TRANSPORTATION LEARNING NETWORK

A partnership with MDT•NDDOT•SDDOT•WYDOT and the Mountain-Plains Consortium Universities

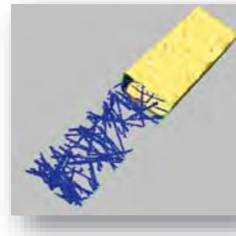
Welcome!

Cracking and Debonding of a Thin Fiber Reinforced Concrete Overlay

Amanda Bordelon, Ph.D., P.E.

Our partners:

MOUNTAIN-PLAINS CONSORTIUM · MONTANA MDT DEPARTMENT OF TRANSPORTATION · NDDOT North Dakota Department of Transportation · South Dakota DOT · WYOMING DOT · NDSU UPPER GREAT PLAINS TRANSPORTATION INSTITUTE TRANSPORTATION LEARNING NETWORK



Cracking and Debonding of a Thin Fiber Reinforced Concrete Overlay

Mountain Plains Consortium

Webinar Dec 17, 2018

Presented by: Amanda Bordelon, Ph.D., P.E.

Utah Valley University

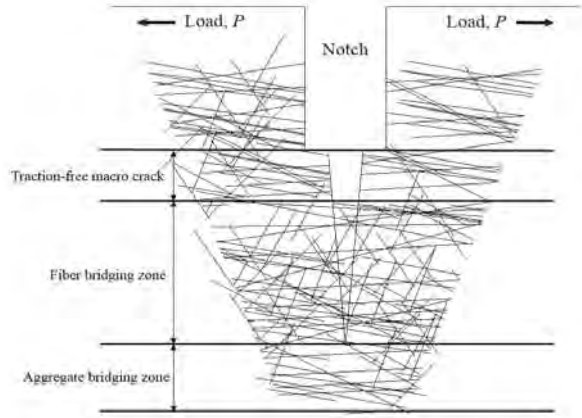
Acknowledgements

- Funding:
  - Mountain Plains Consortium Region 8
- Matching Funds:
  - Utah Department of Transportation
  - University of Utah Startup Funds

- Researchers on Project:
  - Principle Investigator: Amanda Bordelon
  - Doctorate Student: Min Ook "Thomas" Kim
  - Testing performed at University of Utah, Salt Lake City, UT Structures Lab

Fiber-Reinforced Overlays

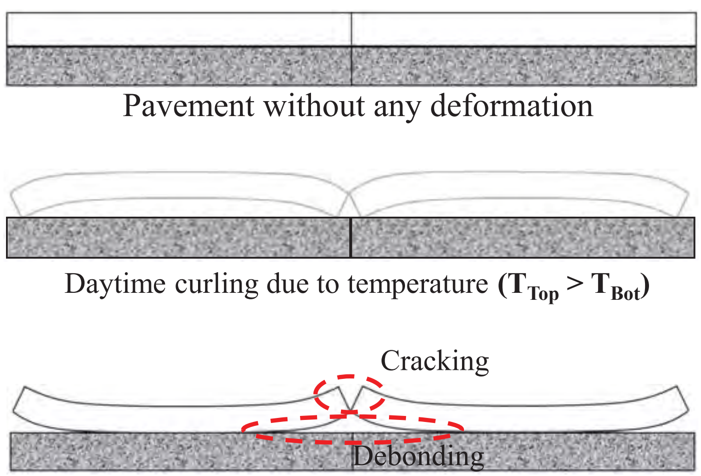
- Fiber-reinforced concrete (FRC) used for thin overlays commonly constructed since 1990s
- Well documented benefits of FRC:
    - Reduced crack widths
    - Reduced or delayed crack growth or propagation
    - Increases load carrying capacity
- Common challenges/questions:
    - Determining how many fibers to add to mixture -> use residual strength value from ASTM C1609 flexure test to check FRC
    - Unknown HOW much it changes crack widths, required joint spacing, or if effected by underlying bond



Schematic representation of fibers bridging across a crack

ASTM C1609 test, courtesy of Univ. of Illinois

Pavement Cracking and Debonding



Pavement without any deformation

Daytime curling due to temperature ($T_{Top} > T_{Bot}$)

Nighttime curling due to drying shrinkage ($\varepsilon_{sh, Top} > \varepsilon_{sh, Bottom}$) or temperature ($T_{Top} < T_{Bot}$)

Why are wide cracks a problem?
1) transport moisture much faster
2) reduced load transfer efficiency

Why is debonding a problem?
1) higher tensile stresses in top layer
2) moisture can be trapped below top layer

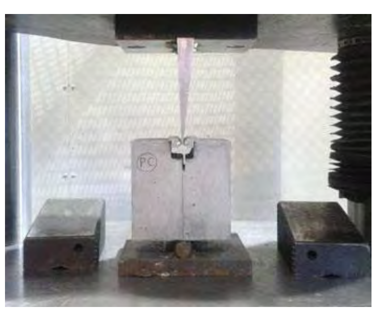
Research Motivation

- Cracking and debonding are important considerations for pavement maintenance
- Field evidence indicates FRC could be placed for larger slabs
- It is unknown how much crack widths can be reduced by implementing FRC let alone by increasing slab sizes

- Equation to predict crack width of FRC overlays
- Finite element model to investigate the cracking and debonding behavior
- Testing to verify FRC bridging and bonding across interfaces

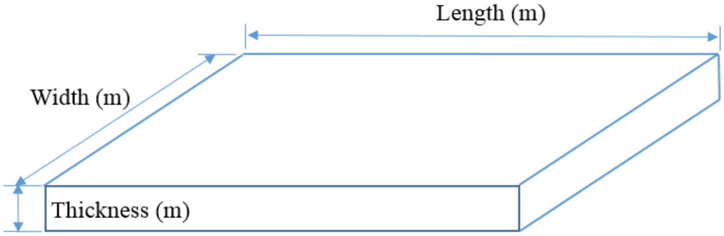
Presentation Contents

✓Background and Motivation
- Crack Widths Predictions
- Finite Element Modeling
- Testing of Fiber Effect on Interfacial Bond
- Conclusions and Recommendations



Field Evidence with FRC

- Roadway cast in Rantoul, IL 2009
- Contains 0.50% volume fraction polymeric fibers
- Monitored for crack width and delaminations over time.
- Environmental loading only (no traffic)



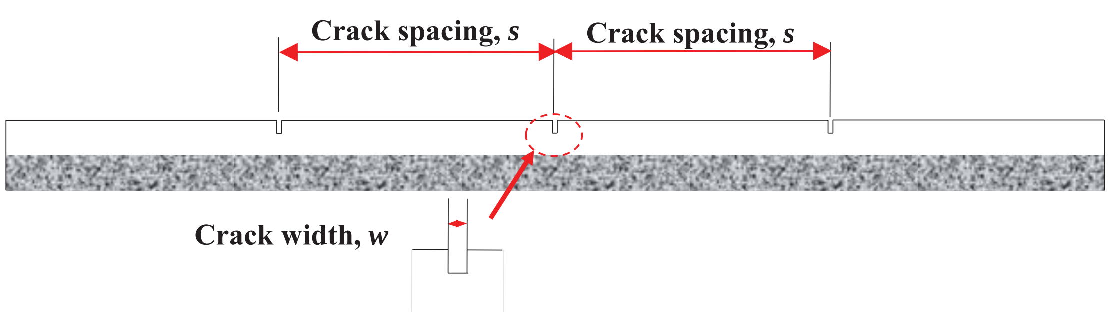
	Section 1	Section 2	Section 3
Length (m)	1.12	1.68	3.35
Width (m)	1.15	1.73	1.72
Thickness (m)	0.05	0.05	0.05

