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Performance of Synthetic Fiber-Reinforced Concrete with Adapted Rheology

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RE-CAST:
REsearch on Concrete Applications for Sustainable Transportation
Tier 1 University Transportation Center

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16. Abstract

The main objectives of this project can be summarized as follows:

1. Optimize the SRA-fiber system of SCC and SWC mixtures to achieve superior performance, including properties, autogenous shrinkage, restrained shrinkage, mechanical properties (tensile and compressive strength), frost durability, and transport properties. The investigation will include the Eclipse 4500 SRA, or equivalent, and two types of synthetic fibers (i.e., STRUX and SINTA from GCP).
2. Evaluate the effect of rheological properties of fiber alignment along the casting-flow direction of structural elements. The rheological properties of concrete will be modified using a viscosity modified admixture (VMA), such as V-MAR from GCP. The incorporation of VMA can improve the stability of the concrete mixture and distribution of the fibers.
3. Investigate the corrosion resistance of reinforcing bars in pre-cracked FR-SCC and FR-SWC mixtures. The cracking will be controlled to achieve different widths for mixtures with different fibers. The transport properties of the concrete matrix will also be investigated.
4. Evaluate the enhancement in tensile/flexural toughness and shrinkage/crack resistance of FRC made with partially replacement of the steel reinforcement in flexural members with different types of and combinations of the STRUX and SINTA fibers.

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Enhance Performance of Fiber-Reinforced Concrete with Adapted Rheology

Progress Report – 1/29/2020

Title: Enhance Performance of Fiber-Reinforced Concrete with Adapted Rheology

Project Number 00064859

Principal Investigator (PI): Kamal H. Khayat, Ph.D., P.Eng.

The main objectives of this project are summarized below.

1. Optimize the SRA-fiber system of fiber reinforced self-consolidating concrete (FR-SCC) and fiber reinforced super workable concrete (FR-SWC) mixtures to achieve superior performance, including drying shrinkage, restrained shrinkage, mechanical properties (tensile and compressive strength), frost durability, and transport properties. The investigation will include the Eclipse 4500 SRA, or equivalent, and two types of synthetic fibers (i.e., STRUX and SINTA from GCP).

2. Evaluate the effect of rheological properties of fiber alignment along the casting-flow direction of structural elements. The rheological properties of concrete will be modified using a viscosity modified admixture (VMA), such as V-MAR from GCP. The incorporation of VMA can improve the stability of the concrete mixture and distribution of the fibers.

3. Investigate the corrosion resistance of reinforcing bars in pre-cracked FR-SCC and FR-SWC mixtures. The cracking will be controlled to achieve different widths for mixtures with different fibers. The transport properties of the concrete matrix will also be investigated.

4. Evaluate the enhancement in tensile/flexural toughness and shrinkage/crack resistance of FRC made with partially replacement of the steel reinforcement in flexural members with different types of and combinations of the STRUX and SINTA fibers.

1. Work currently underway during this reporting period.

The work in progress during this reporting period includes the continuation of tests on workability, drying shrinkage, and mechanical properties of FR-SWC mixtures as in Task I of the project. The purpose of work is to investigate the effect of shrinkage reducing admixtures (SRA), fiber type and fiber content to optimize FR-SWC. The baseline FR-SWC mixture optimized by the research team was employed. The lightweight sand (LWS) content (25% by volume) and moist curing regime (1 day in molds, then by air drying at 23 °C and 50% RH) were applied.

2. Activities and accomplishments during this reporting period.

2.1 Task I: Materials performance optimization for FR-SWC

The purpose of Task I of the research was to optimize the SRA-fiber system of FR-SWC mixtures to achieve superior performance, including mechanical properties (compressive strength and modulus of elasticity), drying shrinkage, frost durability, and transport properties. A factorial design approach will be employed to quantify the effect of different test parameters and contents investigated. **Table 1** presents the coded and actual values of investigated parameters. The coded values (i.e., -1, 0, 1) for fiber combination correspond to the macro1 (STRUX BT50)-macro 2 (STRUX 75/32) fiber ratios of 0.75:0.25, 0.25:0.75, 1:0. At the end of Task I, the optimum mixtures with the best overall performance will be determined, according to the factorial design approach. The experimental design includes 16 mixtures to optimize SRA, fiber combination, and amount of fibers and specify the target mixtures for Task II. The experimental design includes 8 mixtures as factorial design, 3 mixtures as central point, and 5 mixtures as validation Mixtures.

