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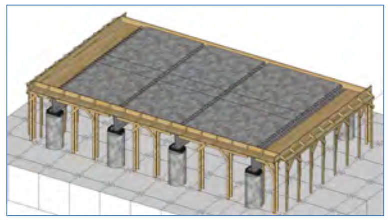
Steel Fibers in Bridge Decks



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Fall 2022 National Concrete Consortium
Detroit, Michigan
September 27-29, 2022

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Presentation Outline

- TxDOT Project 7001 Overview
- Materials and Mixture Proportions
- Laboratory Testing
- Large-Scale Structural Testing
- Summary

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TxDOT Project 7001 – UTILIZING STEEL FIBERS AS CONCRETE REINFORCEMENT IN BRIDGE DECKS

Research Team

- Oguzhan Bayrak (PI)
- Kevin Folliard (Co-PI)
- Thano Drimalas
- Soon Kwang Jeong
- Zach Webb

TxDOT Panel

- Joanne Steele (PM)
- Steven Austin
- Rachel Cano
- Lianxiang Du
- Christina Gutierrez
- Andy Naranjo
- Joe Roche

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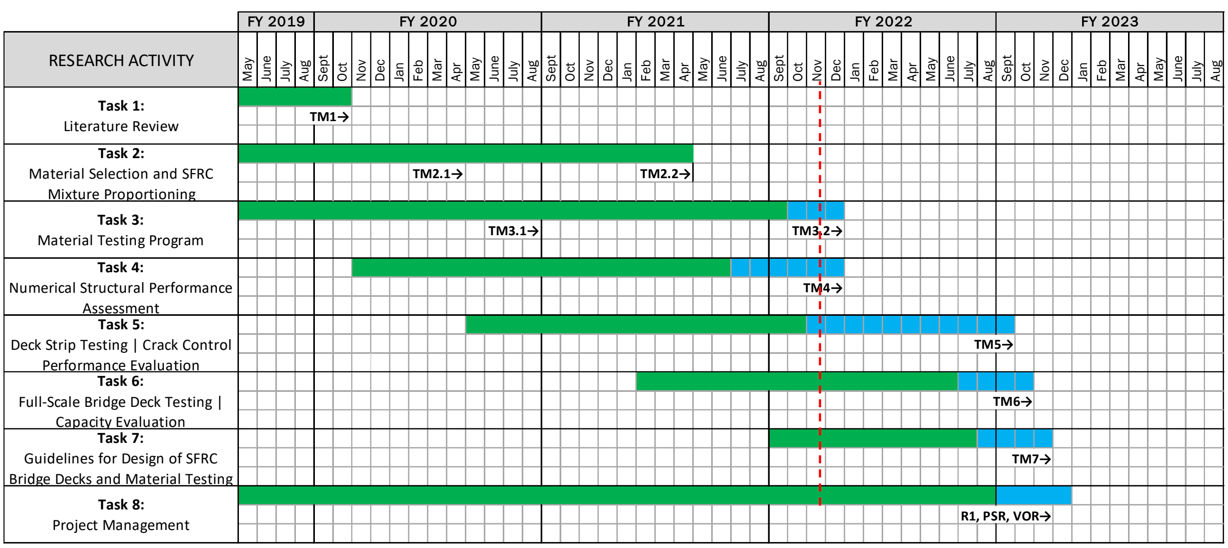
Project Schedule



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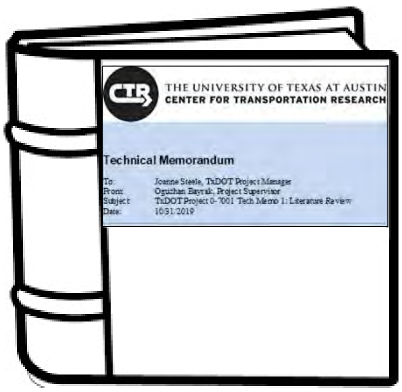
Task 1: Literature Review



STATUS:

- COMPLETED
- SUBMITTED TO TXDOT ON OCTOBER 31, 2019
- REVIEWED AND SYNTHESIZED STATE-OF-THE-ART AND CURRENT PRACTICE RELATED TO SFRC USE IN BRIDGE DECKS.

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Task 2: Material Selection and Mixture Proportioning

Material	Types	Sources
Portland cement	• Type I/II	• Alamo Type I Cement
Supplementary cementing materials	• Class F fly ash • Class C fly ash • Condensed silica fume	• Oak Grove Class F Fly Ash • Jewett Class C Fly Ash • GCP Silica Fume
Fine Aggregates	• River sand • Reactive river sand • Manufactured sand	• Martin Marietta Webberville Natural Sand
Coarse Aggregates	• River gravel • Crushed limestone	• Martin Marietta Webberville #57 Stone
Chemical Admixtures	• High-range water reducer • Air-entraining agent	• Sika 2100 • Sika Air
Fibers	• Steel fibers	• Sika Novocon XR Steel Fiber (1.5”) • Dramix 3D 45/35 Steel Fiber (1.5”) • Helix Steel Fiber (1”)

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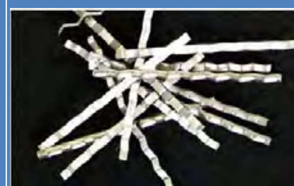
Task 2: Material Selection and Mixture Proportioning

	Dramix 3D (65/35)	Sika Novocon XR (30/38)	Helix 5-25 Micro Rebar Steel Fibers
			
Length	35 mm (1.4 inch)	38 mm (1.5 inch)	25 mm (1 inch)
Diameter	0.55 mm (0.021 inch)	1.14 mm (0.045 inch)	0.55 mm (0.02 inch)
Aspect ratio (L/D)	65	30	50

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Task 2: Material Selection and Mixture Proportioning

w/cm=0.45

Mixture Name	Fiber dosage (% by volume)*	Steel Fiber Source				Class F Fly Ash (%)	Class C Fly Ash (%)	Silica Fume (%)
		Sika	Dramix	Helix	None			
PC-0	0				X			
PC-0.5	0.5	X	X	X				
PC-1.0	1.0	X	X	X				
PC-1.5								
FA(F)-20-0								
FA(F)-20-0.5								
FA(F)-20-1.0								
FA(F)-20-1.5								
FA(C)-35-0								
FA(C)-35-0.5								
FA(C)-35-1.0								
FA(C)-35-1.5	1.5	X					35	
FA(C)-30-SF-5-0	0				X		30	5
FA(C)-30-SF-5-0.5	0.5	X					30	5
FA(C)-30-SF-5-1.0	1.0	X		X			30	5
FA(C)-30-SF-5-1.5	1.5	X					30	5

Mixture Designation

FA (F)-20-1.5

Cementitious System - SCM Replacement Amount - Fiber Dosage %

** 1 percent by volume = 130 lbs/yd^3*

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Task 3: Material Testing Program

Comprehensive testing program

- Evaluate the fresh, hardened, and durability properties of SFRC most relevant to bridge deck applications

Fresh Properties

Air content
Unit weight
Slump
Slump flow
Bleeding
Temperature
Setting time
Heat of hydration

Hardened Properties

Compressive strength
Tensile strength
Flexural strength
Flexural toughness (post-peak)
Elastic modulus
Thermal expansion (CTE)
Drying shrinkage
Autogenous shrinkage
Electrical resistivity
Maturity

Durability Properties

Alkali-silica reaction
Chloride-induced corrosion
Carbonation-induced corrosion
Freezing and Thawing
Salt Scaling
Plastic shrinkage cracking
Restrained shrinkage cracking
Impact resistance
Skid/polishing resistance

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Task 3: Material Testing Program

Fresh Properties

Fresh Property	Test Method	Notes/Comments
Air content	ASTM C 231	Tested on fresh concrete
Unit weight	ASTM C 138	Tested on fresh concrete
Slump	ASTM C 143	Tested on fresh concrete
Slump flow	ASTM C 1611	For high-slump or SCC types of SFRC.
Bleeding	ASTM C 23	
Temperature	ASTM C 1064	For QC testing and for use in maturity testing in lab and field.
Setting time	ASTM C 403	
Heat of Hydration	Isothermal and semi-adiabatic calorimetry	Isothermal calorimetry at 40, 73, and 100 °F Semi-adiabatic calorimetry at 73 °F for 10 days.