3.5', 5.5' and 11' joint spacing

Section 1	Section 2	Section 3
FRC, t = 50 mm — 2" thick	FRC , t = 50 mm	FRC, t = 50 mm
HMA, t = 50 mm	HMA, t = 50 mm	HMA, t = 50 mm
Binder course, t = 370 mm	Binder course, t = 370 mm.	Binder course, t = 200 mm
Lime modified Subgrade, t = 300 mm	Lime modified Subgrade, t = 300 mm	Lime modified Subgrade, t = 300 mm

Slab sizes and layer information

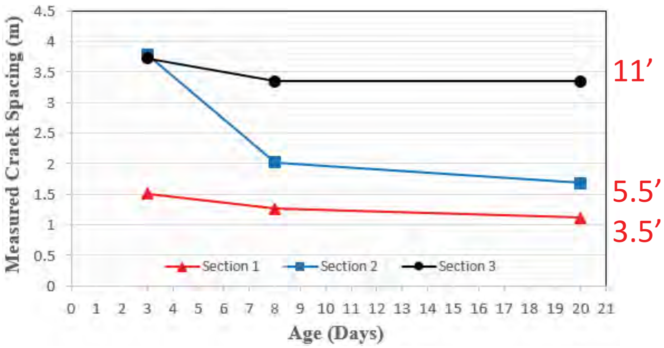
Crack Spacing and Crack Width



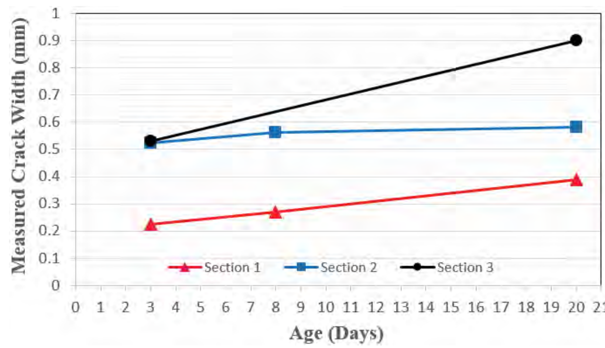
Most FRC overlays (including the observed test section) exhibit few to no mid-panel cracking!

This study considered crack spacing, but since no midpanel cracks, the crack spacing >= construction joint spacing

Field Evidence (Crack Widths)



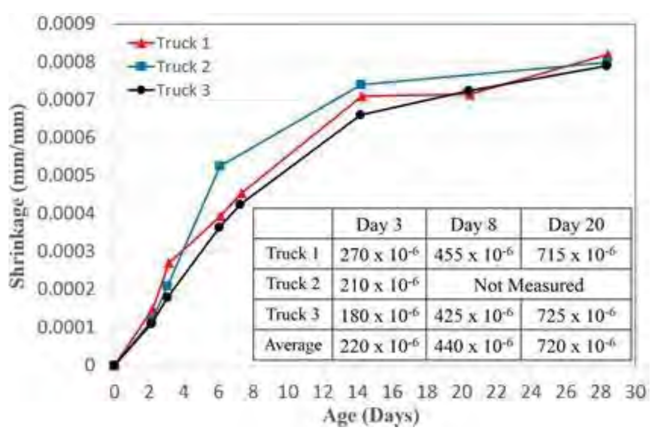
Measured average **crack spacing** vs age (days)



Measured **average crack width** vs age (days)

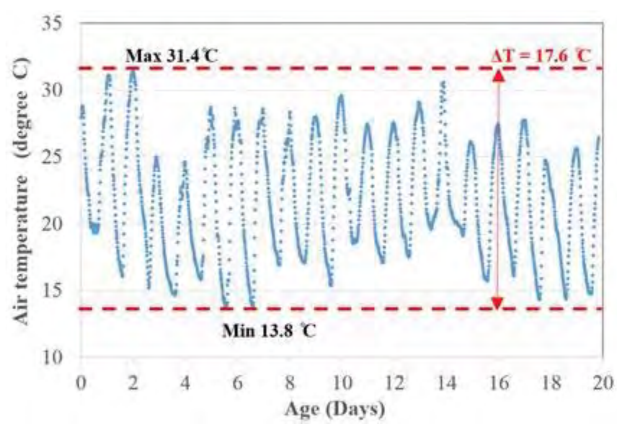
- Crack spacing decreased to saw-cut joint spacing by 20 days age.
- No mid-panel cracking.
- Not all joints cracked at 1 day.
- No significant change on crack width in section-2 with age.

Field Evidence (Shrinkage and Temperature)



	Day 3	Day 8	Day 20
Truck 1	270×10^{-6}	455×10^{-6}	715×10^{-6}
Truck 2	210×10^{-6}	Not Measured	
Truck 3	180×10^{-6}	425×10^{-6}	725×10^{-6}
Average	220×10^{-6}	440×10^{-6}	720×10^{-6}

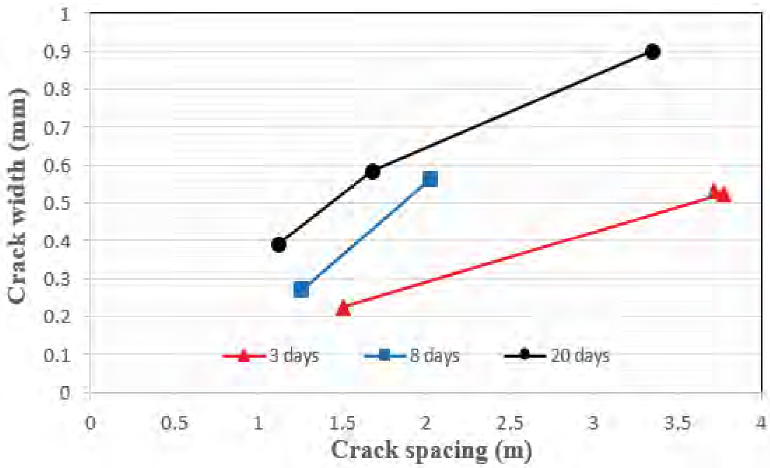
Samples taken during construction to measure the free drying shrinkage



Recorded air and pavement temperature over time

Field Overlay Findings

- Crack width increased as joint spacing was increased.
- The field measured bond strength was about 0.67 to 1.66 MPa at 3 months.
- The crack widths measured in the field (below) were then compared to predicted values using the AASHTO Pavement ME equation



