excessive rutting, moderate fatigue cracking, transvers cracking</td>
<td>Rutting, some surface cracks, aged</td>
<td></td>
</tr>
</tbody>
</table>
Software Demo
Example 1

• Bus Pad:
  – Low volume (<0.1 million ESALs) bus pad
  – Fair to poor condition existing HMA with 3 inches remaining after milling
  – Slabs at 6 ft spacing, 4 inch thick PCC
  – MOR = 600psi
  – Compare FRC design w/ plain un-reinforced overlay

  – Software suggests $f_{150}$ between 125 and 200 psi
  – Software suggests an effective MOR’ = 725psi for structural design (w/ macrofiber mix)
Example with BCOA-ME PITT
Plain Concrete compared to FRC

PCC OVERLAY PROPERTIES

- Average 28-day Flexural Strength (three-point bend): 725
- Estimated PCC Elastic Modulus (psi): 3700000
- Coefficient of Thermal Expansion (10^-6 in/°F/in): 5.3

Fiber Type: No Fibers

JOINT DESIGN

- Joint Spacing (ft): 6 x 6

Use MOReff
Select NO FIBERS

CALCULATE DESIGN
## Example 1, continued

<table>
<thead>
<tr>
<th></th>
<th>Plain Concrete</th>
<th>FRC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BCOA-ME inputs</strong></td>
<td>100,000 ESALs</td>
<td>725 psi MOR’</td>
</tr>
<tr>
<td></td>
<td>3 in HMA remaining</td>
<td>“No Fibers”</td>
</tr>
<tr>
<td></td>
<td>Marginal condition</td>
<td>“No Fibers” still selected</td>
</tr>
<tr>
<td></td>
<td>600 psi MOR</td>
<td></td>
</tr>
<tr>
<td></td>
<td>“No Fibers”</td>
<td></td>
</tr>
<tr>
<td>Calculated PCC</td>
<td>4.73 in</td>
<td>3.8 in</td>
</tr>
<tr>
<td>Thickness</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design PCC Thickness</td>
<td>5 in</td>
<td>4 in</td>
</tr>
</tbody>
</table>

*Keep Elastic Modulus and “No Fibers” inputs the same in the BCOA-ME software*

FRC software states for $f_{150}$ of 125psi the LTE is predicted to be 80-90% and a reduction in crack severity.
Example 2

• **Arterial Roadway**
  – 10 million ESALs
  – Localized pot holes and otherwise moderate distresses in HMA with 3 inches remaining after milling
  – Slabs at 6 ft spacing, 6 inch thick, 600psi concrete
  – Want to compare the basic FRC design against plain unreinforced overlay

  – Due to thin HMA and fair/poor condition, should check unbonded design

  – Software suggests $f_{150}$ between 175 and 250 psi
  – Software suggests an effective MOR’ of 775psi be used in the design
### Example 2 continued

<table>
<thead>
<tr>
<th></th>
<th>Plain Concrete</th>
<th>FRC basic</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BCOA-ME inputs</strong></td>
<td>10M ESALs</td>
<td>775 psi MOR’ “No Fibers” selected</td>
</tr>
<tr>
<td></td>
<td>3 in. HMA remaining Marginal condition</td>
<td></td>
</tr>
<tr>
<td></td>
<td>600 psi MOR “No Fibers”</td>
<td></td>
</tr>
<tr>
<td><strong>Calculated PCC</strong></td>
<td>5.93 in</td>
<td>4.5 in</td>
</tr>
<tr>
<td><strong>Thickness</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Design PCC</strong></td>
<td>6 in</td>
<td>4.5 in</td>
</tr>
<tr>
<td><strong>Thickness</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*FRC software states LTE 80-90% and Yes reduced crack severity for \( f_{150} \) of 175 psi or more*
Design Enhancement Input
(Optional)

• An option in the inputs is or a “design enhancement” based on specific benefits of fibers
  – Enhance Load Transfer Efficiency
  – Reduce Crack Deterioration Rate

• Will increase the recommended $f_{150}$ value
  – Increases by $50 \text{ psi}$ total
Why use this FRC Performance software for Concrete Overlays?

• Other design methods (e.g., AASHTO Pavement ME) do not include benefit of fibers
  – Use this Excel spreadsheet to find how much to change the MOR to MOR’ in other design procedure.

• Can use design methods that have fibers (e.g., BCOA-ME) but include your fiber type through its performance value ($f_{150}$).
  – BCOA-ME and equivalent design procedures use same effective MOR’, but have internal correlation of fiber dosage rate to $f_{150}$ value.

• Written with Excel with pull down menus so it is easy to use
What if I already have a FRC mixture?

• Can skip the inputs portion and go straight to the material properties portion
  – Input the MOR (28 day 4-point bending strength)
  – Input the $f_{150}$ value

• Software will calculate the effective MOR’ to use in structural design

• Software will also predict serviceability parameters
  – Load Transfer Efficiency and Reduced Severity of Cracking
  – Based on existing research and field estimates

<table>
<thead>
<tr>
<th></th>
<th>$f_{150} = 50$ psi</th>
<th>$f_{150} = 100$ psi</th>
<th>$f_{150} = 150$ psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anticipated Load Transfer Efficiency at 10 yrs</td>
<td>60-70%</td>
<td>80-90%</td>
<td>80-90%</td>
</tr>
<tr>
<td>Will the severity of cracking be reduced?</td>
<td>No reduction in severity</td>
<td>No reduction in severity</td>
<td>Yes reduction in severity</td>
</tr>
</tbody>
</table>
What we need from you?

- Try out the FRC Overlay Performance software
- Consider more FRC pavement projects (overlays for streets, highways, parking lots)
- Record actual parameters (thickneses, stiffness, strengths, $f_{150}$ values)
- Submit these parameters to an ACPA representative added in the National Overlay Database
- FRC Software can be updated in future as more FRC overlay projects designed, constructed, and monitored.
FYI:
ACPA National Concrete Overlay Explorer
overlays.acpa.org/webapps/overlayexplorer/index.html
Specifications for FRC Overlays

• ASTM 1116 – types of fibers allowed
  – Type I – steel (ASTM A820), Type II-glass (ASTM C1666), Type III-synthetic (ASTM D7508), etc.

• Fiber geometry (diameter & length)

• Batching and mixing macrofibers in concrete

• Residual strength ($f_{150}$) – ASTM C1609-12
  – e.g., quantity of fiber must achieve $f_{150} = 125$ psi

• Max and min. fiber dosage (lb/cy)
  – Fiber balling (max) & variability in $f_{150}$ (min)
Questions & Further Information

• Contact Speakers:
  – Jeffery Roesler, Ph.D., P.E., University of Illinois Urbana Champaign
    jroesler@illinois.edu
  – Amanda Bordelon, Ph.D., P.E., Utah Valley University
    amanda.bordelon@uvu.edu
Questions?

Bordelon (2011)