TRANSPORTATION LEARNING NETWORK

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

Welcome!

Early-Age Fiber-Reinforced Concrete Properties for Overlays (MPC 18-353)

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

Our partners:

MOUNTAIN-PLAINS CONSORTIUM REGION 8

MONTANA MDT DEPARTMENT OF TRANSPORTATION

NDDOT North Dakota Department of Transportation

South Dakota DOT Connecting South Dakota and the Nation

WYOMING DOT TRANSPORTATION DEPARTMENT

NDSU UPPER GREAT PLAINS TRANSPORTATION INSTITUTE TRANSPORTATION LEARNING NETWORK

Authors and Acknowledgement

- Authors:
  - Min Ook Kim, Ph.D., Senior Research Scientist, Korea Institute of Ocean Science and Technology
  - Amanda Bordelon, Ph.D., P.E., Assistant Professor, Utah Valley University

- Funding from:
  - Mountain Plains Consortium Project 492
  - University of Utah Department of Civil Engineering
  - Utah Department of Transportation

- Academic Supervisory Committee:
  - Chris Pantelides, Ph.D., P.E.
  - Pedro Romero, Ph.D., P.E.
  - Luis Ibarra, Ph.D., P.E.
  - Eunhye Kim, Ph.D., P.E.

FRC as used in Overlay Design

- Fiber-reinforced concrete used in concrete pavements since 1990s
  - known to improve performance over unreinforced plain concrete
  - delays crack initiation and slows crack propagation
- In design of FRC for overlays, we use flexural residual strength (f_{150} or R_{150})

$$SR_{total} = \frac{\sigma_{total}}{MOR_{eff}} \; or \; = f_{150} \qquad MOR_{eff} = MOR(1 + R_{150})$$

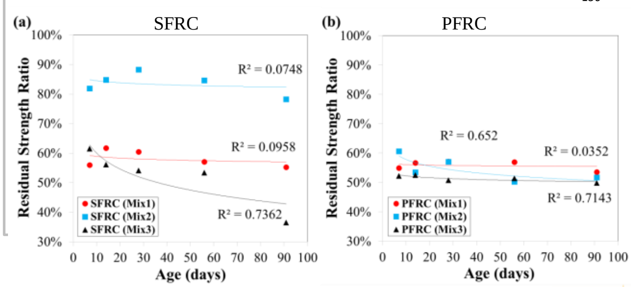
- Fresh material parameters used for consistency between mixtures properties: slump, unit weight, air content
- Design software also uses material properties (these are not expected to change with age); these measured as well for this study
  - Compressive or flexural strength
  - Shrinkage
  - Coefficient of thermal expansion

Pavement Design Methodology that uses FRC:
- Illinois DOT Chapter 53 *BCOA*
- ACPA *BCOA* thickness designer or *StreetPave*
- University Pittsburg *BCOA-ME*
- *OptiPave* 2.0
- CPTech Center *Residual Strength Estimator*

Research Motivation and Hypothesis

- The test to determine residual strength ratio R_{150} (ASTM C1609) does not specify the age of concrete during testing, presumed to be 28 days, but some labs do as early as 7 days for faster results
- Hypothesized (based on past experimental and field findings) that the R_{150} significantly changes with age of concrete
  - At early ages concrete loosely bonded with fiber, fiber debonds more than pulls out, not effectively using fiber to its maximum benefit (designed to stretch)
  - By later ages, concrete bond stronger so fiber stretches as designed

Past study by Bernard 2015 found R_{150} to decrease with age



Test Variables

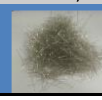
- Different ages (3, 7, 14, 28, 56, and 90 days)
- Four different types of fiber (2 steel, and 2 polymeric)
  - Synthetic is more common for pavements, steel has been tried in bridge decks
- Two different fiber volume contents (0.5% and 1.0%)
  - Note: typical pavement mixtures use 0.2% – 0.5% V_f
- Statistics calculated
  - 3 Replicates for Plain Concrete
  - 1 Replicate for FRC at 0.5% V_f
  - 2 Replicates for FRC at 1.0% V_f
  - Low p-value (<0.05) then FRC property statistically different than plain concrete