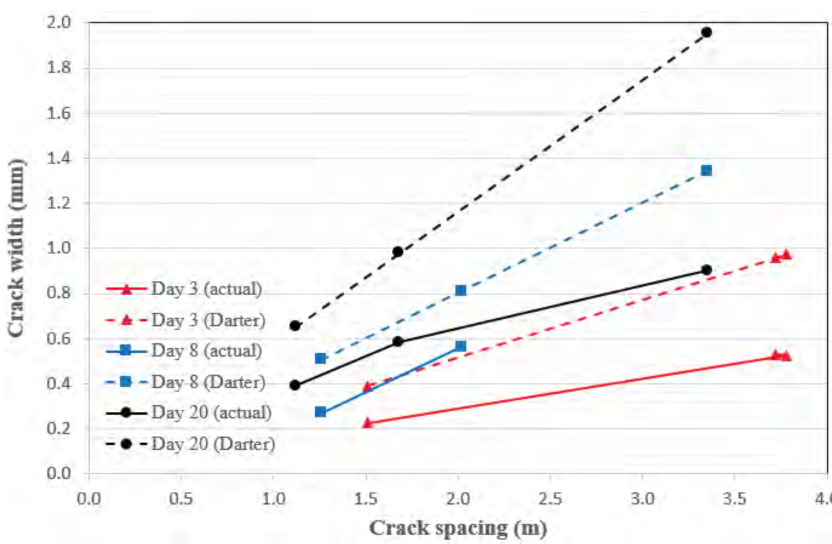
Relation between crack spacing and crack width in FRC overlay

Experiment vs. Darter and Barenberg's equation

- Darter and Barenberg's equation (AASHTO Pavement ME).
- Crack widths were **two times higher** than measurements.
- This is because the equation **does not consider fiber effect.**

Darter and Barenberg's equation

$$\Delta L = CL(\alpha_t \Delta T + \epsilon)$$



Effect of fiber on crack width-RILEM TC 162-TDF

- **Crack width**

$$w_k = \beta s_{rm} \varepsilon_{sm}$$

where,

w_k: the final crack width, β: coefficient relating the average crack width the design value,

s_{rm}: the average final crack spacing, ε_{sm}: the mean strain in the tension reinforcement

- **Crack spacing**

$$S_{rm} = \left(50 + 0.25 k_1 k_2 \frac{\phi_b}{\rho_r}\right)\left(\frac{50}{L_f/D_f}\right)$$

(Tensile reinforcement effect on crack width) (Fiber effect on crack width)

where,

k_1: coefficient of bond properties of tensile reinforcement

k_2: coefficient which takes account of the form of strain distribution

ϕ_b: tensile reinforcement bar diameter, ρ_r: effective tensile reinforcement ratio

L_f/D_f : aspect ratio of fiber reinforcement

Effect of fiber on crack width-Löfgren's equation

- **Crack Width**

$$w_k = s_{r,max}(\varepsilon_{sm} - \varepsilon_{cm})$$

where,

ε_{sm}: the mean strain in the reinforcement (non-fiber), ε_{cm}: the mean strain in the remaining concrete between the cracks

- **Crack Spacing**

$$S_{r,max} = 3.4c + 0.425 k_1 k_2 k_5 \frac{\phi}{\rho_{p,eff}}$$

$$k_5 = \left(1 - \frac{f_{residual}}{f_{mor}}\right)$$

(Fiber effect on crack width)

where,

k_1 and k_2 are the same as in RILEM method

$f_{residual}$: measured residual flexural stress of SFRC (RILEM TC 162-TDF)

f_{mor}: measured flexural strength of SFRC (RILEM TC 162-TDF)

c: concrete cover depth, ϕ: (non-fiber) reinforcing bar diameter, $\rho_{s,eff}$: effective reinforcement ratio (non-fiber)

Modified equation

- Coefficients which express the effect of fiber were added to Darter and Barenberg's equation.
- **Modified equation to predict crack width of FRC overlay**

$$w = Cs(\alpha_t \Delta T + \varepsilon_{sh})\{k_a \; or \; k_b\}$$

$$k_a = \frac{50}{L_f/D_f} \leq 1.0 \;\; or \; k_b = 1 - \frac{f_{res,FRC}}{f_{mor,FRC}}$$

in which,

w: crack width caused by temperature change and drying shrinkage of FRC overlay

C: adjustment factor due to slab-subbase friction (0.65 for stabilized base and 0.8 for granular subbase)

s: crack spacing or slab length, α_t: Coefficient of thermal expansion of FRC

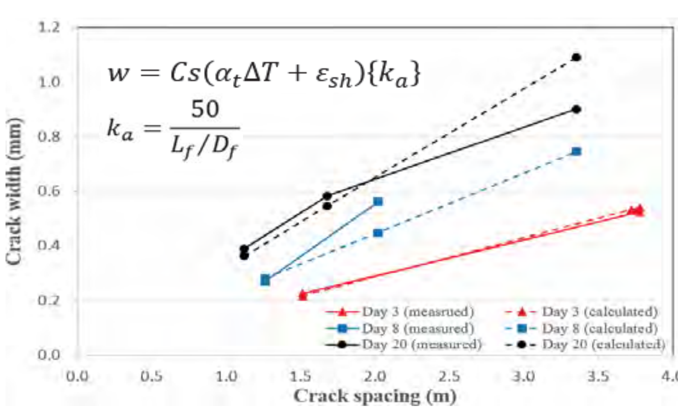
ΔT: Temperature at placement minus the lowest mean monthly temperature

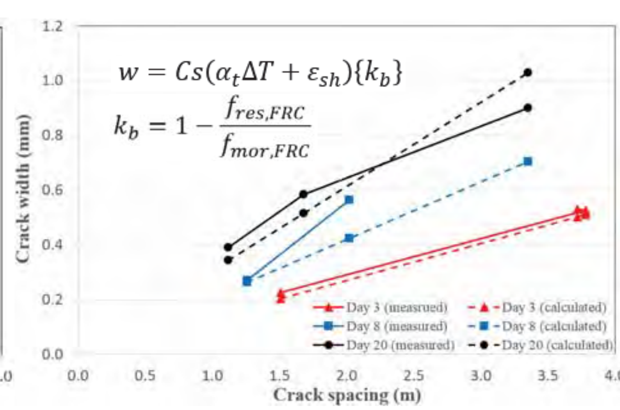
ϵ: Drying shrinkage coefficient of FRC, L_f/D_f : aspect ratio of fiber reinforcement

$f_{res,\ FRC}$:residual flexural stress of FRC from flexural beam test - ASTM C1609 (MPa), $f_{mor,FRC}$: flexural strength of FRC (MPa).

Experiment vs Modified equation

- Aspect ratio (L_f/D_f) of synthetic fiber from field (40 mm long) is 90 for k_a.
- Field FRC measured f_{res} and f_{mor} are used for k_b.

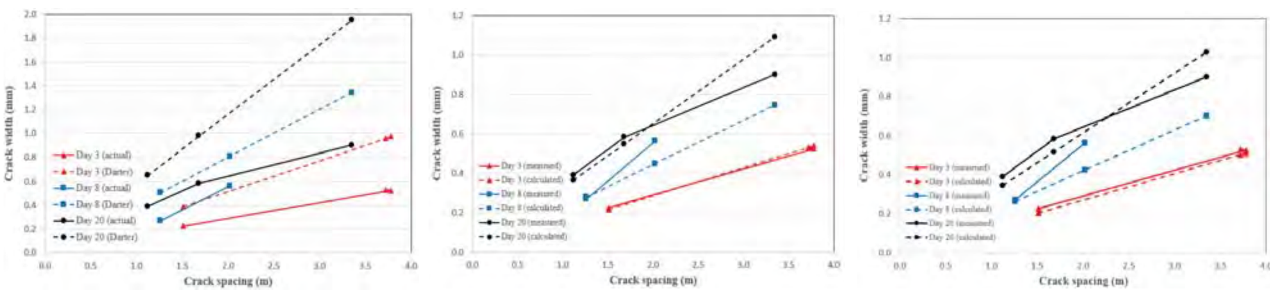




- This new proposed equation is able to predict the crack width within 25% for the thin FRC overlay at different joint spacings.

