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Performance-Based Specifications of Fiber-Reinforced Concrete with Adapted Rheology to Enhance Performance and Reduce Steel-Reinforcement in Structural Members

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The investigation was conducted in cooperation with the U. S. Department of Transportation.

16. Abstract
Objectives for this project include:

- Optimization of fiber characteristics-EA-LWS-moist curing system to develop high resistance to cracking and enhanced mechanical properties and corrosion resistance for Eco-Bridge-Crete and FR-SWC.
- Development of a prediction model to predict the performance of FR-SCC and FR-SWC (two separate models) given the EA, LWS and fiber contents and curing conditions.
- Quantification of the amount of steel reinforcement that can be reduced by fibers in FR-SWC.
- Evaluation of the enhancement in flexural toughness and crack resistance due to partial replacement of steel reinforcement with fibers.

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Fiber-Reinforced Concrete; Adapted Rheology	No restrictions. This document is available to the public.

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Performance-Based Specifications of Fiber-Reinforced Concrete with Adapted Rheology to Enhance Performance and Reduce Steel-Reinforcement in Structural Members

Progress Report – 12/1/2019

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

1. Work currently underway during this reporting period.

The work in progress during this reporting period includes the final phase of the project. In this stage, the optimum contents for the expansive agent (EA), lightweight sand (LWS), fibers (FR), and moist curing conditions that were identified in this reporting period are used for optimization of fiber-reinforced super workable concrete (FR-SWC) mixtures to minimize shrinkage and enhance flexural strength. Mechanical properties (compressive and flexural strengths), frost durability (freeze and thaw and deice salt scaling), transport properties (sorptivity, resistivity) and visco-elastic properties (drying shrinkage, restrained expansion) will be evaluated for four types of fibers (macro synthetic fibers, macro steel fibers, micro-macro steel fibers, and 5D steel fibers). The corrosion assessment of FR-SWC with embedded reinforcing bars is in progress.

2. Activities and accomplishments during this reporting period.

2.1. Factorial design, statistical models, and selection process

Factorial design

A factorial design approach was employed to quantify the effect of the contents of EA, LWS, and FR as well as moist curing conditions on mechanical properties, shrinkage, and restrained expansion of the Eco-Bridge-Crete mixtures. The coded and actual values of the different test parameters are shown in **Table 1**. In total, 25 mixtures were required to complete the factorial design, as shown in **Table 2**. A total of 16 mixtures and four central point mixtures were used to develop the statistical models. Five additional mixtures were used for the validation of the established modes. The water-to-binder ratio (w/b) was maintained at 0.40 for all investigated mixtures.

Table 1 – Coded and actual values of investigated parameters

Test parameter	**Coded factor**		
	-1	0	1
CaO-based EA (%)	0	5	10
LWS (%)	0	12.5	25
Moist curing (day)	1	7	14
Fiber (%)	0	0.25	0.5

Table 2 – Mixtures used in factorial design

Type	No of mixes	Coded Value				Absolute value			
		EA	LWS	Moist curing	Fiber	EA (%)	LWS (%)	Moist curing (day)	Fiber (%)
Factorial Design	1	-1	-1	-1	-1	0	0	1	0
	2	1	-1	-1	-1	10	0	1	0
	3	-1	1	-1	-1	0	25	1	0
	4	1	1	-1	-1	10	25	1	0
	5	-1	-1	1	-1	0	0	14	0
	6	1	-1	1	-1	10	0	14	0
	7	-1	1	1	-1	0	25	14	0
	8	1	1	1	-1	10	25	14	0
	9	-1	-1	-1	1	0	0	1	0.5
	10	1	-1	-1	1	10	0	1	0.5
	11	-1	1	-1	1	0	25	1	0.5
	12	1	1	-1	1	10	25	1	0.5
	13	-1	-1	1	1	0	0	14	0.5
	14	1	-1	1	1	10	0	14	0.5
	15	-1	1	1	1	0	25	14	0.5
	16	1	1	1	1	10	25	14	0.5
Central Points	17	0	0	0	0	5	12.5	7	0.25
	18	0	0	0	0	5	12.5	7	0.25
	19	0	0	0	0	5	12.5	7	0.25
	20	0	0	0	0	5	12.5	7	0.25
Validation points	21	2/3	-1/3	1	-1	6.67	8.33	14	0
	22	2/3	-1/3	1	-1	6.67	8.33	14	0
	23	-1/3	1/3	-1/3	1	3.33	8.33	4.67	0.5
	24	- 1/3	1/3	-1/3	1	3.33	8.33	4.67	0.5
	25	1	2/3	1	1/3	10	16.67	14	0.17

Statistical models

Statistical models were established to estimate the effect of three mixture design parameters (EA, LWS, and fiber content) and moist curing period on critical parameters of Eco-Bride-crete. The mixture parameters with significant effects are summarized in **Table 3**. Based on the factorial design, models for the different properties are established. The derived statistical models for predicting the critical concrete properties are listed in **Table 4**. The R-square values for all the models are higher than 0.9, and the probability value (under the null hypothesis) is less than 0.1, which shows the reliability of the model.

Table 3 – Derived statistical models

Parameters	28-d Compressive (MPa)	56-d Flexural (MPa)	7-d Shrinkage (um/m)	56-d Shrinkage (um/m)	7-d Expansion (um/m)	56-d Expansion (um/m)
Intercept	44.15*	7.96*	112.2*	-30.8*	60.7*	-12.4*
EA	-2.98*	1.18*	27.1*	/	15.6*	/
LWS	-8.91*	0.54*	20.8*	73.4*	/	27.8*
Curing	7.95*	/	38.9*	66.5*	21.0*	40.9*
Fiber	-6.93*	1.08*	/	/	/	/
EA*LWS	/	-0.94*	/	-62.8*	/	-25.5*
EA*Curing	/	/	/	/	-9.6*	/
LWS*Curing	/	/	/	/	/	16.1*
EA*Fiber	/	/	/	37.7*	-11.0*	-
LWS*Fiber	-3,19*	-0.9*	/	-44.9*	-13.9*	-26.4*
Curing*Fiber	/	/	/	/	/	/
EA*LWS*Curing	/	/	/	/	/	/
EA*LWS*Fiber	5.08*	-2.0*	29.5*	-50.4*	19.5*	-26.4*
EA*Curing*Fiber	/	/	/	/	/	/
LWS*Curing*Fiber	/	/	/	/	/	/
EA*LWS*Curing*Fiber	/	/	/	/	/	/

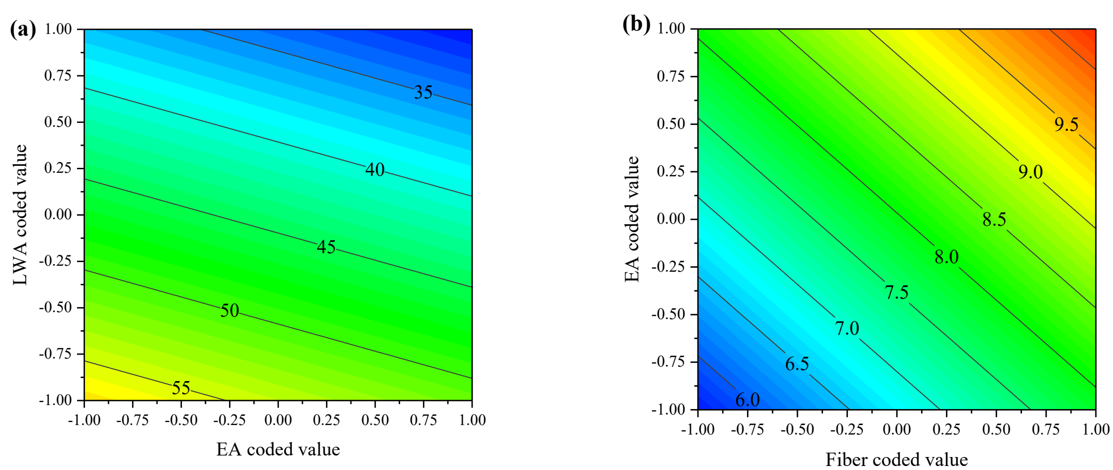
Note: * denotes the effect of the parameter is significant; / means the effect of the parameter is less or not significant

Based on the statistical models, the effects of EA, LWS, fiber content, and moist curing (denoted as MC) on fundamental concrete properties were analyzed using the JMP statistical software. **Figure 1** illustrates contour diagrams showing the trade-off between the various modeled parameters where two of the four modeled are held constant. The derived statistical models are summarized in **Table 5**.

The derived statistical models are indicating that the increase in EA has an adverse effect on the compressive strength, while the increase in curing duration increases the compressive strength. When EA, MC coded values are set as -1 and -1, respectively, the increase in LWS and fiber contents slightly increases the compressive strength. When EA, MC coded values are set as -0.5 and -0.5, respectively, the increase in LWS and fiber reduces the compressive strength.

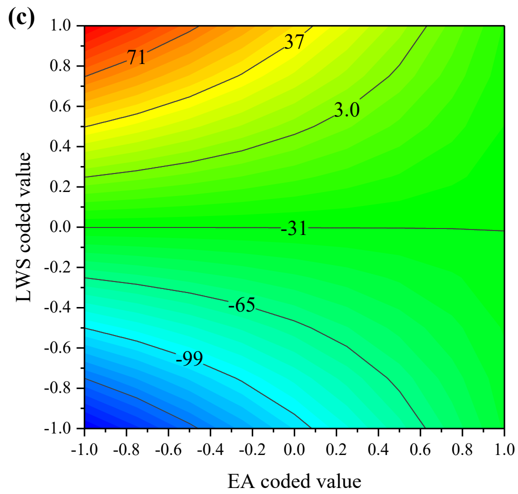
Table 4 – Derived statistical models (based on coded values)

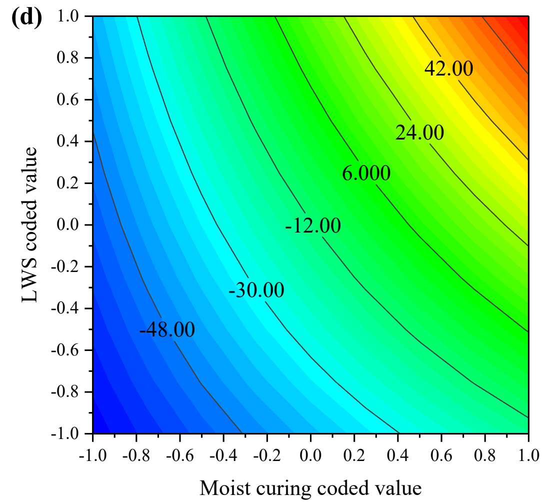
Derived statistical models (based on coded value)
Response 28-d Compressive (RSq=0.99, PValue=0.0032)
44.15-8.91LWS +7.95MC-6.93Fiber+5.08EA*LWS*Fiber -3.19LWS*Fiber-2.98EA
Response 56-d Flexural strength (RSq=0.99, PValue=0.0038)
7.96-2.0EA*LWS*Fiber+1.18EA+1.08Fiber -0.94EA*LWS-0.9LWS*Fiber +0.54LWS
Response 7-d drying shrinkage (RSq=0.94, PValue=0.0591)
112.2+38.9MC -29.5EA*LWS* Fiber +27.1EA+20.8LWS
Response 56-d drying shrinkage (RSq=0.97, PValue=0.0127)
-30.8+73.4*LWS+66.5*MC-62.8EA*LWS-50.4 EA*LWS*Fiber -44.9LWS*Fiber +37.7EA*Fiber
Response 7-d Restrained expansion (RSq=0.94, PValue=0.0786)
60.7+21MC+19.5EA*LWS*Fiber +15.6EA-13.9LWS*Fiber-11EA*Fiber-9.6EA*MC
Response 56-d Restrained expansion (RSq=0.95, PValue=0.0758)
-12.4+40.9MC+27.8LWS -26.4LWS*Fiber-26.4 EA*LWS*Fiber -25.5EA*LWS+16.1LWS*MC



Fiber and MC coded values as 0, 0

LWS and MC coded values as 0, 0





Fiber and MC coded values as 0, 0 EA and Fiber coded values as 0, 0

Figure 1 – Contour diagrams of the effects of EA, LWS, Moist curing (MC) and Fiber content on (a) compressive strength; (b) flexural strength; (c) 56-d drying shrinkage; and (d) 56-d restrained expansion – each contour diagram has two values that are fixed at coded values of 0.

Table 5 – Relative effect of four parameters on the different properties

Recommended mixtures				28-d Compressive	56-d Flexural	7-d shrinkage	56-d shrinkage	7-d Expansion	56-d Expansion
Coded value									
EA	LWS	Curing	Fiber						
↑	-1	-1	-1	-	+	---	--	+++	++
↑	-0.5	-0.5	-0.5	--	++	--	-	++	+
↑	0	0	0	--	++	--	-	++	+
↑	0.5	0.5	0.5	-	+	-	-	+	+
-1	↑	-1	-1	+	+	---	---	+++	+++
-0.5	↑	-0.5	-0.5	-	+	--	---	++	++
0	↑	0	0	---	+	-	-	+	++
0.5	↑	0.5	0.5	---	-	-	-	=	=
-1	-1	↑	-1	+++	=	--	---	++	++
-0.5	-0.5	↑	-0.5	+++	=	--	---	++	++
0	0	↑	0	+++	=	--	-	++	+
0.5	0.5	↑	0.5	++	=	--	-	+	+
-1	-1	-1	↑	+	+	--	--	++	++
-0.5	-0.5	-0.5	↑	-	++	=	=	+	++
0	0	0	↑	--	++	=	=	=	=
0.5	0.5	0.5	↑	--	+	=	=	=	=

Note: the number of + sign or – sign means the extent of the increase or decrease, while = sign means the responsible properties do not change.

Furthermore, the increase in EA and fiber contents improves flexural strength. The increase in LWS up to coded value of 0.5 is shown to slightly increase the flexural strength; beyond that limit, a reduction in flexural strength can take place. For samples with less EA, with the LWS and MC parameters set at coded values < 0, the increase in EA, LWS, and moist curing duration have positive effect on inhibiting drying shrinkage, especially at a long-term. The FR-SWC can exhibit a significant expansion at 7 d of age but did not significantly affect the long-term shrinkage. The incorporation of the higher content of EA and LWS and extending the moist curing period from coded values of 0 to 1 does not change the 56-d drying shrinkage and restrained expansion significantly.

Optimized mixture selection process

Four FR-SWC mixtures were selected for further optimization to evaluate shrinkage and cracking resistance. Accordingly, the EA, LWS, fiber volume, and moist curing period were changed with a step sizes of 2.5%, 6.3%, 0.13%, and 7 d, respectively, within the range of mixture proportioning variables (0 to 10% for EA, 0 to 25% for LWS, 0 to 0.5% for fiber, and 1 to 14 d curing). The significance level of each factor was set based on the significance of associated property in performance of the structural element (Task II), as shown in **Table 6**. The EA, LWS, moist curing, and fiber content coded values of the mixture with the highest desirability (D) are 1, -1, 0, 1, respectively. Then, the curing value was set as 0, and the overall desirability values of all mixtures were calculated and compared. The seven mixtures with the highest desirability are listed in **Table 7**.

In order to investigate the chemical prestressing effect of the EA-LWS system on the performance of fiber-reinforced concrete, two mixtures with high desirability values and two mixtures made with low desirability values with hybrid systems of EA and LWS at varying contents are selected, as listed in **Table 8**. According to the proposed selection process, the four retained FR-SCC basic mixtures included a constant fiber content of 0.5%, a moist curing regime of 7 days, and a varying content of EA and LWS that included: 1) 10% EA and 0 LWS; 2) 5% EA and 12.5% LWS; 3) 5% EA and 25% LWS; and 4) 10% EA and 25% LWS. The properties of these mixtures will be validated in the future task with the micro-macro steel fibers and 5D steel fibers.

Table 6 – Mixture optimization criteria and weighted averages used to evaluate the overall desirability (D)

Properties	Significant Level	Set
28-d Compressive	2	Maximize
56-d Flexural	5	Maximize
7-d Drying shrinkage	1	Match 0
56-d Drying shrinkage	2	Match 0
7-d Restrained expansion	1	Match 0
56-d Restrained expansion	2	Match 0

.

Table 7 – Selected seven mixtures with high overall desirability values

Recommended mixtures								Desirability	28-d Compressive	56-d Flexural	7-d shrinkage	56-d shrinkage	7-d expansion	56-d expansion
Coded value				Absolute value										
EA	LWS	Curing	Fiber	EA (%)	LWS (%)	Curing (d)	Fiber (%)							
1	-1	0	1	10	0	7	0.5	0.778776	44	13.5	105	-8	61	-1
0.5	-1	0	1	10	0	7	0.5	0.718556	46	11.4	99	-39	62	-7
1	-0.5	0	1	10	6.3	7	0.5	0.702504	41	11.8	110	-1	61	-2
0	-1	0	1	5	0	7	0.5	0.639142	48	9.4	94	-69	64	-14
0.5	0	0	1	7.5	12.5	7	0.5	0.61749	40	9.6	105	-16	58	-7
0	0	0	1	5	12.5	7	0.5	0.607669	40	9.0	94	-41	54	-12
0	0.5	0	1	5	18.8	7	0.5	0.584619	36	8.9	95	-27	49	-11

Table 8 – Four selected mixtures with different desirability values

Recommended mixtures								Desirability	28-d Compressive	56-d Flexural	7-d shrinkage	56-d shrinkage	7-d expansion	56-d expansion
Coded value				Absolute value										
EA	LWS	Curing	Fiber	EA (%)	LWS (%)	Curing (d)	Fiber (%)							
1	-1	0	1	10	0	7	0.5	0.778776	44	13.5	105	-8	61	-1
0	0	0	1	5	12.5	7	0.5	0.607669	40	9.0	94	-41	54	-12
0	1	0	1	5	25	7	0.5	0.554097	33	8.7	95	-12	45	-11
1	1	0	1	10	25	7	0.5	0.440343	33	6.8	128	24	64	-4

2.2. Accelerated corrosion testing

The corrosion test setup included two salt tanks made with eight selected Eco-Bridge-Crete mixtures, as described in **Table 9**. The mixtures were selected based on their performance in drying shrinkage, restrained expansion and flexural strength. The EA content of the mixtures was set at 0 and 5%, by mass of binder, LWS content at 0 and 25%, by mass of total sand, and FR volume was 0 and 0.5%, by volume of concrete. For one of the mixtures, the steel fibers were replaced with a synthetic (SY fibers).

Table 9 – Investigated mixtures for the corrosion test

Salt tank	Mixture*
1	REF7D
	5EA0.5FR(SY)7D
	5EA25LWS0.5FR7D
	5EA25LWS0.5FR1D
2	0.5FR7D
	25LWS0.5FR1D
	5EA0.5FR7D
	5EA0.5FR1D
*REF7D denotes reference mixture with no EA or LWS or FR and subjected to 7d moist curing. 5EA0.5FR(SY)7D indicates mixture contains 5% EA, 25% LWS, 0.5% SY fibers and subjected to 7d moist curing.	

The test samples had dimensions of 25”x8”x3.5” with reinforcing bars embedded at different cover depths of 1, 1.5, and 2 in., as shown in **Figure 2**. The samples were subjected to moist curing for 1 or 7 d, followed by drying at 50% ± 4% relative humidity and curing temperature of 73 ± 3 °F for 90 days before corrosion testing. At the end of the drying period, the salt tanks were prepared and the tanks were filled with a 5% NaCl solution. The reinforcing bars were attached to a potential of 5 V with the rebars acting as the anode and a stainless steel mesh being as the cathode, as shown in **Figure 3.**

The current across the 1Ω resistors was recorded over time and the results are shown in **Figures 4(a-d)**. The time at which there was an abrupt increase in the current was used as an indicator of the corrosion initiation time.The variations in the electrical current in **Figures 4c and 4d** indicate the corrosion initiation for rebars at 1” cover embedded in 25LWS0.5FR1D and 5EA0.5FR1D mixtures after 50 and 45 days of testing, respectively. This was also evident from the cracking on the surface of the test samples, as shown in **Figure 5**. Comparing the samples from same mixture and subjected to 1 and 7 d of moist curing, the current values were higher for mixtures subjected to 1 d of moist curing. This could be due to high porous matrix. Also, the low current results for the REF7D and 5EA0.5FR(SY)7D mixtures in **Figure 4a** indicate the presence of steel fibers in the other mixtures resulted in decrease in the electrical resistivity of the tested concrete beams.

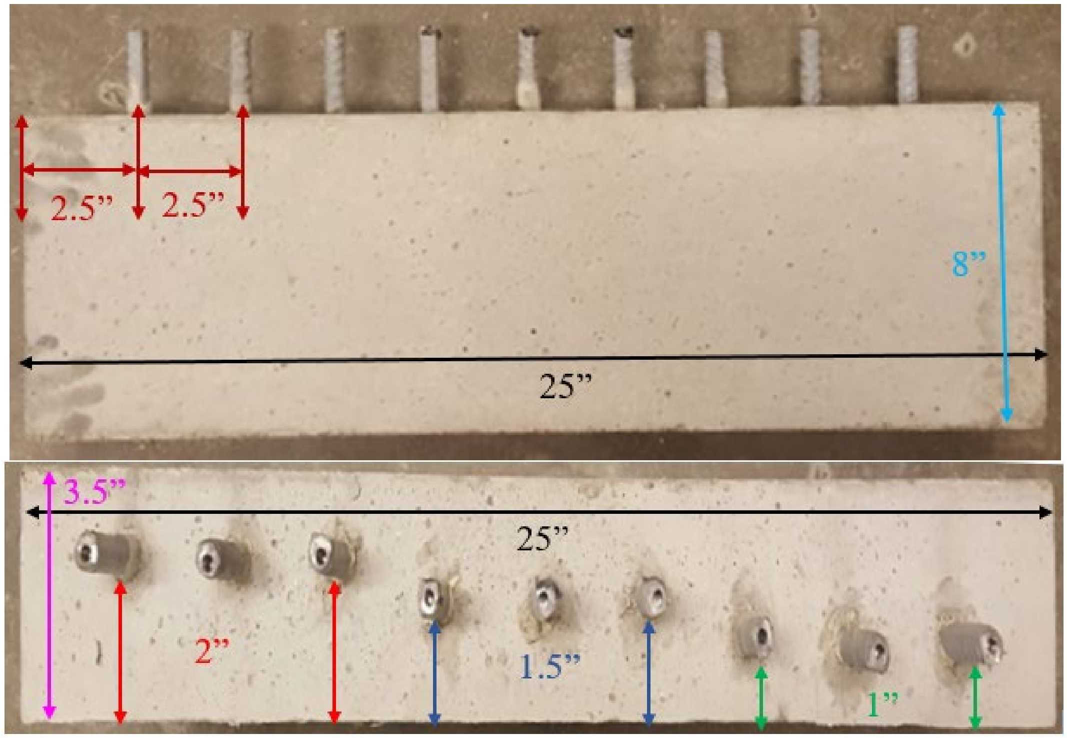


Figure 2 – Dimensions of concrete samples used in the corrosion test.

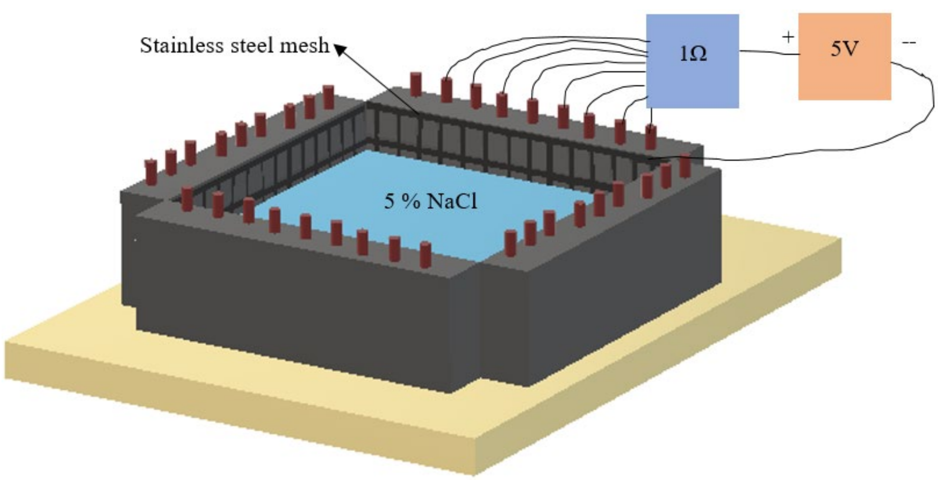
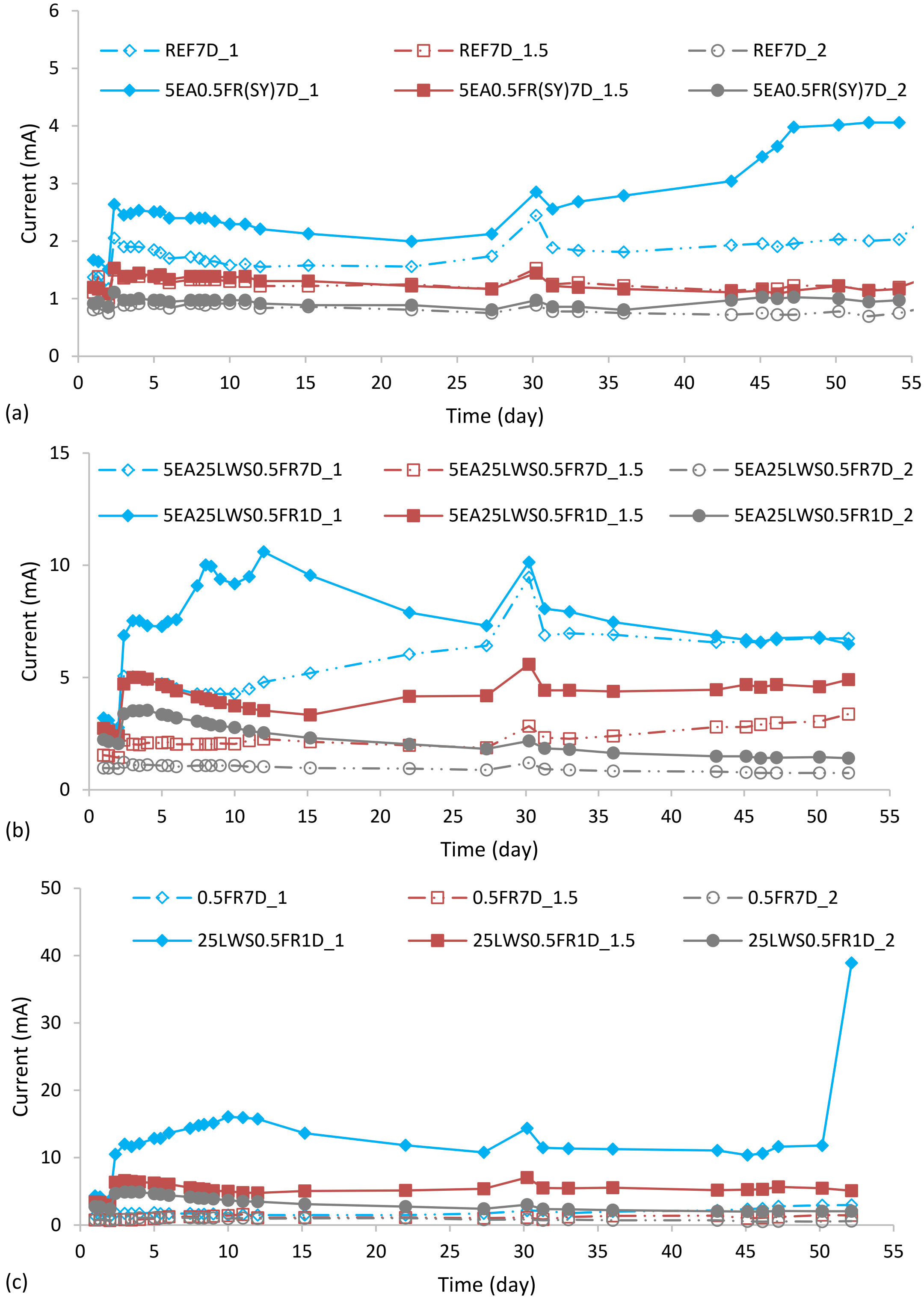


Figure 3 – Schematic of the accelerated corrosion test setup for measuring the corrosion resistance of embedded rebars in Eco-Bridge-Crete samples.


REF7D_1
REF7D_1.5
REF7D_2
5EA0.5FR(SY)7D_1
5EA0.5FR(SY)7D_1.5
5EA0.5FR(SY)7D_2
Current (mA)
Time (day)
(a)
5EA25LWS0.5FR7D_1
5EA25LWS0.5FR7D_1.5
5EA25LWS0.5FR7D_2
5EA25LWS0.5FR1D_1
5EA25LWS0.5FR1D_1.5
5EA25LWS0.5FR1D_2
Current (mA)
Time (day)
(b)
0.5FR7D_1
0.5FR7D_1.5
0.5FR7D_2
25LWS0.5FR1D_1
25LWS0.5FR1D_1.5
25LWS0.5FR1D_2
Current (mA)
Time (day)
(c)

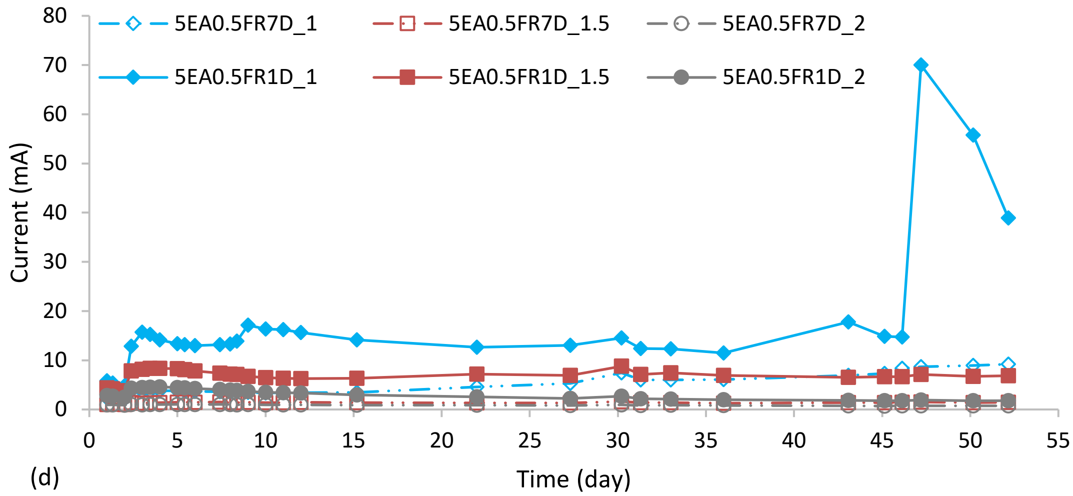


Figure 4 – Variations in electrical current with time.

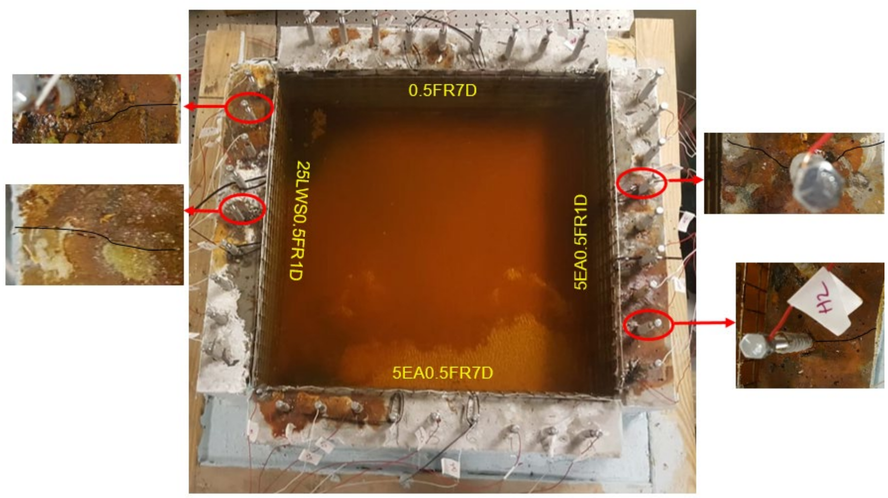


Figure 5 – Corrosion test samples from salt tank 2.

Issues or problems that need to be addressed.

The shortage of fibers during this reporting period resulted in some delay in the work progress of one month. Efforts are being made to accelerate the work and compensate for the lost time.

Next progress report due:

This project is a still underway with the other sponsor, Missouri Department of Transportation, 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/performance-basedspecificationsoffrcwithar/

The remaining portion of the work is scheduled to be completed by 5/1/2020.