NDSU UPPER GREAT PLAINS TRANSPORTATION INSTITUTE TRANSPORTATION LEARNING NETWORK

Properties of Fibers

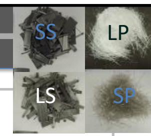
Fiber Type	Short Steel SS	Long Steel LS	Long Polymeric LP	Slender and Long Polymeric SP
Material	Hooked steel	Hooked steel	Polypropylene	Polypropylene-polyethylene
Cross section	Circular	Circular	Rectangular (bi-tapered)	Rectangular (straight)
Length	35 mm (1.4 in.)	60 mm (2.4 in.)	50 mm (2.0 in.)	40 mm (1.6 in.)
Diameter or Thickness & Width	0.55 mm (0.022 in.)	0.9 mm (0.035 in.)	0.4 mm (0.016 in.) x 1.2 mm (0.047 in)	0.11 mm (0.004 in.) x 1.4 mm (0.055 in.)
Aspect ratio	65	65	75	90
Tensile strength	1345 MPa (195 ksi)	1160 MPa (168 ksi)	550 MPa (79.8 ksi)	620 MPa (89.9 ksi)
Elastic modulus	210 GPa (30.5 Msi)	210 GPa (30.5 Msi)	7.0 GPa (1.01 Msi)	9.5 GPa (1.38 Msi)



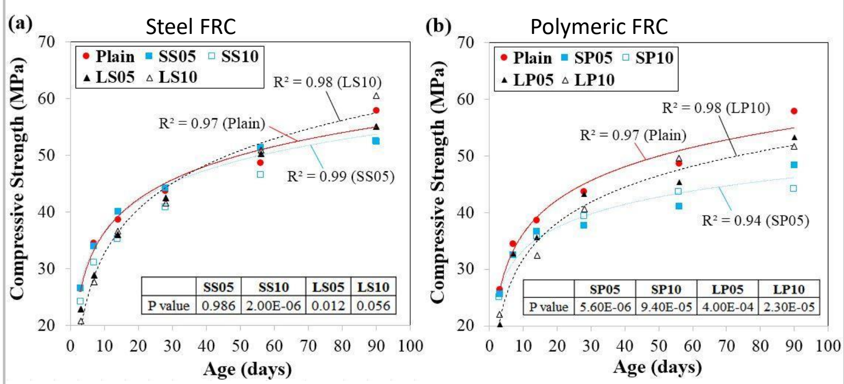



Plain Concrete and FRC Mixture Proportions

Material		Plain P	Short Steel SS	Long Steel LS	Long Polymeric LP	Slender and Long Polymeric SP
Water		167 kg/m³ (281 pcy)				
Cement		292 kg/m³ (492 pcy)				
Fly Ash		125 kg/m³ (211 pcy)				
Coarse Aggregate		1052 kg/m³ (1773 pcy)				
Fine Aggregate		857 kg/m³ (1445 pcy)				
High Range Water Reducer		1028 mL/m³ (26.4 fl.oz./yd³)				
Air Entraining Admixture		107 mL/m³ (2.7 fl.oz./yd³)				
Fiber	(for 0.5% volume fraction)	0	40 kg/m³ (67 pcy)	40 kg/m³ (67 pcy)	4.5 kg/m³ (7.6 pcy)	4.5 kg/m³ (7.6 pcy)
	(for 1.0% volume fraction)	0	79 kg/m³ (133 pcy)	79 kg/m³ (133 pcy)	9.0 kg/m³ (15 pcy)	9.0 kg/m³ (15 pcy)