Summary from theoretical approach

- Prediction equation created uses a fiber effect factor multiplied to the existing Darter and Barenberg equation for crack width vs crack spacing.
- Predicted crack widths showed good agreements with measured crack widths (within 0.19 mm).
- k_b version of the fiber effect factor accommodates for alternative fiber geometries.



Darter and Barenberg's equation

$$\Delta L = CL(\alpha_t \Delta T + \epsilon)$$

Modified equations

$$w = Cs(\alpha_t \Delta T + \varepsilon_{sh})\{k_a\}$$

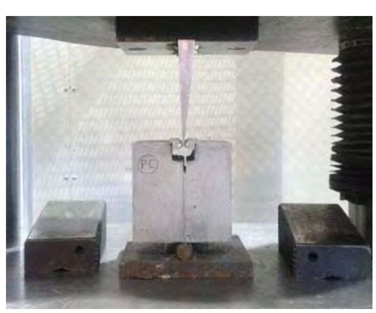
$$k_a = \frac{50}{L_f / D_f}$$

$$w = Cs(\alpha_t \Delta T + \varepsilon_{sh})\{k_b\}$$

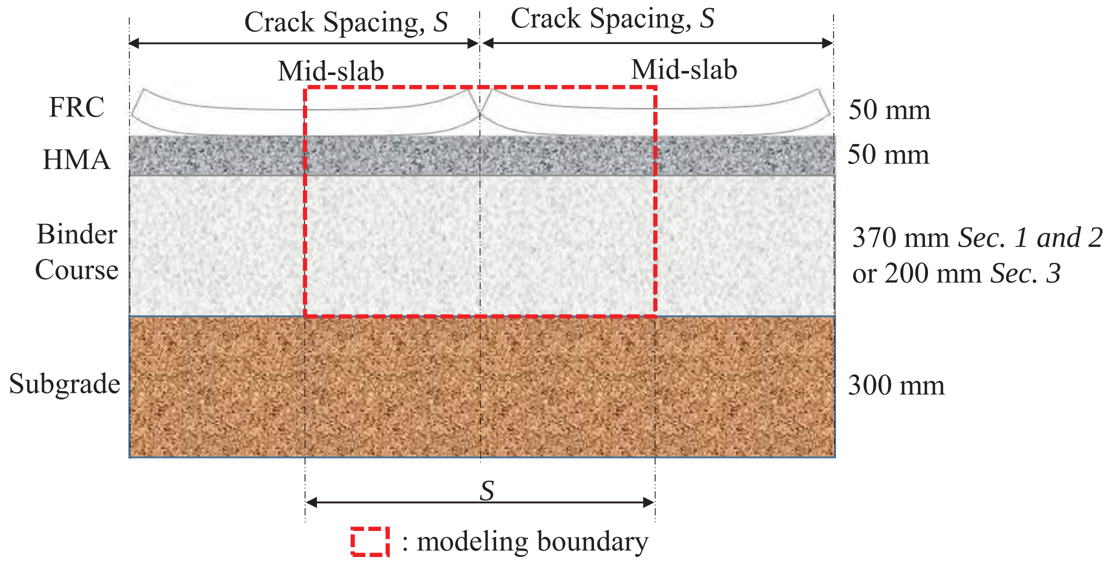
$$k_b = 1 - \frac{f_{res,FRC}}{f_{mor,FRC}}$$

Presentation Contents

✓Background and Motivation
✓Crack Widths Predictions
- Finite Element Modeling
- Testing of Fiber Effect on Interfacial Bond
- Conclusions and Recommendations

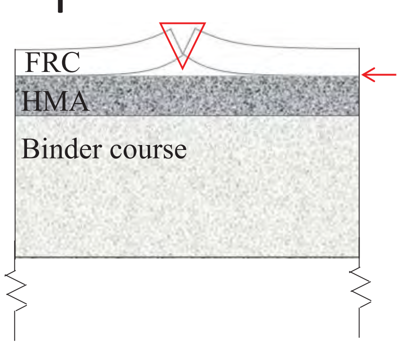


Finite element model description



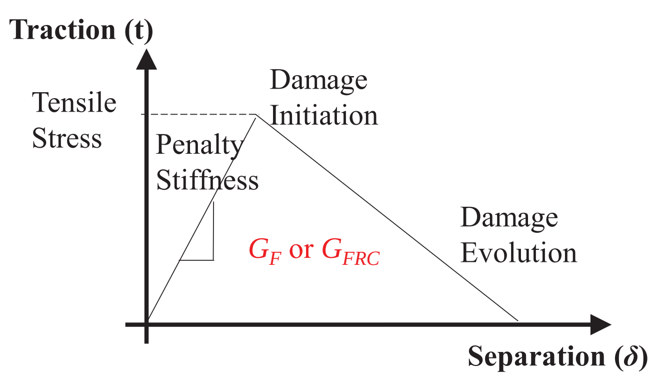
The modeling is simplified because this study focuses on cracking and debonding in FRC layer.
The subgrade was idealized using elastic foundation (the stiffness of elastic foundation is 150 kPa/mm).

Cohesive Strength and Fracture Properties



- Cohesive behavior were defined at the joint location and FRC-HMA interface.

	FRC stress vs opening	Bond interface stress vs opening
Penalty stiffness (Pa/m)	1e12 (Fixed)	1e12 (Fixed)
Cohesive strength (Pa)	2e6 (Fixed)	0.5e6 (Fixed)
Fracture energy (N/m)	**80 to 3500 (varies)**	70 (Fixed)



Traction-separation relation for linear softening curve

$$\mathbf{t} = \begin{Bmatrix} t_n \\ t_s \end{Bmatrix} = \begin{bmatrix} K_{nn} & K_{ns} \\ K_{ns} & K_{ss} \end{bmatrix} \begin{Bmatrix} \delta_n \\ \delta_s \end{Bmatrix} = \mathbf{K\delta} \quad \textbf{Eq. (1)}$$

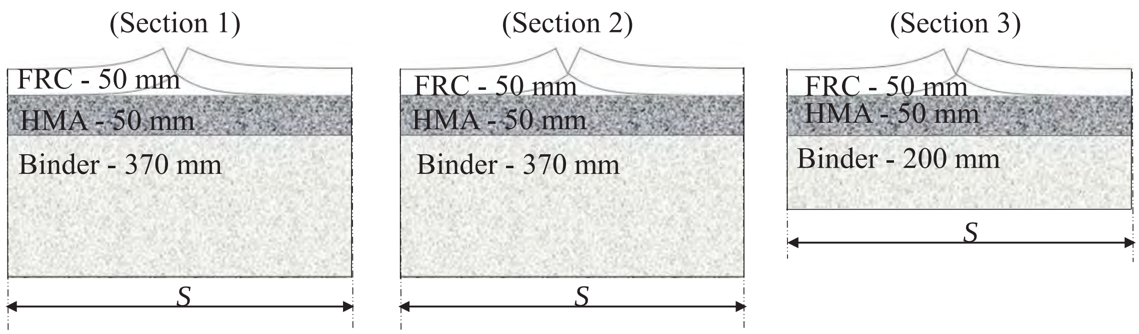
$$max\left\{\frac{\langle t_n \rangle}{t_n^o}, \frac{\langle t_s \rangle}{t_s^o}, \frac{\langle t_t \rangle}{t_t^o}\right\} = 1 \quad \textbf{Eq. (2)}$$