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Mixture Name	Fiber dosage (% by volume)*	Slump (in.)	Air Content (%)	Fresh Temperature (F)
PC-0	0	5	2.2	72.6
PC-0.5 (S)	0.5	4.5	2.1	73.1
PC-1.0 (S)	1.0	5	2.2	72.2
PC-1.5 (S)	1.5	4.5	1.9	72.2
FA(F)-20-0	0	6.5	2.4	71.8
FA(F)-20-0.5 (S)	0.5	6.5	1.8	71.4
FA(F)-20-1.0 (S)	1.0	5.5	1.8	72.8
FA(F)-20-1.5 (S)	1.5	6	2.2	73.1
FA(C)-35-0	0	5.5	2.3	72.2
FA(C)-35-0.5 (S)	0.5	6	1.8	72.3
FA(C)-35-1.0 (S)	1.0	4.5	2.1	72.2
FA(C)-35-1.5 (S)	1.5	6.5	1.9	71.9
FA(C)-30-SF-5-0	0	6	2.1	71.8
FA(C)-30-SF-5-0.5 (S)	0.5	4.5	2.4	72.2
FA(C)-30-SF-5-1.0 (S)	1.0	4	2.2	73.2
FA(C)-30-SF-5-1.5 (S)	1.5	5	2.3	72.5

Mixture Name	Fiber dosage (% by volume)*	Slump (in.)	Air Content (%)	Fresh Temperature (F)
PC-0	0	5	2.2	72.6
PC-0.5 (D)	0.5	4.5	1.8	73.4
PC-1.0 (D)	1.0	5.5	2.3	73.6
PC-1.5 (D)	1.5	5	2.1	74.0
FA(F)-20-0	0	6.5	2.4	71.8
FA(F)-20-1.0 (D)	1.0	4	1.6	72.3
FA(C)-35-0	0	5.5	2.3	72.2
FA(C)-35-0.5 (D)	0.5	4.5	2.1	71.8
FA(C)-35-1.0 (D)	1.0	5	2.3	72.0

Mixture Name	Fiber dosage (% by volume)*	Slump (in.)	Air Content (%)	Fresh Temperature (F)
PC-0	0	5	2.2	72.6
PC-0.5 (H)	0.5	6.5	2.1	72.8
PC-1.0 (H)	1.0	7	1.7	73.2
PC-1.5 (H)	1.5	5.5	2	71
FA(F)-20-0	0	6.5	2.4	71.8
FA(F)-20-1.0 (H)	1.0			
FA(C)-35-0	0	5.5	2.3	72.2
FA(C)-35-1.0 (H)	1.0			
FA(C)-30-SF-5-0	0	6	2.1	71.8
FA(C)-30-SF-5-1.0 (H)	1.0			

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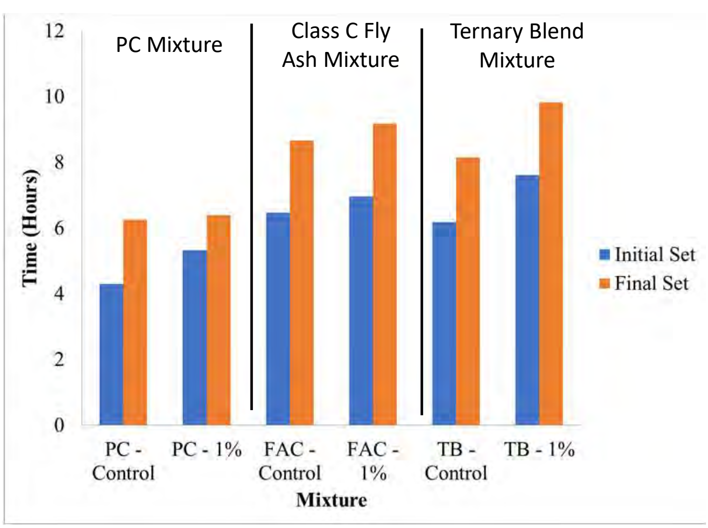
Task 3: Material Testing Program (Time of Set)



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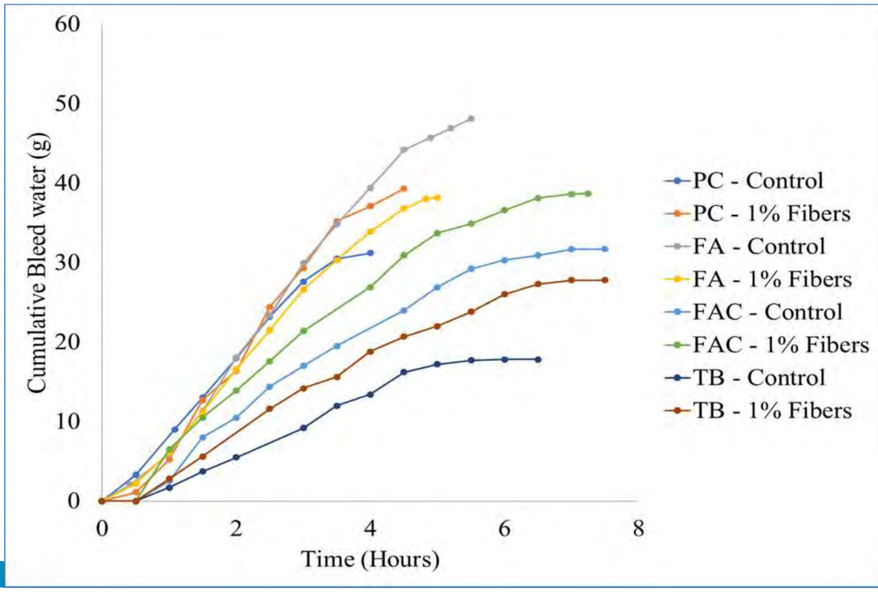
Task 3: Material Testing Program (Bleed Water)



- ***Bleeding affected more by SCMs***
- ***Slight increase in bleeding for mixtures with steel fibers***

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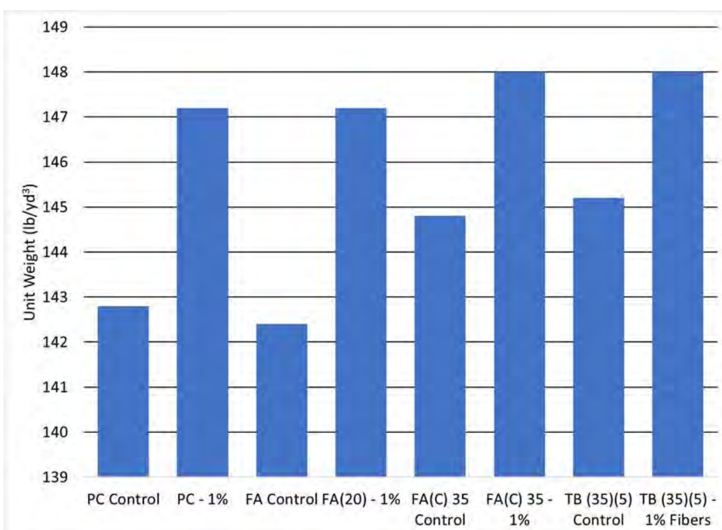
Task 3: Material Testing Program (Unit Weight)



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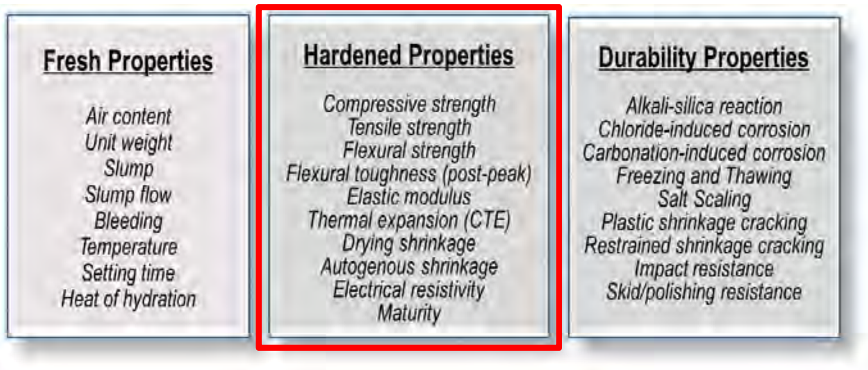
Task 3: Material Testing Program

Comprehensive testing program

- Evaluate the fresh, hardened, and durability properties of SFRC most relevant to bridge deck applications



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Task 3: Material Testing Program

Hardened Property	Test Method	Notes/Comments
Compressive strength	ASTM C 39	Tested at 1, 7, 28, and 91 days
Tensile strength	ASTM C 496	Tested at 1, 7, 28, and 91 days
Flexural strength	ASTM C 78	Tested at 7 and 91 days
Flexural toughness	ASTM C 1399 ASTM C 1609	Tested at 91 days (only for selected mixtures) Tested at 91 days
Elastic modulus	ASTM C 469	Tested at 7 and 91 days
Thermal expansion (CTE)	Tex-428-A	Tested at 28 days
Drying shrinkage	ASTM C 157	Six-months drying after 7-10 day moist curing
Autogenous shrinkage	Unrestrained shrinkage frame	Measured for 7-10 days
Electrical resistivity	ASTM C 1202	To be performed for selected SFRC mixtures, with and without fibers sieved out of mixture.
Maturity	ASTM C 918	Maturity parameters will be calculated for select SFRC mixtures – this allows for in-situ strength, stress prediction, and cracking potential using ConcreteWorks.

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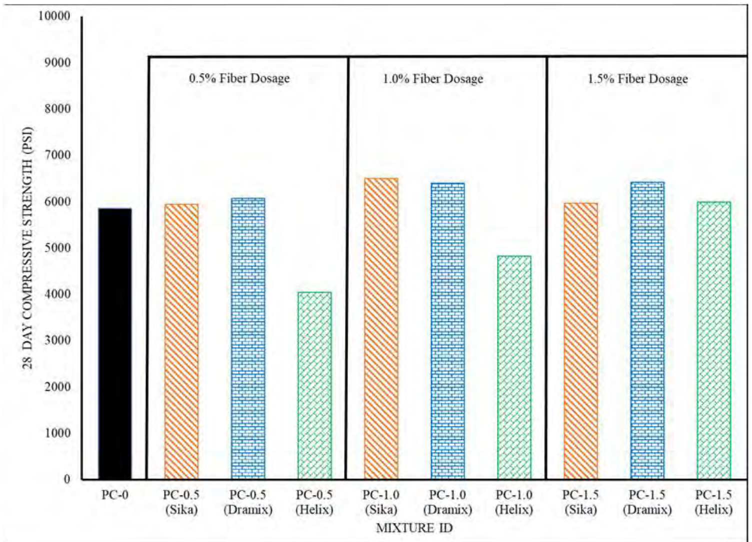
Task 3: Material Testing Program (Compressive Strength)



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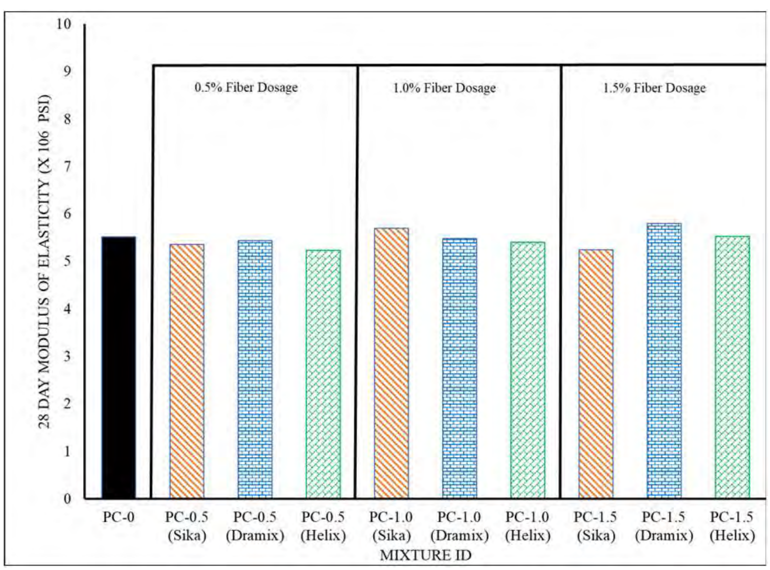
Task 3: Material Testing Program (Elastic Modulus)



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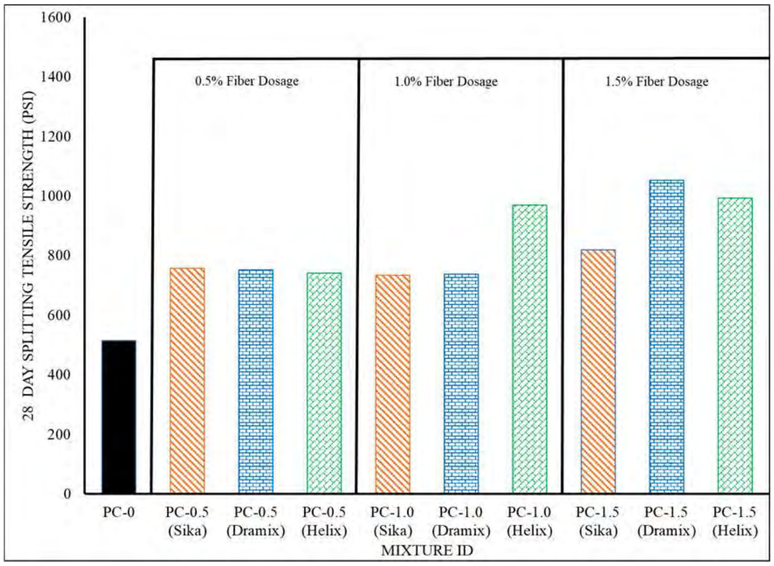
Task 3: Material Testing Program (Splitting Tensile Strength)



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Task 3: Material Testing Program (Direct Tensile Test)

Specimen ID/ Description	Direct tension test	
	f'_t [ksi]	f^t_{res} [ksi]
L-PC-8	-	-
L-D1-18	0.545	0.148
L-S1-18	0.439	0.091
L-H1-18	0.467	0.118
L-S1-0	0.516	0.094
T-PC-9	-	-
T-D1-18	0.524	0.099
T-D15-18	0.471	0.163
T-S1-18	0.487	0.162
T-D1-0	-	-

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Flexural Toughness Testing (ASTM C1609)

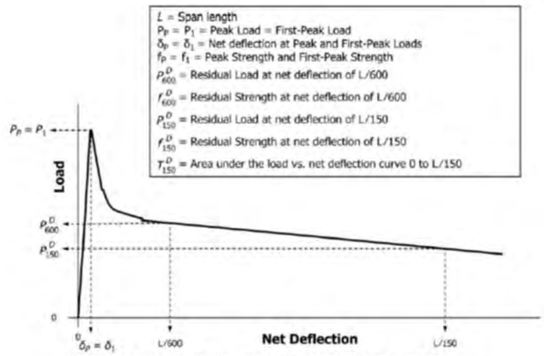

FIG. 3 Example of Parameter Calculations for First-Peak Load Equal to Peak Load (Not to Scale)

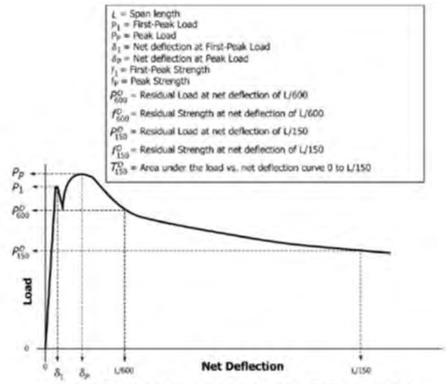

FIG. 4 Example of Parameter Calculations when Peak Load is Greater than First-Peak Load (Not to Scale)

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Flexural Toughness Testing (ASTM C1609)

Mixture ID (Fiber) - Sample	f1	fp	f600	f150	Toughness	$f^d_{e,150}$	$R^D_{T,150}$
PC-1.0 (Dramix) - A	3555		2600	2180	256	2400	0.68
PC-1.0 (Sika) - A	3150		1490	1175	91	860	0.27
PC-1.5 (Dramix) - A	3600	3940	3500	2300	317	2970	0.83
PC-1.5 (Dramix) - B	3470		2620	1830	168	1580	0.45
FA(F)-20-1.0 (Dramix) - A	3410	3515	2890	1790	165	1550	0.45
FA(C)-35-0.5 (Dramix) - A	3975		2050	1580	208	1960	0.49
FA(C)-35-1.0 (Sika) - A	2490	2490	2330	1410	207	1950	0.78
FA(C)-35-1.0 (Sika) - B	3040		1790	1120	102	960	0.32
FA(C)-35-1.0 (Dramix) - A	3700		2680	1900	153	1440	0.39
FA(C)-30-SF-5-1.5 (Sika)	3460		3035	1790	256	2405	0.69

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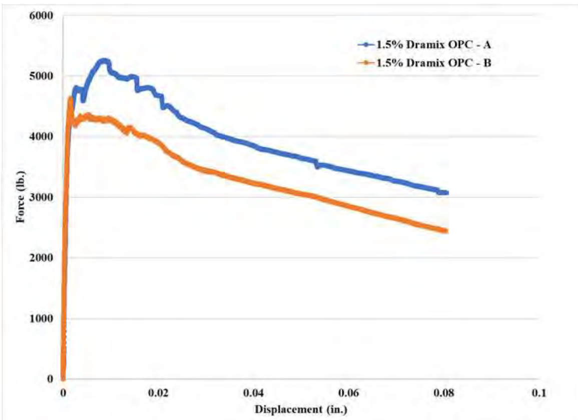
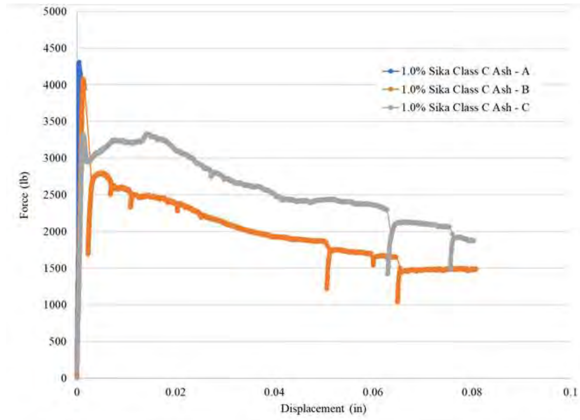
Repeatability and Variability (2 or 3 beams from same mix)





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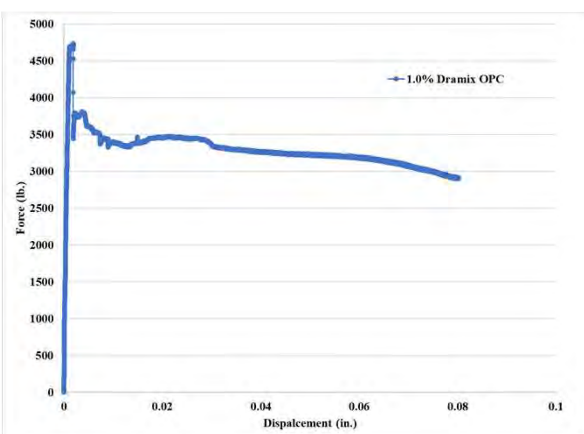
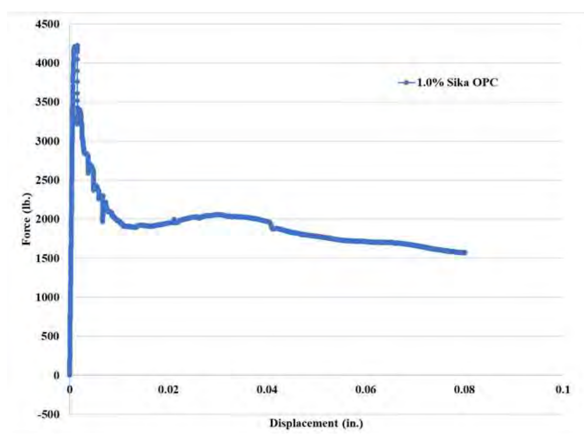
Dramix vs. Sika (1.0% OPC)





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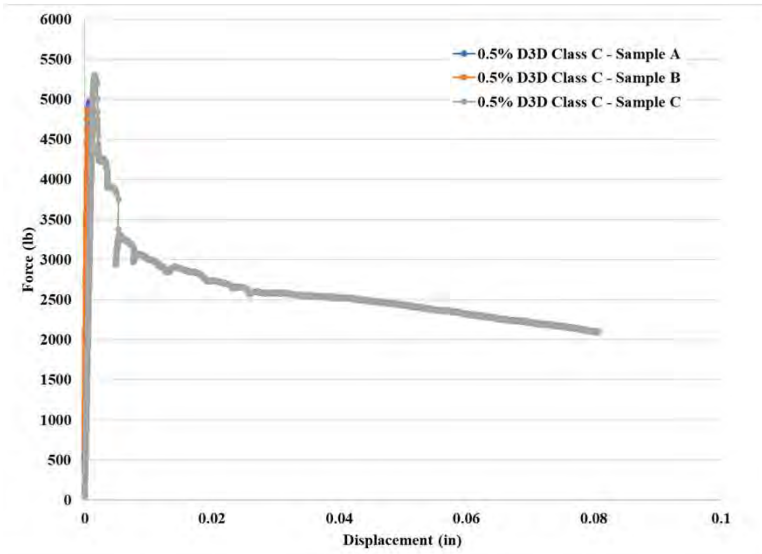
Challenges with testing lower steel fiber contents



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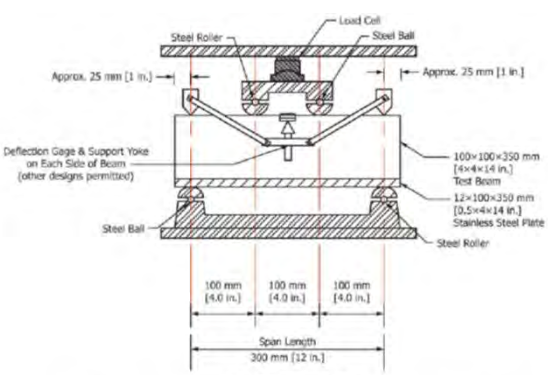
Flexural Toughness Testing (ASTM C1399)



Note: All Dimensions ± 2%

FIG. 1 Schematic of a Suitable Apparatus Where the Deflection Gauge Support Frame is Seated on the Beam

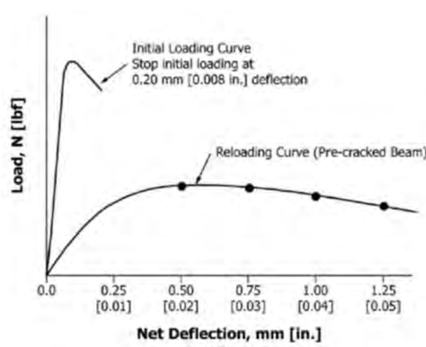


FIG. 2 Load-Deflection Curves

9.1 Calculate the average residual strength (ARS) for each beam to the nearest 0.01 MPa [2 psi] using the loads determined at reloading curve deflections of 0.50, 0.75, 1.00, and 1.25 mm [0.020, 0.030, 0.040, and 0.050 in.] as follows:

$$ARS = ((P_A + P_B + P_C + P_D)/4) \times k \quad (1)$$

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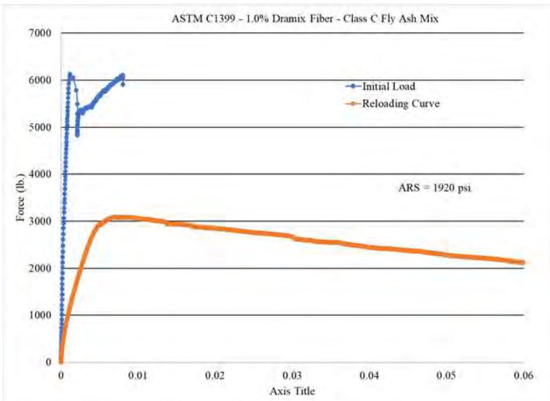
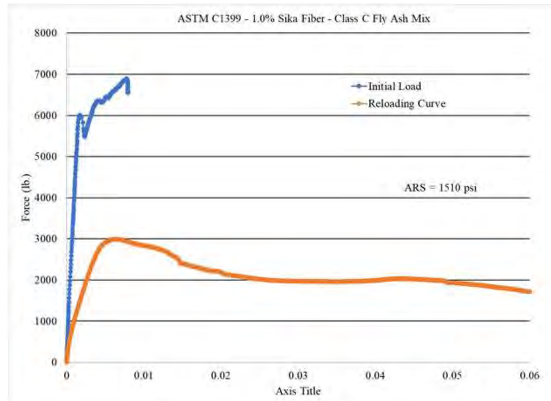
Flexural Toughness Testing (ASTM C1399)





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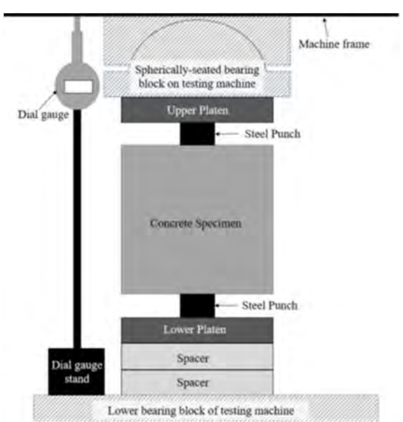
Simplified Double Punch Test (after Riding et. al, 2022)

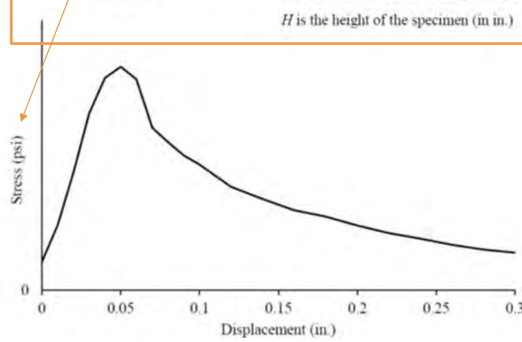


$$f_t = \frac{4\,P_f}{9\,\pi\,a\,H}$$

Where: P_f is the load (in lb)

a is the diameter of the loading disk (in in.), equal to 1.5 in.

H is the height of the specimen (in in.)



Calculate the toughness as the area under the stress vs. crosshead displacement curve up until the endpoint of 0.30 inches by using Equation 2.

$$T = \sum \frac{f_{t,n-1} + f_{t,n}}{2} \times (y_n - y_{n-1}) \qquad [2]$$

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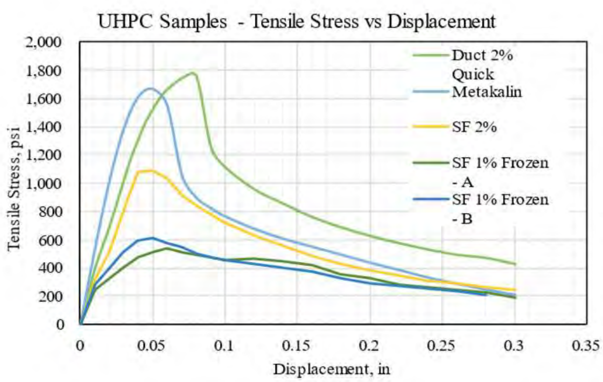

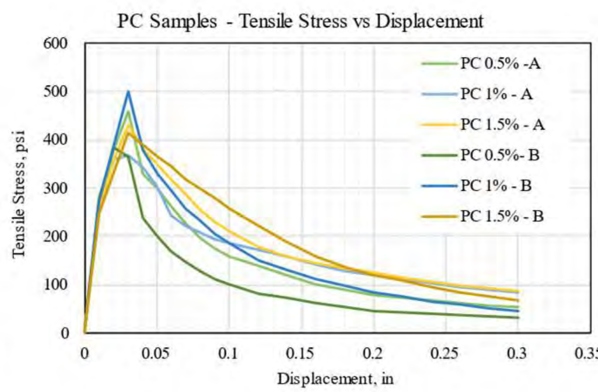

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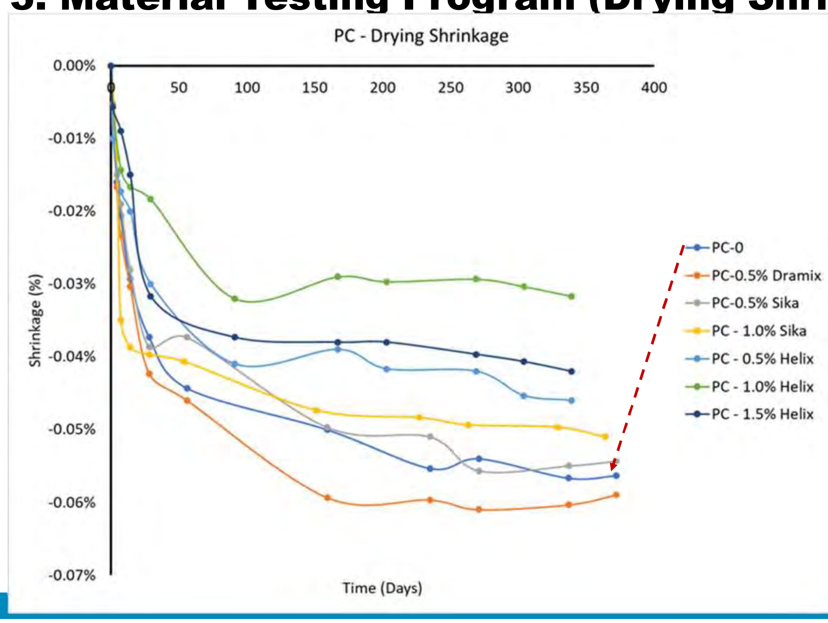
Task 3: Material Testing Program (Drying Shrinkage)



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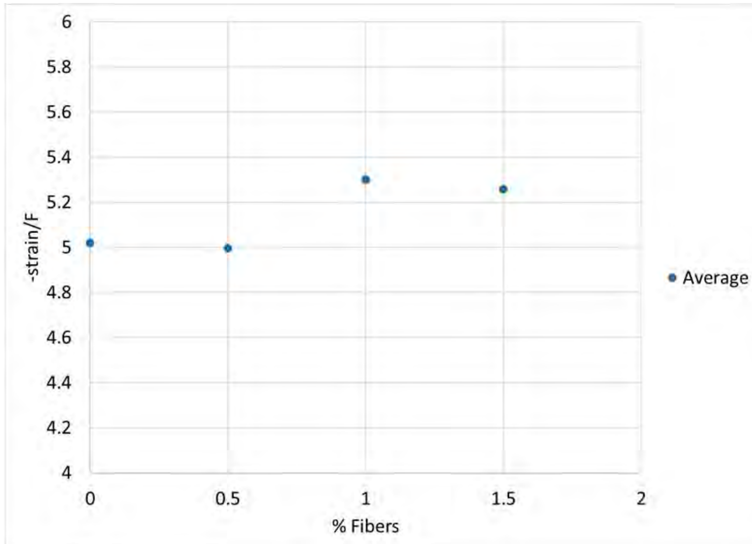
Task 3: Material Testing Program (COTE)



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Task 3: Material Testing Program

Comprehensive testing program

- Evaluate the fresh, hardened, and durability properties of SFRC most relevant to bridge deck applications

Fresh Properties

Air content
Unit weight
Slump
Slump flow
Bleeding
Temperature
Setting time
Heat of hydration

Hardened Properties

Compressive strength
Tensile strength
Flexural strength
Flexural toughness (post-peak)
Elastic modulus
Thermal expansion (CTE)
Drying shrinkage
Autogenous shrinkage
Electrical resistivity
Maturity

Durability Properties

Alkali-silica reaction
Chloride-induced corrosion
Carbonation-induced corrosion
Freezing and Thawing
Salt Scaling
Plastic shrinkage cracking
Restrained shrinkage cracking
Impact resistance
Skid/polishing resistance

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Task 3: Material Testing Program

Durability Property	Test Method	Notes/Comments
Alkali-silica reaction	ASTM C 1260/1567 ASTM C 1293 Outdoor exposure blocks	The concrete prism test shall be run for 24 months; The accelerated mortar bar test shall be run for 28 days. 15" x 15" exposure blocks to be stored at UT outdoor site.
Chloride-induced corrosion	ASTM G 109 ASTM C 1556 Marine exposure blocks	Half-cell potential measured as indicator of corrosion likelihood. Chloride diffusion coefficients shall be measured for SFRC. Reinforced exposure beams composed of SFRC shall be exposed to the Gulf of Mexico at UT MSI Exposure Site.
Carbonation-induced corrosion	Accelerated carbonation (4% CO_2) Outdoor carbonation (sheltered and unsheltered)	A computer-controlled accelerated carbonation chamber shall be used to evaluate the rate of carbonation of SFRC mixtures. Select SFRC mixtures shall be subjected to outdoor exposure in both a sheltered (Stevenson screen) and unsheltered manner.
Freezing and Thawing	ASTM C 666	Frost resistance shall be evaluated using ASTM C 666, using NDT evaluation to estimate dynamic modulus and durability factor.
Salt Scaling	ASTM C 672	Select SFRC mixtures will be exposed to NaCl, MgCl, or brine solution.
Plastic shrinkage cracking	ASTM C 1579	Select SFRC mixtures will be evaluated for plastic shrinkage cracking; SFRC with and/without 1 pcy of synthetic monofilament microfibers)
Restrained shrinkage cracking	Rigid cracking frame, tested in parallel with free shrinkage frame	Select SFRC mixtures will be subjected to time-temperature based on ConcreteWorks prediction of heat generation for SFRC used in bridge decks.
Impact resistance	ACI 544 drop weight method	Measured at 28 days
Polish resistance	Wheel polishing device	Measured at 28 days (selected mixtures)

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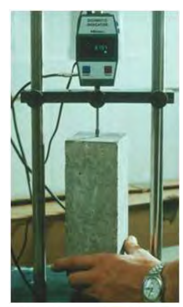
Task 3: Material Testing Program (ASR)

Exposure Blocks and ASTM C1293 Testing

- Control – 0.0% Fiber
- Control – 1.0% Sika Fiber
- Control – 1.5% Sika Fiber
- 35% Class C Fly Ash – 0% Fiber
- 35% Class C Fly Ash – 1.0% Fiber



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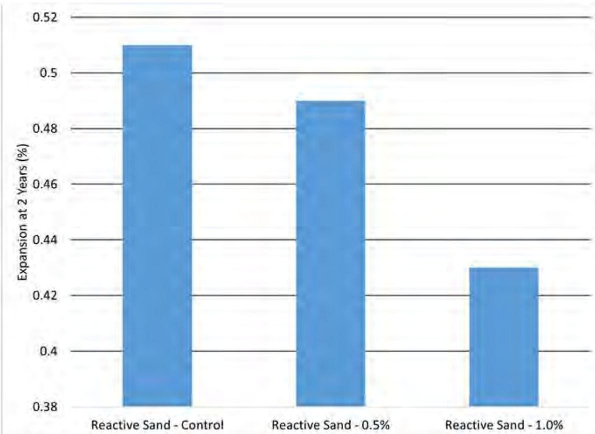
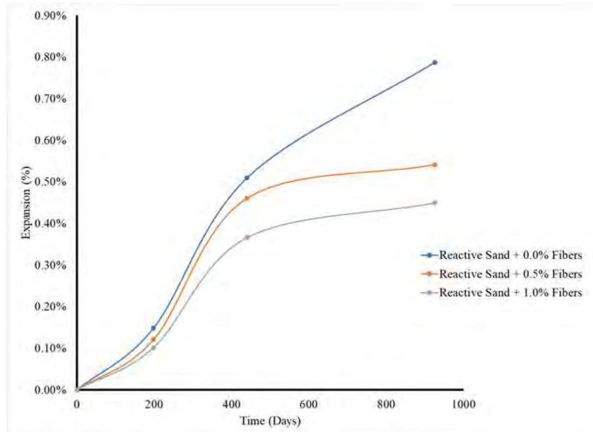
Task 3: Material Testing Program (ASR)



ASTM C1293 Concrete Prisms



Outdoor Exposure Block Expansions

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Task 3: Material Testing Program (ASR)

0% Steel Fiber

0.5 % Sika Novocon XR Steel Fiber

1.0 % Sika Novocon XR Steel Fiber

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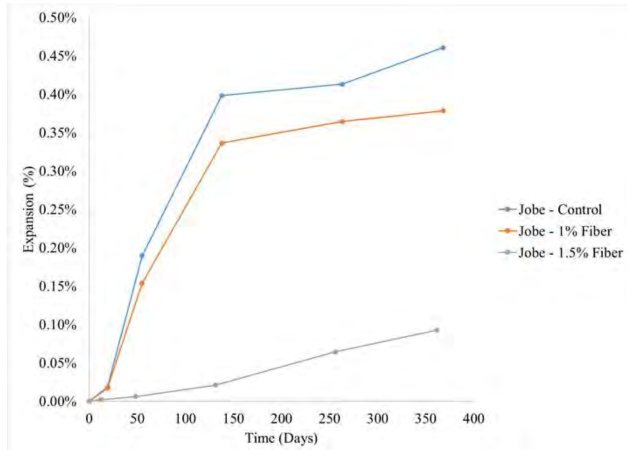
ASTM C1293

- ASTM C1293 results show large reduction of expansion at 1.5% Fiber dosage



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Task 3: Material Testing Program (Corrosion)

- Chloride-Induced Corrosion
  – ASTM G109
  – Marine Exposure Blocks
  – ASTM C1556
- Carbonation Corrosion
  – Outdoor Carbonation
    - (Stevenson Screen and Outdoors)
  – Accelerated Corrosion (4%)

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Task 3: Material Testing Program (Corrosion)

- Corrosion Mixtures
  - PC – 0.0% Fiber
  - PC – 1.0% Sika Fiber
  - PC – 1.5% Sika Fiber (from deck strip pour)
  - FA(C) – 35% Ash – 0.0% Fiber
  - FA(C) – 35% Ash – 1.0% Sika Fiber

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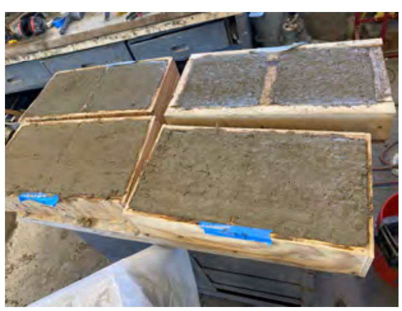
Task 3: Material Testing Program (C666 and C672)

- Freeze/Thaw and Salt Scaling Samples
  - PC Control
  - PC – 1% Sika Fibers
  - FA(C) 35 Control
  - FA(C) 35 1% Sika Fibers
- Air-Entrained between 5-7%



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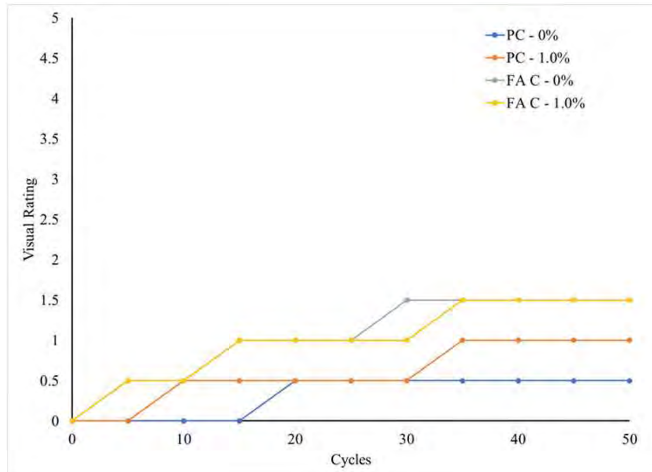
ASTM C672

- Test is complete at 50 Cycles
- Visual rating of samples
- Very minor scaling in all samples



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ASTM C672 – 50 Cycles

Class C Fly Ash Mixture

Class C Fly Ash Mixture – 1% Fiber

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Task 3: Material Testing Program (Impact Testing)

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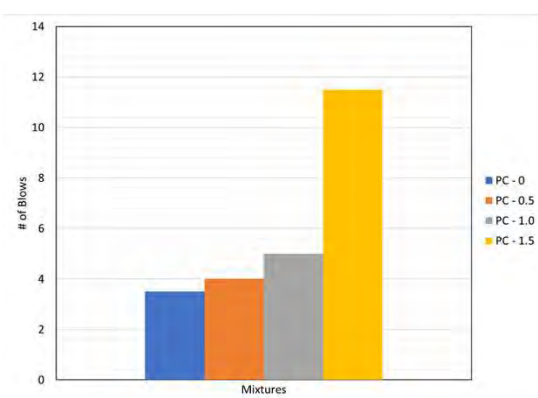
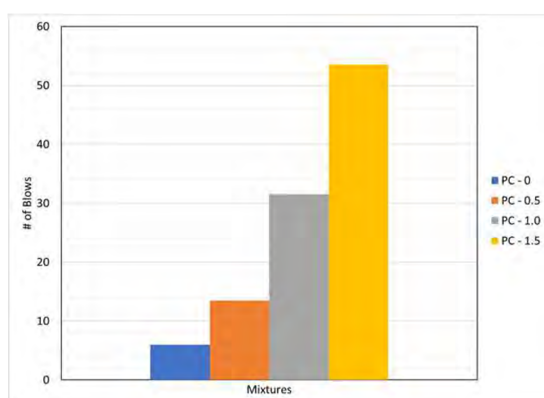
Task 3: Material Testing Program (Impact Testing)

of Blows to First Crack



# of Blows to Failure



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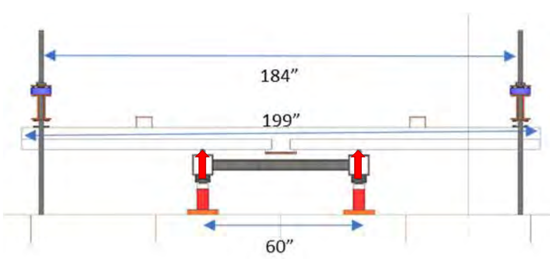
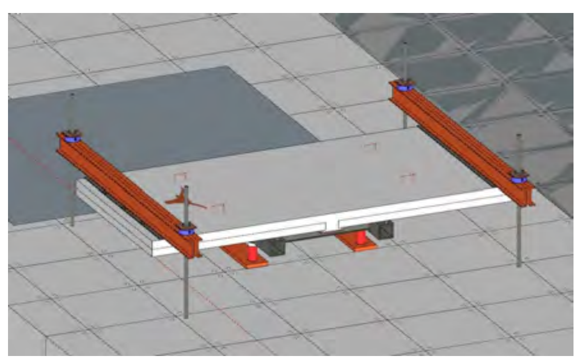
Task 5: Deck Strip Testing

- **Objective**
  - Evaluation of crack control performance.
    - Crack spacing
    - Maximum crack width
  - Assessment of Load-resisting performance.
    - Ultimate load capacity
    - Strength limit state performance
  - Identify most suitable SFRC mix design and top mat reinforcement details for Task 6 full scale test.

Task 5: SFRC CIP-PCP Slab Strips test

- **Loading location and span**





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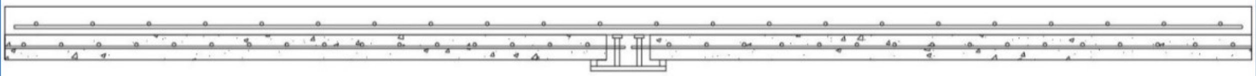
Task 5: SFRC CIP-PCP Slab Strips test

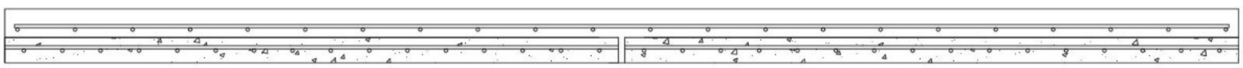
Longitudinal direction specimen

Longitudinal direction specimens, indicated by an 'L' for specimen ID, have dimensions 8.5 in. x 8 ft. x 16ft.-7in. and have transverse panel direction that incorporates prestressing through strands. In addition, the panel joint replicates the girder line with bedding strips.



Transverse direction specimen

Transverse specimens, denoted by a 'T' for specimen ID, are 8.5 in. x 8ft. x 16ft.-1in. and have longitudinal panel direction that has welded wire reinforcement. In addition, the panel joint for the transverse specimen accommodates 1 in. gap between panels.



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Task 5: SFRC CIP-PCP Slab Strips test

Existing TxDOT top mat reinforcement details were tested to compare the structural cracking performance of SFRC bridge decks built with various top mat details and SFRC mix designs. Standard detail requires #4 standard reinforcing bars spaced 9 in. (0.27 sq. in./ft.) for longitudinal and transverse directions. Specimens with SFRC differ in fiber types and reinforcement ratios.

Specimen ID	DIrection	Fiber type	Volume fraction	Reinforcement layout
L-PC-9	Longitudinal	Plain concrete	-	#4@9"
L-D1-18	Longitudinal	Dramix 3D	1%	#4@18"
L-S1-18	Longitudinal	Sika Novocon	1%	#4@18"
L-H1-18	Longitudinal	Helix	1%	#4@18"
L-S1-0	Longitudinal	Sika Novocon	1%	None
T-PC-9	Transverse	Plain concrete	-	#4@9"
T-D1-18	Transverse	Dramix 3D	1%	#4@18"
T-D15-18	Transverse	Dramix 3D	1.5%	#4@18"
T-S1-18	Transverse	Sika Novocon	1%	#4@18"
T-D1-0	Transverse	Dramix 3D	1%	None

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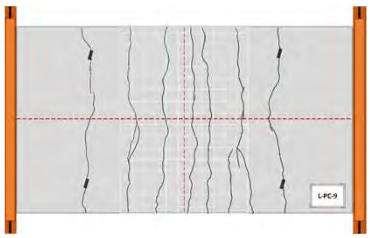
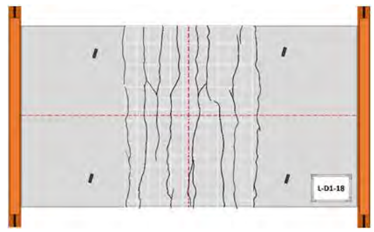
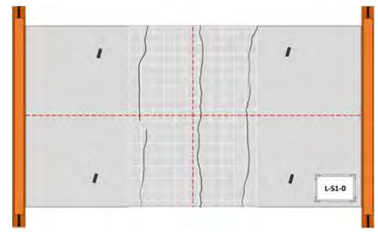
Longitudinal testing results



L-PC-9



L-D1-18



L-S1-0

The specimen could maintain the load-bearing capacity until a service level load occurred. However, steel fibers alone could not withstand a crack from widening.

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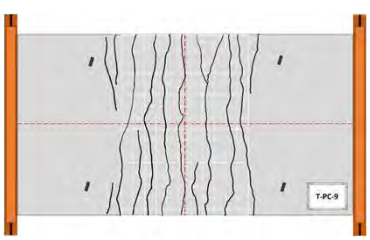
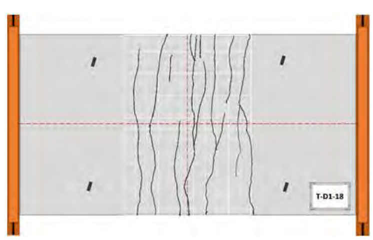
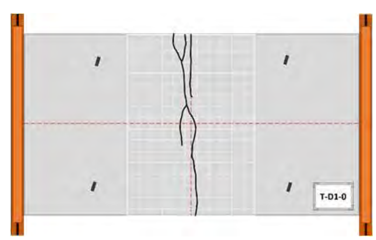
Transverse testing results



T-PC-9



T-D1-18



T-S1-0

The specimen could maintain the load-bearing capacity until a service level load occurred. However, steel fibers alone could not withstand a crack from widening.

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Task 6: Full-Scale Bridge Deck Testing (planned)

- **Objective**
  - Assessment of predetermined SFRC mix and reinforcement details
    - Crack control performance
    - Load resisting performance
  - Evaluate and recommend reinforcement details for overhang with SFRC

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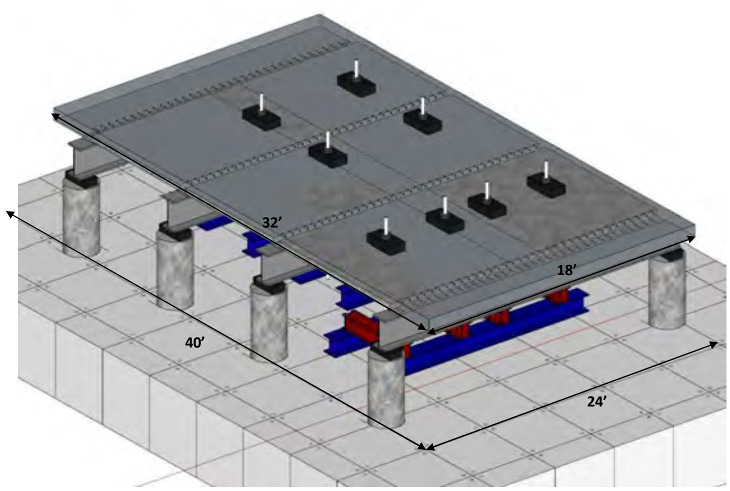
Task 6: Full-Scale Bridge Deck Testing

- **Test layout**



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Summary

1. Comprehensive materials and structural testing of SFRC used in bridge decks is in progress.
2. Results are overall quite encouraging, with preliminary findings suggesting that half of the steel in the cast-in-place deck section can be removed when using ~1% steel fibers.
3. Final conclusions are pending completion of full-scale structural testing and long-term durability evaluations.

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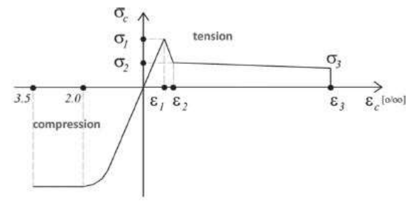
Task 5: Inverse analysis for SFRC mixes

- ACI 544:4R suggests RILEM TC 162-TDF (2003) for Uniaxial Tension behavior of SFRC
- After cracking, the residual stress of the SFRC decreases linearly.
- Lost all capacity at 0.025 strain.



Post-cracking behavior of concrete and fiber-reinforced concrete

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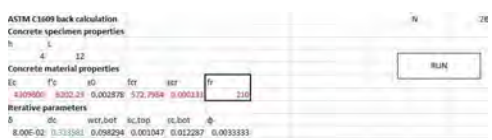
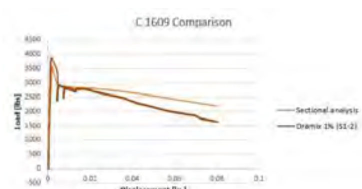
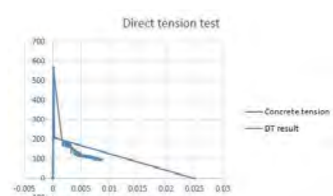
Task 5: Inverse analysis methods





Curve fitting C1609 result

- Require Ec, f’c, and C1609 results.
- Adjust residual stress values.
- Obtain direct tensile strength curves for SFRC



Comparison to DT result

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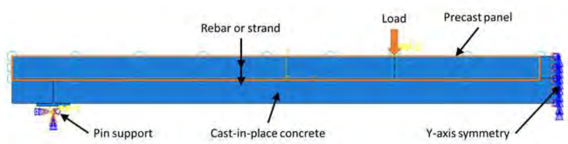
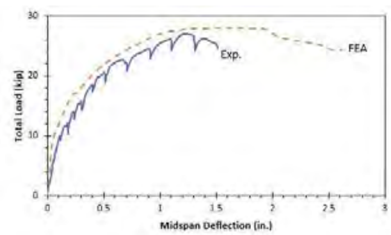
Task 5: FEA analysis with inverse analysis



Representative model for Series 1



S1-2 FEA result

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Task 5: Inverse analysis results

Specimen	SFRC	Ec [ksi]	f'c [ksi]	fcr [ksi]	fr [ksi]
S1-2	Dramix 1%	4309	6.2	0.572	0.21
S1-3	Sika 1%	3814	5.3	0.531	0.12
S1-4	Helix 1%	3886	5.7	0.549	0.25
S1-5	Sika 1%	5157	6.9	0.607	0.12
S2-2	Dramix 1%	4443	6.3	0.576	0.2
S2-3	Dramix 1.5%	4197	5.5	0.541	0.22
S2-4	Sika 1%	4718	6.1	0.567	0.14

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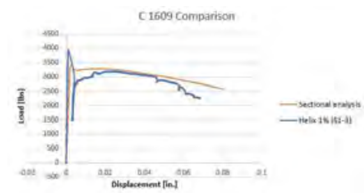
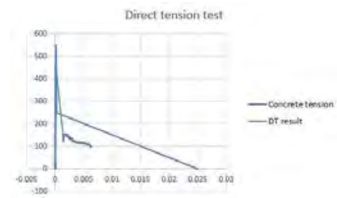
Task 5: Limitation of Inverse analysis

- Short length fiber overestimates ASTM C1609 test capacity.
- Helix 1%, 1 in, showed high residual strength in ASTM C1609 tests.
- The results from Direct tension and structural tests showed smaller residual strength.



Curve fitting C1609 result



Comparison to DT result

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