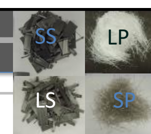
Compressive Strength



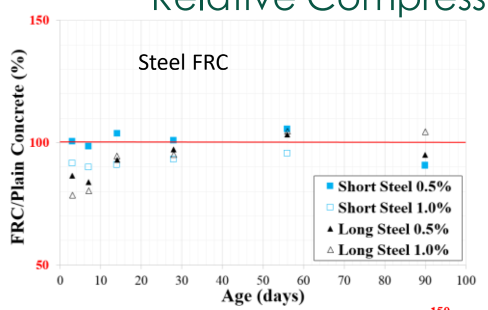
	SS05	SS10	LS05	LS10
P value	0.986	2.00E-06	0.012	0.056

	SP05	SP10	LP05	LP10
P value	5.60E-06	9.40E-05	4.00E-04	2.30E-05

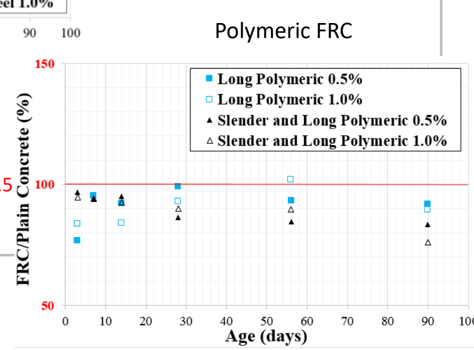
- Strength of all mixtures (plain, SFRC and PFRC) all increased with age
- Rate of increase in strength versus age was found the same among all mixtures

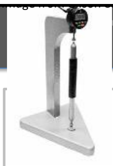


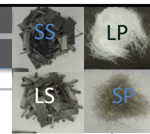
Relative Compressive Strength



- Most have a p-value < 0.05 so they are statistically different (SFRC similar or reduced, all PFRC reduced strength)
- Compaction or mixing difficulties at V_f of 0.5 to 1% can lead to reduced strengths

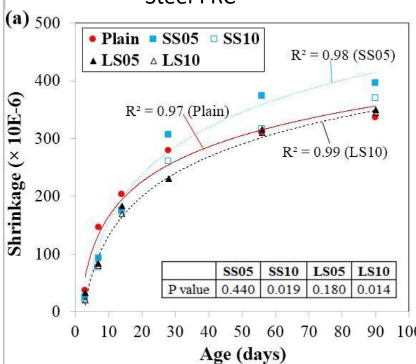




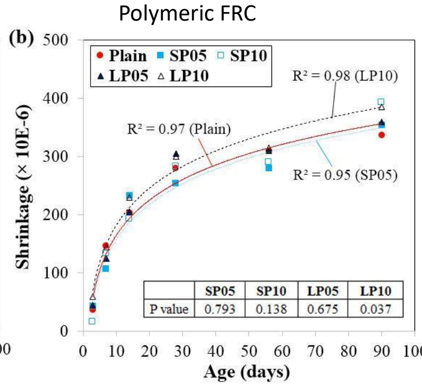


Free Drying Shrinkage

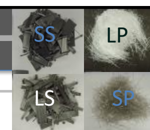
Steel FRC



Polymeric FRC

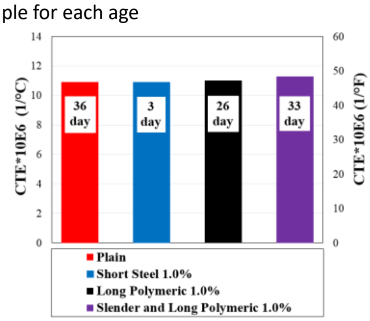


- Shrinkage of all mixtures (plain, SFRC and PFRC) all increased with age
- All had a high p-value > 0.05 meaning there is no statistical difference found (same free shrinkage values between plain and FRC) This is also found by other researchers.
- Note: restrained [ring] shrinkage shows benefit of fibers with delayed shrinkage crack age