Plain Concrete 80 N/m
FRC (from field) 3600 N/m

ASTMC1609 f150 = 205 psi, R150= 28%

Dimensions

- A different 2D model for each section (Total of 3) was developed based on average crack spacing to mimic the field data geometry



Day 3	Day 8	Day 20	Average
1510	1260	1120	**1300**

Crack spacing (mm)

Day 3	Day 8	Day 20	Average
3720	3350	3350	**3500**

Day 3	Day 8	Day 20	Average
3780	2020	1680	**2500**

Loading - Thermal Deflection

$$\Delta\varepsilon_{sh} = \varepsilon_{sh,free} - \varepsilon_{sh,restrained}$$ **Eq. (3)**

$$\delta_T = \frac{(\Delta\varepsilon_{sh} + \alpha_T \Delta T) l^2}{2h}$$ **Eq. (4)**

where,

$\varepsilon_{sh,\,top}$: measured free shrinkage by experiment (mm/mm)

α_T: coefficient of thermal expansion of FRC (˚C)

ΔT: measured temperature differentials between top and bottom of FRC slab (˚C)

l : slab length (mm)

h: slab thickness (mm)

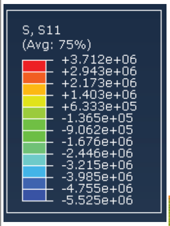
It was assumed that the shrinkage at the top of FRC slab is equal to the free shrinkage $\varepsilon_{sh,\,free}$ measured by experiment (under controlled temperature and humidity).

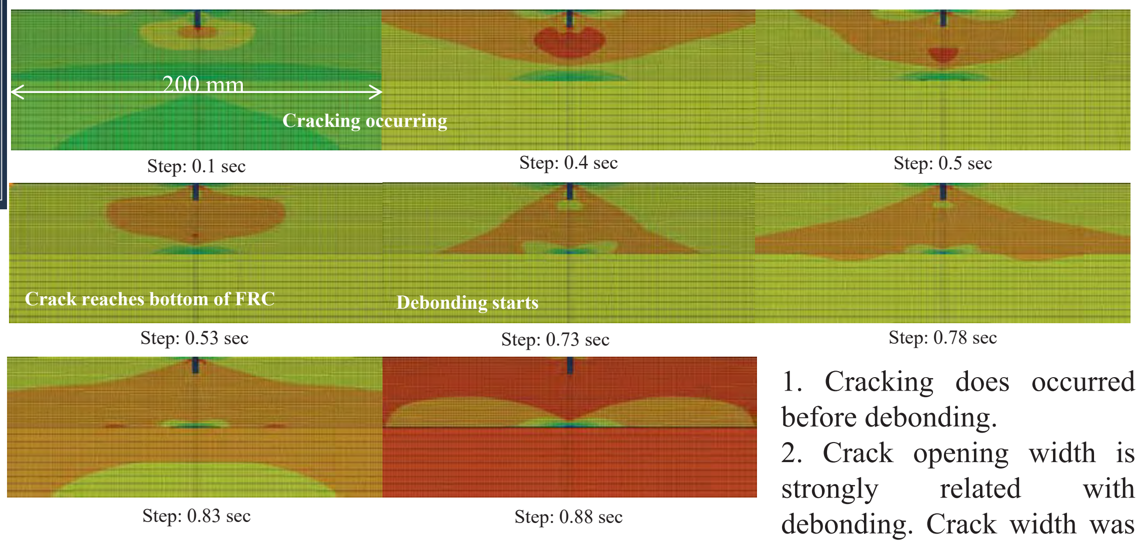
It was also assumed that the shrinkage at the bottom of slab is frictional restraint with a value of $\varepsilon_{sh,\,restrained}$ = 25 x 10^{-6}.

Section 1	Age (days)		
	Day 3	Day 8	Day 20
$\varepsilon_{sh,\,free}$ (mm/mm)	220 x 10^{-6}	440 x 10^{-6}	720 x 10^{-6}
$\Delta\varepsilon_{sh}$ using Eq. (3)	195 x 10^{-6}	415 x 10^{-6}	695 x 10^{-6}
ΔT (˚C)	2	2	2
δ_T using Eq. (4), mm	0.91	1.84	3.02

Analytical Results – Stress Distribution

Zoomed in Stress distribution, Section 1 Day 3 (Top: FRC layer, Bottom: HMA)





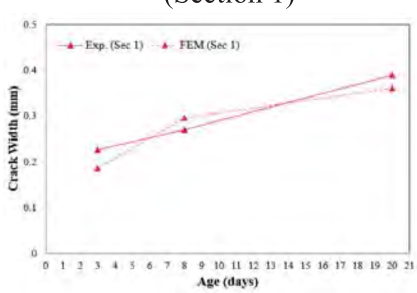
FRC strength = 2.0 Mpa

Bond strength = 0.5 MPa

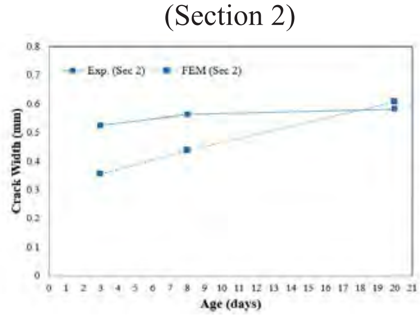
1. Cracking does occurred before debonding.
2. Crack opening width is strongly related with debonding. Crack width was increased by 1.5 times once the slab was debonded.

Validation (Crack Width Comparison)

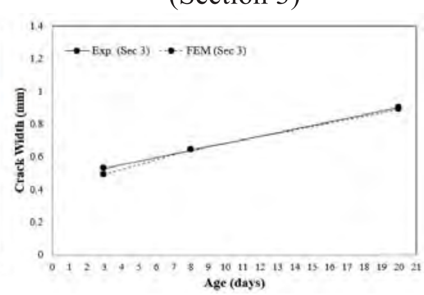
(Section 1)



(Section 2)



(Section 3)



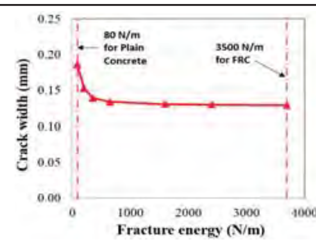
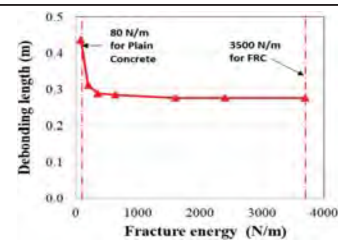
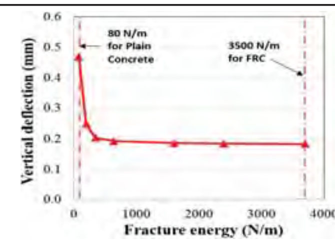
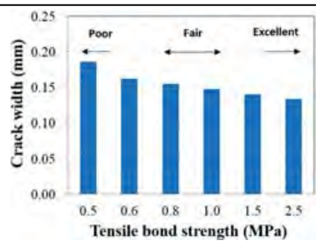
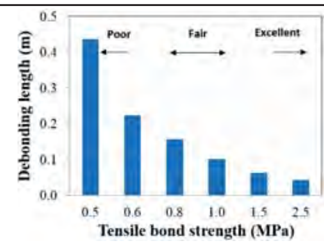
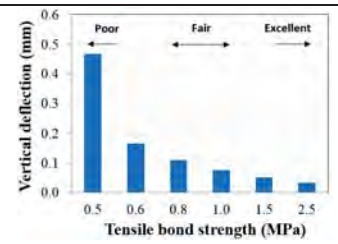
Age (days)	Experiment	FEM
Day 3	0.226	0.186
Day 8	0.270	0.297
Day 20	0.390	0.362