Table 1- Coded and actual values of investigated parameters

Test parameter	Coded factor		
	-1	0	1
SRA (%)	0	2.5	5
Fiber combination	1:0	0.75:0.25	0.25:0.75
Fiber (%)	0.1	0.33	0.66

The summary of mixtures design is listed in **Table 2**.

Table 2 – Experimental design for mixtures

Specification		Coded value			Absolute value		
Type	No of mixes	SRA (%)	Fiber Comb	Fiber (%)	SRA (%)	Fiber comb.	Fiber (%)
Factorial Design	1	-1	-1	-1	0	1	0.1
	2	-1	-1	1	0	1	0.66
	3	-1	1	-1	0	0.25	0.1
	4	-1	1	1	0	0.25	0.66
	5	1	-1	-1	5	1	0.1
	6	1	-1	1	5	1	0.66
	7	1	1	-1	5	0.25	0.1
	8	1	1	1	5	0.25	0.66
Central Points	9	0	0	0	2.5	0.75	0.33
	10	0	0	0	2.5	0.75	0.33
	11	0	0	0	2.5	0.75	0.33
Validation Points	12	0.33	1	-0.67	3.3	0.25	0.36
	13	0.33	0	0.67	3.3	0.75	0.55
	14	-0.33	-1	0.33	1.7	1	0.44
	15	-0.33	-1	-0.33	1.7	1	0.22
	16	-1	0	0.33	0	0.25	0.44

Table 3 shows the experimental program of Task I. In this reporting period, a total of 10 FR-SWC concrete mixtures (out of 16 mixtures) were cast. The investigated mixtures included those made with intermediate contents of SRA, Fiber combinations, and fiber contents. The unit weight, air content, slump flow, modified J-ring, and bleeding were tested. Furthermore, 160 cylindrical samples (4″x8″), 20 flexural beams (16″x3″x3″), 20 drying shrinkage prisms (11.25″x3″x3″) were prepared. For all the mixtures, water-to-binder ratio (w/b) was maintained at 0.43 and samples were prepared for 1 day of moist curing, then by air drying at 23 °C and 50% RH.

Table 3 – Experimental program of Task (60% completed)

Task I –Material Performance Optimization for FR-SWC (10 Mixtures)		
Concrete property	No. of Samples	Test
Workability	*	Unit weight (ASTM C 138), Air vol. (ASTM C 173)
	*	Slump, up to 90 min
Passing ability	*	Modified J-Ring
Stability	*	Bleeding (ASTM C 232)
Mechanical properties	36	Compressive strength, N=3 (ASTM C 39), 1, 7, 28, 56
	12	Modulus of elasticity, N=2 (ASTM C 469), 3, 56 days
Volume change	20	Drying shrinkage, N=2 (ASTM C 157)
Total	68	

2.2 Materials Characterization

In order to prepare the concrete mixtures for Task I, the following materials were used. Portland cement (Type I) and fly ash (Class C). The chemical composition of cement and fly ash is shown in **Table 4**.

The mixtures contained 9/16 in. minus coarse aggregate (from Capital quarry, Sullivan), river sand (from Capital quarry, Jeff city), LWS, shrinkage reducing admixtures (Eclipse 4500 SRA), two types of synthetic fibers (i.e., STRUX 75/32 and STRUX BT50 from GCP), high range water reducer (HRWR- ADVA 198), air-entrained agent (DAREX® AEA), and viscosity-modifying admixture (CONCERA CP 1124).

Table 4 – Chemical composition of cement and fly ash (wt%)

Component	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	MgO	K_2O	Na_2O	Minors	LOI
Cement	65.87	18.72	4.04	3.55	2.41	1.74	0.66	0.97	0.86	1.18
Fly ash	9.81	56.80	23.41	4.92	0.72	1.69	1.06	0.05	0.48	1.06

Figure 1 shows the particle size distribution of the coarse aggregate (9/16 in.) sand and LWS**. Table 5** presents properties of the sand and LWS, including specific gravity (SSD SG), oven-dry specific gravity (OD SG), and saturated surface dry (SSD) absorption, oven-dry water (ODW) absorption.

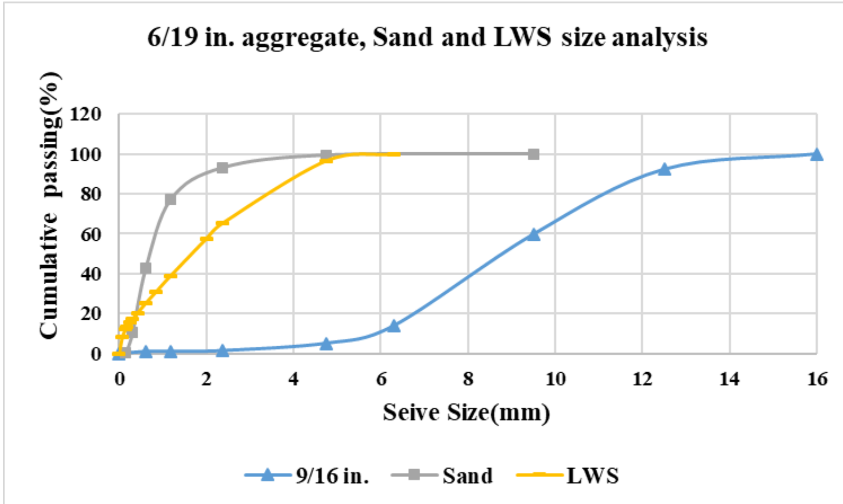


Figure 1. The sieve size analysis coarse aggregate, sand, and LWS

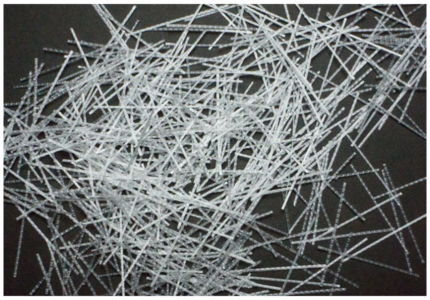
Table 5 – 9/16 in. aggregate Sand and LWS properties

Properties	SSD SG	OD SG	SSD Absorption	ODW absorption (%)
9/16 in.	2.68	2.66	0.77	0.21
Sand	2.58	2.52	2.24	1.64
LWS	1.83	1.48	23.46	100%

Table 6 shows the properties of the macro1 (STRUX BT50) and macro2 (STRUX 75/32) fiber. **Figure 2** shows two types of fibers that were used in this project. The length and aspect ratio of macro1, macro2 are 2 in. (50 mm) and 1.26 in. (32 mm), 75 and 22.86, respectively. The tensile strength and elastic modulus of the macro1, macro2 are 89.8 ksi (550 MPa) and 89.9 ksi (620 MPa), 1015 ksi (7 Gpa) and 1305 ksi (9 Gpa), respectively.

Table 6 – The properties of fibers

Types	**STRUX ®BT50**	**STRUX®75/32**
Material	Synthetic macro-fiber	polypropylene
Shape	straight	straight
Color	white	grey
Cross-section	rectangle	rectangle
Specific gravity	0.91	0.92
Length (in.)	2	1.26
width(in.)	0.03	0.55
Aspect ratio	75	22.86
thickness(in.)	0.01	0.004
Modulus of elasticity (ksi)	1015	1305
Tensile Strength (ksi)	89.8	89.9



STRUX BT50 STRUX 75/32

Figure 2. STRUX fibers proposed in this research

2.3 Mixing procedure of FR-SWC and mixture proportions

The mixing procedure of the FR-SWC was as follows: first, the sand and LWS were homogenized in the mixer for 30 seconds. Then, the coarse aggregate was added, and half of the water mixed with the AEA was gradually introduced to the mixture. The mixed time was 2 minutes. Afterward, the binder powder, including cement and fly ash, was included and mixed for one minute. Subsequently, 1/4 of the water mixed with 3/4 mount of the HRWR was added to the mixture for one and half minutes. The remaining 1/4 amount water with VMA was then added, and the concrete mixed for two minutes. And then the SRA was introduced into mixer for one minute. At this step, the mixer was switched off for a one-minute rest. The volume needed for HRWRA was corrected with the remaining HRWRA volume. Finally, the concrete was mixed for 2 additional minutes. The concrete temperature during and testing was approximately 20 ºC (68 ºF). The cast samples were demolded after 24 hours. The samples were subjected to 1 day of moist curing, which was followed by drying in a chamber with standard curing condition suggested by ASTM C157 at a relative humidity of 50% ± 4% and a temperature of 23 ± 2 ℃.

Table 7 shows the mixture proportions of the 10 investigated FR-SWC mixtures. The mixtures are denoted based on the contents of SRA, Fiber combination, and fiber content. For example, the 0.1FR-1:0-5.0SRA mixture refers to the mixture with 0.1% fiber, by volume of total concrete, 1:0, by the macro1 (STRUX BT50)-macro2 (STRUX 75/32) fiber ratios, and 5.0%SRA, by mass of binder. The REF mixture denotes the reference concrete made without any SRA and fibers. **Figure 3** shows the materials were used in this research.

Table 7 – Mixture proportions of FR-SWC

# Mix	Cement Ib/ft3	Fly-ash Ib/ft3	Sand Ib/ft3	LWS Ib/ft3	Agg. 4/9" Ib/ft3	SRA %	Fiber Comb.	FR %
The REF	14.04	6.86	40.82	13.60	49.94	0	0	0
0.1FR-1:0-0.0SRA	14.04	6.86	45.45	10.74	46.95	0	1:0	0.1
0.1FR-0.25:0.75-0.0SRA	14.04	6.86	45.46	10.75	46.93	0	0.25:0.75	0.1
0.66FR-1:0-0.0SRA	14.04	6.86	47.98	11.34	42.76	0	1:0	0.66
0.1FR-0.25:0.75-5.0SRA	14.04	6.86	45.46	10.75	46.93	5.0	0.25:0.75	0.1
0.1FR-1:0-5.0SRA	14.04	6.86	40.82	13.60	49.94	5.0	1:0	0.1
0.33FR-0.75:0.25-2.5SRA	14.04	6.86	46.50	11.00	45.21	2.5	0.75:0.25	0.33
0.36FR-0.25:0.75-3.3SRA	14.04	6.86	46.68	11.05	44.93	0.36	0.25:0.75	0.36
0.44FR-0.25:0.75-0.0SRA	14.04	6.86	47.05	11.13	44.32	0.44	0.25:0.75	0.44
0.22FR-1:0-1.7SRA	14.04	6.86	46.03	10.89	46.01	0.22	1:0	0.22

Figure 3. Materials used in this research

2.4. Fresh Properties

Table 8 shows the fresh properties of the tested FR-SWC mixtures. The slump flow values of all tested samples ranged between 22.0 in. and 15.9 in. For fiber-reinforced mixtures. The temperature, air content, and unit weight values of the mixtures ranged between 66.7 °F and 70.7 °F, 4.9% and 6.1%, and 142.4 lb/ft^3 and 146.8 lb/ft^3, respectively.

Table 8 – Fresh properties of the selected investigated FR-SWC mixtures.

# Mix	Slump Flow, in. 0 min	Slump flow, in. 30min	Slump flow, in. 60min	Slump flow, in. 90min	Modified J-ring In.	Temp., °F	Air content, %	Bleeding, %	Unit weight, lb/ft^3
The REF	20.8	17.5	16.7	15.9	19.6	67.6	5.1	1.0	143.2
0.1FR-1:0-0.0SRA	20.6	19.2	18.1	15.7	17.7	67.6	5.2	1.0	145.2
0.1FR-0.25:0.75-0.0SRA	20.8	19.6	17.9	15.9	20.0	66.7	4.9	1.0	146.8
0.66FR-1:0-0.0SRA	18.1	16.1	13.9	11.8	16.3	67.5	5.3	1.0	142.4
0.1FR-0.25:0.75-5.0SRA	20.0	16.9	13.5	12.9	18.8	68.5	4.8	1.0	145.8
0.1FR-1:0-5.0SRA	21.6	18.5	13.5	12.9	20.0	68.7	6.1	1.0	143.6
0.33FR-0.75:0.25-2.5SRA	20.8	17.3	13.4	12.2	19.1	70.7	4.9	1.0	144.8
0.36FR-0.25:0.75-3.3SRA	20.4	18.7	13.3	12.4	18.3	69.2	5.4	1.0	144.0
0.44FR-0.25:0.75-0.0SRA	19.5	17.9	14.3	12.3	17.91	69.4	4.9	1.0	145.0
0.22FR-1:0-1.7SRA	22.0	17.3	14.7	12.4	19.8	69.6	5.0	1.0	144.4

2.5. Mechanical properties

2.5.1 Compressive strength results

The compressive strength tests were conducted on 4″x8″ (100 x 200 mm) cylinders as per ASTM C39. **Table 9** shows the compressive strength results of the FR-SWC samples tested after 1, 7, and 28 days of age (1-day moist curing and air curing afterward). The results indicate that the 5% SRA showed lower compressive strength and SRA did not improve compressive strength, while the macro1 (STRUX BT50) -macro2 (STRUX 75/32) fiber increased the compressive strength slightly.

Table 9 – Compressive strength results of FR-SWC at 1, 7, and 28 days.

Mix #	3-day Compressive strength, psi	Avg., psi	7-day Compressive strength, psi	Avg., psi	28-day Compressive strength, psi	Avg., psi
REF*	4880	4890	6190	6420	7120	7100
	4910		6560		7060	
	4900		6500		7130	
0.1FR-1:0-0.0SRA	4880	4840	6190	6450	7320	7310
	4910		6580		7260	
	4730		6560		7350	
0.1FR-0.25:0.75-0.0SRA	4520	4380	6240	6360	7260	7210
	4200		6580		7210	
	4410		6260		7160	
0.66FR-1:0-0.0SRA	4130	4190	x		7160	7230
	4250		x		7300	
	4190		x		7240	
0.1FR-0.25:0.75-5.0SRA	x		x		6770	6880
	x		x		6880	
	x		x		6990	
0.1FR-1:0-5.0SRA	x		x		x	
	x		x		x	
	x		x		x	
0.33FR-0.75:0.25-2.5SRA	x		x		x	
	x		x		x	
	x		x		x	
0.36FR-0.25:0.75-3.3SRA	x		x		x	
	x		x		x	
	x		x		x	
0.44FR-0.25:0.75-0.0SRA	x		x		x	
	x		x		x	
	x		x		x	
0.22FR-1:0-1.7SRA	x		x		x	
	x		x		x	
	x		x		x	

X Denotes the test is in process; results will be reported in the next reporting period.

2.5.2 Modulus of elasticity results

Table 10 provides the result of the modulus of elasticity for the 10 mixtures at 3. The results show that the highest modulus of elasticity was obtained for 0.1FR-1:0-0.0SRA, which conforms with the compressive test results, however, test is still in process and more results are needed to make a scientific judgment.

2.6. Drying shrinkage

The drying shrinkage test was conducted on 11.25″x3″x3″ (75x75x285 mm) beams according to ASTM C157. **Figures 4** and **5** show the total shrinkage results of selected the investigated mixtures with and without fibers for the moist curing of 1 day during this reporting period. The results of non-fiber mixtures and fiber-reinforced mixtures show that the addition of fibers was not effective in reducing shrinkage within the tested duration. The reason can be related to the large diameter of two types of fibers, which could not restrain the micro-crack effectively. However, the effect of SRA in reducing the total shrinkage is significant.

Table 10 –Modulus of elasticity results of FR-SWC at 3 days.

Mix #	3-day Modulus of elasticity, ksi	Avg., ksi
REF*	5100	5100
	5250	
	5050	
0.1FR-1:0-0.0SRA	5250	5200
	5150	
	5200	
0.1FR-0.25:0.75-0.0SRA	5250	5270
	5300	
	5280	
0.66FR-1:0-0.0SRA	5080	5110
	5100	
	5150	
0.1FR-0.25:0.75-5.0SRA	x	
	x	
	x	
0.1FR-1:0-5.0SRA	x	
	x	
	x	
0.33FR-0.75:0.25-2.5SRA	x	
	x	
	x	
0.36FR-0.25:0.75-3.3SRA	x	
	x	
	x	
0.44FR-0.25:0.75-0.0SRA	x	
	x	
	x	
0.22FR-1:0-1.7SRA	x	
	x	
	x	

X Denotes the test is in process; results will be reported in the next reporting period.

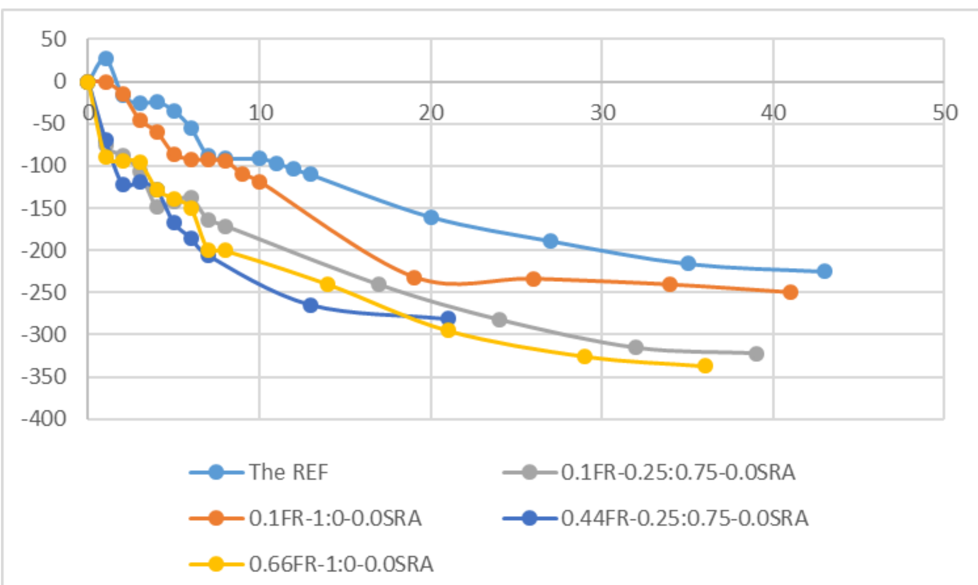


Figure 4. Shrinkage of FR-SWC without SRA

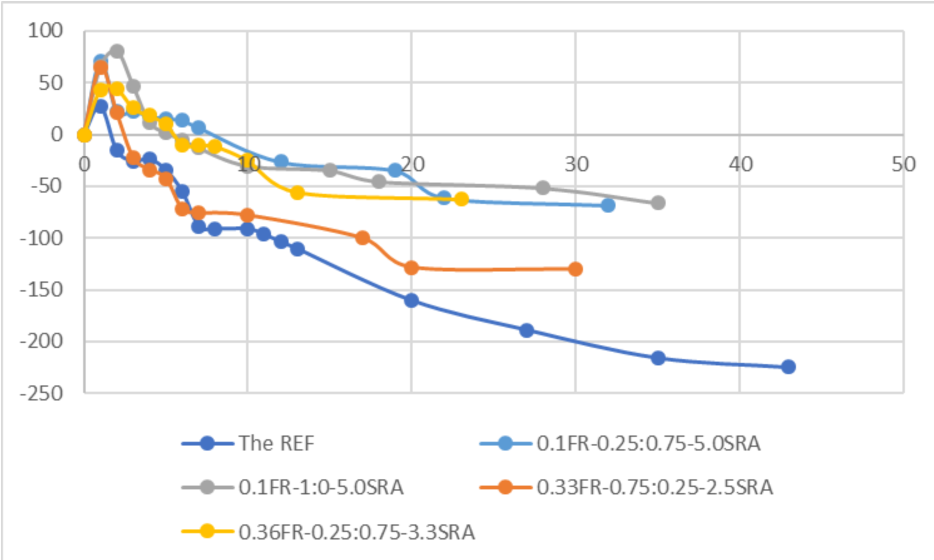


Figure 5. Shrinkage of FR-SWC with SRA

Additional notes:
Activities planned for the next reporting period will include:

1. Continuation of tests for the modulus of elasticity of the casted mixtures at 3, 56 days, and compressive and flexural strength at 28, 56 days. Besides, the splitting tensile strength and bulk electrical conductivity of the casted mixtures will be obtained.
2. Conduct surface settlement and rheology tests of the reported mixtures.
3. Conduct fresh property, dry shrinkage, modulus of elasticity, the compressive and flexural strength tests of mixtures with different curing regimes at 1 day, 3 days, 7days, 28days.

Final project report/update:

This project is a still underway with the other sponsor, GCP Applied Technologies, and the final results will be published at the end of that period. The final report will uploaded on the RE-CAST project website at:
https://recast.mst.edu/projects/performanceofsyntheticfiber-reinforcedconcrete/

The remaining portion of the work is scheduled to be completed by 8/31/2020.