Coefficient of Thermal Expansion

- Used in pavement design like AASHTOWare *Pavement ME*
- Used test apparatus at Utah DOT facility
- One plain and FRC sample for each age



- No statistical analysis carried out (only 1 sample)
- Even with limited data, negligible influence at 1% V_f found for any FRC versus plain concrete

FRC Flexural Test

- Values from the ASTM C1609 are primarily test parameters for FRC design in pavements
- Uses the same 6x6x21" beam as ASTM C78 flexural strength but measures post-cracking performance

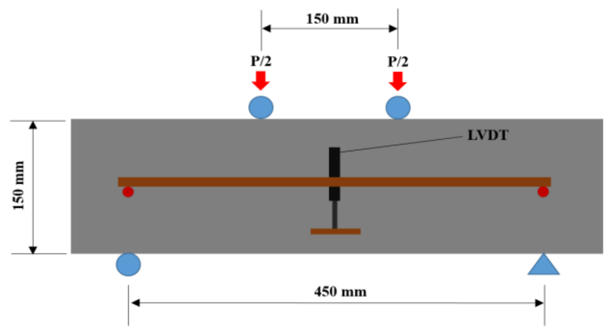
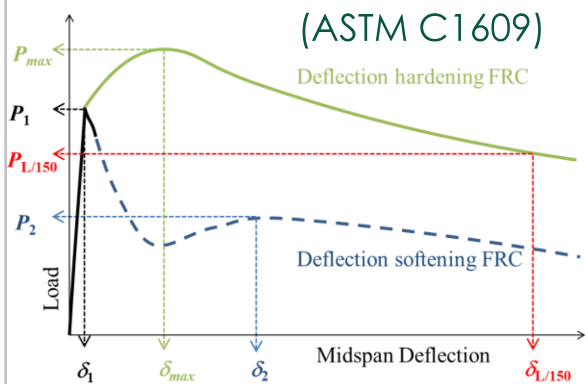


Image from Roesler et al. 2019

Parameters from FRC Flexural Test (ASTM C1609)



Typical Load-Deflection Curves of FRC

P_1: First-crack load

MOR: Modulus of rupture or flexural strength corresponding to the first-crack

P_{max}: Maximum peak load for deflection hardening

P_2: Second peak load for deflection softening

$P_{L/150}$: the load reading for when the mid-span deflection reaches 1/150 of the span

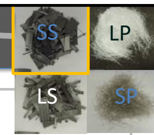
f_{150}: Residual strength

R_{150}: Residual strength ratio

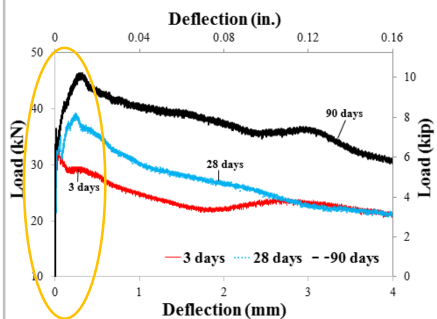
$$MOR = \frac{P_1 L}{bh^2}$$

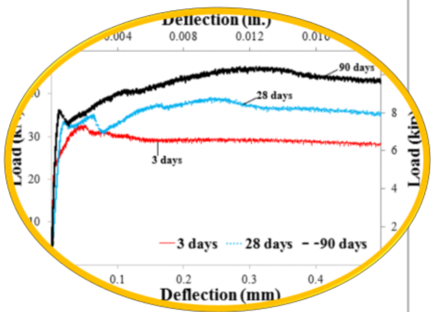
$$f_{L/150} = \frac{P_{L/150} \cdot L}{bh^2}$$

$$R_{150} = \frac{f_{150}}{MOR} \times 100$$

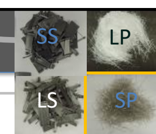


Flexural Strength (ASTM C1609)
Short Steel Fiber 1% Vf

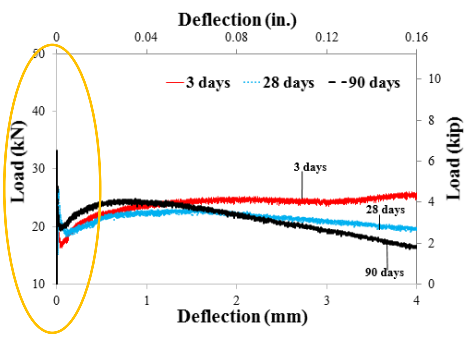


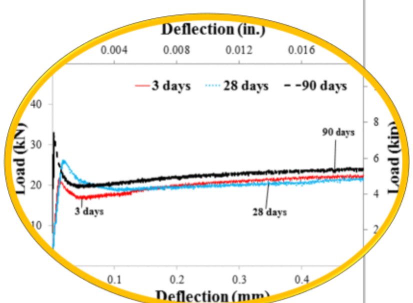


pg. 14



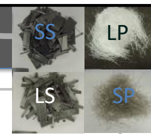
Flexural Strength (ASTM C1609)
Slender and Long PP Fiber 1% Vf



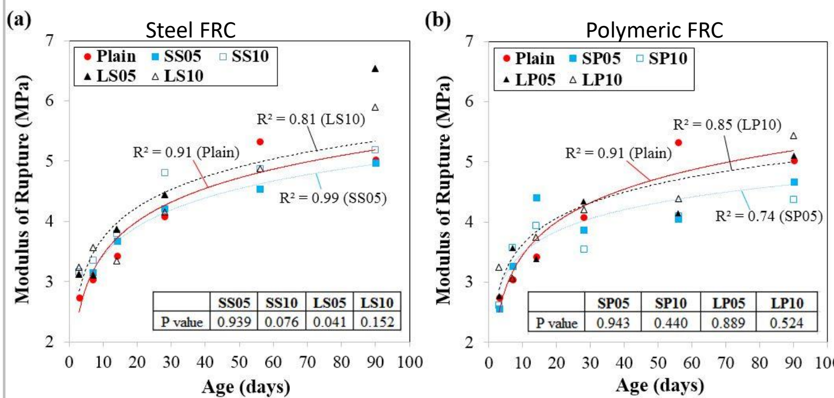


pg. 15

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



"Flexural Strength" or MOR

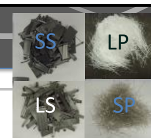


	SS05	SS10	LS05	LS10
P value	0.939	0.076	0.041	0.152

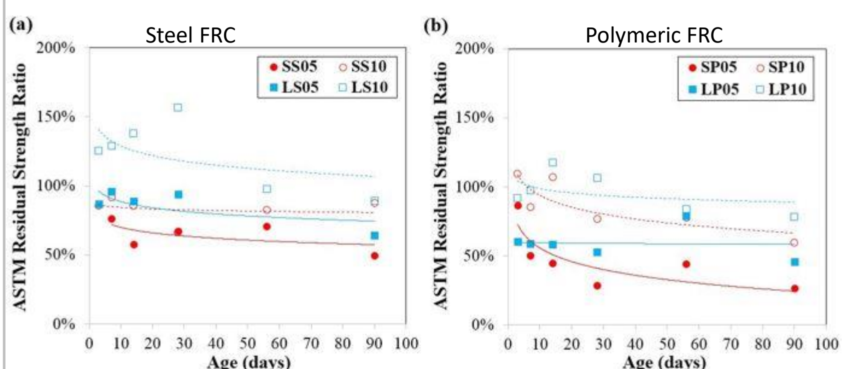
	SP05	SP10	LP05	LP10
P value	0.943	0.440	0.889	0.524

- Flexural strength increases with age, similar to compressive strength
- Most p-values high, indicating no statistical difference found (same MOR between plain and FRC)
- This also matches the past research, hence why we use ASTM C1609 for post-cracking strength

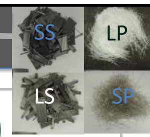
$$R_{150} = \frac{f_{150}}{MOR} \times 100$$



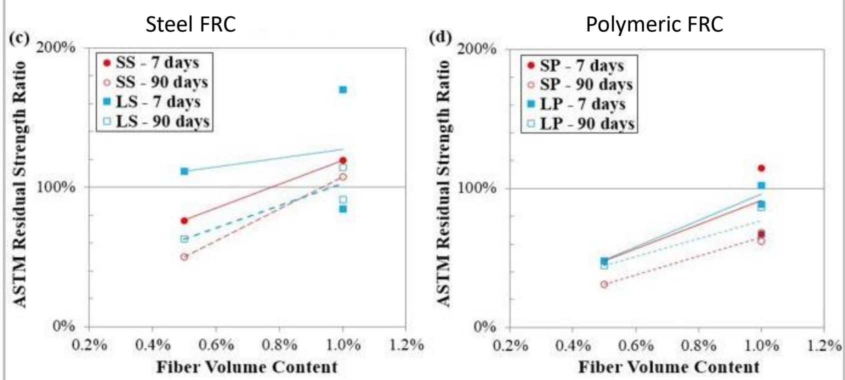
Residual Strength Ratio (R_{150})



- Residual strength ratio used in ACPA *BCOA* and *Streetpave,* Illinois DOT, and U Pittsburg *BCOA-ME* for FRC overlays
- Since strength increases, the R_{150} expected and verified to decrease with age!
- 9% reduction from 7 to 28 days, 28% reduction from 7 to 90 days
- Plain concrete does not carry load after cracking (f_{150} =0 and R_{150} =0)



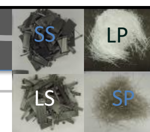
Trends in Residual Strength Ratio(R_{150})



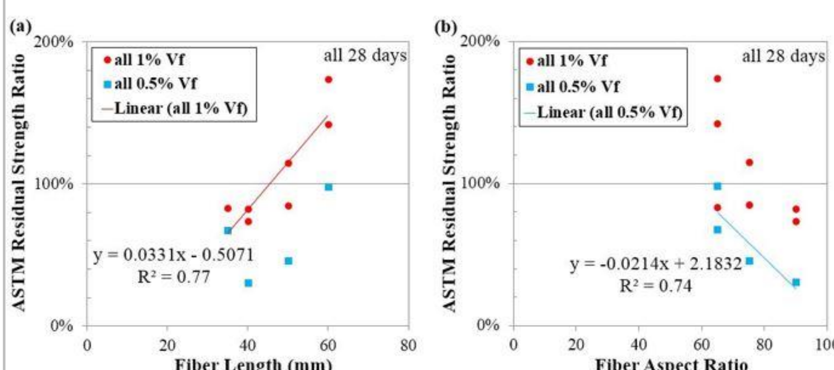
- Increase volume fraction V_f = increase R_{150}
- This is well documented in the literature

pg. 18

NDSU | UPPER GREAT PLAINS TRANSPORTATION INSTITUTE TRANSPORTATION LEARNING NETWORK



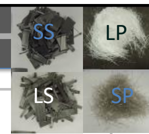
Trends in Residual Strength Ratio(R_{150})



- Increase fiber length L_f OR increase fiber aspect ratio L_f/d_f, both increase R_{150}
- These are stated in the literature

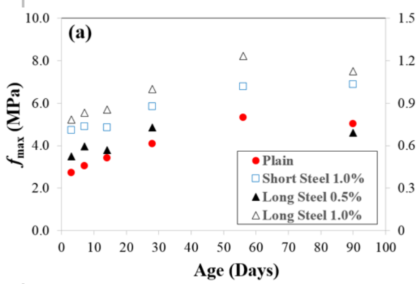
pg. 19

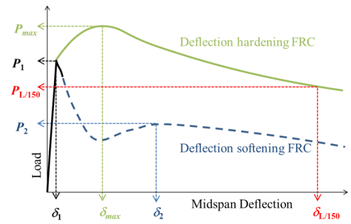
NDSU | UPPER GREAT PLAINS TRANSPORTATION INSTITUTE TRANSPORTATION LEARNING NETWORK



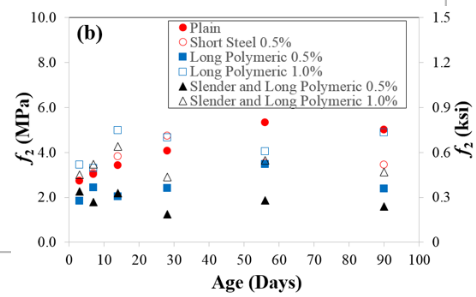
Deflection Hardening vs Softening

Steel FRC at higher V_f exhibit deflection hardening





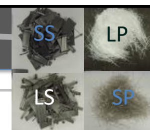
All Polymeric FRC and Steel FRC at lower V_f exhibit deflection softening



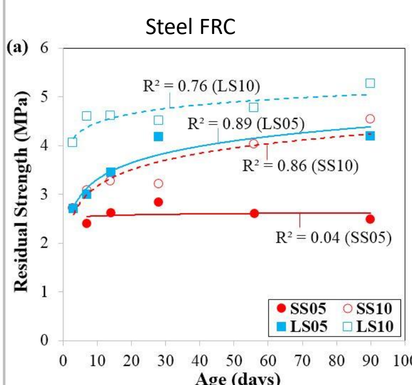
pg. 20

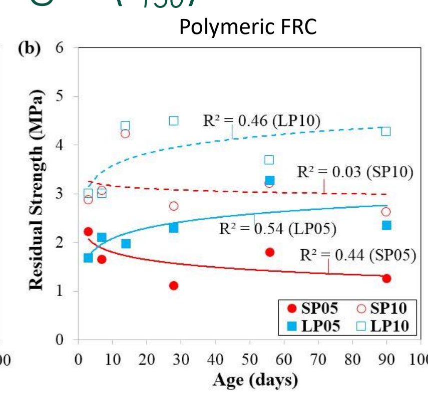
NDSU | UPPER GREAT PLAINS TRANSPORTATION INSTITUTE
TRANSPORTATION LEARNING NETWORK

$$f_{150} = \frac{P_{L/150} \cdot L}{bh^2}$$



Residual Strength (f_{150})





- Residual strength (post-cracking strength) used in CPTech Center *Residual Strength Estimator* software for FRC overlays.
- f_{150} can decrease by 24% or increase by 47% form 7 to 90 days.
- Longer fibers > 45mm had 34% average increase, shorter fibers <45mm had 3% average increase in f_{150} from 7 to 90 days.

pg. 21

NDSU | UPPER GREAT PLAINS TRANSPORTATION INSTITUTE
TRANSPORTATION LEARNING NETWORK

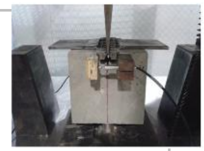
Wedge Split Fracture Testing

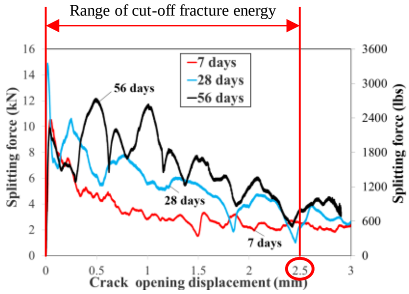
$$G_{FRC,2.5mm} = \frac{area(F_s \cdot COD)|_0^{2.5}}{A}$$

$G_{FRC,\,2.5\,mm}$ from a field project (Bordelon 2011)

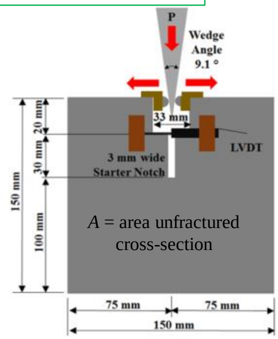
7 days: 588.3 N/m (4% COV)

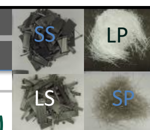
28 days: 482.6 N/m (14% COV)



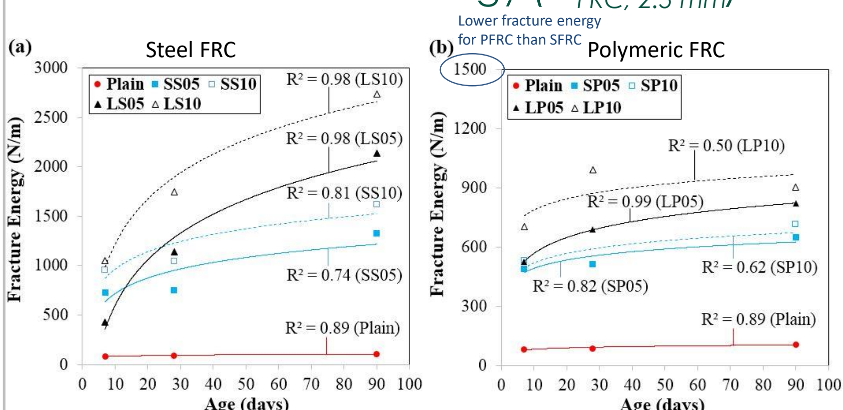


Typical splitting force F_s versus *COD* Curves of SFRC





Cut-off Fracture Energy ($G_{FRC,\,2.5\,mm}$)



- Fracture energy increases with age for plain (31% increase), SFRC (179% increase), and PFRC (38% increase from 7 to 90 days).
- The magnitude of increase in fracture energy for FRC/plain also increases with age (fibers are 8 times tougher at 7 days or 13 times tougher by 90 days).

Summary and Recommendations

- Known trends related to FRC properties were verified:
  - Slump and compressive strength can decrease with increasing fiber content or volume fraction
  - Free Shrinkage, Flexural Strength (MOR) and Coefficient of Thermal Expansion (CTE) do not change with addition of FRC (at least up to 1% by volume)
  - Polymeric fibers (such as typically used in pavements today) only produce deflection softening responses. Steel fibers at higher V_f would be needed if one wanted the pavement to exhibit deflection hardening (higher strength than MOR)
- Fiber-reinforced concrete exhibits a reduced R_{150} value with age
  - From 7 to 90 days, MOR increased by 60%, the residual strength f_{150} depended on the fiber type and dosage but overall increased on average by 15%, and the residual strength ratio R_{150} decreased by 28%.
  - As a minimum, one should report the age of the measured flexural testing
  - An additional recommendation is to specifying an age for which the FRC is tested, in order to improve correlation and prediction with future designs

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:
"Early-Age Fiber-Reinforced Concrete Properties for Overlays"
Mountain Plains Consortium MPC 18-353
https://www.mountain-plains.org/research/details.php?id=385
or
https://www.ugpti.org/resources/reports/downloads/mpc18-353.pdf

Additional Publications/Presentations from This Study

- “Age-Dependent Properties of Fiber Reinforced Concrete Used in Thin Overlays” *Construction and Building Materials*, Vol. 137, 2017, pp. 288-299. http://www.sciencedirect.com/science/article/pii/S0950061817301381
- POSTERS “Age-Dependent Properties of Fiber Reinforced Concrete Used in Thin Overlays”
  - 11th International Conference on Concrete Pavement in San Antonio, Texas, August 2016
  - 96th Annual Meeting of the Transportation Research Board (Poster #16-6248) in Washington DC, January 2016

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: Mountain-Plains Consortium, Montana MDT Department of Transportation, NDDOT North Dakota Department of Transportation, South Dakota DOT, Wyoming Department of Transportation