Age (days)	Experiment	FEM
Day 3	0.525	0.355
Day 8	0.563	0.437
Day 20	0.583	0.608

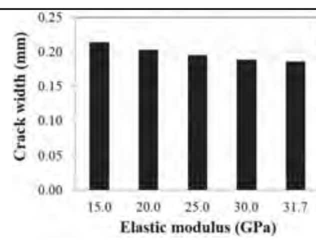
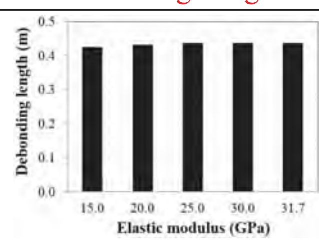
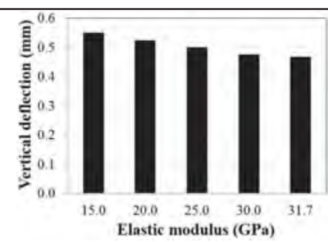
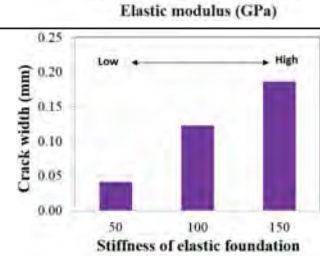
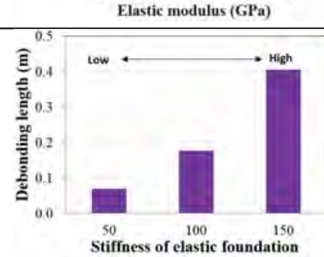
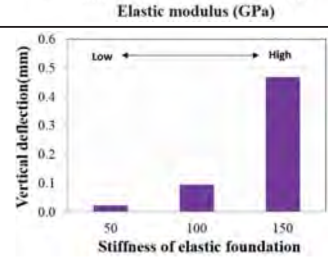
Age (days)	Experiment	FEM
Day 3	0.530	0.491
Day 8	-	0.645
Day 20	0.900	0.889

Overall: within 0.17 mm of prediction on crack width with FEM model

Fracture Energy and Tensile Bond Strength

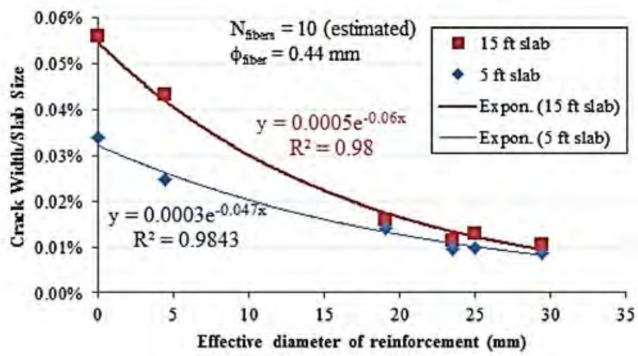
	Crack Width	Debonding Length	Vertical Deflection
FRC Fracture Energy			
Tensile Bond Strength			

FRC Modulus and Foundation Stiffness

	Crack Width	Debonding Length	Vertical Deflection
Concrete Stiffness			
Foundation Stiffness			

Effect of Dowel Bar with FRC

- An additional study attempted using the same FEM, but adding a dowel rod to the mid-height
  - NOTE: dowels are not commonly used in thin overlays
- The addition of the dowel rod drastically reduced the crack widths and reduced the amount of debonding.
- The modeling has several assumptions, so at this time it is not enough evidence to determine whether fibers can replace dowels.



$\phi_{eff} = N_{reinforcement} * \phi_{reinforcement}$

Summary and Findings (Predictions)

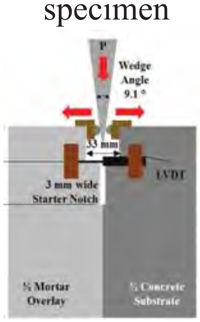
- The proposed equation was able to predict the crack width within 0.19 mm.
- The k_b rather than k_a is promising to predict the crack width for variety of FRC.
- The developed model was able to predict crack widths within 0.17 mm.
- The modeling predicted for the field scenario, 1000 N/m of fracture energy was enough to achieve the low crack opening width.

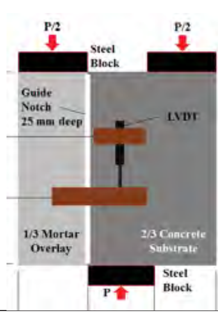
Presentation Contents

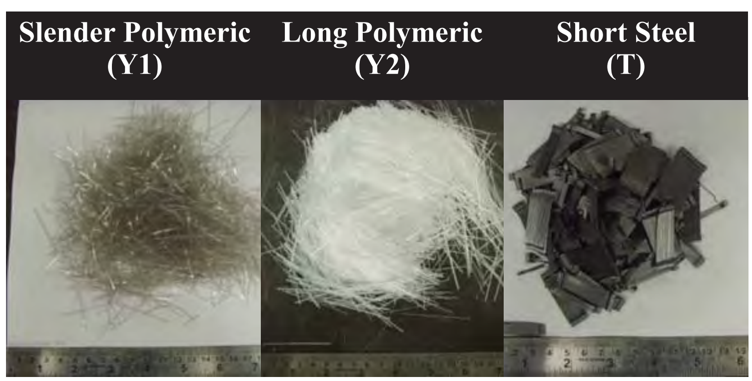
- ✓Background and Motivation
- ✓Crack Widths Predictions
- ✓Finite Element Modeling
- Testing of Fiber Effect on Interfacial Bond
- Conclusions and Recommendations

Test Variables

- Two different testing methods (Tensile and Shear bond)
- Three different types of fiber (2 polymeric and 1 steel)
- Two different fiber volume contents (low and high)
- 2 replicates for composite specimen



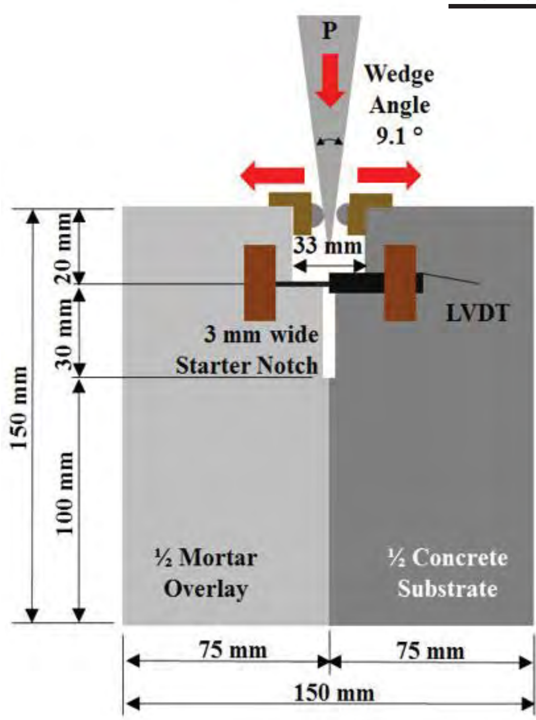




	Fiber Type	Low Fiber Volume Content (L)	High Fiber Volume Content (H)
Y1	Slender and Long Polymeric	0.40%	0.78%
Y2	Long Polymeric	0.50%	1.0%
T	Short Steel	1.0%	2.0%

