CERTIFIED TEST REPORT

PRELIMINARY EVALUATION OF COMPOSITE BFRP BARS FOR CONCRETE REINFORCEMENT

Report Number: R-5.10_OLIN-B.1
Date: January 11, 2019

REVISION 1

REPORT PREPARED FOR:

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PROJECT:

Evaluation of physio-mechanical properties of BFRP rebars made with Epx/ANHYD resin

Quality System: The Structures and Materials Laboratory (SML) maintains a quality system in compliance with ISO 17025-2017, accredited under International Accreditation Service (IAS), testing laboratory, TL-478 and qualified laboratory by the Florida Department of Transportation (FDOT) ISM028.

Procedures: All tests and services are done in accordance with the SML Quality Manual (Version 2.4) revised January 31, 2017; relevant standard operating procedures (SOPs); and with the applicable requirements of the reference standard test methods.

Test Data: All the test results presented herein are linked through unbroken chain to the raw data files recorded on the day of the test. Analyzed data is obtained directly from the recorded raw data during testing, from which the test results are presented. This report contains analyzed tabulated data results of each test.

Controls:	
Superseded Report	R-5.10_OLIN-B
Reason for Revision	Update of additional test results, discussion and conclusion.
Effective Date	January 11, 2019
Superseded Report	New Report
Reason for Revision	n/a
Effective Date	April 12, 2018

Test Report Approval Signature:	
Quality review Approval	I indicate that I have reviewed this Test Report and agree with the contents it presents, and find it meets all applicable laboratory requirements and policies. I approve for its release to the customer. Name: Francisco De Caso Signature: Date: January 11, 2019
Technical review Approval	I indicate that I have reviewed this Test Report and agree with the contents it presents, and find it meets all applicable laboratory requirements and policies. I approve for its release to the customer. Name: Guillermo Claure Signature: Date: January 11, 2019

EXECUTIVE SUMMARY

This report provides experimental results to evaluate fundamental physio-mechanical and more importantly durability properties of nominal #3, #4 and #5 BFRP rebars made with an epx/anhyd based resin formulation and a sand coated surface with a helically wrapped cord around it. Based on the results presented herein, the following preliminary conclusions can be inferred based on the data set presented.

Thermal/mechanical properties of specimens prior to durability immersion tests:

- All experimental tests are conducted in accordance with ASTM and/or ISO standard test methods (refer to section 2 for the summary results), and thus results are applicable towards BFRP rebar certification and material approval per applicable requirements.
- Overall as indicated quantitatively herein, the evaluated mechanical properties of un-aged BFRP rebars result in equivalent or higher magnitudes than existing minimum ASTM/FDOT specifications or available GFRP rebars as provided by GFRP manufactures.
- Overall qualitatively, based on SEM imaging the BFRP bars result in a homogeneous cross-section were not anomalies or large voids are found, comparable within all bar sizes.
- The relative increasing of the cross-sectional area of the tested rebars to be in the mid-upper-bound of the specified ASTM allowable range is recommended.

The durability tests, post immersion in a high alkaline solution for 90 days at 60°C:

- Durability exposures immersed in alkaline solution (without sustained load as applicable) are conducted in accordance with ASTM and/or ISO standard test methods (refer to section 2 for the summary results), and thus results are applicable towards BFRP rebar certification and material approval per applicable requirements.
- Overall as indicated quantitatively herein, the evaluated mechanical properties of aged BFRP rebars result in equivalent or higher magnitudes than existing minimum ASTM/FDOT specifications or available GFRP rebars as provided by GFRP manufactures.
- Overall qualitatively, based on SEM imaging post exposure no visible degradation within the cross-section of the rebar or the surface are present; moreover, no signs of inadequate compatibility between fiber/sizing/epoxy is visible, providing additional evidence on the durability of the BFRP rebars under evaluation.
- More specifically, the tensile properties under the aggressive exposure post immersion in alkaline solution with a sustained load exceed the required retention strength FDOT 932 specification requirements.

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1. INTRODUCTION

1.1. BACKGROUND

This report presents experimental results on basalt fiber reinforced polymer (BFRP) bars for concrete reinforcement, made with an epx/anhyd based resin formulation and a sand coated surface with a helically wrapped cord around it. The report provides results to evaluate fundamental mechanical and durability properties of nominal #3, #4 and #5 BFRP rebars. The results are as part of a strategic plan to fully implement, safely and reliably the use of BFRP rebars made with Epx/ANHYD resin as concrete reinforcement in infrastructure applications. Refer to Figure 1 which shows different sample types (longitudinal and bends/stirrups).

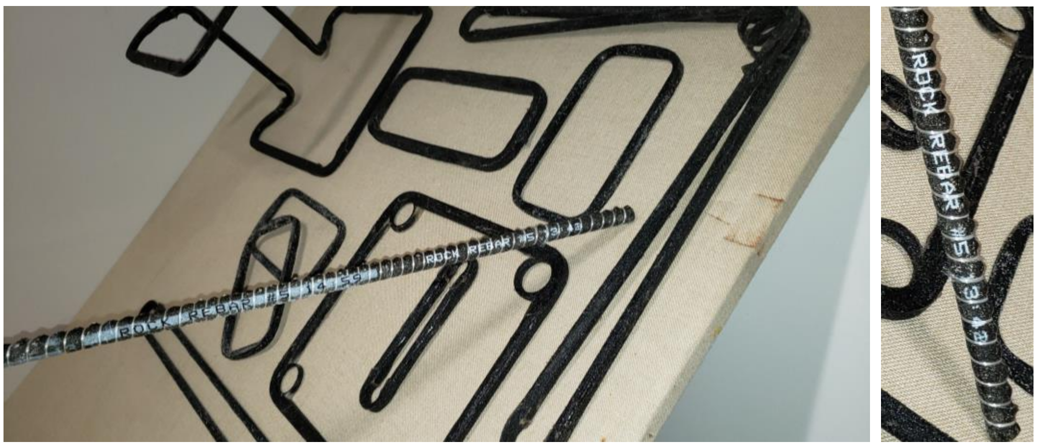


Figure 1 – BFRP made with Epx/ANHYD resin 'Rock Rebar' samples

1.2. OBJECTIVE

This report presents experimental physio-mechanical results on BFRP bars for concrete reinforcement. The report provides results to evaluate fundamental mechanical and durability properties of nominal #3, #4 and #5 BFRP rebars, where the three-fold objective is:

i) Determine if the evaluated properties are within existing international based material specifications (ASTM/ISO/CSA/ICC-ES/DIN) and federal based agencies (FDOT) standards for Glass FRP rebar, including ASTM D7957 (2017) '*Standard Specification for Solid Round Glass Fiber Reinforced Polymer Bars for Concrete Reinforcement*' as well as Florida Department of Transportation Specification 932.
ii) Provide preliminary recommendations for BFRP rebars with Epx/ANHYD resin standardization specifications and how it may be in alignment with FDOT incentives (e.g. State Transportation Innovation Councils 'STIC' project – summer 2019).
iii) Provide recommendations on how BFRP rebars made with Epx/ANHYD resin can be provide competitive value in terms of relative higher durability and improved mechanical properties.

Refer to Section 2 which provides summary tables with the average results for each bar size for each different physio-mechanical property based on the standard tests methods. Section 3 provides the fundamental test information and tabulated results for the unaged tests, while Section 4 presents the information and results for the aged tests. A short discussion and conclusions are provided at the end of the report.

2. SUMMARY OF TEST RESULTS

Test ID	Standard Test Method	Test Description	Spec. ASTM D7957	Test Value*	Test Result
SAMPLE #3					
TSS	ASTM D7617	Guar. Transverse Shear Strength	>19 ksi	19.7 ksi	Pass
FC	ASTM D2584	Fiber Content (by weight)	>70%	79.9 %	Pass
TNS	ASTM D7205	Guar. Tensile Force	13.2 kip	15.5 kip	Pass
		Tensile Modulus of Elasticity	≥ 6.5 Msi	7.0 Msi	Pass
		Strain	≥ 1.1%	2.0 %	Pass
MXA	ASTM D792	Measured Cross Sectional Area	0.104 in^2 to 0.161 in^2	0.109 in^2	Pass
MAS	ASTM D570	Moisture Absorption Short Term	≤ 0.25 %	0.20 %	Pass
MAL		Moisture Absorption Long Term	≤ 1.00 %	0.73 %	Pass
BS	ASTM D7913	Guar. Bond Strength	>1100 psi	1359 psi	Pass
TEP	ASTM E2160	Degree of Cure	>95 %	99.6 %	Pass
		Glass Transition Temperature (DSC)	>100℃	138℃	Pass
Test Properties Post Alkaline Resistance per ASTM D7705, 90 days at 60℃					
ARL	ASTM D7205	Tensile Load Retention (with load)[1]	>70 %	78.3 %	Pass
TSS-AR	ASTM D7617	Trans. Shear Strength Retention	n/a	84.2 %	n/a
TEP-AR	ASTM E2160	Degree of Cure	>95 %	99.06 %	Pass
		Glass Transition Temperature (DSC)	>100℃	139℃	Pass

SAMPLE #4					
TSS	ASTM D7617	Guar. Transverse Shear Strength	>19 ksi	21.4 ksi	Pass
FC	ASTM D2584	Fiber Content (by weight)	>70%	83.3 %	Pass
TNS	ASTM D7205	Guar. Tensile Force	21.6 kip	26.3 kip	Pass
		Tensile Modulus of Elasticity	≥ 6.5 Msi	7.2 Msi	Pass
		Strain	≥ 1.1 %	1.9 %	Pass
MXA	ASTM D792	Measured Cross Sectional Area	0.185 in^2 to 0.263 in^2	0.207 in^2	Pass
MAS	ASTM D570	Moisture Absorption Short Term	≤ 0.25 %	0.21 %	Pass
MAL		Moisture Absorption Long Term	≤ 1.00 %	0.86 %	Pass
BS	ASTM D7913	Guar. Bond Strength	>1100 psi	1711psi	Pass
TEP	ASTM E2160	Degree of Cure	>95 %	99.2 %	Pass
		Glass Transition Temperature (DSC)	>100℃	133℃	Pass
SOB	ASTM D7914	Strength of Bend	> 60 %	165 %	Pass
Test Properties Post Alkaline Resistance per ASTM D7705, 90 days at 60℃					
ARL	ASTM D7705	Tensile Load Retention (with load)[1]	>70%	92.3 %	Pass
TSS-AR	ASTM D7617	Trans. Shear Strength Retention	n/a	107.6 %	n/a
TEP-AR	ASTM E2160	Degree of Cure	>95 %	99.4 %	Pass
		Glass Transition Temperature (DSC)	>100℃	128℃	Pass

n/a - not applicable
** Guaranteed values provided for reference purposes only based on smaller sample group*
[1] Note: this is not an ASTM specification requirement, the criteria is provided by FDOT Specification 932.

Test ID	Standard Test Method	Test Description	Spec. ASTM D7957	Test Value*	Test Result
SAMPLE #5					
TSS	ASTM D7617	Guar. Transverse Shear Strength	>19 ksi	21.0 ksi	Pass
FC	ASTM D2584	Fiber Content (by weight)	>70 %	79.8 %	Pass
TNS	ASTM D7205	Guar. Tensile Force	29.1 kip	33.1 kip	Pass
		Tensile Modulus of Elasticity	≥ 6.5 Msi	7.0 Msi	Pass
		Strain	≥ 1.1%	1.6 %	Pass
MXA	ASTM D792	Measured Cross Sectional Area	0.288 in^2 to 0.388 in^2	0.292 in^2	Pass
MAS	ASTM D570	Moisture Absorption Short Term	≤ 0.25 %	0.17 %	Pass
MAL		Moisture Absorption Long Term	≤ 1.00 %	0.67 %	Pass
BS	ASTM D7913	Guar. Bond Strength	>1100 psi	1227 psi	Pass
TEP	ASTM E2160	Degree of Cure	>95%	99.1 %	Pass
		Glass Transition Temperature (DSC)	>100℃	139℃	Pass
Test Properties Post Alkaline Resistance per ASTM D7705, 90 days at 60℃					
ARL	ASTM D7705	Tensile Load Retention (with load)[1]	>70 %	89.8 %	Pass
TSS-AR	ASTM D7617	Trans. Shear Strength Retention	n/a	106.2 %	n/a
TEP-AR	ASTM E2160	Degree of Cure	>95 %	99.1 %	Pass
		Glass Transition Temperature (DSC)	>100℃	139 ℃	Pass

n/a - not applicable

** Guaranteed values provided for reference purposes only based on smaller sample group*

[1] Note: this is not an ASTM specification requirement, the criteria is provided by FDOT Specification 932.

3. BENCHMARK TEST RESULTS

The test results presented herein provides the control (benchmark, un-aged) physio-mechanical properties for the samples under valuation. Specimens or sample test data is uniquely identified in the report using the following nomenclature: “XY-Z” where ‘X’ refers to the test ID as referenced in the first column of Section 2; ‘Y’ refers to the sample number as referenced in the first row of Section 2; and ‘Z’ is the test sample repetition number. Note dates referenced within this report use the mm/dd/yyyy format.

Guaranteed (Guar.) values are defined as the average experimental value minus three standard deviations, typically based on a minimum set of test results that includes three productions lots and eight test repetitions per lot, for a total of 24 data points (i.e. n=24). Guaranteed values are provided herein for reference purposes only based on the reported set of results (n=5).

3.1. TRANSVERSE SHEAR STRENGTH (TSS)

Test Standard Method: ASTM D7617, Standard test method for Transverse Shear Strength.
Test Description: Transverse Shear Strength
Technician/s: Guan Wang
Specimen Size: 12 in. length
Reference TDS: TDS-TSS-ASTM-D7617-OLIN-B
Test Data:

Bar Size	Specimen ID	Peak Load P^{max}		Nominal Area A_{nom}		Nominal Transverse Shear Strength τ_u		Failure Mode
		kN	lbs	mm²	in²	MPa	ksi	
#3	TSS3-01	24.75	5563	71.22	0.110	173.74	25.20	Shear Failure
	TSS3-02	28.12	6321			197.39	28.63	Shear Failure
	TSS3-03	25.44	5719			178.59	25.90	Shear Failure
	TSS3-04	27.86	6264			195.62	28.37	Shear Failure
	TSS3-05	22.99	5169			161.43	23.41	Shear Failure
	Average	**25.83**	**5807**			**181.35**	**26.30**	
	S_{n-1}	2.16	486			15.19	2.20	
	CV (%)	8.4	8.4			8.4	8.4	
	Guar. Value					**135.78**	**19.69**	
#4	TSS4-01	43.69	9822	126.45	0.196	306.74	25.06	Shear Failure
	TSS4-02	44.42	9987			311.88	25.48	Shear Failure
	TSS4-03	42.10	9465			295.58	24.14	Shear Failure
	TSS4-04	42.47	9547			298.15	24.36	Shear Failure
	TSS4-05	40.26	9050			282.62	23.09	Shear Failure
	Average	**42.59**	**9574**			**298.99**	**24.42**	
	S_{n-1}	1.60	360			11.25	0.92	
	CV (%)	3.8	3.8			3.8	3.8	
	Guar. Value					**265.24**	**21.67**	
#5	TSS5-01	64.22	14438	198.06	0.307	450.87	23.51	Shear Failure
	TSS5-02	64.22	14437			450.84	23.51	Shear Failure
	TSS5-03	69.53	15631			488.14	25.46	Shear Failure
	TSS5-04	63.09	14184			442.94	23.10	Shear Failure
	TSS5-05	68.35	15366			479.85	25.03	Shear Failure
	Average	**65.88**	**14811**			**462.53**	**24.12**	
	S_{n-1}	2.86	643			20.08	1.05	
	CV (%)	4.3	4.3			4.3	4.3	
	Guar. Value					**402.30**	**20.98**	

Test Results: Pass: T_u > 19 ksi (guaranteed value); > 22 ksi (typical for average value)

Test Setup:

Representative Failure Mode:

3.2. FIBER CONTENT (FC)

Test Standard Method: ASTM D2584-11, Standard Test Method for Ignition Loss of Cured Reinforced Resins
Test Description: Fiber content by weight
Technician/s: Roger Solis
Specimen Size: 25.0 mm (1.0 in.) long segment cut at different locations from the rebar
Reference TDS: TDS-FC-ASTM-D2584-OLIN-B
Test Data:

Nominal Rebar	Specimen ID	Weight of Crucible Wc g	Weight prior burnout Wi g	Weight post burnout Wf g	W1 (=Wc- Wi) g	W2 (=Wf- Wc) g	Fiber Content FC %
#3	FC3-01	37.799	41.596	40.831	3.797	3.032	79.85
	FC3-02	40.273	43.917	43.181	3.644	2.907	79.78
	FC3-03	39.663	43.450	42.696	3.787	3.033	80.09
	FC3-04	40.391	44.132	43.364	3.741	2.973	79.47
	FC3-05	39.628	43.368	42.635	3.740	3.007	80.40
						Average	**79.92**
						Sn-1	0.35
						CV (%)	0.44
#4	FC4-01	41.264	47.629	46.561	6.366	5.298	83.22
	FC4-02	42.438	48.668	47.611	6.230	5.172	83.02
	FC4-03	40.266	46.954	45.852	6.688	5.587	83.53
	FC4-04	40.540	47.472	46.314	6.932	5.774	83.29
	FC4-05	42.711	50.446	49.149	7.735	6.439	83.24
						Average	**83.26**
						Sn-1	0.18
						CV (%)	0.22
#5	FC5-01	40.385	49.704	47.768	9.319	7.383	79.23
	FC5-02	39.638	48.100	46.336	8.461	6.697	79.15
	FC5-03	40.272	49.858	48.013	9.586	7.741	80.75
	FC5-04	37.797	47.213	45.331	9.416	7.535	80.02
	FC5-05	40.246	49.552	47.679	9.306	7.433	79.87
						Average	**79.80**
						Sn-1	0.65
						CV (%)	0.82

Test Results: Pass: FC > 70% by weight

Test Setup up:

3.3. TENSILE PROPERTIES (TNS)

Test Standard Method: ASTM D7205 Standard test method for Tensile Properties of Fiber Reinforced Polymer Matrix Composite Bars
Test Description: Determine the ultimate tensile load carrying capacity, tensile modulus of elasticity and computed ultimate strain based on nominal area and an assumed linear elastic behavior
Technician/s: Guillermo Claure, and Roger Solis
Specimen Preparation: The specimens were cut to the prescribed dimensions. Steel pipe type anchors were installed as indicated in ASTM D7205 using expansive grout after machining the ends of the rebar as to center the bars in the anchors.
Reference TDS: TDS-TNS-ASTM-D7205-OLIN-B
Test Data:

Nominal Rebar	SPECIMEN ID	Peak Load P^{max}		Nominal Area A_{nom}		Nom. Tensile Strength F^{tu}_{nom}		Nom. Elastic Modulus E^*		Strain ε_u
		kN	**lbs**	**mm²**	**in²**	**MPa**	**ksi**	**GPa**	**Msi**	**%**
#3	TNS3-01	75.6	16987	71.22	0.110	1061	153.9	48.91	7.09	2.04
	TNS3-02	73.5	16532			1033	149.8	48.62	7.05	2.00
	TNS3-03	73.8	16583			1036	150.2	47.44	6.88	2.05
	TNS3-04	73.1	16439			1027	148.9	47.28	6.86	2.04
	TNS3-05	71.5	16079			1004	145.7	47.95	6.96	1.97
	Average	**73.5**	**16524**			**1032**	**149.7**	**48.04**	**6.97**	**2.02**
	S_{n-1}	1.4	325			20	2.9	0.71	0.1	0.0
	CV((%)	2.0	2.0			2.0	2.0	1.5	1.5	1.8
	Guar. value		**15548**							
#4	TNS4-01	126.5	28447	126.61	0.196	999	145.0	51.99	7.54	1.80
	TNS4-02	127.1	28566			1004	145.6	51.93	7.53	1.81
	TNS4-03	128.1	28804			1012	146.8	51.00	7.40	1.86
	TNS4-04	122.5	27534			967	140.3	44.80	6.50	2.02
	TNS4-05	122.3	27504			966	140.1	48.85	7.08	1.85
	Average	**125.3**	**28171**			**990**	**143.5**	**49.71**	**7.21**	**1.87**
	S_{n-1}	2.7	609			21	3.1	3.03	0.4	0.1
	CV((%)	2.2	2.2			2.2	2.2	6.1	6.1	4.7
	Guar. value		**26345**							
#5	TNS5-01	172.1	38694	197.83	0.307	870	126.2	51.05	7.40	1.53
	TNS5-02	158.5	35624			801	116.2	46.47	6.74	1.53
	TNS5-03	159.2	35792			805	116.7	47.82	6.94	1.50
	TNS5-04	166.9	37514			844	122.3	47.46	6.88	1.59
	TNS5-05	167.4	37643			846	122.8	46.95	6.81	1.61
	Average	**164.8**	**37054**			**833**	**120.8**	**47.95**	**6.95**	**1.55**
	S_{n-1}	5.8	1312			30	4.3	1.81	0.3	0.0
	CV((%)	3.5	3.5			3.5	3.5	3.8	3.8	3.1
	Guar. value		**33117**							

Test Results: PASS: Refer to summary table Section 2.0

Test Setup & Representative Failure Mode:

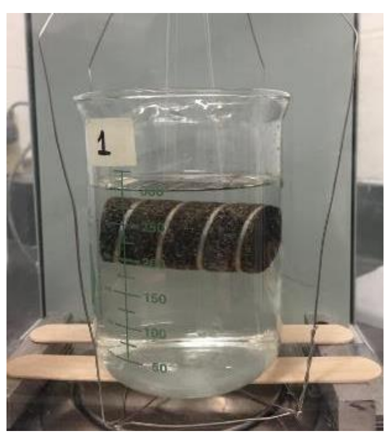
3.4. CROSS-SECTIONAL AREA (MXA)

Test Standard Method: ASTM D7205 Standard test method for Tensile Properties of Fiber Reinforced Polymer Matrix Composite Bars. ASTM D792 Standard Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement.
Test Description: Measurement of cross-sectional area by volume of water displacement method.
Technician/s: Guillermo Claure, and Roger Solis.
Specimen Size: Specimen length dimensions were 50 mm (2.0 in.).
Reference TDS: Technical Data Sheet: TDS-MXA-ASTM-D792-OLIN-B
Test Data:

Nominal Rebar	Specimen ID	W_{wet} g	$L_{Ave.}$ in.	$L_{Ave.}$ mm	ΔW g	Volume mm^3	Measured Area mm^2	Measured Area in^2
#3	MXA3-01	3.686	2.023	51.372	3.443	3453.39	67.22	0.104
	MXA3-02	3.365	1.953	49.610	3.545	3555.70	71.67	0.111
	MXA3-03	3.443	1.991	50.567	3.661	3671.74	72.61	0.113
	MXA3-04	3.556	2.048	52.028	3.656	3667.13	70.48	0.109
	MXA3-05	3.282	1.950	49.526	3.478	3488.10	70.43	0.109
						Average	**70.48**	**0.109**
						Sn-1	2.04	0.003
						CV (%)	2.89	2.89
#4	MXA4-01	5.868	1.881	47.773	6.232	6250.15	130.83	0.203
	MXA4-02	6.356	2.037	51.736	6.853	6873.46	132.86	0.206
	MXA4-03	5.914	1.864	47.341	6.325	6343.33	133.99	0.208
	MXA4-04	6.086	1.894	48.099	6.525	6544.62	136.07	0.211
	MXA4-05	6.259	1.974	50.127	6.698	6717.73	134.01	0.208
						Average	**133.55**	**0.207**
						Sn-1	1.91	0.003
						CV (%)	1.43	1.43
#5	MXA5-01	9.342	1.983	50.368	9.338	9365.65	185.94	0.288
	MXA5-02	9.094	1.910	48.522	9.196	9222.83	190.07	0.295
	MXA5-03	9.242	1.962	49.826	9.522	9550.19	191.67	0.297
	MXA5-04	9.049	1.985	50.415	9.282	9309.68	184.66	0.286
	MXA5-05	9.348	2.018	51.245	9.619	9647.48	188.26	0.292
						Average	**188.12**	**0.292**
						Sn-1	2.88	0.004
						CV (%)	1.53	1.53

Test Result: PASS: Measured Cross-Sectional Area Limits is as follow for each rebar size
#3 - 0.104 in^2 to 0.161 in^2;
#4 - 0.185 in^2 to 0.263 in^2;
#5 - 0.288 in^2 to 0.388 in^2

Test Setup:



3.5. WATER ABSORPTION (MA)

Test Standard Method: ASTM D570, Standard Test Method for Water Absorption of Plastics. ASTM D5229D/D229M - 12, Standard Test Method for Moisture Absorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials (Procedure B). ASTM D7957/D7957M – 17, Standard Specification for Solid Round Glass Fiber Reinforced Polymer Bars for Concrete Reinforcement.

Test Description: Short term (24hr) level of moisture absorption when immersed in distilled water at 50ºC temperature. Long term (Saturation) level of moisture absorption when immersed in distilled water at 50oC temperature.

Technician/s: Guillermo Claure, and Roger Solis.

Specimen Size: 25.0 mm (1.0 in.) long segment cut at different locations from the rebar.

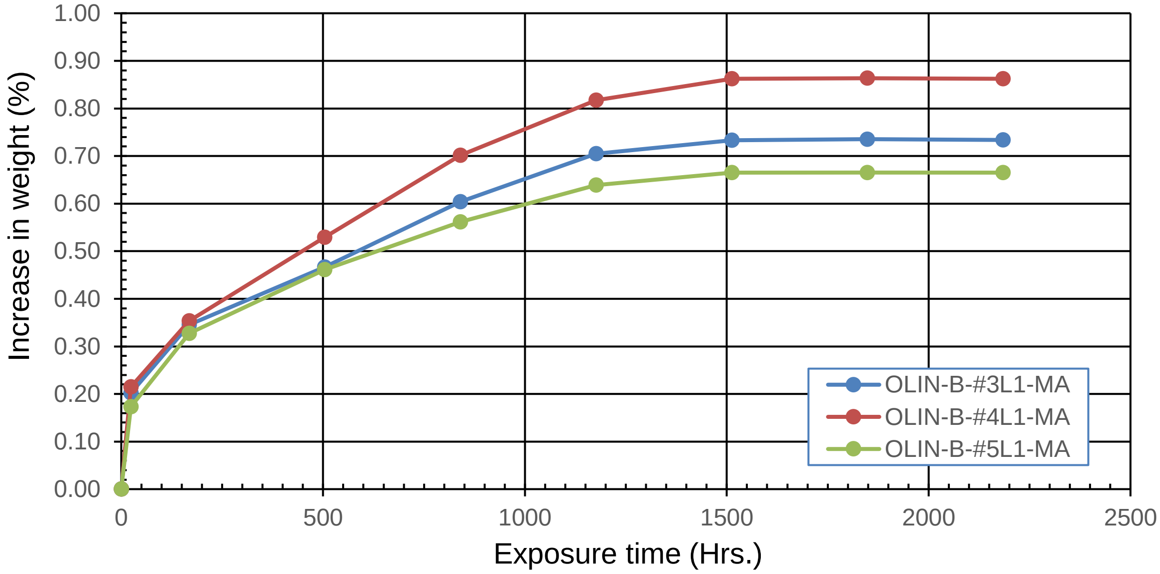
Reference TDS: TDS-MA-ASTM-D570-OLIN-B

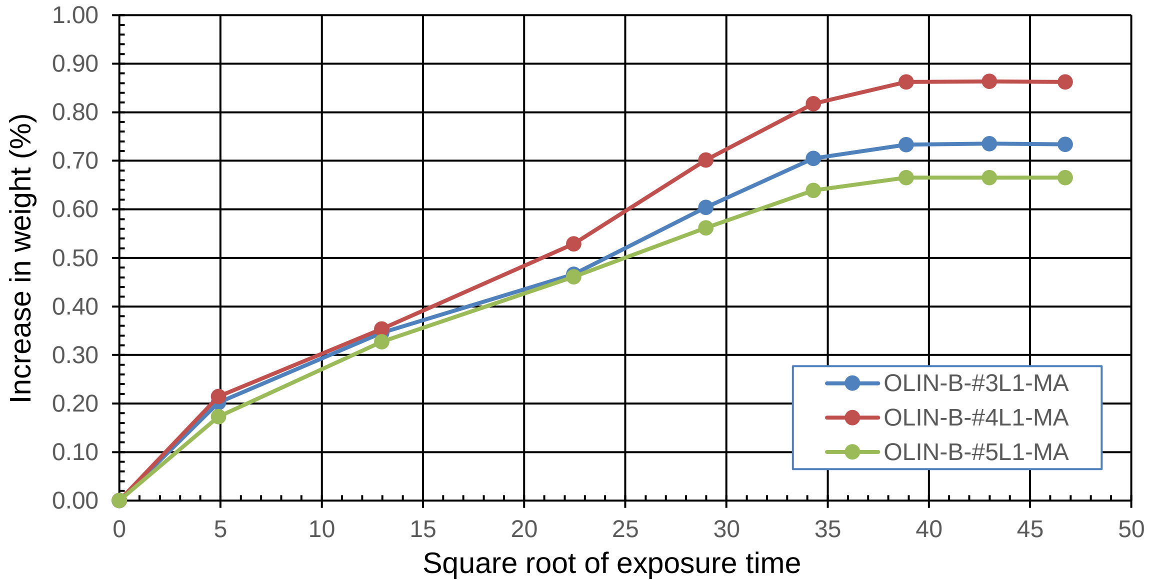
Test Data:

Nominal Rebar Denominatio n	**Specimen ID**	**W_i**	**W_{24}**	**Short term immersion (24 hrs.) W_{24}**	**W_S**	**Long term immersion (13 weeks) W_S**
		g	**g**	**%**	**g**	**%**
#3	MA3-01	3.8805	3.8881	0.20	3.9054	0.64
	MA3-02	3.6374	3.6447	0.20	3.6639	0.73
	MA3-03	3.7608	3.7690	0.22	3.7851	0.65
	MA3-04	3.7045	3.7124	0.21	3.7373	0.89
	MA3-05	3.5839	3.5904	0.18	3.6114	0.77
	Average			**0.20**		**0.73**
	S_{n-1}			0.01		0.10
	CV (%)			7.22		13.7
#4	MA4-01	6.1986	6.2120	0.22	6.2570	0.94
	MA4-02	6.8895	6.9039	0.21	6.9421	0.76
	MA4-03	7.0581	7.0723	0.20	7.1163	0.82
	MA4-04	6.8941	6.9103	0.23	6.9564	0.90
	MA4-05	6.3813	6.3948	0.21	6.4374	0.88
	Average			**0.21**		**0.86**
	S_{n-1}			0.01		0.07
	CV (%)			5.9		8.1
#5	MA5-01	8.4651	8.4808	0.19	8.5261	0.72
	MA5-02	9.6544	9.6694	0.16	9.7182	0.66
	MA5-03	9.1223	9.1400	0.19	9.1870	0.71
	MA5-04	9.3691	9.3830	0.15	9.4221	0.57
	MA5-05	9.9416	9.9597	0.18	10.0081	0.67
	Average			**0.17**		**0.67**
	S_{n-1}			0.02		0.07
	CV (%)			11.5		9.2

Test Result: PASS: W_{24} < 0.25%; PASS: W_S < 1.00%

Graphical Representation of Result:





Test Setup:

3.6. BOND STRENGTH TO CONCRETE (BS)

Test Standard Method: ASTM D7913, Standard Test Method for Transverse Shear Strength of Fiber-reinforced Polymer Matrix Composite Bars.

Test Description: Test to determine the bond strength for a rebar size under evaluation by pullout test method.

Technician/s: Guillermo Claure, and Roger Solis.

Specimen Size: After applying a steel anchor pipe to one end, the re-bar specimens were installed within solid plain concrete 205 mm (8.00 in.) cubes in the other end with a de-bonded length to the concrete so that the total bonded length to concrete was equivalent to five times the diameter of the re-bar.

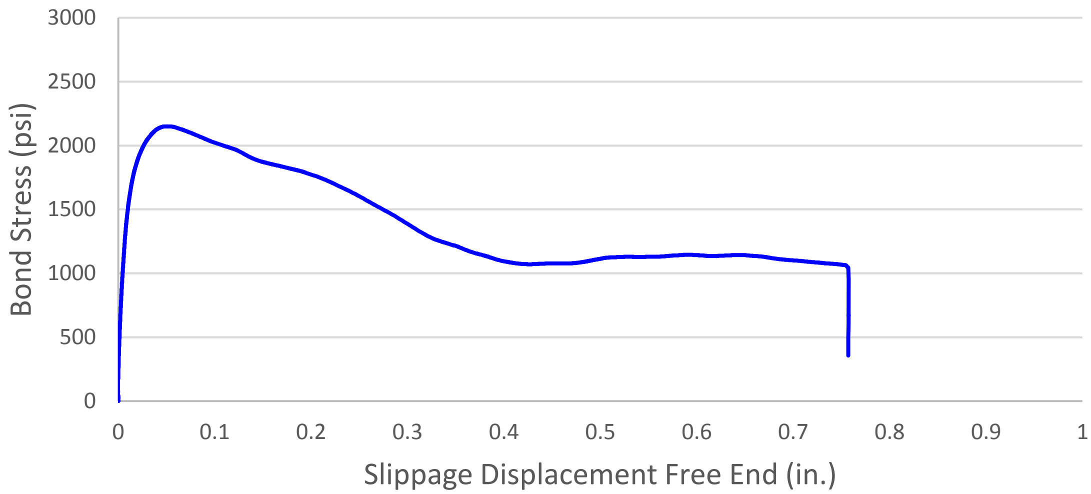
Reference TDS: TDS-BS-ASTM-D7913-OLIN-B

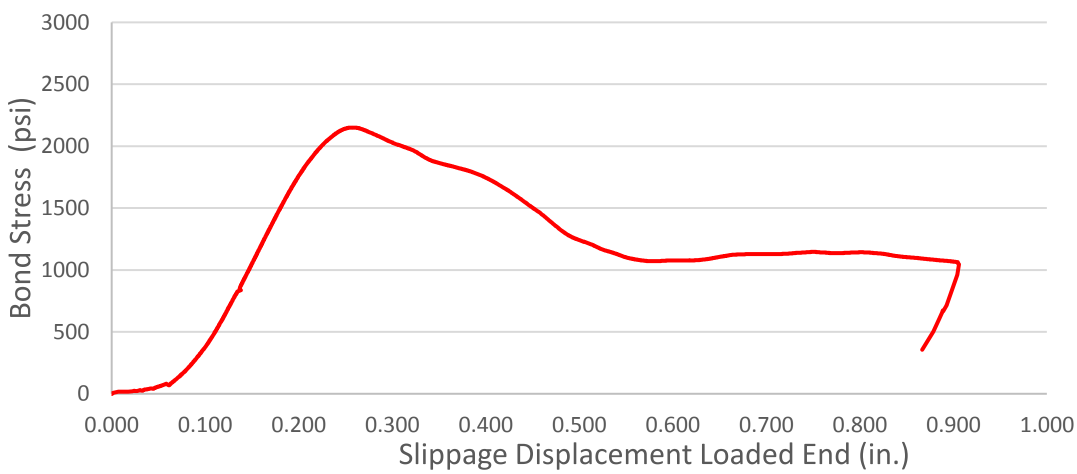
Test Data:

Nominal Rebar	SPECIMEN ID	Peak Load P_{max} Lbs	Maximum Bond Strength τ psi
#3	BS3-01	4034	1826
	BS3-02	3585	1623
	BS3-03	4406	1995
	BS3-04	3834	1735
	BS3-05	3796	1719
	Average	**3931**	**1780**
	S_{n-3}	310	140
	CV (%)	7.9	7.9
	Guaranteed Value		**1359**
#4	BS4-01	9009	2294
	BS4-02	9812	2499
	BS4-03	7980	2032
	BS4-04	8480	2159
	BS4-05	8595	2189
	Average	**8775**	**2235**
	S_{n-3}	686	175
	CV (%)	7.8	7.8
	Guaranteed Value		**1711**
#5	BS5-01	12119	1975
	BS5-02	9266	1510
	BS5-03	11444	1865
	BS5-04	12233	1994
	BS5-05	10773	1756
	Average	**11167**	**1820**
	S_{n-3}	1214	198
	CV (%)	10.9	10.9
	Guaranteed Value		**1227**

Test Results: Pass τ > 1100 psi (guaranteed value); > 1400 psi (typical for average value)

Graphical Representation of Results: (Representative specimen)





Test Setup:

Representative Failure Mode: Slippage/sliding

3.7. TOTAL ENTHALPY OF POLYMERIZATION (TEP)

Test Standard Method: ASTM E2160, Standard test method for heat of reaction of thermally reactive materials by differential scanning calorimetry (DSC).
ASTM E1356, Standard test method for assignment of the glass transition temperatures by differential scanning calorimetry.

Test Description: Degree of cure as a reference value and corresponding glass transition temperature by DSC. The exothermic heat flow produced by the reaction is recorded as a function of temperature and time by a differential scanning calorimeter. Integration of the exothermic heat flow over time yields the heat of reaction.

Technician/s: Guillermo Claure

Specimen Size: 5.0 ±0.5 mg and /or 2-mm thick specimen is cut/extracted from the geometrical center of the rebar sample.

Reference TDS: TDS-TPE-ASTM-E2160-OLIN-B

Test Data:

Nominal Rebar	**Specimen ID**	**Normalized heat of reaction**	**Onset Temperature**		**First deviation Temperature**		**Degree of Cure**	**Glass Transition Temperature**	
		H	**T_o**		**T_f**		**DC**	**T_g**	
		J/g	**°C**	**°F**	**°C**	**°F**	**%**	**°C**	**°F**
#3	TEP3-01	0.4802	91	196	122	252	99.52	138	281
	TEP3-02	0.3796	98	208	119	246	99.62	136	276
	TEP3-03	0.4661	82	179	118	244	99.53	138	280
	TEP3-04	0.3893	97	207	131	268	99.61	142	288
	TEP3-05	0.4566	78	173	110	229	99.54	134	273
	Average						**99.57**	**138**	**280**
	Stand. Dev.						0.05	3.0	5.4
	COV (%)						0.0	2.2	1.9
#4	TEP4-01	0.4598	71	160	117	242	99.54	134	273
	TEP4-02	0.8129	63	145	114	237	99.19	136	278
	TEP4-03	0.8200	65	150	108	226	99.18	132	270
	TEP4-04	0.5663	63	146	115	238	99.43	128	262
	TEP4-05	1.5170	68	155	117	242	98.48	132	270
	Average						**99.16**	**133**	**271**
	Stand. Dev.						0.41	3.2	5.7
	COV (%)						0.4	2.4	2.1
#5	TEP5-01	0.7658	83	182	126	259	99.23	141	286
	TEP5-02	0.7755	74	165	118	244	99.22	139	282
	TEP5-03	1.1830	60	140	113	235	98.82	137	279
	TEP5-04	1.0880	60	140	112	234	98.91	140	284
	TEP5-05	0.9202	63	145	112	234	99.08	139	282
	Average						**99.05**	**139**	**283**
	Stand. Dev.						0.19	1.4	2.5
	COV (%)						0.2	1.0	0.9

Test Result: Pass DC > 95%; T_g > 100°C

Test Setup:

3.8. SCANNING ELECTRON MICROSCOPY IMAGING (SEM)

Test Method: Imaging to observe microscopic features of the cross-section of the bars up to 50 nm in size accomplished with SEM.

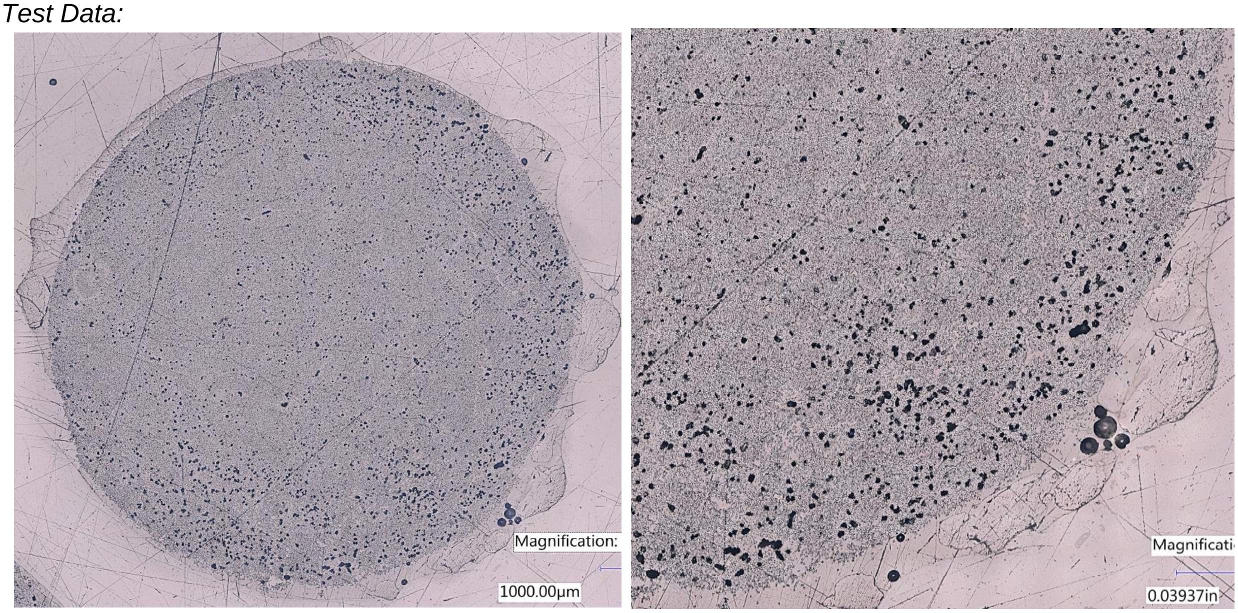
Test Description: SEM is used to qualitatively evaluate the cross-section and determine the 'finger-print' for the manufactured rebar, the void and fiber dispersion, cross-sectional pattern of manufactured product can be parametrically measured.

Technician/s: Guillermo Claure and Guan Wang

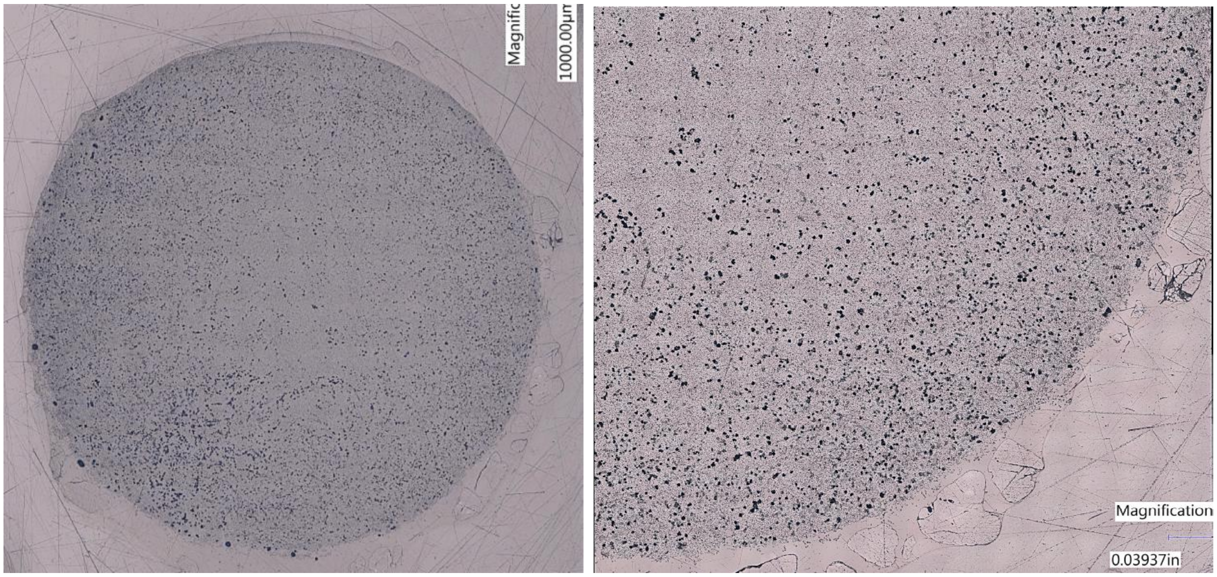
Specimen Preparation: The specimens included acquisition of a sample that will fit into the SEM chamber and some accommodation to prevent charge build-up on electrically insulating samples. Electrically insulating samples were coated with a thin layer of conducting material, commonly metal/alloy. Metal coatings are most effective for high resolution electron imaging applications.

Reference TDS: TDS-SEM-OLIN-B

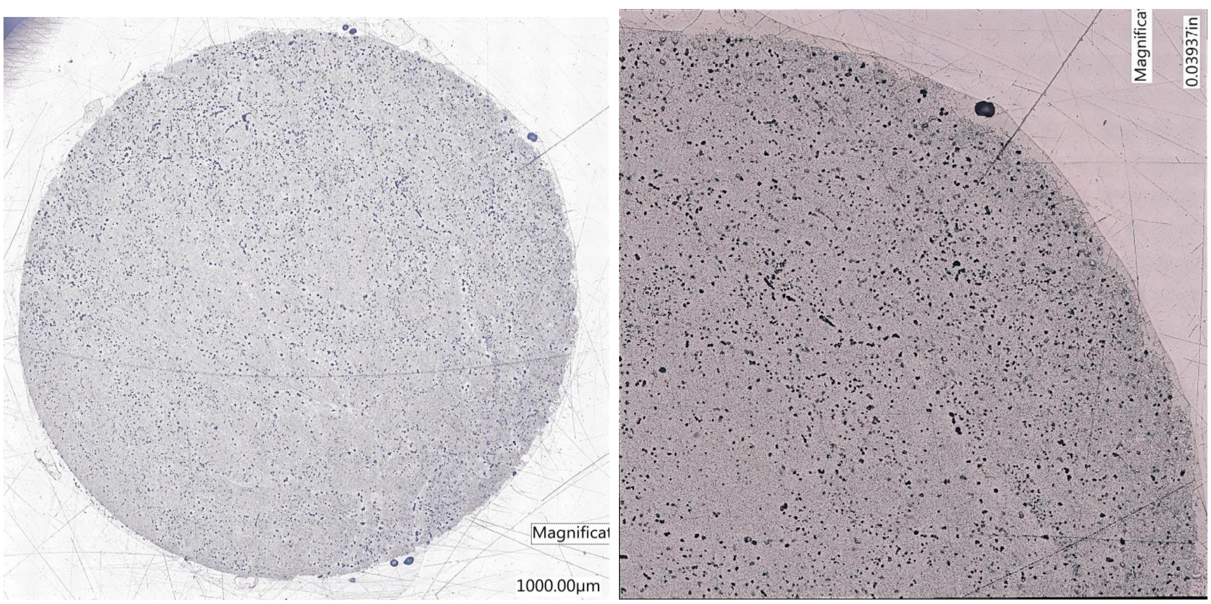
Test Data:



Representative SEM image #3 rebar



Representative SEM image #4 rebar



Representative SEM image #5 rebar

3.9. STRENGTH OF BEND TESTS (SOB)

Test Method: ASTM D7914, Standard Test Method for Strength of Fiber Reinforced Polymer (FRP) Bent Bars in Bend Locations.

Test Description: Test to determine the strength of the bend bar (90° bend) and compare to the strength (longitudinal rebar).

Technician/s: Phil Lavonas

Specimen Preparation: The specimens were composed of a closed or continuous stirrup (hoop), where manufacturing was via a “layer wound” method with the same heat cure as the continuous straight (longitudinal) basalt fiber reinforced epoxy / anhydride formulation.

Reference TDS: TDS-SOB-OLIN-B

Test Data:

Bar Size	**Specimen ID**	**Total Max force F_{ub}**		**Nominal Area A_{nom}**		**Nominal Bend Capacity of FRP stirrup f^{ub}_{nom}**		**$\chi_{spec.}$ ($F^{ub}/2/0.6*P_{guar.}$)**
		kN	**lbs**	**mm²**	**in²**	**Mpa**	**ksi**	
	SOB4-01	193.9	43600			1362	197.5	1.68
	SOB4-02	175.3	39400			1230	178.5	1.52
4	SOB4-03	175.7	39500	71.22	0.110	1234	178.9	1.52
	SOB4-04	224.2	50400			1574	228.3	1.94
	SOB4-05	181.5	40800			1274	184.8	1.57
	Average	**190.1**	**42740**			**1335**	**193.6**	**1.65**
	S_{n-1}	20.5	4605			144	20.9	0.18
	CV (%)	10.8	10.8			10.8	10.8	10.8

Test Results: Pass: $\chi_{spec.}$ > 1.0 (guaranteed value)
Reference values: $P_{guar.}$ = 12,960 lbs (57.6 kN), corresponding to 60% of the minimum guaranteed ultimate tensile force per ASTM D7957 Table 3.

Test Setup:

4. DURABILTY RESULTS - POST ALKALINE EXPOSURE

The test results presented herein provides the aged physio-mechanical properties of samples under evaluation post standard accelerated alkaline conditioning exposure. Accelerating condition protocol consisted in the submersion of samples in an aqueous alkaline solution with a pH value to 12.6 to 13.0, as measured by ASTM E70, (Standard Test Method for pH of Aqueous Solutions with the Glass Electrode). The alkaline solution was set to a constant temperature of 60 ± 3°C (140 ± 5°F) for a period of 90 days (2160 hrs.). This solution reproduces the concrete alkalinity, while the high temperature aims at accelerating any potential degradation mechanisms that may occur in the composite rebars.

After exposure, a visual inspection was conducted immediately after the removal of the specimens from the alkaline resistance chamber. Prior to physical and mechanical testing, a recovery period long enough so that the samples reached moisture equilibrium with laboratory testing conditions was established (minimum 72 hours). Samples were then prepared and tested in accordance to each standard test method of reference.

4.1. TENSILE PROPERTIES WITH LOAD (TNS-ARL)

Test Standard Method: ASTM D7705, Standard test method for Alkali Resistance of Fiber Reinforced Polymer (FRP) Matrix Composite Bars used in Concrete Construction, Procedure B. ASTM D7205, Standard test method for Tensile Properties of Fiber Reinforced Polymer Matrix Composite Bars.

Test Description: Determine the tensile capacity retention of the products under evaluation, after exposure with and with load to an aqueous alkaline environment intend to represent concrete pore water.

Technician/s: Guillermo Claure, Guan Wang and Roger Solis

Specimen Preparation: The specimens were prepared following ASTM D7205 by which steel pipe type anchors were installed using expansive grout after machining the ends of the rebar as to center the bars in the anchors. Aging chambers were attached to each specimen where the alkaline solution was set to have a constant temperature of 60 ± 3°C (140 ± 5°F) for a period of 90 days (2160 hrs.) and a sustained load equivalent to 3000 micro-strain was individually applied to each specimen.

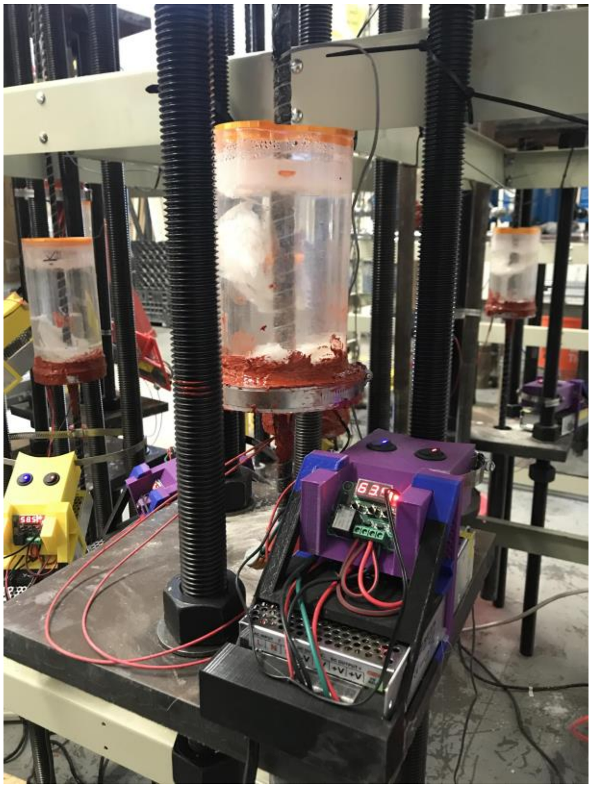
Reference TDS: TDS-TNS-ARL-ASTM-D7705-OLIN-B

Test Data:

Nominal Rebar	SPECIMEN ID	Benchmark Load P_{max} lbs	Peak Load Post-exposure P_{max} lbs	Modulus of Elasticity E Msi	Strain ε_u %	Tensile Load Retention %
#3	TNS_ARL3-01	16524	13790	8.83	1.42	83.5
	TNS_ARL3-02		13441	8.38	1.46	81.3
	TNS_ARL3-03		11567	5.36	1.96	70.0
	Average		**12196**	**7.52**	**1.61**	**78.3**
	S_{n-3}		1767	1.89	0.30	
	CV (%)		14.5	25.1	18.8	
#4	TNS_ARL4-01	28171	24513	6.39	1.96	87.0
	TNS_ARL4-02		26629	7.88	1.72	94.5
	TNS_ARL4-03		12652	7.38	1.86	95.4
	Average		**22668**	**7.21**	**1.85**	**92.3**
	S_{n-3}		6761	0.76	0.12	
	CV (%)		29.8	10.5	6.4	
#5	TNS_ARL5-01	37054	34217	7.64	1.46	92.3
	TNS_ARL5-02		28256	6.48	1.42	76.3
	TNS_ARL5-03		14620	6.63	1.83	100.7
	Average		**28598**	**6.92**	**1.57**	**89.8**
	S_{n-3}		10046	0.63	0.23	
	CV (%)		35.1	9.2	14.5	

Test Results: Pass: Tensile load retention > 70%

Test Setup:



Representative Failure Mode:


Olin-B-ARL-#4_004

4.2. TRANSVERSE SHEAR STRENGTH (TSS-AR)

Test Standard Method: ASTM D7617, Standard test method for Transverse Shear Strength. ASTM D7705, Standard test method for Alkali Resistance of Fiber Reinforced Polymer (FRP) Matrix Composite Bars used in Concrete Construction.
Test Description: Transverse Shear Strength
Technician/s: Guillermo Claure, Guan Wang and Roger Solis
Specimen Preparation: The specimens were cut to the prescribed dimensions with ends sealed with epoxy coating. Conditioning/exposure as referenced in section 4. After exposure, test specimens were cut to test size per standard test method of reference.
Reference TDS: Technical Data Sheet: TDS-TSS-AR-ASTM-D7617-OLIN-B
Test Data:

Nominal Rebar	Specimen ID	Peak Load P_{max} lbs	Transverse Shear Strength τ_u ksi	Reference Transverse Shear Strength ksi	Transverse Shear Strength Retention R %
#3	TSS_AR3-01	4742	21.48	26.30	81.66
	TSS_AR3-02	5081	23.02		87.50
	TSS_AR3-03	4779	21.65		82.30
	TSS_AR3-04	5074	22.98		87.38
	TSS_AR3-05	4776	21.63		82.25
	Average	**4891**	**22.15**		**84.22**
	S_{n-1}	171	0.78		2.95
	CV (%)	3.5	3.5		3.5
#4	TSS_AR4-01	10899	49.37	43.37	113.84
	TSS_AR4-02	9918	44.92		103.59
	TSS_AR4-03	11143	50.47		116.38
	TSS_AR4-04	10227	46.32		106.82
	TSS_AR4-05	9310	42.17		97.24
	Average	**10299**	**46.65**		**107.57**
	S_{n-1}	742	3.36		7.75
	CV (%)	7.2	7.2		7.2
#5	TSS_AR5-01	15433	69.90	67.08	104.20
	TSS_AR5-02	14736	66.75		99.50
	TSS_AR5-03	15868	71.87		107.13
	TSS_AR5-04	17077	77.35		115.30
	TSS_AR5-05	15514	70.27		104.74
	Average	**15725**	**71.23**		**106.17**
	S_{n-1}	860	3.89		5.80
	CV (%)	5.5	5.5		5.5

Test Results: Not applicable.

Test Setup:

Representative Failure Mode:

4.3. TOTAL ENTHALPY OF POLYMERIZATION (TEP-AR)

Test Standard Method: ASTM E2160, Standard test method for heat of reaction of thermally reactive materials by differential scanning calorimetry.
ASTM E1356, Standard test method for assignment of the glass transition temperatures by differential scanning calorimetry

Test Description: Degree of cure as a reference value.

Technician/s: Francisco De Caso

Specimen Size: 5.0 ±0.5 mg and /or 2-mm thick specimen is cut/extracted from the geometrical center of the rebar sample. Conditioning/exposure as referenced in section 4. After exposure, test specimens were cut to test size per standard test method of reference.

Reference TDS: TDS-TEP-AR-ASTM-E2160-OLIN-B

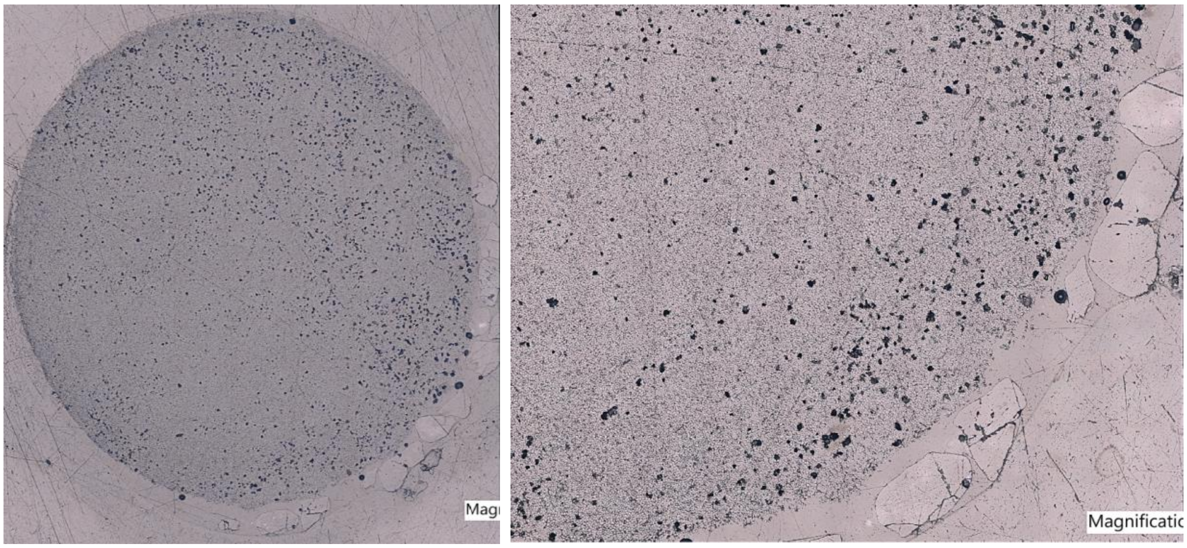
Test Data:

	Specimen ID	Normalized heat of reaction	Onset Temperature		First deviation Temperature		Degree of Cure	Glass Transition Temperature		Ref.	Degree of Cure Retention	Ref.		Glass Transition Temperature Retention
		H	To		Tf		DC	Tg		DC	R	Tg		R
		J/g	°C	°F	°C	°F	%	°C	°F	%	%	°C	°F	%
#3	TEP_AR3-01	1.2680	75	166	112	233	98.73	141	285		99.16			102.15
	TEP_AR3-02	0.7961	65	150	102	216	99.20	136	277		99.64			98.89
	TEP_AR3-03	0.4838	84	183	112	233	99.52	140	285	99.57	99.95	138	280	102.13
	TEP_AR3-04	1.1940	79	173	114	237	98.81	138	281		99.24			100.48
	TEP_AR3-05	0.9524	57	135	94	201	99.05	138	280		99.48			100.33
	Average						**99.06**	**139**	**282**		**99.49**			**100.80**
	Stand. Dev.						0.32	1.9	3.4		0.32			1.38
	COV (%)						0.3	1.4	1.2		0.3			1.4
#4	TEP_AR4-01	0.4241	65	149	91	196	99.58	127	261		100.41			96.02
	TEP_AR4-02	0.7569	60	140	97	206	99.24	129	264		100.08			97.31
	TEP_AR4-03	0.7875	60	140	94	201	99.21	127	261	99.16	100.05	133	271	95.91
	TEP_AR4-04	0.5448	62	143	98	208	99.46	128	263		100.29			96.88
	TEP_AR4-05	0.6089	62	144	95	203	99.39	127	261		100.23			96.06
	Average						**99.38**	**128**	**262**		**100.21**			**96.44**
	Stand. Dev.						0.15	0.8	1.5		0.15			0.62
	COV (%)						0.2	0.6	0.6		0.2			0.6
#5	TEP_AR5-01	0.6060	78	172	117	243	99.39	138	280		100.16			99.08
	TEP_AR5-02	0.8392	82	179	124	255	99.16	140	284		99.93			100.66
	TEP_AR5-03	0.6889	84	184	119	246	99.31	139	282	99.05	100.08	139	283	99.85
	TEP_AR5-04	0.8398	78	173	119	246	99.16	140	283		99.93			100.52
	TEP_AR5-05	0.6618	78	173	117	243	99.34	137	278		100.10			98.24
	Average						**99.27**	**139**	**281**		**100.04**			**99.67**
	Stand. Dev.						0.11	1.4	2.5		0.11			1.01
	COV (%)						0.1	1.0	0.9		0.1			1.0

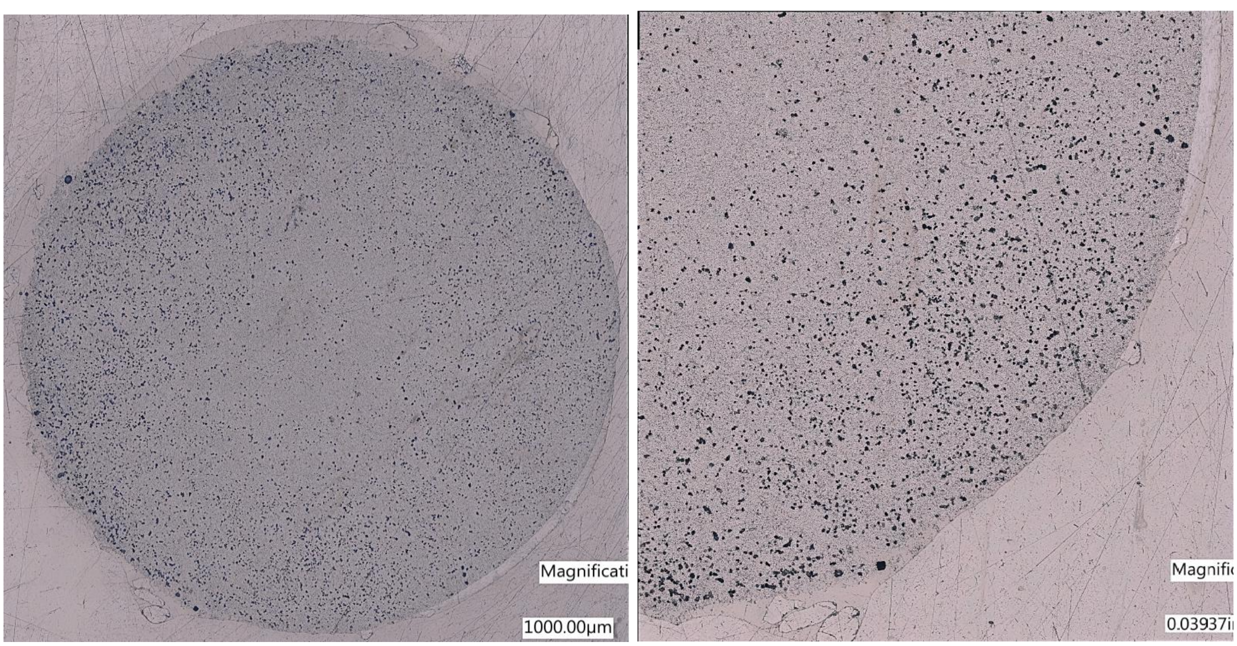
Test Result: *Pass DC > 95%; Tg > 100°C*

4.4. SCANNING ELECTRON MICROSCOPY IMAGING (SEM-AR)

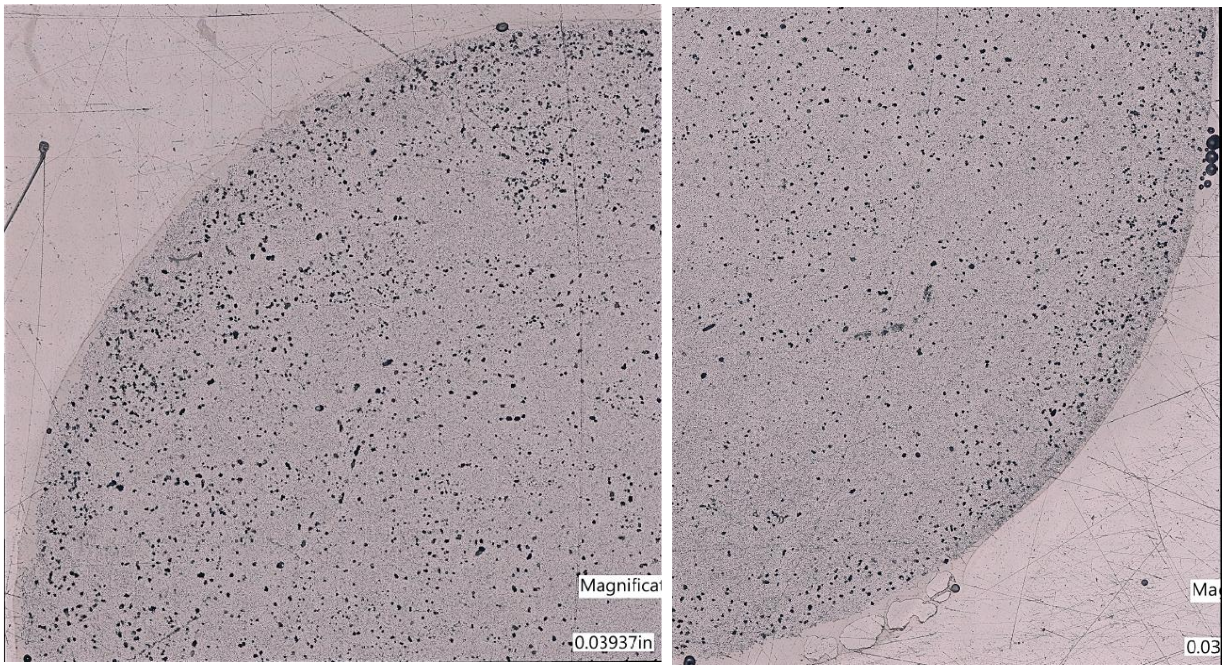
Test Method:	Refer to Section 3.9.
Test Description:	Refer to Section 3.9.
Technician/s:	Guillermo Claure, and Guan Wang
Specimen Preparation:	Refer to Section 3.9. Conditioning/exposure as referenced in section 4.
Reference TDS:	Technical Data Sheet: TDS-SEM-AR-OLIN-B
Test Data:	No visible degradation in the core of specimen.



Representative SEM image #3 post exposure



Representative SEM image #4 post exposure



Representative SEM image #5 post exposure

5. DISCUSSION

In the following section, the test results reported in section 4 are briefly reviewed and commented in terms of relevance, meaningfulness and context when compared to typical comparable results of GFRP with vinyl ester matrix.

5.1. BENCHMARK TESTS

- Transverse Shear Strength (ASTM D7617):
  The perpendicular shear strength is a property directly associate with the fibers of a composite rebar. Although this value is not typically used for design purposes of reinforced concrete elements with composite rebars, it is a fundamental physio-mechanical property to verify minimum transverse shear strength; given that the innate properties of fibers used in composite rebar/strands (basalt, glass and carbon) has a relatively low transverse shear strength. The experimental results provided here in show an increasing transverse shear load resistance with increase in bar size (i.e. area), which is expected. The experimental results of the BFRP are well above the typical minimum expected experiential magnitudes (> 22 ksi) and when compared to GFRP are within typical ranges (22 to 30 ksi). The results exceed the minimum guaranteed values even for the small sample group (> 19 ksi).

- Fiber Content (ASTM D2584):
  The fiber content test serves two general purposes, on the one hand it serves to filter manufactured rebars that are below the 70% requirement and thus may not meet other mechanical properties; on the other, that minimum fiber content requirement translates indirectly to the need to ensure adequate rebar manufacturing process in terms of fiber wettability, wet resin properties and overall fiber positioning. Overall the experiential results of the BFRP rebar are in the upper range of fiber content when compared to other composite GFRP rebars, with a typically range of 70-78%, and #4 is significantly higher. The results exceed the minimum requirement of 70% fiber content by weight.

- Tensile Properties (ASTM D7205):
  The values from the tensile properties test are the primary design material values and are associated primarily to the fiber properties as well as to the effectiveness of load transfer between the resin/fiber layers. The values are directly used and specified in reinforced concrete structures with composite rebars. The results are computed based on nominal area per specifications. The minimum guaranteed ultimate tensile load (strength) results in a significantly higher value than required specification as summarized in Section 2, even for the small sample group. The corresponding modulus of elasticity (a measure of stiffness of the composite rebar) results in a value 7 to 10% higher than the minimum required, and the computed ultimate strain exceeds the minimum requirement of 1.1%, of values in the range of other available GFPR rebars.

- Cross-Sectional Area (ASTM D7205/D792):
  The cross-sectional area is a critical value of composite rebars to ensure that when detailing reinforced concrete elements, proper relationships are maintained that are a function of dimeter (i.e. area) such as: cover, spacing, aggregate size, position of rebar in element…etc. The results for the BFRP rebars are within the lower range of the specified cross-sectional area range and approximate the nominal area, and are lower when compared to other available GFRP rebars that are in the upper range.

- Water Absorption (ASTM D570):

  Moisture or water absorption can be considered as an indirect measure of durability of the composite rebar, where a high level of voids or other absorbent constituent materials, where water can be absorbed may result in lower durability. Although limited research is found to determine how the magnitude of voids in composite rebars can affect the durability of the rebar, a long term moisture intake (saturation) of more than 1%, and a short term (24 hrs.) absorption of 0.25% are not acceptable. Additionally, this parameter can be qualitatively compared and correlated with the cross-sectional structural of the composite rebar as seen by the scanning electron microscopy (SEM) imaging (refer to Section 3.8). The results of the BFRP rebars are well within the specifications and are relatively lower or equivalent when compared to other GFRP rebars.

- Bond Strength to Concrete (ASTM D7913):

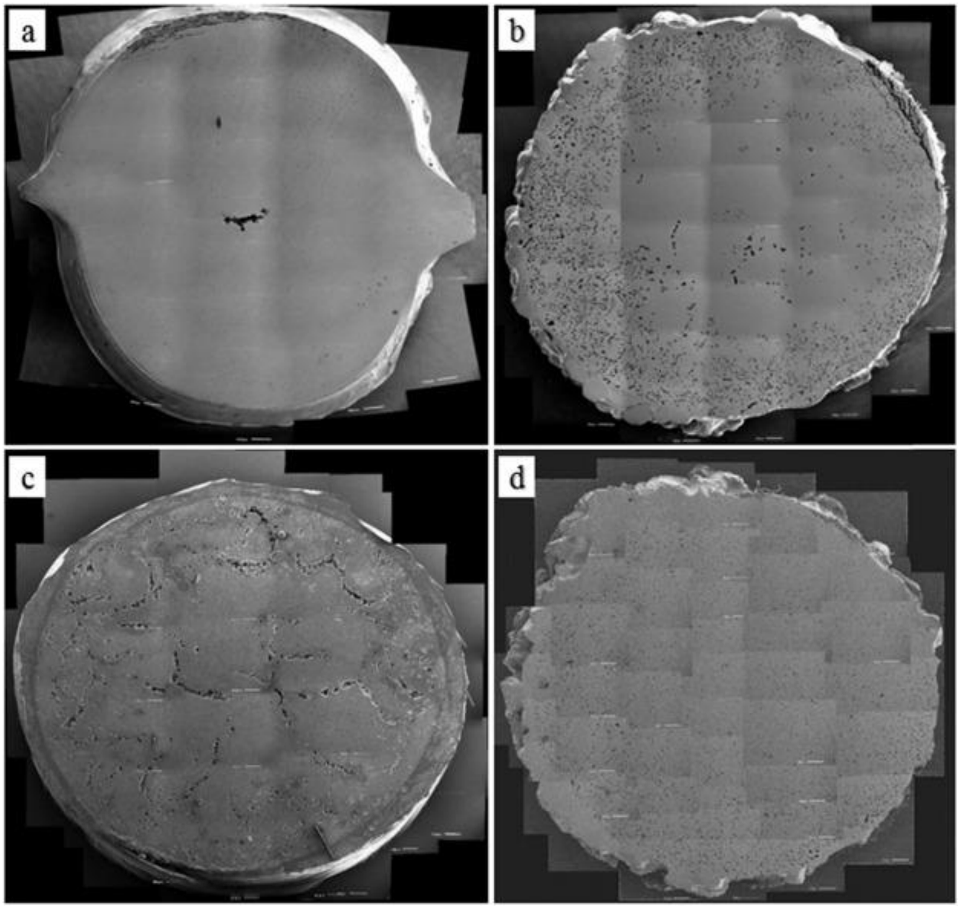
  Bond strength is critical to ensure the proper transfer of load from the concrete to the rebar. Inadequate bond strength to concrete may result in an ineffective reinforced concrete action. This is a pass/fail test that must have adequate slippage failure mode of the concrete block. Too high of a bond strength may result in splitting of the block, caused by high tensile stress applied to the concrete block and an inacceptable mode of failure. Too low of a bond strength (< 1100 psi guaranteed or < 1400 psi typical average value) will not meet the specifications. The BFRP rebar results in an appropriate bond strength and failure mode, even for the small sample group.

- Total Enthalpy of Polymerization (ASTM E2160) and Glass Transition Temperature (ASTM E1356):

  The total enthalpy of polymerization is a measure of the degree of cure that resin matrix of the composite rebar has reaching during manufacturing, and thus is an indirect parameter to ensure adequate rebar manufacturing process. Ensuring maximum degree of cure of the rebar under controlled (manufacturing) conditions is critical so that any post cure under uncontrolled (in-situ) conditions that may take place is minimal. The glass transition temperature (T_g) is also a parameter related to the manufacturing process, but also to the resin properties. Ensuring that the minimum specified magnitude is reached is critical to avoid softening of the composite rebars at temperature below the specification, specially during handling. The BFRP rebars results showed a more than 99% degree of sure, and T_g was well above the minimum, higher bound when compared to other available GFRP rebars (non-epoxy) as well as in the same relative range for the different rebar sizes, showing consistency of curing during the manufacturing process.

- Scanning Electron Microscopy (SEM) Imaging:

  SEM does not form part of the composite rebar specifications, but has been included in this study for qualitative purposes, since SEM can be effectively used to study the microstructural characteristics of composite rebars. The difference in microstructural patterns can found between different manufactures, and these patterns have been demonstrated to significantly contribute to durability properties. The BFRP results can be used as a benchmark for the microstructure and compared to aged bars. Also, the SEM can serve as a base for monitoring possible changes after any conditioning or testing or for quality control in manufacturing, establishing a ‘finger-print’ for each rebar size. The BFRP results showed homogeneity between he different rebar sizes, showing consistency of the manufacturing process, as well as no significant voids or imperfections, as seen form the representative SEMs provided. As a comparison and reference to other GFRP rebars, the SEM from four different commercially available GFRP rebars is provided below for comparison purposes (Gooranorimi, et. al. 2017. Microstructural investigation of glass fiber reinforced polymer bars. Composites Part B: Engineering, 110, pp.388-395):



- Strength of Bend Tests (ASTM D7914):

  The strength of the bend test provides a relative measure of the bend of composite rebar. The minimum strength must exceed 60% of the value of the guaranteed ultimate tensile force, as reported in Table 3 of ASTM D7957. This will assure that proper load transfer is provided within the internal bend composite bars of reinforced concrete elements. The BFRP #4 bend tests (only size available for testing) resulted in 65% higher performance that required by the specification (i.e. an average value of 1.65), this is significantly higher when compared to other available bend GFRP rebars.

5.2. DURABILITY TESTS (Alkaline Resistance)

- Tensile Load Retention with Load (ASTM D7705/D7205):

  This durability exposure applies a dual mode of aging, on the one hand the high temperature combined with the high alkalinity solution: the solution reproduces the concrete alkalinity, while the high temperature aims at accelerating any potential degradation mechanisms that may occur in the composite rebars. On the other, the sustained load, which is equivalent to a serviceability level of strain, aims at opening any potential micro-cracks in the composite rebar, thus allowing the solution to penetrate further in the rebar and further degrade the composite rebar. This exposure represents an aggressive environment and thus provides quantitatively a measure the of durability of the rebar. Typically protection of the rebar to aggressive environments is attributed to both manufacturing quality process and the cured resin properties. It should be noted that this test exposure is not a requirement of the ASTM specification, however it is a requirement by the FDOT Specification 932. The BFRP results are significantly high, with a relatively high load retention values, which reflects a durable composite rebar. Moreover, the tensile mode of failure for all rebars samples was adequate, engaging the full cross-section resulting in a 'broom' or explosive failure as seen from the representative figure in Section 4.1.

- Transverse Shear Strength (ASTM D7705/D7617):

  Although the strength retention of transverse shear is not a composite rebar specification, it was conduced to evaluate the possible degradation of the basalt fibers within the BFRP rebars post immersion in the high temperature alkaline solution. Therefore, there is not an applicable specification requirement. Nevertheless, the specification percentage used in the tensile load retention (without load) may be used as a suggested specification, which is equivalent to 80%. To this end, the BFRP rebar results in adequate performance, where #4 and #5 rebars do not show any degradation, and is a reflection of the durability of basalt fibers when used in composite rebars for concrete reinforcement.

- Total Enthalpy of Polymerization and Glass Transition Temperature (ASTM D7705/E2160/E1356):

  Similarly to the strength retention of transverse shear, the degree of cure and glass transition temperature post immersion to alkaline solution at high temperature are not a composite rebar specification. It is used a reference to understand possible changes in the degree of cure and glass transition temperature. Therefore the are no specification values, however it is assume that the same levels as the control (benchmark) tests should be maintained, therefore degree of cure should be more than 95% and the glass transition temperature should also be more than 100°C based on DSC method. The BFRP rebar results show that there are no significant changes in degree of cure or glass transition temperate with retention values close to 100% (i.e. no change).

- Scanning Electron Microscopy (SEM) Imaging:

  SEM post exposure to the alkaline environment was conducted as a qualitative to evaluate if there was any visible degradation at core of the rebar specimen or the surface, of between interfaces. Based on the results, no signs of inadequate compatibility between fiber/sizing/epoxy was visible, nor changes to the surface of overall core of the rebar specimen. In other available studies, hairline cracks have been detected in GFRP rebars at the fiber/sizing/epoxy interfaces, and been attributed to degradation of the overall composite rebar. The SEM study post exposure provides additional evidence on the durability provided by the BFRP rebars under evaluation.

6. CONCLUSIONS

In summary, this report provides experimental results to evaluate the fundamental the physio-mechanical and durability properties of nominal #3, #4 and #5 BFRP rebars made with an epx/anhyd based resin formulation. Based on the results presented herein, the following preliminary conclusions can be inferred:

Properties of specimens prior to durability immersion tests:

- All experimental tests conducted within this project are in accordance with ASTM or ISO standard test methods, and thus can be used towards BFRP rebar certification and approval per applicable requirements.
- Overall as indicated quantitatively herein, the evaluated mechanical properties of un-aged BFRP rebars result in equivalent or higher magnitudes than existing minimum ASTM/FDOT specifications or available GFRP rebars as provided by GFRP manufactures.
- Overall qualitatively, based on SEM imaging the BFRP bars result in a homogeneous cross-section were not anomalies or large voids are found, comparable within all bar sizes.
- The relative increasing of the cross-sectional area of the tested rebars to be in the mid-upper-bound of the specified ASTM allowable range is recommended.
- Strength of bend BFRP closed stirrups (hoops) show a significant higher level of load carrying capacity compared to other available GFRP open bends.

Properties of specimens post alkaline resistance 90 days at 60°C:

- Durability exposures immersed in alkaline solution (without sustained load as applicable) are conducted in accordance with ASTM and/or ISO standard test methods (refer to section 2 for the summary results), and thus results are applicable towards BFRP rebar certification and material approval per applicable requirements
- The tensile properties post alkaline resistance with sustained load met or exceed required retention strength. This is of special interest since the likelihood of micro cracks being induced in samples during testing provide much more aggressive conditions than submerged samples and hence provide evidence of the durability of the BFRP.
- Transvers shear strength post alkaline resistance also show additional evidence in pure shear state of stress that there are no degradation in epx/anhyd protected BFRP rebars.
- SEM imaging does not reveal any visible degradation in the core of specimen or the surface, moreover no signs of inadequate compatibility between fiber/sizing/epoxy is visible, providing additional evidence on the durability of the BFRP rebars under evaluation.
- STIC project (FDOT funded) is using the same BFRP rebar under evaluation, leveraging the tests being conducted and additional data to support and validate results. Results are expected by the end of the first quarter 2019.

In conclusion, based on the results presented herein BFRP rebars made with an epx/anhyd based resin formulation can provide a durable and safe concrete reinforcement solution.

♦ END OF TEST REPORT ♦