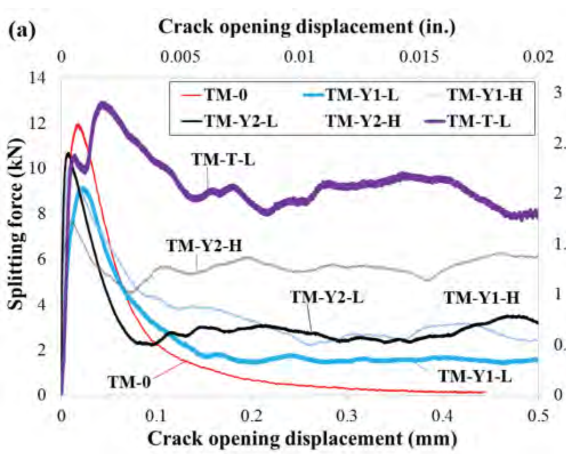
Test Methods and Specimens

Tensile Bond

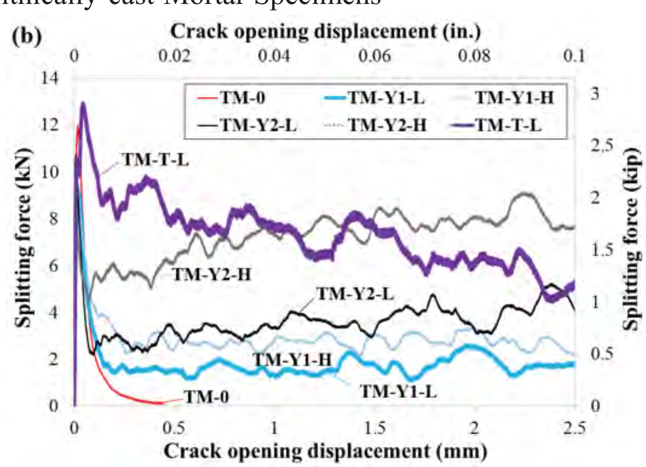


Tensile Splitting Results (Monolithic Specimens)

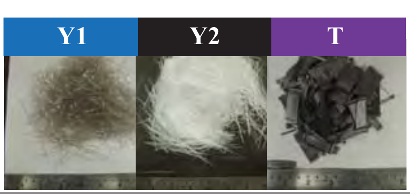
T = Tensile Bond M = Monolithically-cast Mortar Specimens



(a) Showing zoomed in



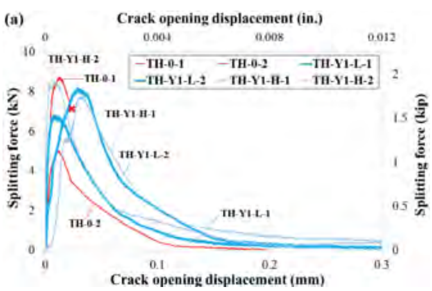
(b) Showing full displacement range



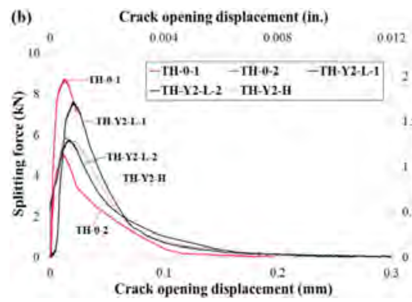
	Fiber Type	Low Fiber Volume Content (L)	High Fiber Volume Content (H)
Y1	Slender and Long Polymeric	0.40%	0.78%
Y2	Long Polymeric	0.50%	1.0%
T	Short Steel	1.0%	2.0%
0	No Fibers	0%	

Tensile Splitting Results (Overlay Interface)

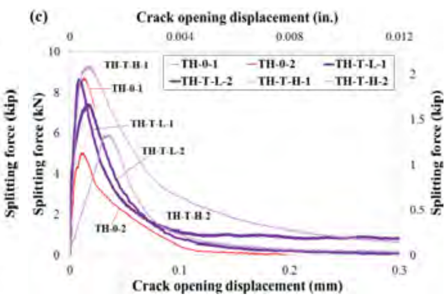
T = Tensile Bond H = Mortar Overlay against Concrete Substrate Specimens



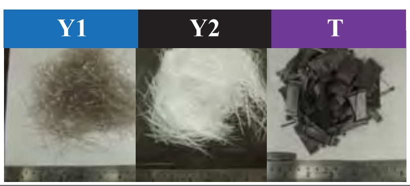
Slender and Long Polymeric (6 times higher G_{bond} than Plain)



Long Polymeric (2 times higher G_{bond} than Plain)

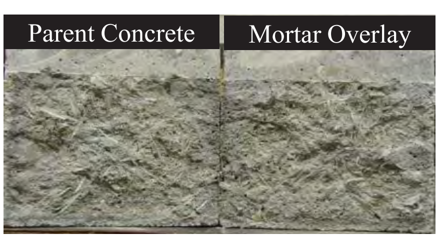


Short Steel (5 times higher G_{bond} than Plain)



	Fiber Type	Low Fiber Volume Content (L)	High Fiber Volume Content (H)
Y1	Slender and Long Polymeric	0.40%	0.78%
Y2	Long Polymeric	0.50%	1.0%
T	Short Steel	1.0%	2.0%
0	No Fibers	0%	

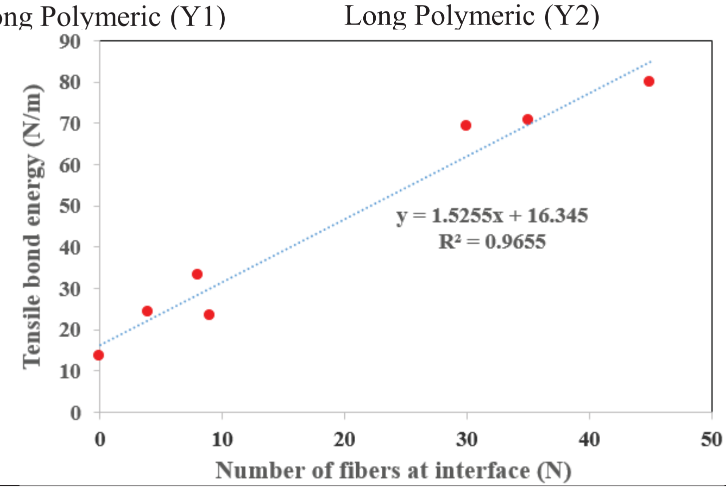
Overlay Tensile Splitting Results (Fibers crossing interface)



Slender and Long Polymeric (Y1)

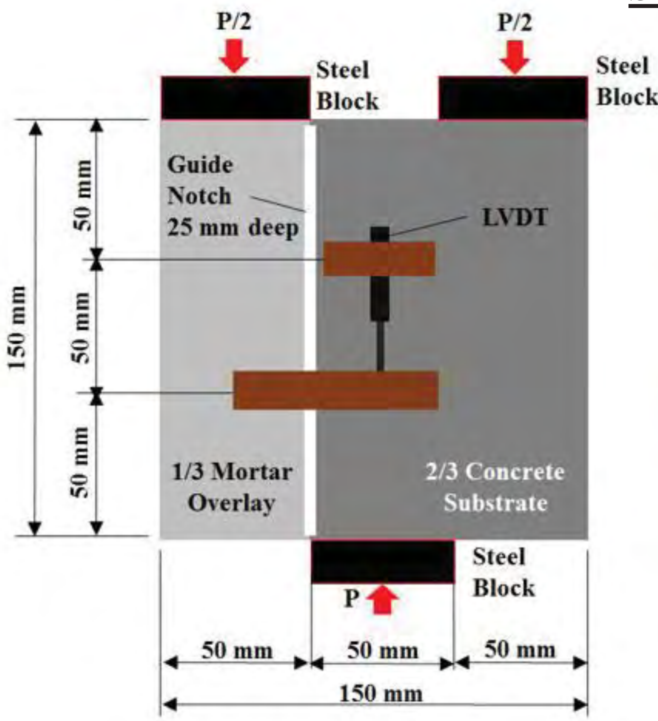
Long Polymeric (Y2)

Short Steel (T)



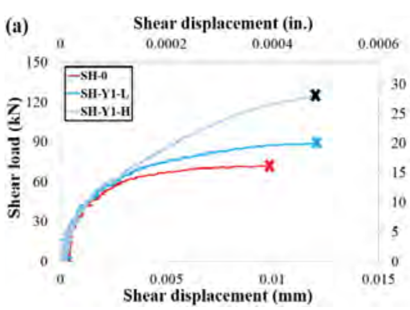
Test Methods and Specimens

Shear Bond

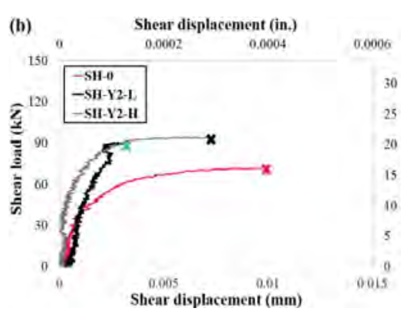


Bi-Surface Shear Test Results

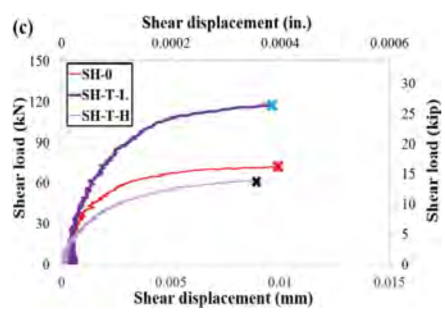
S = Shear Bond H = Mortar Overlay against Concrete Substrate Specimens



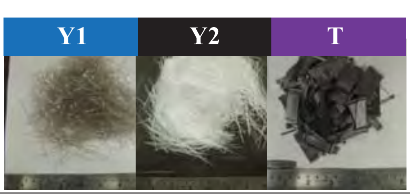
Slender and Long Polymeric (Y1)



Long Polymeric (Y2)

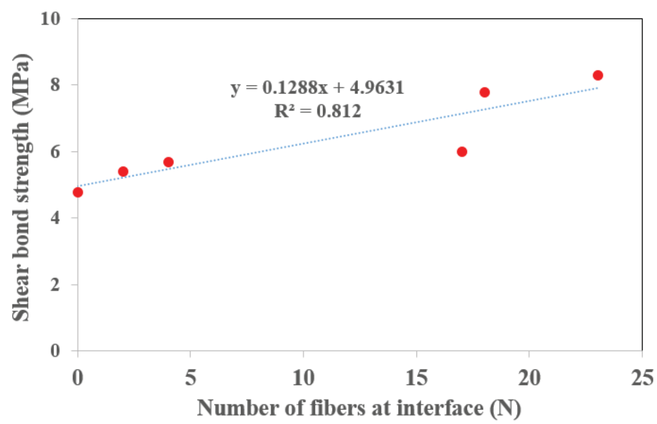


Short Steel (T)



	Fiber Type	Low Fiber Volume Content (L)	High Fiber Volume Content (H)
Y1	Slender and Long Polymeric	0.40%	0.78%
Y2	Long Polymeric	0.50%	1.0%
T	Short Steel	1.0%	2.0%
0	No Fibers	0%	

Bi-Surface Shear Test Results (Fibers crossing interface)



Comments on bi-shear results:

- One 2% short steel specimen appeared to be outlier and not shown above
- Test difficult to perform
- Higher coefficient of variation, low regression coefficient

Summary and Findings (Testing)

- The variability was too high for a trend to be confirmed at this time.
- All monolithic specimens showed an improved split tensile strength and the tensile fracture energy for increased fiber content as expected.
- Specimens with FRC overlay showed higher tensile interfacial bond energy.
- The number of fibers crossing the fractured path was correlated with this measured tensile interfacial bond energy.

Presentation Contents

✓Background and Motivation

✓Crack Widths Predictions

✓Finite Element Modeling

✓Testing of Fiber Effect on Interfacial Bond

• Conclusions and Recommendations

Conclusions and Recommendations

- The proposed modified crack width equation was able to predict the crack width of a field project using FRC within 0.19 mm.

$$w = Cs(\alpha_t \Delta T + \varepsilon_{sh})\{k_a \; or \; k_b\}$$

$$k_a = \frac{50}{L_f/D_f} \leq 1.0 \;\; or \; k_b = 1 - \frac{f_{res,FRC}}{f_{mor,FRC}}$$

- A finite element model was able to predict the same field FRC pavement crack width within 0.17 mm.
- Overlay specimens were found to have higher tensile bond energy compared to monolithic specimens.
    - Higher fiber contents near the interface were anticipated to cause this higher tensile bond energy.

Questions?

Contact:
Amanda Bordelon, Ph.D., P.E.
Utah Valley University, Orem, Utah
Amanda.Bordelon@uvu.edu

Min Ook Kim, Ph.D.
Korea Institute of Ocean Science and Technology, Busan, South Korea
tominookkim@gmail.com

Paper:
"Cracking and Debonding of a Thin Fiber Reinforced Concrete Overlay"
Mountain Plains Consortium MPC 17-319
https://www.ugpti.org/resources/reports/downloads/mpc17-319.pdf
or
https://www.ugpti.org/resources/reports/details.php?id=872&program=mpc

TRANSPORTATION LEARNING NETWORK

A partnership with MDT•NDDOT•SDDOT•WYDOT and the Mountain-Plains Consortium Universities

Thank you for participating!

You will be automatically directed to a short survey, please take a moment to provide your feedback.

Transportation Learning Network Contact Information

TLN Help Desk
Office: (701) 231-1087
shannon.l.olson@ndsu.edu

Office: (701) 231-7766
susan.hendrickson@ndsu.edu

https://tln.learnflex.net/
https://www.translearning.org/

Thank you to our partners: