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			Project	**TidGen®**

Revision History

Rev. Num.	**EC Num.**	**Description**	**Prep.**	**Date**	**Chck.**	**Date**	**Appr.**	**Date**
01		Initial draft	ACK	02Jan2020				
02		Comments by MB	ACK	04Jan2019				
03		Comments by JM	ACK	05Jan2020				
A		Initial release	ACK	05Jan2020	MB	05Jan2020	JM	05Jan2020

CONTENTS

1. ACRONYMS

CERL: Composites Engineering Research Laboratory
DIC: Digital Image Correlation
ILSS: Inter-Laminar Shear Strength
MHK: Marine Hydro-Kinetic
MSU: Montana State University
ORPC: Ocean Renewable Power Company
SBS: Short Beam Strength (or Shear)
SEM: Scanning Electron Microscope
UTS: Ultimate Tensile Strength
VE: Vinyl ester

2. REFERENCES

[1] Seawater Durability of Epoxy / Vinyl Ester Reinforced with Glass / Carbon Composites – Auth: Murthy et al., Journal of Reinforced Plastics and Composites, Vol. 29, No. 10/2010. This is attached in Appendix A.
[2] Presentation for ORPC – prepared by Andrew Schoenberg, September 26, 2018. This is a presentation showing the results of testing of and research performed by CERL into understanding composite response to prolonged immersion in water. This is attached in Appendix B.
[3] MSU, ORPC Test Data V1.0, 11Dec2019 – This is a summary of the test results of composite coupon immersion mechanical testing that was performed by MSU. This is attached in Appendix C.

3. PURPOSE

3.1. The purpose of this document is to satisfy the requirements for deliverable 8.1 under the following project:

Award No.:	DE-EE0007820, effective 11/1/2016
Project Title:	Advanced TidGen® Power System
Prime Recipient:	ORPC Maine
Principal Investigator:	Jarlath McEntee, P.E.

This document reports on the research and testing that was performed on composite materials to characterize their suitability for use in TidGen® turbine foils.

4. PARTNERSHIP

4.1. ORPC partnered with CERL, and MSU to perform the research and testing.

5. OVERALL TEST AND RESEARCH PHILOSOPHY

5.1. Foils for MHK applications must withstand loads caused by fluid forces, inertial forces, and reactive forces due to bonding and fastening. Material selection is therefore critical in order to attain the desired mechanical properties. There are many possible combinations of fibers, resins and coatings, as well as process variations that all contribute to the mechanical properties.

5.2. Foils for both the wind power industry and the MHK industry are commonly made of composites consisting of fibers in a resin matrix. The fibers are most often either glass (fiberglass), or carbon. The resin is usually epoxy or vinyl ester even though there are polyester and phenolic resins available. The fibers are available in many different forms with fiber size, sizing, material, weave, and thickness among the variables. Resins are available in many different commercially available formulations that cure to different hardnesses and strengths. Phase 1 of the research was to examine these 4 material families (2 fiber types – carbon and glass, and 2 resin systems – epoxy and vinyl ester) and see which ones are most suitable for ORPC's TidGen turbine. Phase 2 of the research was to sample and test different fibers and resins that were found most suitable from phase 1 to arrive at an optimum material combination.

5.3. Of primary importance is determining how prolonged immersion in water affects the composites' mechanical properties. Testing and research were undertaken to assess the effects of water immersion on the mechanical properties of different combinations of composites' fiber and resins. The results of this research then guided the selection of fibers and resins for further testing. This testing was general in nature, looking at carbon vs. glass fibers, and epoxy vs. VE resins.

5.4. After the general families of fiber and resins were determined, more detailed, specific tests of different commercially available materials were performed. In addition, composite coatings were investigated for effectiveness. Materials and application process (in-mold and post-mold) were considered during the testing.

6. PHASE 1

6.1. Overview

6.1.1. CERL introduced ORPC to research described in Reference [1]. ORPC examined this research in order to narrow down the choice of materials for more detailed testing. In addition, CERL examined different resin systems, fibers (both carbon and glass), and coatings in order to determine the best material candidates for further testing.

6.2. Results summary

6.2.1. Reference [1] compared maximum moisture uptake of carbon and glass in both epoxy and VE resins. The materials were soaked in seawater for 450 days. The maximum moisture uptake is shown in Table 1.

TABLE 1: MAXIMUM MOISTURE UPTAKE

Fiber	**Resin**	**Maximum Moisture Uptake (weight %)**
Glass	Epoxy	.780
Glass	VE	.475
Carbon	Epoxy	.625
Carbon	VE	.390

6.2.2. Reference [1] also measured the flexural strength, ILSS, and UTS at different durations of soaking. The results of the flexural testing are shown in Figure 1. ILSS testing results are shown in Figure 2, and those of the UTS testing are shown in Figure 3.

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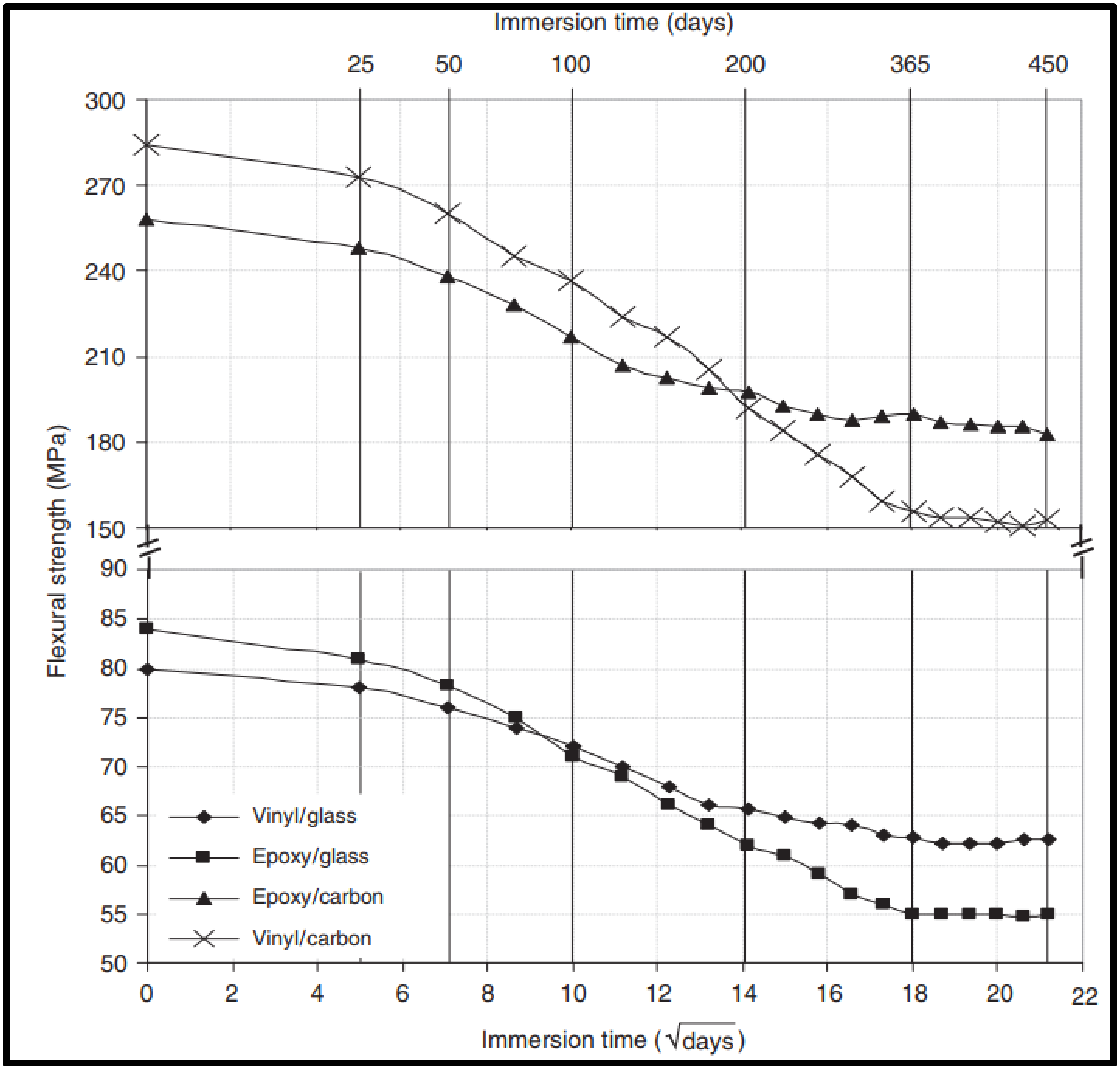

FIGURE 1: FLEXURAL STRENGTH WITH INCREASING IMMERSION TIME (REFERENCE [1])

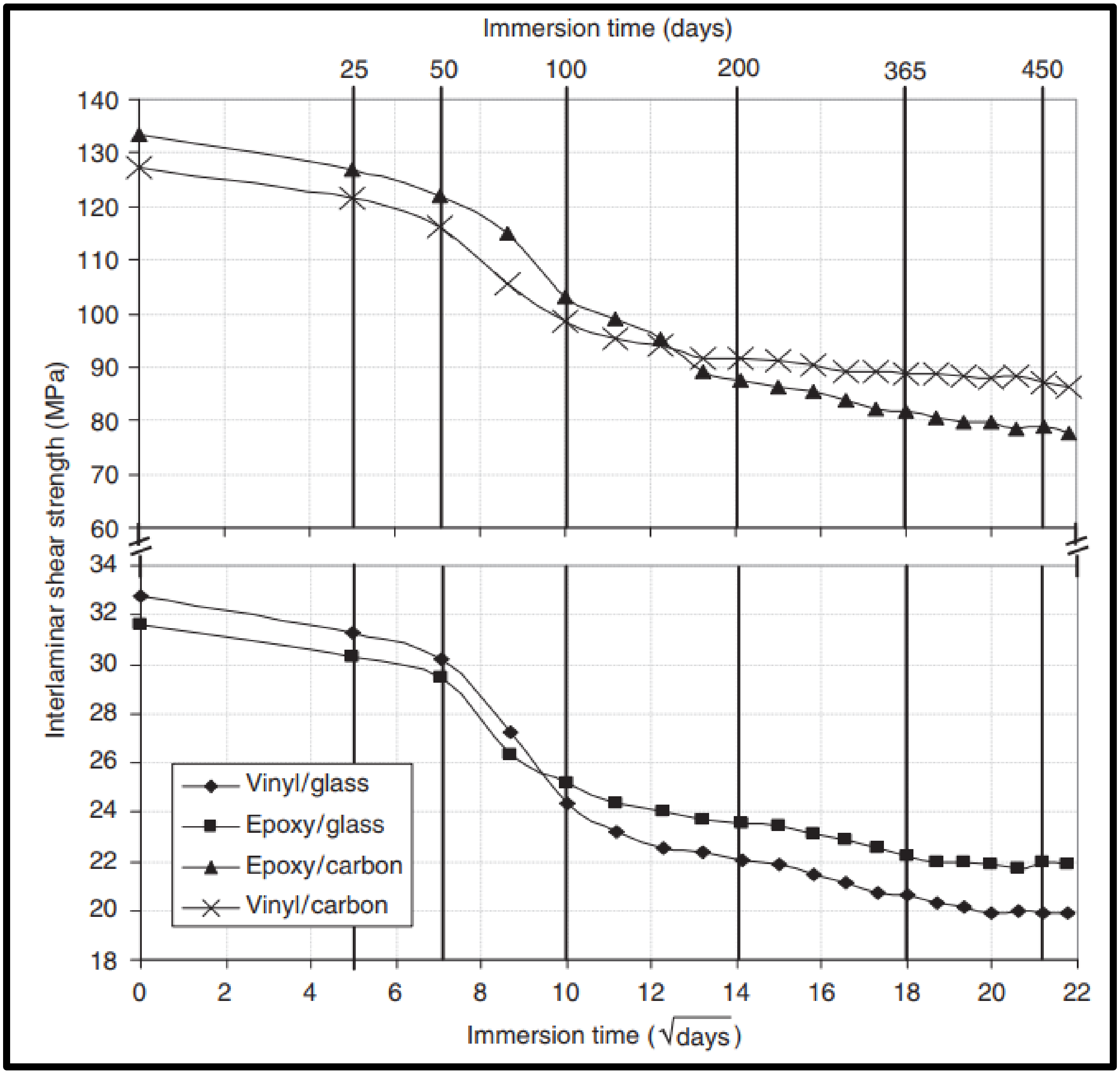

FIGURE 2: ILSS WITH INCREASING IMMERSION TIME (REFERENCE [1])

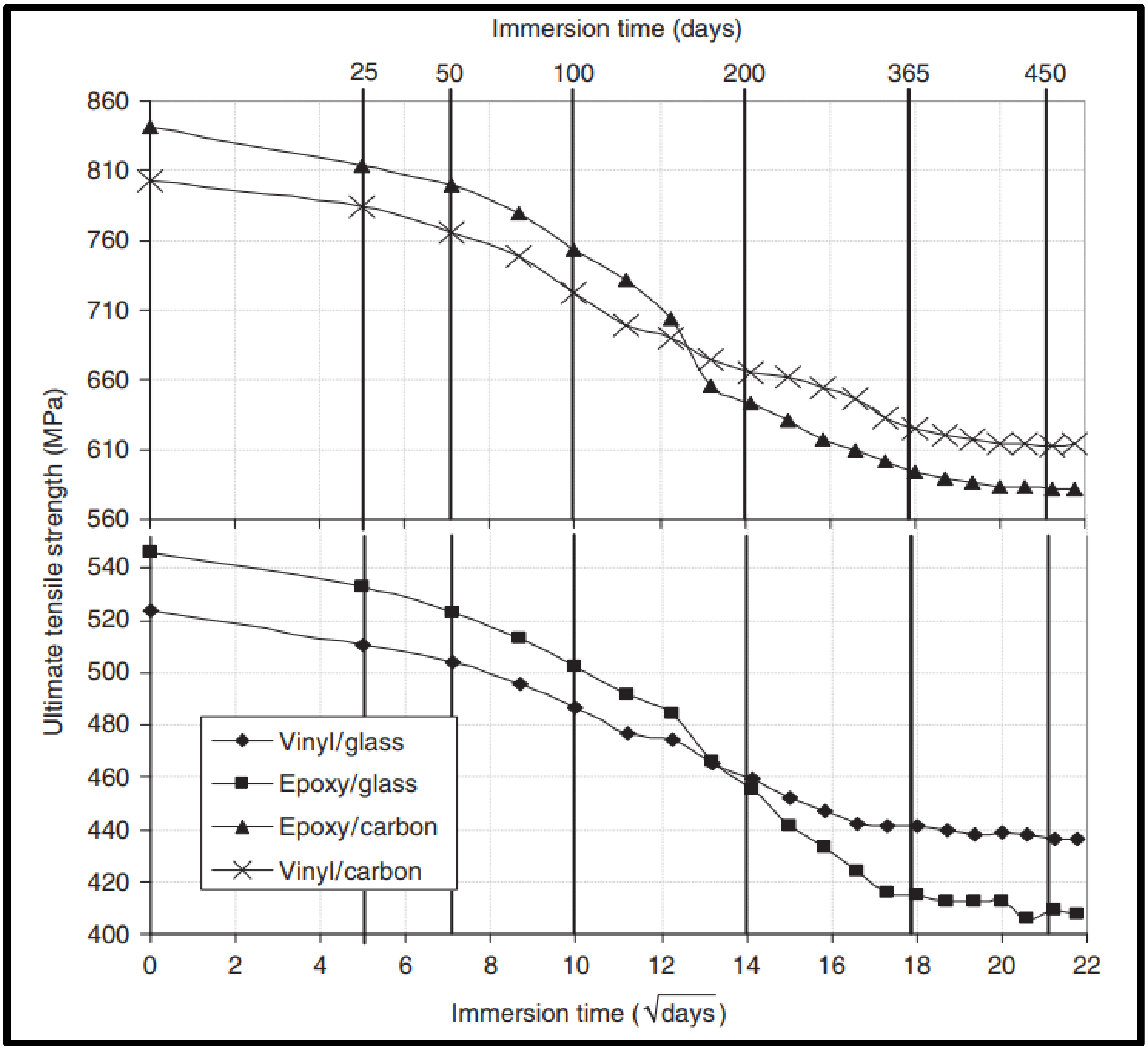

FIGURE 3: UTS WITH INCREASING IMMERSION TIME (REFERENCE [1])

6.2.3. Reference [1] also performed fracture analysis of glass fibers in both an epoxy resin matrix and a VE matrix using SEM. The results are shown in Figure 4.

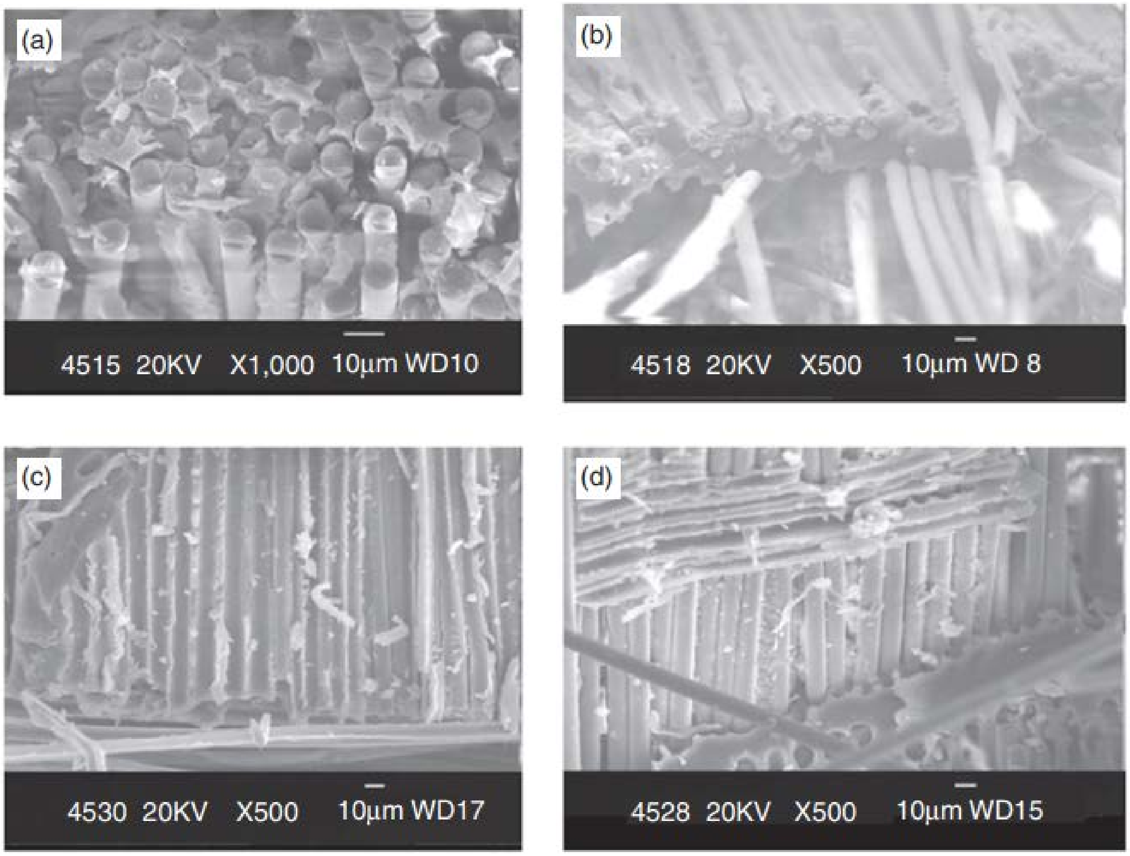

Figure 5. *SEM of fractured flexural specimens (a) epoxy/glass without immersion, (b) epoxy/glass after 1 year immersion in seawater, (c) vinyl ester/glass specimens without immersion and (d) vinyl ester/glass specimens after 1 year of immersion.*

FIGURE 4: SEM COMPARING GLASS AND EPOXY VS. VE RESIN FRACTURE (REFERENCE [1])

6.2.4. Reference [1] looked at different fibers, resin systems, coatings and coating application processes for use in ORPC's MHK foils.

6.3. Discussion

6.3.1. Table 1 show 2 things: 1) Carbon composites absorb less water over time than those made of glass, and 2) Composites with VE resin absorb less water over time than those made with epoxy.

6.3.2. Figure 1 through Figure 3 show that while the strength of carbon matrices with either epoxy or VE resin deteriorates significantly with increased saturation, it is still stronger at saturation than the glass matrices ***in dry condition.*** While carbon fiber with epoxy resin retained more flexural strength when saturated, the carbon fiber with VE resin retained more ILSS and UTS.

6.3.3. Both paragraphs 6.3.1 and 6.3.2 strongly point to the use of carbon fiber rather than glass, as this will result in foils with higher mechanical strengths.

6.3.4. Figure 4 shows that with glass fibers, a saturated glass/epoxy matrix exhibited greater debonding than glass/VE.

6.3.5. CERL, using mostly data from reference [2], selected the materials shown in Table 2 for further investigation. It based its selections on a comparison of mechanical properties and discussions with manufacturers.

TABLE 2: MATERIALS FOR PHASE 2 INVESTIGATION

Material	#1	#2
Fiber	Zoltek 13	Zoltek 72
Resin	Epovia RF1001	Signia 411-350
Coating	Belzona 1341	Belzona 1331

In addition, a manufacturing process variable was identified for investigation. This is applying the coating in the mold during the layup, or applying post mold.

6.3.6. The fibers chosen are both carbon. The Zoltek 72 differs from the Zoltek 13 in that is specially formulated to work better with VE resins. From the discussion in paragraph 6.3.2, the resins chosen are both VE resins but with an epoxy base. Epoxy based VE resins differ from epoxy resins in that they contain styrene. The styrene can vary the mechanical properties, the viscosity, and the cost of the resin.

7. PHASE 2

7.1. Overview

7.1.1. The results from Phase 1 led ORPC to decide to do further testing with carbon fiber over glass fiber, and VE resins over epoxies. MSU performed the actual testing, and their report is reference [3] and is attached as appendix C. Testing in phase 2 would look at the influence of fiber type, resin type, coating type and coating process (in-mold or post-mold). Two properties of concern that were tested are shear strength and shear modulus. Shear strength was determined through SBS testing and V-notch testing. Shear modulus was determined through DIC testing.

7.1.2. To encompass all the different combinations, 16 material sets need to be considered. However, due to material availability 14 plates were made. The plates measured either 2 ft x 3 ft, or 2 ft x 2 ft, and test coupons were cut from these plates. The plate designations and configurations are shown in Table 3. “S” designates coupons used for SBS testing, and “V” designates those for V-notch testing.

TABLE 3: TEST PLATE AND COUPON DESIGNATION

Panel #	Pattern	Resin	Process	Reinforcement	Coating	Coupon reference	Panel sq. in.
1	−−−+	1	In Mold	CF 1	1	1S, 1V	576
2	+−−+	2	In Mold	CF 1	1	2S, 2V	576
3	−+−+	1	Post Mold	CF 1	1	3AS, 3AV	864
3	−+−−	1	Post Mold	CF 1	2	3BS, 3BV	864
4	++++	2	Post Mold	CF 2	1	4AS, 4AV	864
4	+++−	2	Post Mold	CF 2	2	4BS, 4BV	864
6	−+++	1	Post Mold	CF 2	1	6AS, 6AV	864
6	−++−	1	Post Mold	CF 2	2	6BS, 6BV	864
10	++−+	2	Post Mold	CF 1	1	10AS, 10AV	864
10	++−−	2	Post Mold	CF 1	2	10BS, 10BV	864
11	+−++	2	In Mold	CF 2	1	11S, 11V	576
12	−−++	1	In Mold	CF 2	1	12S, 12V	576
17		2	N/A	CF2	None	17S,17V	
18		2	N/A	CF1	None	18S,18V	

7.2. Test Description and Results

For the SBS testing, 20 coupons were made from each plate. Ten were tested in the dry condition, and ten were soaked in distilled water in an oven at 50°C for 2370 hours. Mass measurement were taken periodically to measure water absorption. The SBS testing was performed per ASTM standard D2344 using a generic test fixture as shown in Figure 5. The maximum load was recorded for each coupon. Per the ASTM standard, calculating the shear strength meant multiplying the maximum load by .75 and dividing by the cross-sectional area. The results of the SBS testing are shown in Table 4.

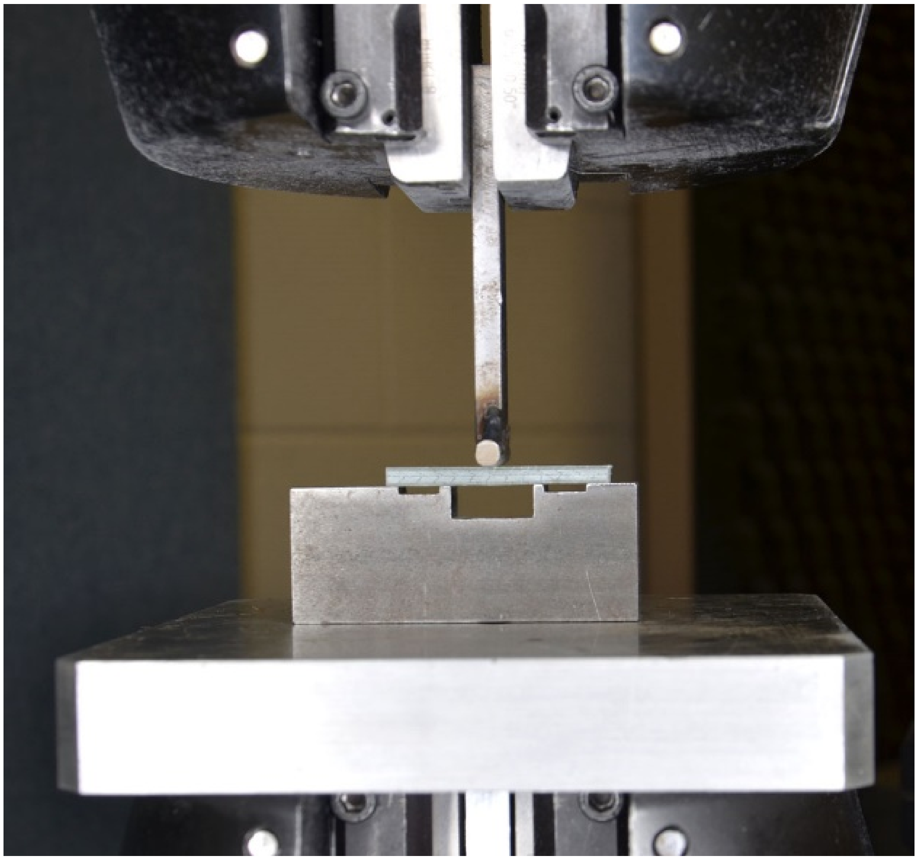

FIGURE 5: GENERIC TEST FIXTURE FOR SBS TESTING

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TABLE 4: SBS SHEAR STRENGTH RESULTS

		Conditioning	Average Max Stress	Standard Deviation	Shear Strength Loss
Material System	**No. of Tests**	**% Increase in Mass**	**(PSI)**	**(PSI)**	**%**
1S-Dry	10	0.00	6019	754	
1S-Cond.	10	1.05	5320	497	11.6%
2S-Cond.	10	0.00	5931	479	
2S-Cond.	10	0.88	4337	406	26.9%
3AS-Dry	10	0.00	7040	789	
3AS-Cond.	10	1.06	6211	630	11.8%
3BS-Dry	10	0.00	6348	588	
3BS-Cond.	10	0.53	5533	677	12.8%
4AS-Dry	10	0.00	7662	582	
4AS-Cond.	10	0.66	7139	418	6.8%
4BS-Dry	10	0.00	7888	357	
4BS-Cond.	10	0.59	7143	424	9.4%
6AS-Dry	10	0.00	7749	595	
6AS-Cond.	10	0.60	8267	553	-6.7%
6BS-Dry	10	0.00	8265	734	
6BS-Cond.	10	0.59	7330	568	11.3%
10AS-Dry	10	0.00	6435	736	
10AS-Cond.	10	0.64	4637	516	27.9%
10BS-Dry	10	0.00	6939	528	
10BS-Cond.	10	0.62	5238	624	24.5%
11S-Dry	10	0.00	8297	893	
11S-Cond.	10	0.80	7670	399	7.6%
12S-Dry	10	0.00	7814	434	
12S-Cond.	10	0.77	7349	424	6.0%
17S-Dry	10	0.00	6490	515	
17S-Cond.	10	0.40	4814	316	25.8%
18S-Dry	10	0.00	8963	677	
18S-Cond.	10	0.34	7295	597	18.6%

7.2.1. For the V-notch testing between 20 and 23 coupons were made from each plate. Again, 10 were tested in the dry condition, and the remaining coupons were soaked in distilled water in an oven at 50°C for 3340 hours. The V-notch testing was performed per ASTM standard D5379 using a Wyoming test fixture as shown in Figure 6. The maximum load was recorded for each coupon. Per the ASTM standard, taking the maximum load and dividing by the cross-sectional area of the notch. The results of the V-notch testing are shown in Table 5.

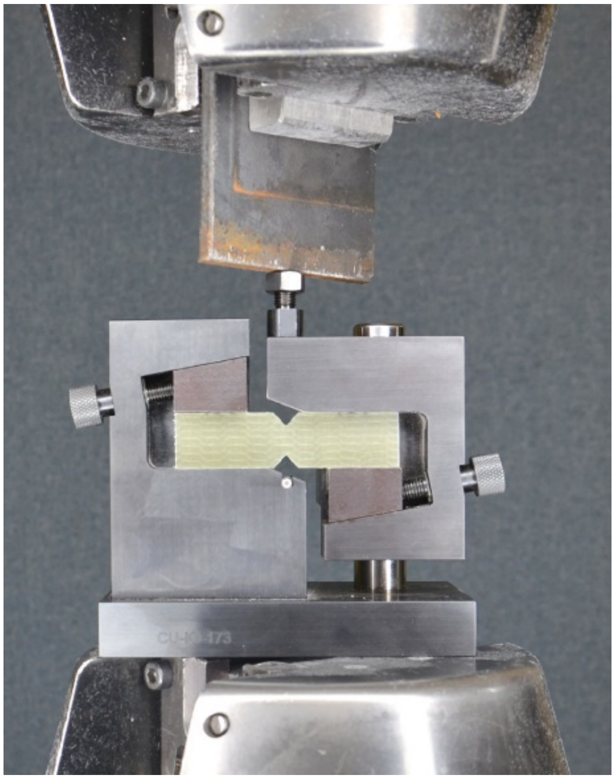

FIGURE 6: WYOMING TEST FIXTURE FOR V-NOTCH TESTING

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TABLE 5: V-NOTCH SHEAR STRENGTH RESULTS

Material System	# of	Conditioning	Average Max Stress	Standard Deviation	Shear Strength Loss
		% Increase in	(PSI)	(PSI)	%
1V- Dry	10	0.00	9815	631	
1V- Cond.	10	1.05	8422	869	14.2%
2V- Dry	10	0.00	10134	868	
2V- Cond.	11	0.96	8136	453	19.7%
3AV- Dry	10	0.00	10040	433	
3AV- Cond.	10	0.67	8766	447	12.7%
3BV- Dry	10	0.00	9233	659	
3BV- Cond.	12	0.66	8259	422	10.6%
4AV- Dry	10	0.00	12387	709	
4AV- Cond.	12	0.76	10810	682	12.7%
4BV- Dry	10	0.00	11834	435	
4BV- Cond.	10	0.67	10363	651	12.4%
6AV- Dry	10	0.00	11874	768	
6AV- Cond.	10	0.68	10953	195	7.8%
6BV- Dry	10	0.00	11388	441	
6BV- Cond.	10	0.76	10032	359	11.9%
10AV- Dry	10	0.00	10001	555	
10AV- Cond.	11	0.78	7814	289	21.9%
10BV- Dry	10	0.00	9385	424	
10BV- Cond.	12	0.80	7027	323	25.1%
11V- Dry	10	0.00	12241	551	
11V- Cond.	13	0.96	10452	389	14.6%
12V- Dry	10	0.00	11807	498	
12V- Cond.	12	0.92	10346	263	12.4%
17V- Dry	10	0.00	12466	880	
17V- Cond.	12	0.45	10669	784	14.4%
18V- Dry	10	0.00	9450	816	
18V- Cond.	13	0.49	7686	525	18.7%

7.2.2. For 2 coupons of each unique resin, conditioning and reinforcement system, or 28 coupons in total, an Aramis 2018 DIC strain measurement system was used to measure the complete 2-D shear strain. Figure 7 shows the shear strain on coupon 1V-3 at the final point during the test. Crack propagation can be seen near the initial notch. Only one of these images is included, because all coupons closely resemble each other. Force throughout the test was also recorded, allowing for the calculation of stress and strain through the entire test. These tests allow for the shear modulus of the materials to be determined. The values for modulus for each coupon are found in Table 6.

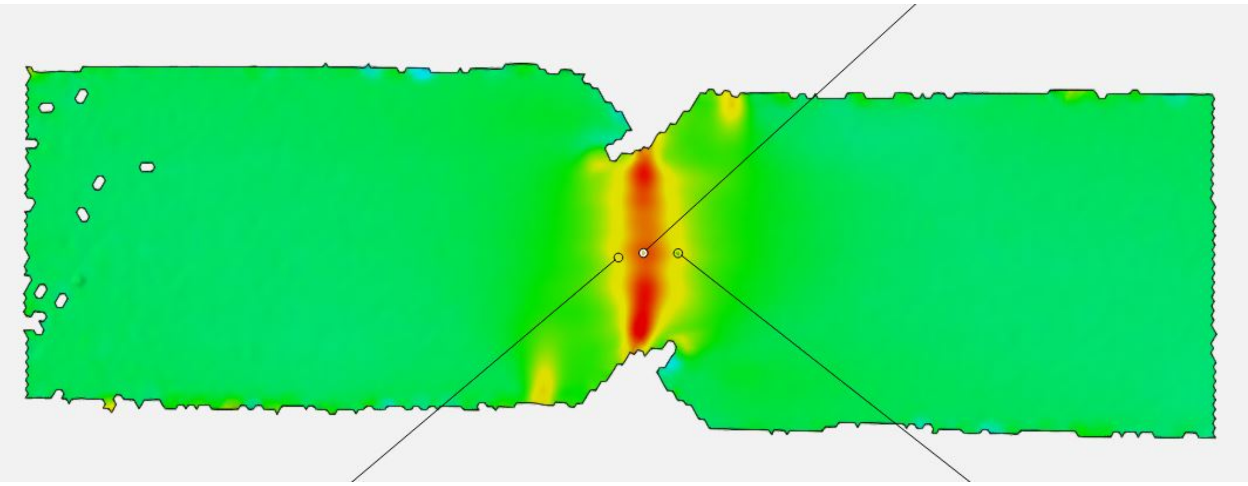

FIGURE 7: DIC SNAPSHOT SHOWING SHEAR STRAIN AT FINAL DEFORMATION FOR COUPON 1V-3

TABLE 6: MODULUS FOR EACH SET OF COUPONS

Coupon	Shear Modulus (PSI)
1V-3	7.5E+05
1V-11	4.2E+05
1V-12	3.4E+05
2V-1	5.5E+05
2V-2	3.8E+05
2V-11	2.7E+05
2V-12	3.5E+05
3AV-1	4.0E+05
3AV-2	3.0E+05
3AV-11	2.5E+05
3AV-12	3.8E+05
4AV-1	5.1E+05
4AV-2	6.4E+05
4AV-11	4.0E+05
4AV-12	3.5E+05
6AV-1	4.0E+05
6AV-2	4.9E+05
6AV-11	4.5E+05
6AV-12	4.2E+05
17V-1	4.6E+05
17V-2	3.9E+05
17V-11	4.2E+05
17V-12	4.7E+05
18V-1	5.0E+05
18V-2	4.6E+05
18V-11	3.1E+05
18V-12	5.2E+05

7.3. Analysis and Discussion

7.3.1. The results of the SBS and V-notch testing are shown in Figure 8. Examination of Figure 8 reveals that the coupons with the highest saturated V-notch shear strengths were all made with fiber 2. They are coupons 4A, 4B, 6A, 6B, 11, 12, and 17. In addition, the coupons with the highest saturated SBS shear strengths were also all made with fiber 2. They are also coupons 4A, 4B, 6A, 6B, 11, 12, and 17. This data shows that fiber 2 is superior to fiber 1 regarding shear strength.

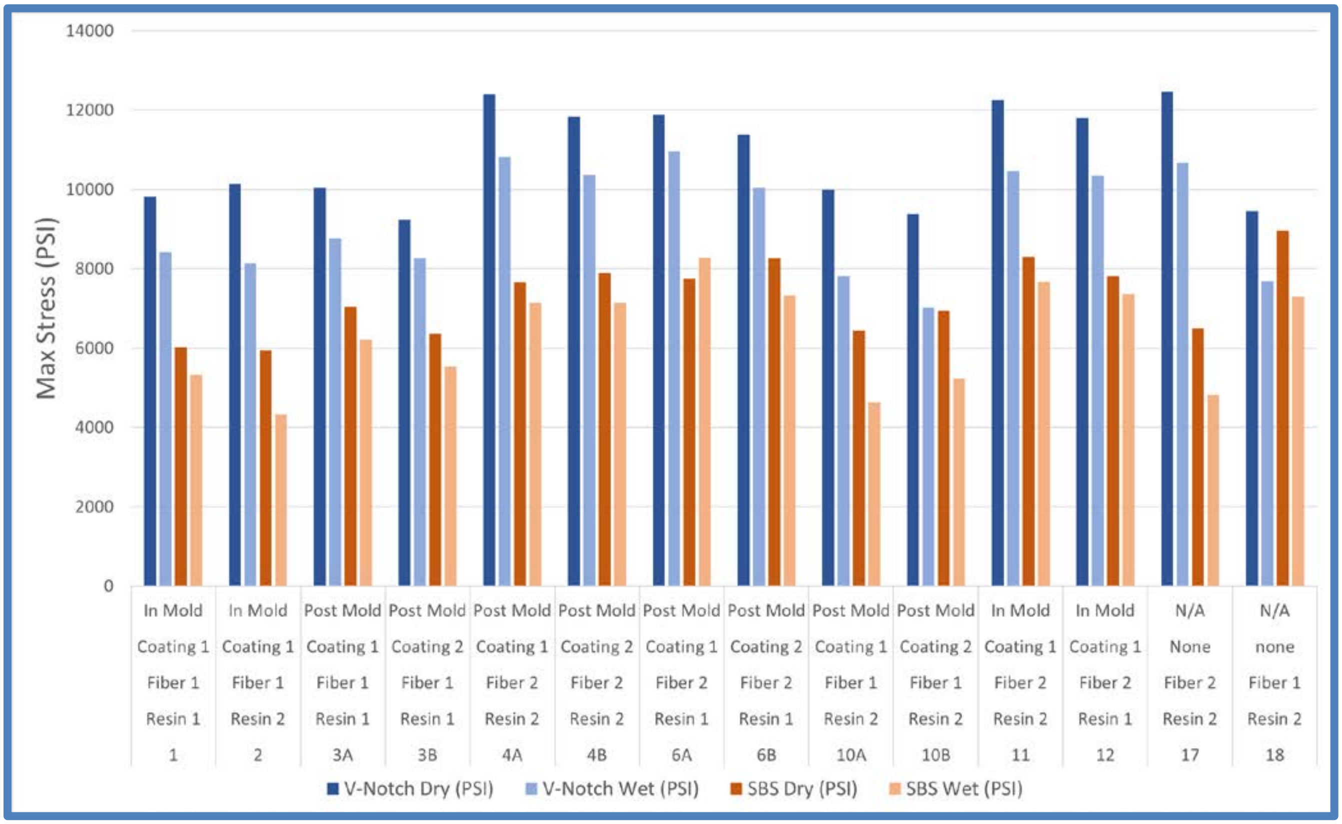

FIGURE 8: RESULTS OF SBS AND V-NOTCH TESTING

7.3.2. Looking further at the fiber 2 results a graph can be constructed, shown in Figure 9. This shows that resin 1 resulted in slightly higher shear strength than resin 2.

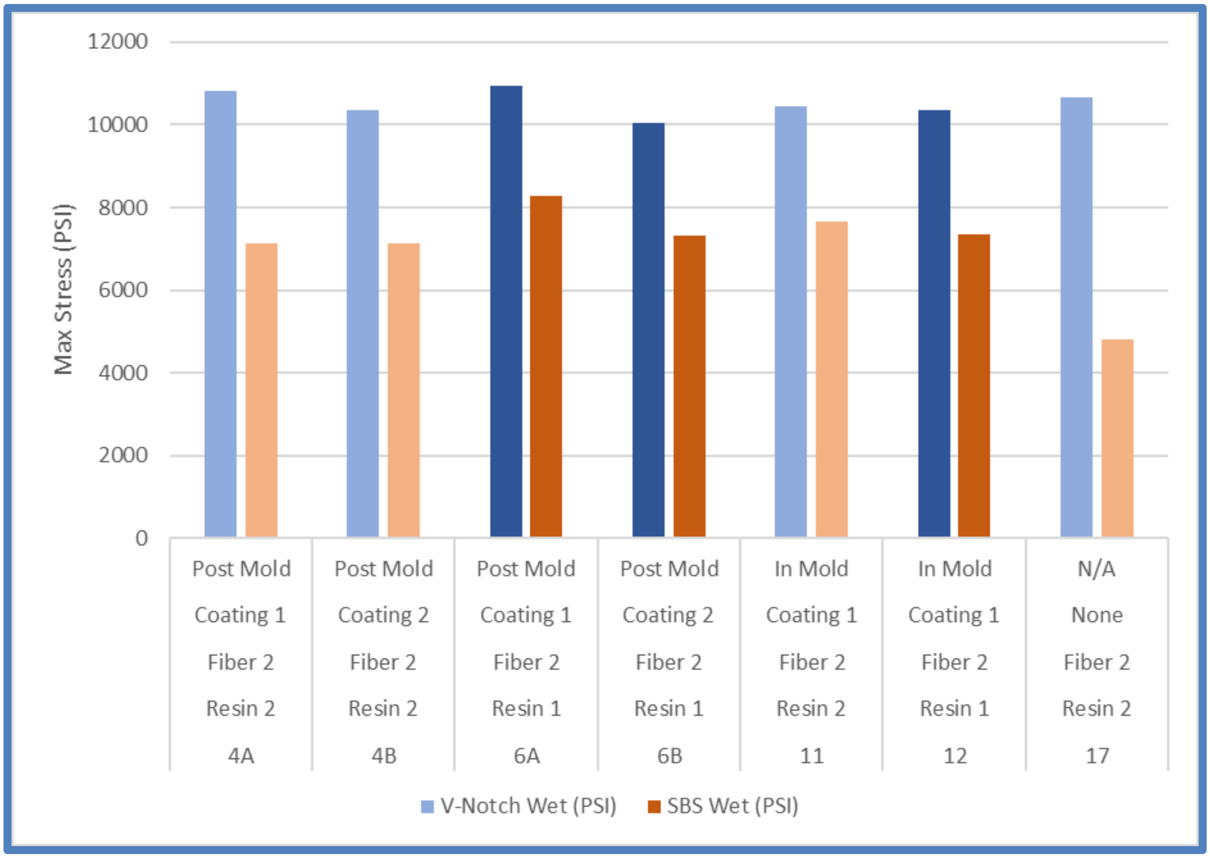

FIGURE 9: TEST RESULTS FOR FIBER 2

7.3.3. Looking to see the influence of coatings on fiber 1 and resin 2, one can construct another graph, shown in Figure 10. These results are not as significant as the results controlling for fiber and resin, but one can see that coating 1 has higher shear strength than coating 2, and post-mold processing has higher shear strength than in-mold processing.

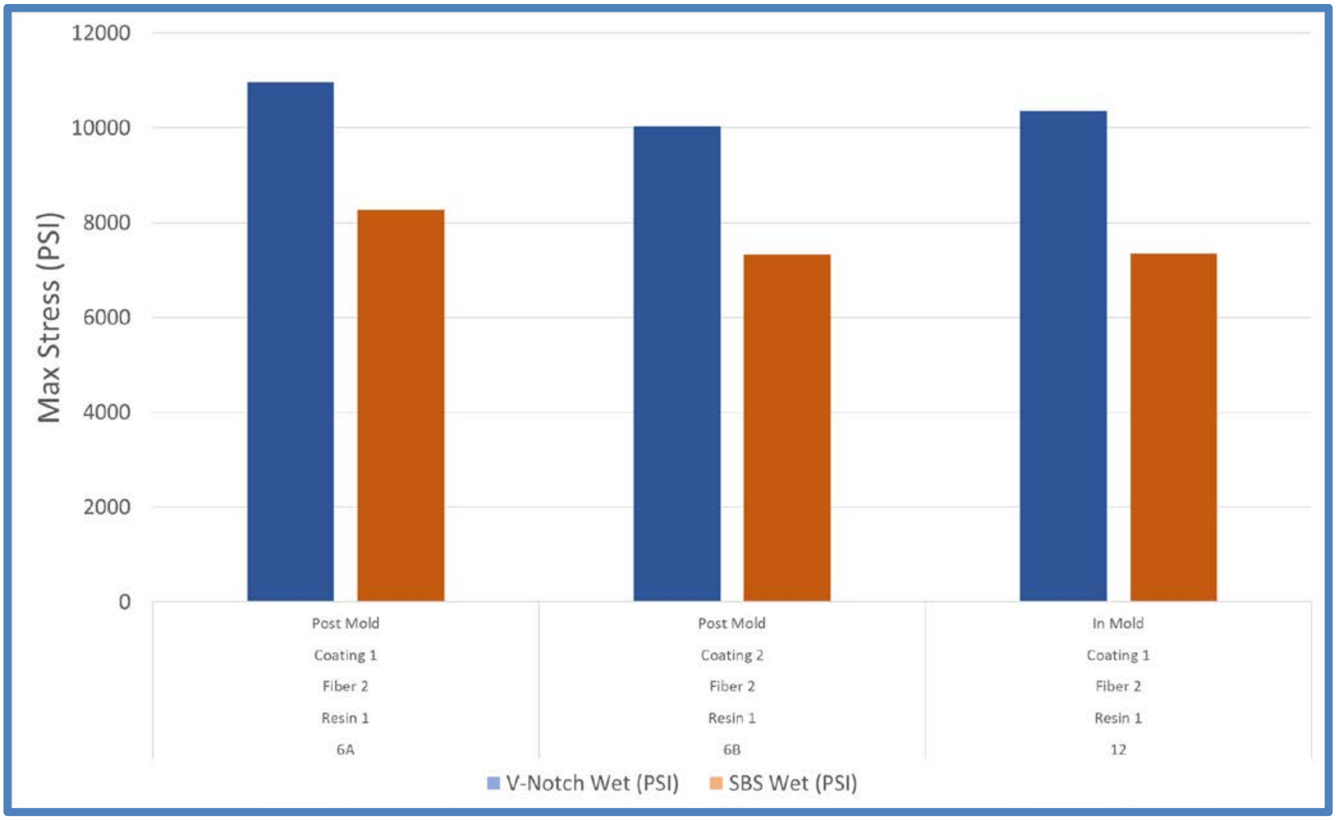

FIGURE 10: TEST RESULTS FOR FIBER 1 AND RESIN 2

8. CONCLUSIONS

8.1. Phase 1 showed that out of 4 combinations of carbon fiber, glass fiber, epoxy resin and VE resin, a carbon fiber and VE resin matrix was deemed most suitable for further development and testing. This was due to more favorable water uptake, and mechanical strength considerations. Phase 2 investigated specific combinations of fiber type, resin type, coating type and coating application process and found that the combination with the highest shear strengths was fiber 2, resin 1, coating 1 and post-mold processing.

9. APPENDIX A: SEAWATER DURABILITY OF EPOXY/VINYL ESTER REINFORCED WITH GLASS/CARBON COMPOSITES

Seawater Durability of Epoxy/Vinyl Ester Reinforced with Glass/Carbon Composites

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ABSTRACT: Seawater aging response was investigated in marine-grade glass/epoxy, glass/vinyl ester, carbon/epoxy and carbon/vinyl ester composites with respect to water uptake, interlaminar shear strength, flexural strength, tensile strength, and tensile fracture surface observations. The reduction of mechanical properties was found to be higher in the initial stages which showed saturation in the longer durations of seawater immersion. The flexural strength and ultimate tensile strength (UTS) dropped by about 35% and 27% for glass/epoxy, 22% and 15% for glass/vinyl ester, 48% and 34% for carbon/epoxy 28%, and 21% carbon/vinyl ester composites respectively. The water uptake behavior of epoxy-based composites was inferior to that of the vinyl system.

KEY WORDS: polymer-matrix composites (PMCs), seawater degradation, mechanical properties.

INTRODUCTION

ALL ENGINEERING PLASTICS/FIBER-REINFORCED plastics are affected by weather. Weather and radiation factors that contribute to degradation in plastics include temperature variations, moisture, sunlight, oxidation, microbiological attack, and other environmental elements. The structural integrity and lifetime performance of fibrous polymeric composites are strongly dependent on the stability of the fiber/polymer interfacial region [1]. One of the main drawbacks of thermoset plastics in seawater is that the polymer matrix and fiber/matrix interface can be degraded by a hydrolysis reaction of unsaturated groups within the resin [2]. Seawater degradation can cause swelling and plasticization of the polyester matrix and debonding at the fiber/matrix interface that may reduce the mechanical properties. This problem can be alleviated by using vinyl ester-based composites that generally have superior chemical stability in seawater [3,4]. When used in marine applications, the glass/vinyl ester composites retain their mechanical properties and do not degrade when immersed in seawater even for many years [5]. The modulus of glass/vinyl composites possesses values less than 40 GPa due to the lower modulus of glass fibers (70 GPa) and it is difficult to build marine structures like

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unmanned underwater vehicles using these composites. Glass counterpart carbon fiber has very high modulus (250 GPa), which can replace glass in marine applications especially for unmanned underwater applications [6].

Although much research has been done on seawater degradation of polymer-matrix composite laminates, less work has been done on carbon/vinyl ester composites. Thus, the present work gains importance and hence a thorough investigation of seawater degradation for both glass and carbon fiber reinforced in epoxy and vinyl ester composites has been undertaken. The aim of the research work is to compare the water uptake levels, the resulting degradation of mechanical properties, and degradation mechanism of glass/epoxy, glass/vinyl ester, carbon/epoxy, and carbon/vinyl ester composites in seawater immersion conditions.

EXPERIMENTAL

Materials and Processing

The materials tested were glass/epoxy, glass/vinyl ester, carbon/epoxy, and carbon/vinyl ester composites. All the composites were cured in ambient condition according to the standard curing cycle recommended by the material supplier. The specimens were fabricated using wet hand-lay process into flat panels measuring 250 mm × 250 mm with a thickness of 3 mm. The specimens were cut to sizes as per ASTM standards. The composites were cured at room temperature without elevated temperature post curing because most of the marine composite structures are cured under ambient conditions.

Seawater Durability Tests

The composite panels were immersed in a large tank containing artificial seawater prepared according to ASTM D 1141 (chemical composition given in Table 1) with salinity content of about 2.9% at room temperature for different time periods. The artificially prepared seawater in the tank was renewed periodically. Specimens were periodically withdrawn from the tank and weighed for water uptake. The water uptake was plotted against square root of immersion duration to enable an estimation of the diffusion coefficient using the equation:

$$\frac{M_t}{M_\infty} = \frac{4}{\sqrt{\pi}}\left(\frac{Dt}{d^2}\right)^{1/2} \tag{1}$$

where M_t is the water uptake at time t and M_∞ the maximum water uptake, d the specimen thickness (mm), and D the diffusion coefficient (mm^2/s) [7].

Table 1. Composition of artificial seawater according to ASTM D 1141.

Constituent	Amount in g/l
NaCl	29.2215
$CaCl_2$	1.5437
$MgCl_2$	11.1821
$NaHCO_3$	0.1680
Na_2CO_3	0.0212

Mechanical Testing

The flexural strength of the specimens (12.7 mm width, 127 mm length, and 3 mm thickness) were determined for different immersion times using the three-point bend test as per ASTM-D790 using UTM. The flexural strength of the composite was computed using the relation:

$$\sigma_f = \frac{3PL}{2bd^2} \tag{2}$$

where L is the span length 90 mm, b the width, and d the thickness. At least three specimens were tested for each immersion time. Interlaminar shear strengths (ILSS) were computed based on the flexural test data using the relation:

$$\mathrm{ILSS} = \frac{0.75P}{(bt)} \tag{3}$$

where P is the maximum load, b the width, and t the thickness of the specimen.

Tensile tests were performed on the specimens for different immersion times as per ASTM-D638 using a strain rate of 1 mm/min. The specimen dimensions were 216 mm × 19 mm × 3 mm length, width, and thickness respectively and the sample size was maintained as three in each case. The tensile fracture surfaces were examined for seawater degradation effect using scanning electron microscopy.

RESULTS AND DISCUSSION

Seawater Uptake Behavior

Figure 1 shows the seawater uptake (% weight gain) vs. the square root of seawater immersion times. In all the cases the rate of uptake and moisture content were seen to increase with immersion time. Overall results in terms of maximum percentage weight gain, over the 450-day period of investigation, and diffusion coefficient determined from the mass uptake curves are listed in Table 2. The percentage of water uptake with time is far greater in the case of epoxy-based composites than the vinyl ester-based composites. Both types of composite specimens showed saturation due to water uptake but vinyl ester-based specimens stabilized at much lower values of moisture uptake. Since the saturated levels of moisture uptake dictate the property degradations in the materials employed for underwater applications, vinyl ester-based composites proved superior to epoxy-based specimens. As the sample expands and shrinks, debonding between the matrix and fiber occurs creating voids which act as a reservoir for moisture thereby increasing its overall saturation level.

The values of maximum water uptake and diffusion coefficient of the specimens are presented in Table 2. The moisture uptake was the highest in case of epoxy/glass and the lowest for vinyl ester/carbon which had the lowest value of diffusion coefficient. Seawater induces microcracks leading to increased weight gain and increased level of interfacial degradation, resulting in wicking along the fiber surfaces. The stronger interfacial bond observed in carbon/vinyl ester and glass/vinyl ester contributes to lesser water-absorption rate due to seawater exposure. The moisture does not penetrate into the composite due to

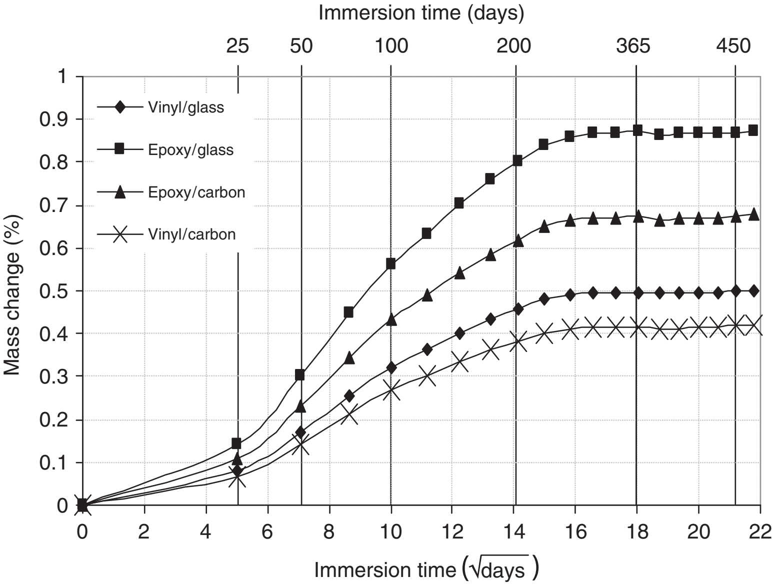

Figure 1. *Effect of seawater immersion duration on the water uptake of vinyl/glass, epoxy/glass, epoxy/carbon, and vinyl/carbon composites.*

Table 2. Diffusion co-efficient and maximum moisture uptake in wt% for different composites.

	VE/glass	VE/carbon	Epoxy/glass	Epoxy/carbon
Diffusion coefficient, D (10^{-7} mm^2/s)	2.1153	2.4028	2.1019	2.3322
M_∞	0.475	0.390	0.780	0.625

capillary process but only via the diffusion route. The glass or carbon fiber does not absorb water, therefore it is only the resins which absorb water and thereby weaken the matrix/reinforcement interface. As with the epoxy-based composites, the higher water uptake of the epoxy/glass fiber composite is probably due to the emulsion sizing of the glass fibers facilitating greater moisture absorption at the matrix/fiber interphase.

Effect of Seawater Uptake on Flexural Properties

Figure 2 shows change in flexural strengths of epoxy/glass, epoxy/carbon, vinyl ester/glass, and vinyl ester/carbon composites with respect to different seawater-exposure times. Though all the specimens showed drop in flexural strength with respect to immersion time because of moisture uptake, vinyl ester-based specimens showed lower levels of degradation. While epoxy-based specimens showed a drop of 48% in flexural strength for an exposure time of 450 days, the same was 28% in the case of vinyl ester. Vinyl ester composites showed higher strength than the epoxy-based composites after 90 days in glass-based composites and 200 days in carbon-based composites. This was true for both ILSS and tensile strength also. The vinyl ester/carbon composites showed stability even after 150 days, epoxy/carbon after 365 days, and similarly, vinyl ester/glass composites showed stability after 200 days and epoxy/glass, after 365 days. All the specimens tested conformed

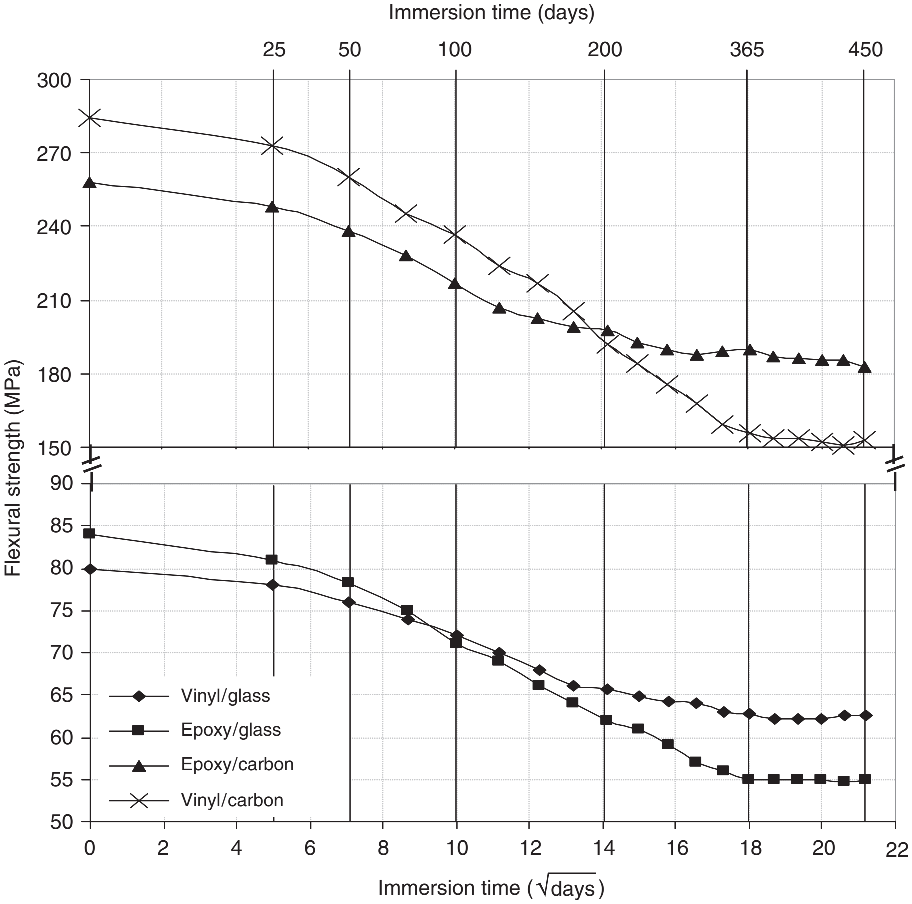

Figure 2. *Flexural strength of composite specimens vs. time of exposure to seawater.*

to Fick's law of diffusion with respect to moisture uptake and hence the moisture uptake values stabilized in these specimens beyond a certain period of time of exposure. Mechanical properties also should naturally show stability with respect to time.

The difference in the extent of degradation in the specimens is due to the much greater resistance of the vinyl ester resin to hydrolytic degradation than that of the epoxy resin [3]. The quantity of leached organic species is very low in vinyl ester-based composites because of the superior chemical stability of these composites in seawater [5]. Water can cause chemical degradation of glass fiber resulting in lower fracture energies in the presence of moisture [8]. Hence glass-based composites show greater degradation compared to carbon-based composites.

Effect of Seawater on ILSS Properties

The behavior of vinyl ester-based composites was observed to be very similar with respect to drop in ILSS values also (Figure 3). ILSS is one of the important properties in composites, which determine the load sharing by the fibers, that is, the interfacial strength. Thus, vinyl ester-based specimens are superior to the other ones tested. Ishai reported [9]

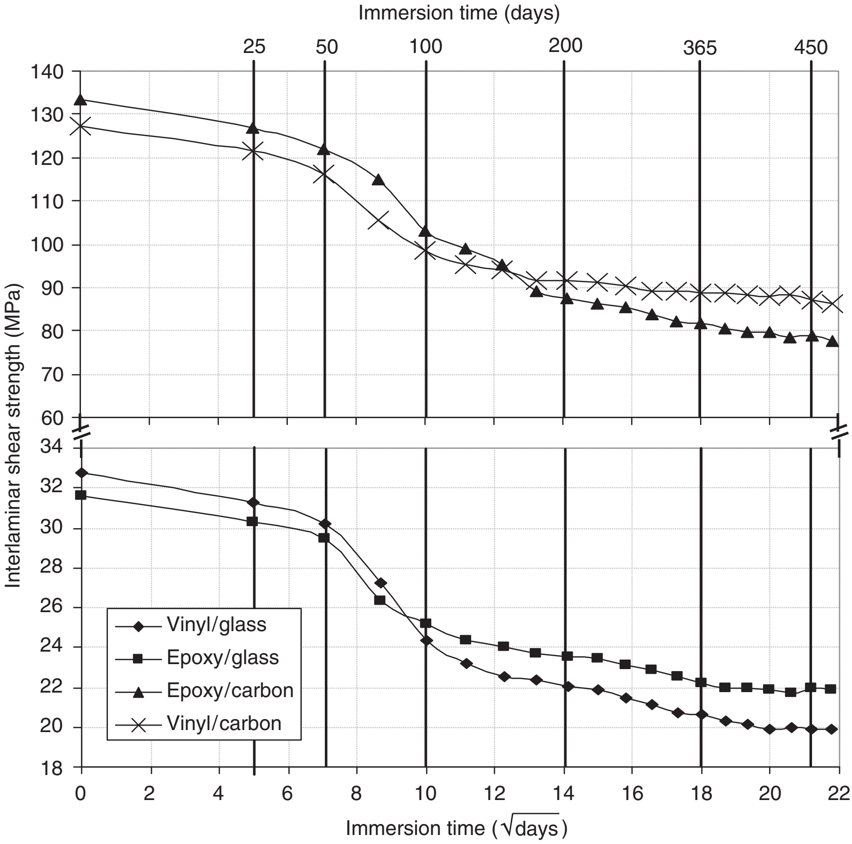

Figure 3. ILSS curve of composite specimens vs. time of exposure to seawater.

that moisture is seen to attack the glass fiber surface with the free hydroxides that form, further degrading the silica structure at higher temperature. But this work was conducted under room-temperature conditions and hence higher degradation was not observed in glass. This indicates that most of the damage mechanisms initiated by seawater exposure are at the interface rather than at the fiber level.

Effect of Seawater on Tensile Property

A progression of change in tensile strength as a function of immersion time is shown in Figure 4 for the specimens immersed in seawater. It clearly shows that the degradation increases substantially with increase in immersion time. It is of significant interest to note greater degradation for 200 days followed by almost saturation behavior. The amount of water uptake by the epoxy-based composites is significantly greater than that of the vinyl ester-based composites. This results in a mismatch in the moisture-induced volumetric expansion at interfaces. This leads to the evolution of localized residual stress fields in the composites. The water uptake most often leads to change in the thermal, physical, mechanical, and chemical properties of the composites. Integrity of the composites in terms of matrix cracking and fiber/matrix debonding/discontinuity by humid aging may be reflected by studies on tensile strength [10].

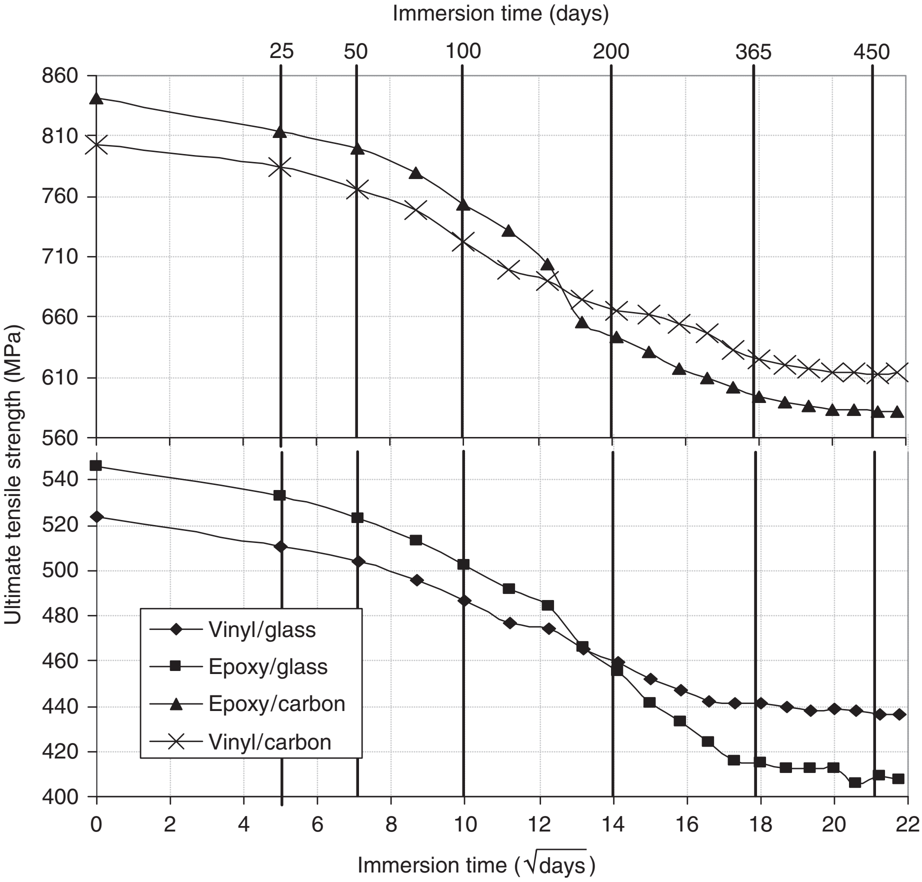

Figure 4. *Tensile strength of composite specimens vs. time of exposure to seawater.*

Fracture Studies

To examine the physical condition of the specimens exposed to the environmental conditions at the microlevel, typical SEM images were taken at the fracture section after the tensile tests. Figure 5 shows the fracture section of (a) epoxy/carbon without seawater immersion, (b) epoxy/carbon with 1 year of seawater exposure, (c) vinyl/carbon without seawater immersion, and (d) vinyl/carbon after 1 year of seawater immersion. Figure 5(a) and 5(c) are almost similar, the fiber fracture can be observed and no clean fiber surfaces can be seen and hence strong fiber–matrix bonding can be observed. On the other hand, Figure 5(b) specimens show relatively clean fiber surfaces resulting from the weak fiber–matrix bonding when compared to Figure 5(d). It is evident from the SEM images that the reduction in bond strength has a strong correlation with the reduction in tensile strength [11]. Figure 5(b) shows a higher level of surface degradation and pitting, and also numerous bare debonded fibers, which substantiates the fact that the reduction in transverse strength is largely due to fiber/matrix interfacial degradation. Images of the fracture section of Figure 5(d) indicate relatively good bonding between the fiber and the matrix at the interface. Only vinyl/carbon specimens in both conditions corresponding to

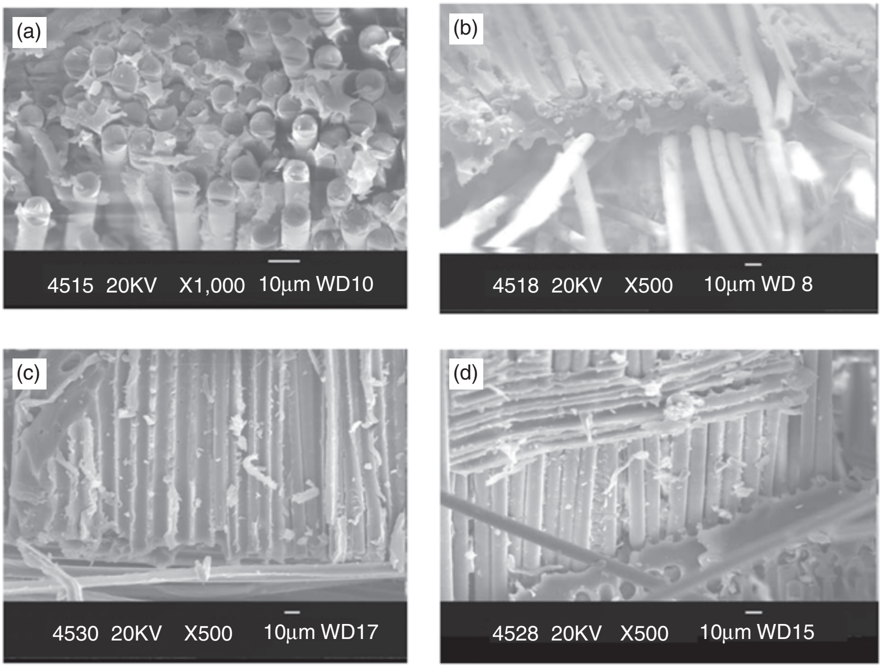

Figure 5. *SEM of fractured flexural specimens (a) epoxy/glass without immersion, (b) epoxy/glass after 1 year immersion in seawater, (c) vinyl ester/glass specimens without immersion and (d) vinyl ester/glass specimens after 1 year of immersion.*

the Figure 5(c) and 5(d) show some hackles on the surface that are absent in the case of epoxy/glass composites.

CONCLUSIONS

The water uptake, flexural strength, ILSS, and tensile properties of vinyl ester/carbon, vinyl ester/glass, epoxy/carbon, and epoxy/glass composite have been studied. Vinyl ester-based composites showed lower values of saturation with respect to the percentage of water uptake corresponding to different exposure times than of the epoxy-based composites. The drop in flexural strength, ILSS, and tensile strength in the case of vinyl ester-based composites were lower than that of epoxy-based composites. Flexural strength, ILSS, and tensile strength showed significant degradation followed by stability for both vinyl ester and epoxy-based composites as water uptake continued toward saturation. The SEM showed that the moisture penetration along the fiber/matrix interfaces caused interfacial debonds leading to rupture or degradation of the interface. The water uptake weakened the fiber/matrix interface exposing the fibers.

ACKNOWLEDGMENTS

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10. APPENDIX B: PRESENTATION FOR ORPC

C.E.R.L.
COMPOSITES ENGINEERING RESEARCH LABORATORY

The Maine Composites Alliance

Presentation for ORPC

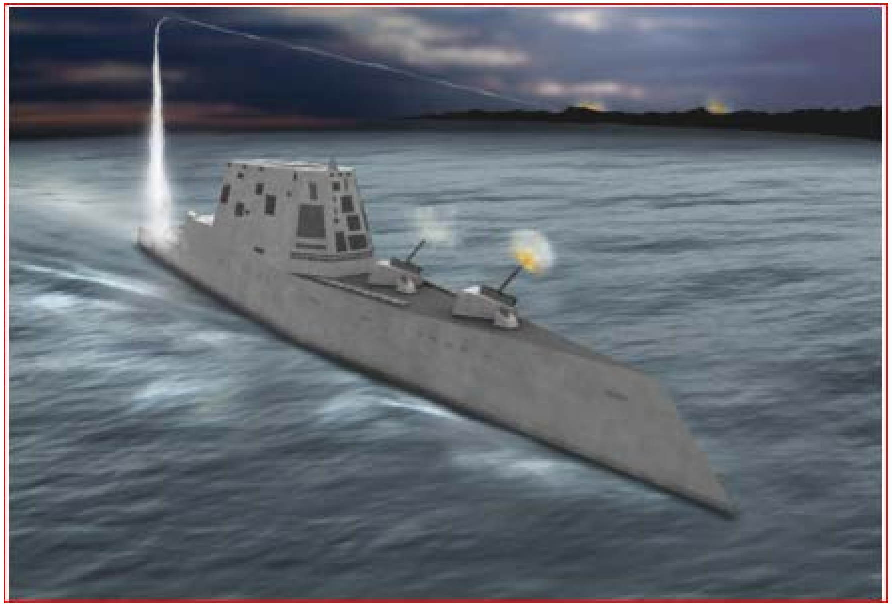
Prepared by
Andrew Schoenberg
September 26, 2018

CERL – OVERVIEW (WHO WE ARE AND WHAT WE DO)

LITERATURE REVIEW – UNDER SEA APPLICATIONS

Vinyl Ester / Carbon Fiber Large Scale Applications in Naval Sea Environment

Swedish Visby Class Destroyer



BIW Zumwalt DDG1000

Both of these Destroyers were made with vinyl ester and carbon fiber composites.
The DDG1000 and the Visby appear to have been made with Derakane 510A-40 and Toray T700S – FOE (Toray's vinyl ester specific sizing for CF).
The Zumwalt was made as a Balsa Core sandwich composite, while the Visby incorporated Foam core. The 510A-40 is a highly brominated Bis-A based VE for flame retardancy

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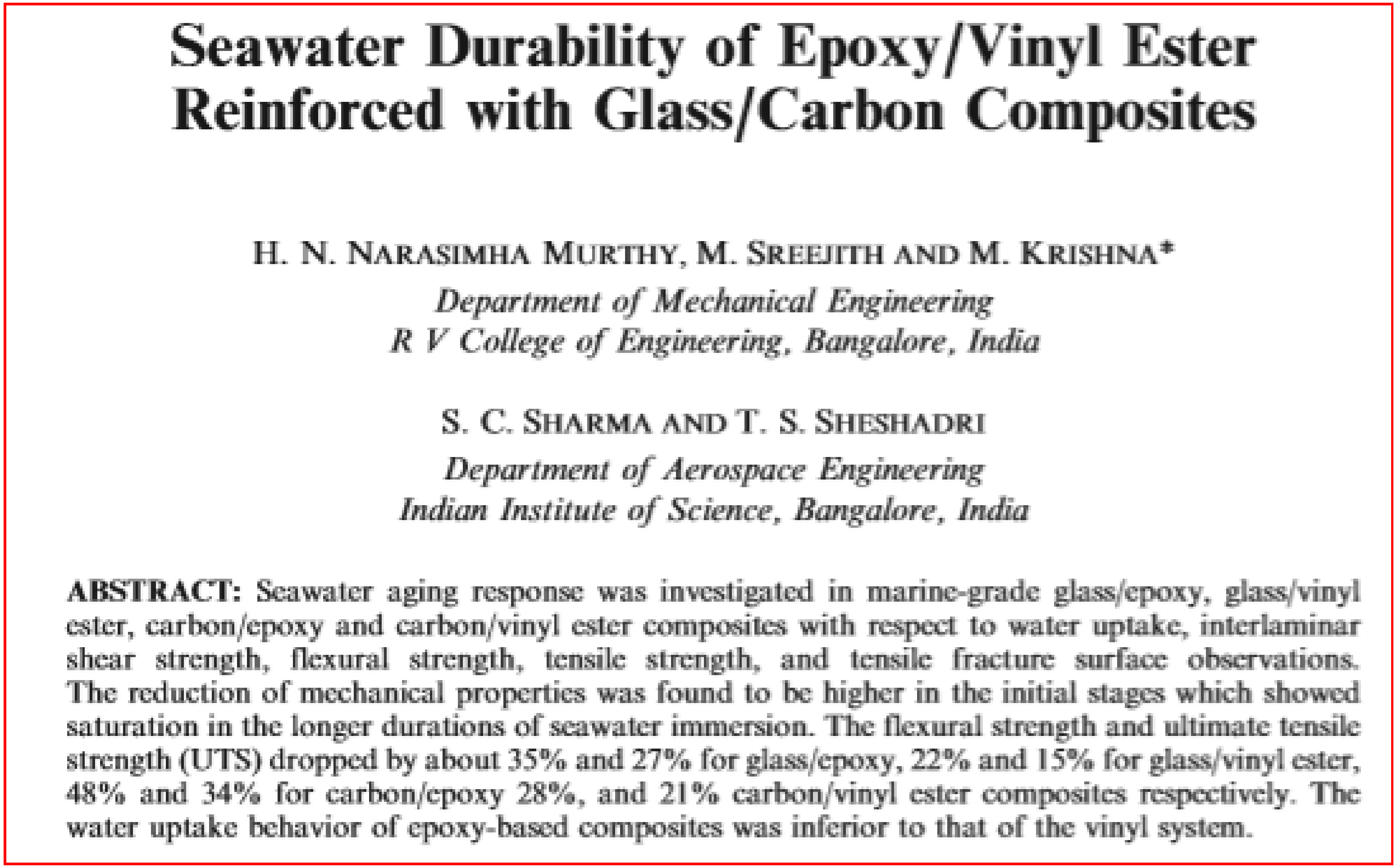

Seawater Durability of Epoxy/Vinyl Ester Reinforced with Glass/Carbon Composites

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ABSTRACT: Seawater aging response was investigated in marine-grade glass/epoxy, glass/vinyl ester, carbon/epoxy and carbon/vinyl ester composites with respect to water uptake, interlaminar shear strength, flexural strength, tensile strength, and tensile fracture surface observations. The reduction of mechanical properties was found to be higher in the initial stages which showed saturation in the longer durations of seawater immersion. The flexural strength and ultimate tensile strength (UTS) dropped by about 35% and 27% for glass/epoxy, 22% and 15% for glass/vinyl ester, 48% and 34% for carbon/epoxy 28%, and 21% carbon/vinyl ester composites respectively. The water uptake behavior of epoxy-based composites was inferior to that of the vinyl system.

Comparative Degradation of Polymer to Reinforcement Interface

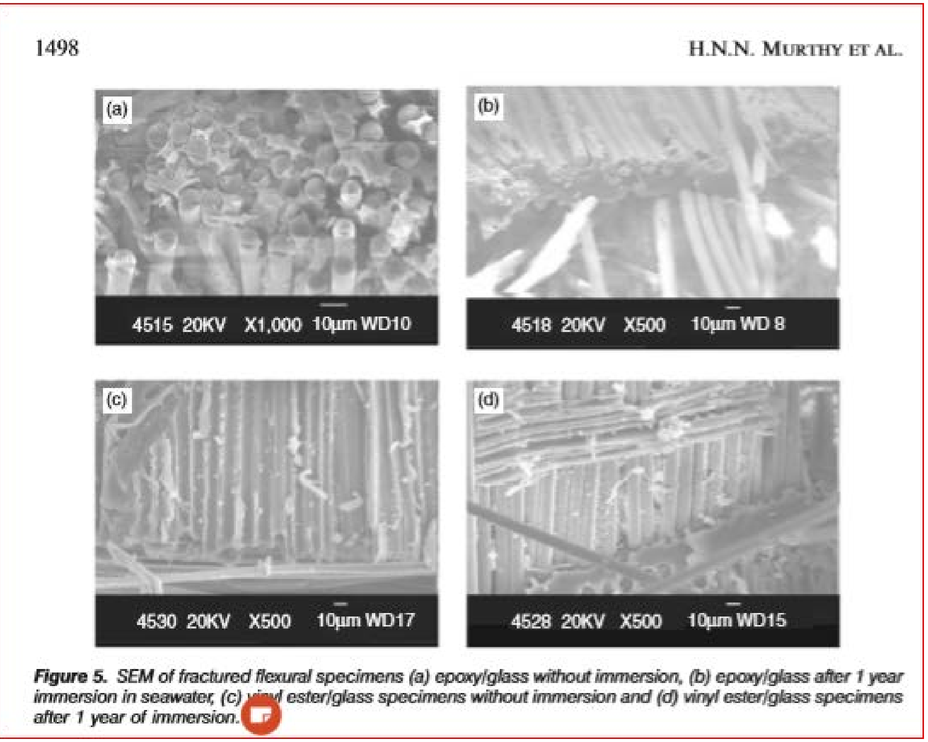
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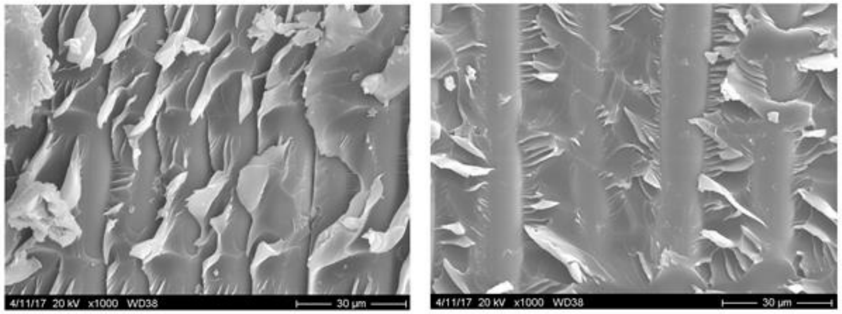
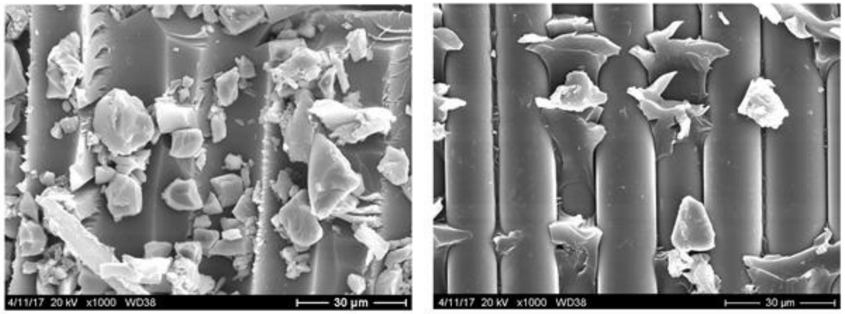
Figure 5. *SEM of fractured flexural specimens (a) epoxy/glass without immersion, (b) epoxy/glass after 1 year immersion in seawater, (c) vinyl ester/glass specimens without immersion and (d) vinyl ester/glass specimens after 1 year of immersion.*

From:Seawater Durability of Epoxy/ Vinyl Ester Reinforced with Glass/ Carbon Composites



4064-100 unconditioned 0° - 90° failure interface



4064-202W water conditioned 0° - 90° failure interface

Image from MSU related to epoxy Degradation – SEM images

CERL / ORPC DATA

Sandia / MSU Accelerated Aging Study 2018

Materials CE1 to CE6 manufacturing summaries.

Material	Layups	Fabrics	Resin	cure
CE1	[V(+/-45)g/0c]$_S$	Veil, E-BX-1700, Zoltek UD600	Pro-set INF 114/211	8h @ 60C
CE2	[V(+/-45)g/0c]$_S$	Veil, E-BX-1700, Vectorply CLA 1812		
CE3	[V(+/-45)g/0c]$_S$	Veil, E-BX-1700, Zoltek UD600	Hexion RIMR 035c/RIMH 0366	12h @ 70C
CE4	[V(+/-45)g/0c]$_S$	Veil, E-BX-1700, Vectorply CLA 1812		
CE5	[V(+/-45)g/0c]$_S$	Veil, E-BX 1700,CLA 1812, E-BX 1700	Crestapol 1250PUL urethane Acrylate	1.3h @ 80C, 1.3h @ 120C
CE6	[V/0/45/-45/0/V]	Veil, E-LT-2900, E-BX 1700, E-LT-2900	AME 6001 VE +1.5% MCP	

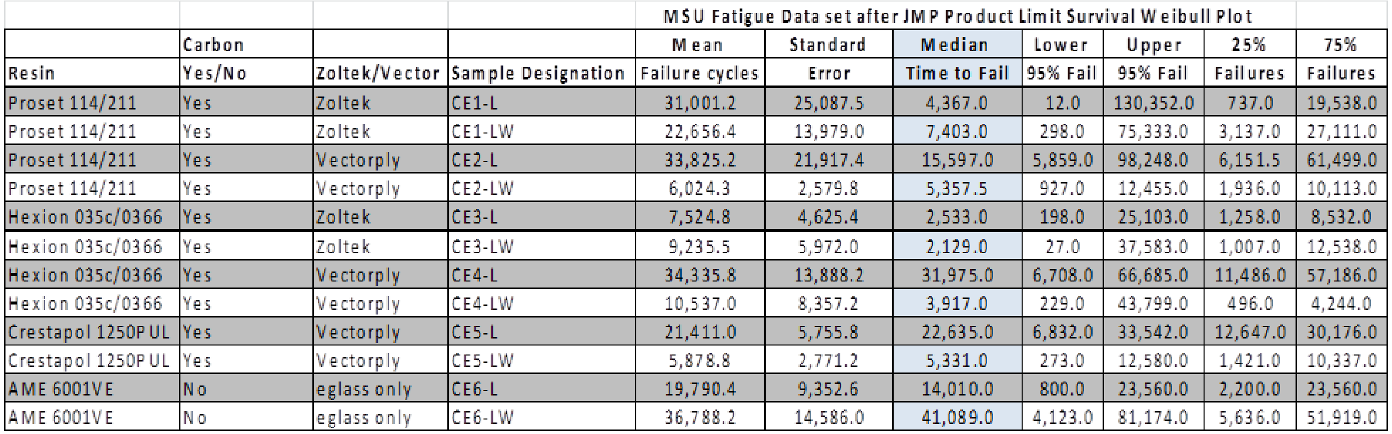
. Materials CE1 to CE6 dimensional and layup summaries.

Material	Average thickness all tests, mm	Maximum thickness mm	Minimum thickness mm	Average fiber volume %	Fiber contents			Layup
					% 0's	% +/- 45's	% 90's	
CE1	2.79	3.04	2.49	41.6	57.6 C	42.2 G	0.4 G	[V/(+/-45)g/0c]$_S$
CE2	3.31	3.67	3.06	36.7	56.6 C	43.4 G	0	
CE3	2.80	3.01	2.55	41.7	57.6 C	42.2 G	0.4 G	
CE4	3.33	3.54	3.09	36.5	56.6 C	43.4 G	0	
CE5	3.14	3.52	3.01	36.6	56.6 C	43.4 G	0	
CE6	2.47	2.73	2.18	42.0	69.2 G	22.5 G	8.3 G	[V/0/45/-45/0/V]

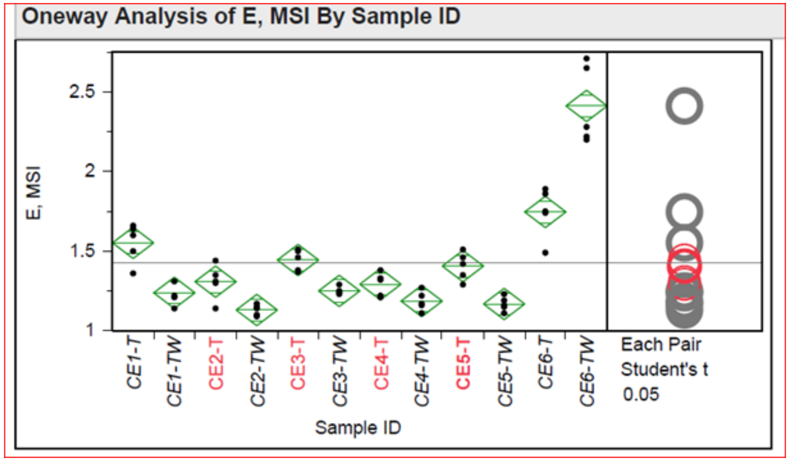
Carbon and glass fiber volume fractions in materials CE1 – CE6.

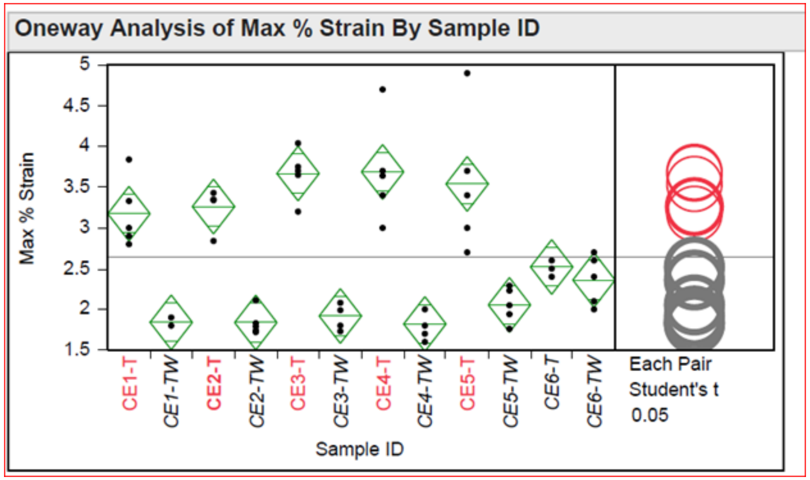
Material	Thickness Ave, mm	Fiber contents (C = carbon, G = glass)			Fabrics	V_F, % glass	V_F, % carbon	V_F, % total
		% 0's	% 45's	% 90's				
CE1	2.78	57.6 C	42.2 G	0.4 G	E-BX-1700, Zoltek UD600	18.4	22.5	40.9
CE2	3.43	56.6 C	43.4 G	0	E-BX-1700, Vectorply CLA 1812	15.4	20.4	35.8
CE3	2.86	57.6 C	42.2 G	0.4 G	E-BX-1700, Zoltek UD600	17.6	23.0	40.7
CE4	3.35	56.6 C	43.4 G	0	E-BX-1700, Vectorply CLA 1812	15.3	20.7	36.1
CE5	3.18	56.6 C	43.4 G	0	E-BX-1700, Vectorply CLA 1812	16.8	19.5	36.4
CE6	2.56	69.2 G	22.5 G	8.3 G	Veil, E-BX 1700,Vectorply CLA 1812	42.3	0	42.3

Sandia / MSU Study (cont.)



				MSU Fatigue Data set after JMP Product Limit Survival Weibull Plot						
	Carbon			Mean	Standard	Median	Lower	Upper	25%	75%
Resin	Yes/No	Zoltek/Vector	Sample Designation	Failure cycles	Error	Time to Fail	95% Fail	95% Fail	Failures	Failures
Proset 114/211	Yes	Zoltek	CE1-L	31,001.2	25,087.5	4,367.0	12.0	130,352.0	737.0	19,538.0
Proset 114/211	Yes	Zoltek	CE1-LW	22,656.4	13,979.0	7,403.0	298.0	75,333.0	3,137.0	27,111.0
Proset 114/211	Yes	Vectorply	CE2-L	33,825.2	21,917.4	15,597.0	5,859.0	98,248.0	6,151.5	61,499.0
Proset 114/211	Yes	Vectorply	CE2-LW	6,024.3	2,579.8	5,357.5	927.0	12,455.0	1,936.0	10,113.0
Hexion 035c/0366	Yes	Zoltek	CE3-L	7,524.8	4,625.4	2,533.0	198.0	25,103.0	1,258.0	8,532.0
Hexion 035c/0366	Yes	Zoltek	CE3-LW	9,235.5	5,972.0	2,129.0	27.0	37,583.0	1,007.0	12,538.0
Hexion 035c/0366	Yes	Vectorply	CE4-L	34,335.8	13,888.2	31,975.0	6,708.0	66,685.0	11,486.0	57,186.0
Hexion 035c/0366	Yes	Vectorply	CE4-LW	10,537.0	8,357.2	3,917.0	229.0	43,799.0	496.0	4,244.0
Crestapol 1250PUL	Yes	Vectorply	CE5-L	21,411.0	5,755.8	22,635.0	6,832.0	33,542.0	12,647.0	30,176.0
Crestapol 1250PUL	Yes	Vectorply	CE5-LW	5,878.8	2,771.2	5,331.0	273.0	12,580.0	1,421.0	10,337.0
AME 6001VE	No	eglass only	CE6-L	19,790.4	9,352.6	14,010.0	800.0	23,560.0	2,200.0	23,560.0
AME 6001VE	No	eglass only	CE6-LW	36,788.2	14,586.0	41,089.0	4,123.0	81,174.0	5,636.0	51,919.0

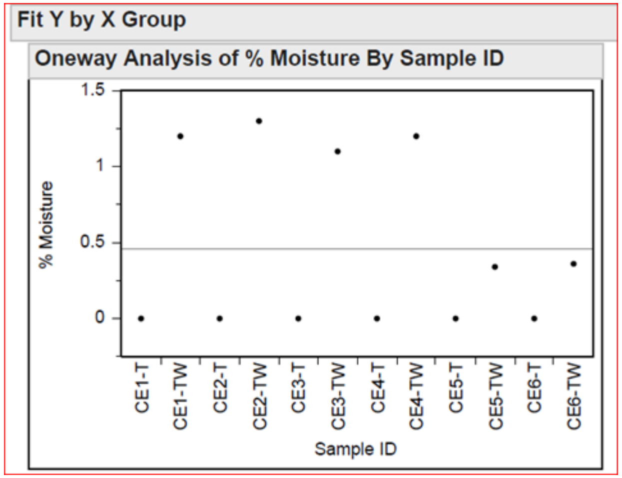




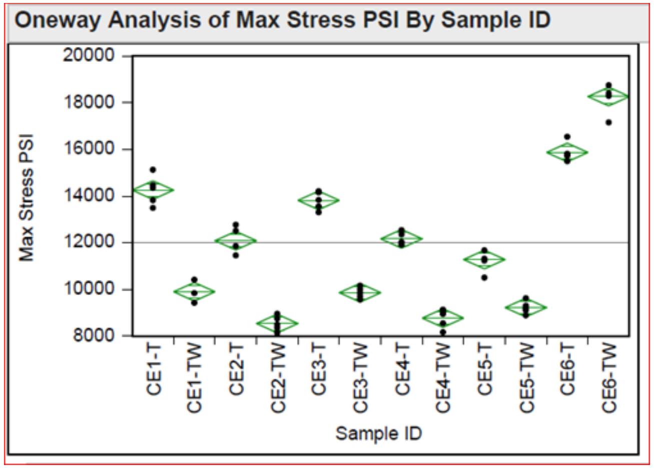
Static E (modulus) comparison wet to dry showed that in all but the CE6 laminate the E decreased after moisture soak except for the CE6 laminate made with E-glass , that also exhibited a significantly higher modulus than the other laminate(significant 90° fiber load compared to other laminate).

The One Way Max % Strain comparison also showed significant reduction in Max % Strain for the post moisture exposure samples compared to the dry, untested samples. The difference appears to be statistically less for the CE6 laminate (VE with E-glass).

Sandia /MSU Study (cont.)



The Oneway Fit for Comparison of % Moisture absorption of the laminate samples after exposure, highlights the significant reduction in moisture of the CE-5 (Polyurethane acrylate) and the CE-6 (VE and E-glass) samples when compared to the carbon fiber containing laminate made with epoxy/hardener resin chemistries. It would have been anticipated that the VE resin chemistry would have absorbed a more similar amount of moisture to the epoxy based on the backbone chemistry, and suggests that either the difference in moisture absorption is associated with the VE resin compared to the epoxy chemistries of CE1-CE4, or that there is a fundamental difference in the moisture absorption characteristics of E-Glass compared to Carbon Fiber.

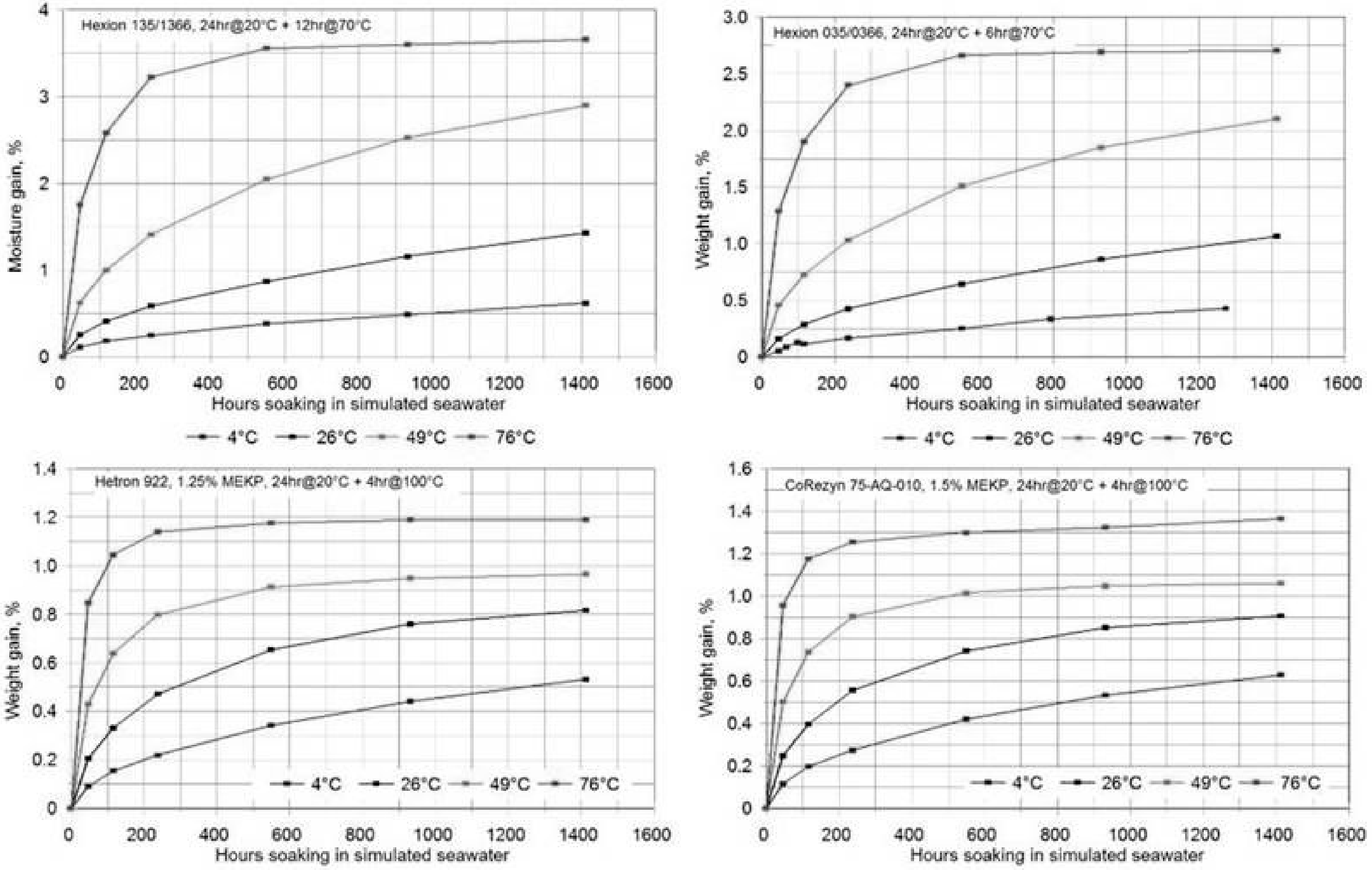


Oneway Analysis Max Stress PSI by sample ID – again there is a statistical difference between the performance of the laminate before and after moisture soak. With all but the CE-6 laminate exhibiting a significant reduction in Max Stress after Moisture soak. For the CE-6 laminate the Max Stress is much higher than that for the other laminate (this again relates to the 90° orientation of fiber tow compared to the carbon fiber based laminate), however, again there is not the same trend of reduction in performance.

Findings From Sandia / MSU Accelerated Aging Study

- Fundamentally the moisture soak in this accelerated testing induced change to the mechanical behavior of the laminate.
- The behavior of laminate CE6 made with all E-glass Vs . the laminate made with a combination of E-Glass and Carbon Fiber (dominate reinforcement of these laminate) which exhibited significantly greater loss of properties, may suggest that either the Carbon fiber and its associated coupling agents are more susceptible to moisture ingress and disbonding or that the fiber itself absorbs moisture and therefore weakens the structural properties of the laminate in the salt water emersion environment.
- The resin matrix utilized in this study specifically the Polyurethane acrylate laminate manufactured with the identical reinforcement schedule as CE-2 and CE-4 fundamentally reduced the overall moisture uptake of the laminate. The VE resin system laminate with reduced moisture absorption, may have been more influenced by the E-glass (which does not absorb moisture and has a robust coupling interface between the glass and resin) then by the VE resin chemistry.
- If the stated belief that the diffusion rate of moisture is higher when the composite laminate is under stress, then these static emersion tests do not fully identify the detrimental effects of moisture absorption. It will be important to further explore and understand the influences of :
- Resin Chemistry
- Reinforcement behavior and absorption characteristics
- coupling agent robustness, stability, and compatibility
- Laminate Coating (in mold and secondary application) to control moisture ingress, biological growth and mechanical wear and degradation
- Mechanical stress induced degradation under sea water

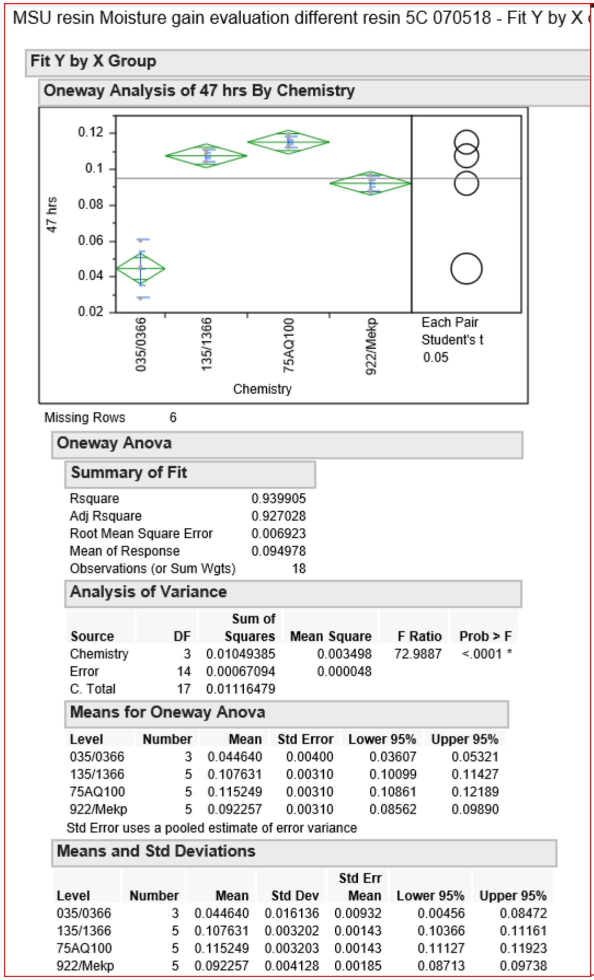
Moisture Uptake from Resin Plaques – Analysis Performed at MSU



Chemistry for Resin Only Sea Water (ASTM 1141) Submersion Study

- Hexion 135/1366: (24 hr 20C initial cure followed by 12 hrs at 70C)- epoxy / amine (cycloaliphatic and ether amine system)
- Hexion 035/0366: (24 hrs 20C initial cure followed by 6 hrs at 70C) – epoxy / amine system
- Hetron 922 w/ 1.25% MEKP: (24 hrs 20C initial cure followed by 4 hrs at 100C) – Epoxy Vinyl Ester / styrene Chemistry
- CoRezyn 75AQ-010 w/ 1.5% MEKP: (24 hrs 20C initial cure followed by 4 hrs at 100C) – Isophthalic based unsaturated polyester / styrene chemistry

Initial 47 Hour Immersion Absorption data



MSU resin Moisture gain evaluation different resin 5C 070518 - Fit Y by X

Fit Y by X Group

Oneway Analysis of 47 hrs By Chemistry

Missing Rows 6

Oneway Anova

Summary of Fit

Rsquare	0.939905
Adj Rsquare	0.927028
Root Mean Square Error	0.006923
Mean of Response	0.094978
Observations (or Sum Wgts)	18

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Chemistry	3	0.01049385	0.003498	72.9887	<.0001 *
Error	14	0.00067094	0.000048		
C. Total	17	0.01116479			

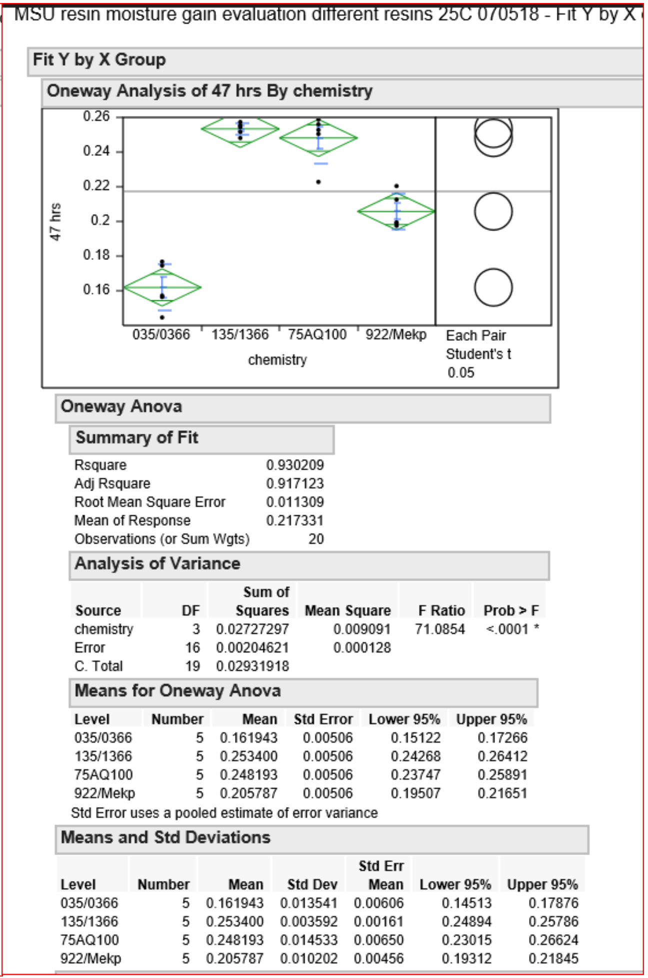
Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
035/0366	3	0.044640	0.00400	0.03607	0.05321
135/1366	5	0.107631	0.00310	0.10099	0.11427
75AQ100	5	0.115249	0.00310	0.10861	0.12189
922/Mekp	5	0.092257	0.00310	0.08562	0.09890

Std Error uses a pooled estimate of error variance

Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
035/0366	3	0.044640	0.016136	0.00932	0.00456	0.08472
135/1366	5	0.107631	0.003202	0.00143	0.10366	0.11161
75AQ100	5	0.115249	0.003203	0.00143	0.11127	0.11923
922/Mekp	5	0.092257	0.004128	0.00185	0.08713	0.09738



MSU resin moisture gain evaluation different resins 25C 070518 - Fit Y by X

Fit Y by X Group

Oneway Analysis of 47 hrs By chemistry

Oneway Anova

Summary of Fit

Rsquare	0.930209
Adj Rsquare	0.917123
Root Mean Square Error	0.011309
Mean of Response	0.217331
Observations (or Sum Wgts)	20

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
chemistry	3	0.02727297	0.009091	71.0854	<.0001 *
Error	16	0.00204621	0.000128		
C. Total	19	0.02931918			

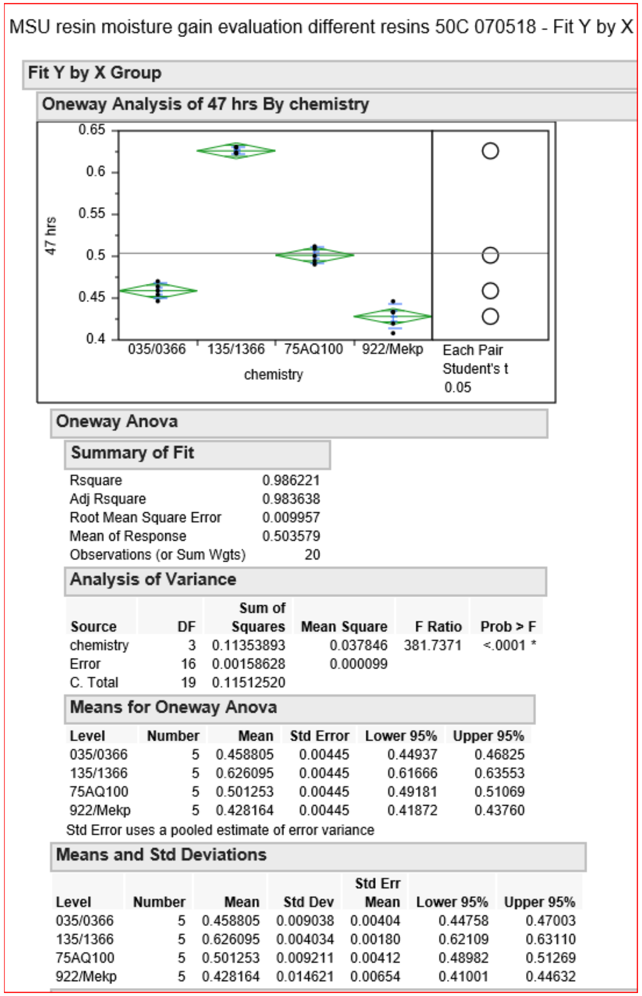
Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
035/0366	5	0.161943	0.00506	0.15122	0.17266
135/1366	5	0.253400	0.00506	0.24268	0.26412
75AQ100	5	0.248193	0.00506	0.23747	0.25891
922/Mekp	5	0.205787	0.00506	0.19507	0.21651

Std Error uses a pooled estimate of error variance

Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
035/0366	5	0.161943	0.013541	0.00606	0.14513	0.17876
135/1366	5	0.253400	0.003592	0.00161	0.24894	0.25786
75AQ100	5	0.248193	0.014533	0.00650	0.23015	0.26624
922/Mekp	5	0.205787	0.010202	0.00456	0.19312	0.21845



MSU resin moisture gain evaluation different resins 50C 070518 - Fit Y by X

Fit Y by X Group

Oneway Analysis of 47 hrs By chemistry

Oneway Anova

Summary of Fit

Rsquare	0.986221
Adj Rsquare	0.983638
Root Mean Square Error	0.009957
Mean of Response	0.503579
Observations (or Sum Wgts)	20

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
chemistry	3	0.11353893	0.037846	381.7371	<.0001 *
Error	16	0.00158628	0.000099		
C. Total	19	0.11512520			

Means for Oneway Anova

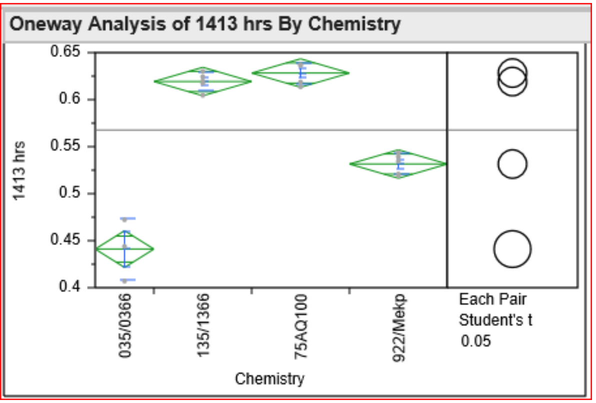
Level	Number	Mean	Std Error	Lower 95%	Upper 95%
035/0366	5	0.458805	0.00445	0.44937	0.46825
135/1366	5	0.626095	0.00445	0.61666	0.63553
75AQ100	5	0.501253	0.00445	0.49181	0.51069
922/Mekp	5	0.428164	0.00445	0.41872	0.43760

Std Error uses a pooled estimate of error variance

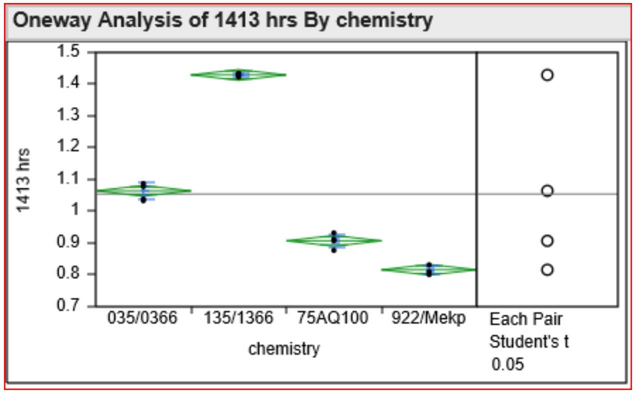
Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
035/0366	5	0.458805	0.009038	0.00404	0.44758	0.47003
135/1366	5	0.626095	0.004034	0.00180	0.62109	0.63110
75AQ100	5	0.501253	0.009211	0.00412	0.48982	0.51269
922/Mekp	5	0.428164	0.014621	0.00654	0.41001	0.44632

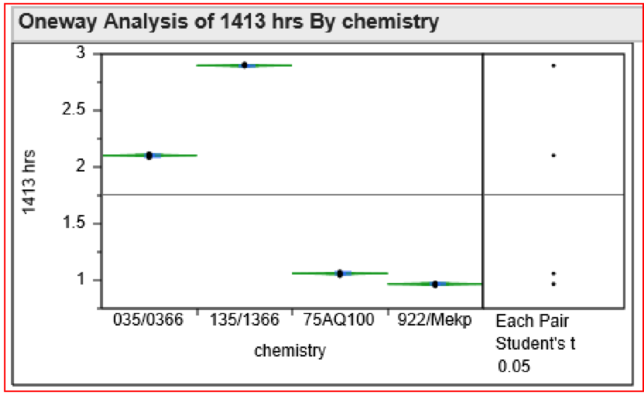
1413 Hours Submersion Response for Each of the Three Temperatures



5C Submersion response



25C submersion response



50C submersion response

Hexion 135/1366 and Hexion 035c/0366 are both Epoxy and amine type hardener systems
Hetron 922 / 1.25% MEKP is an Epoxy based Vinyl Ester
CoRezyn 75AQ-010 / 1.5% MEKP is an isophthalic unsaturated polyester chemistry

RESIN / REINFORCEMENT RECOMMENDATION

Comparative Database of Vinyl Ester Resins for First Article ORPC MHK Foils at RAM

Manufacturer	Reichhold	Ashland	**Ashland**	Interplastic Corp	Interplastic Corp	**Polynt**
Resin Family name	Hydrex	AME	**Derakane**	CoREZYN Corve	CoREZYN / Corve	**Epovia**
Resin model #	100HF 33375-00	6001 INF 35	**411-350 (411-100 for VIP)**	VE8300	VE8100	**RF1001L-35**
Chemistry	Marine VE	epoxy VE	**Bis-A epoxy VE**	Bis-A epoxy VE	Bis-A epoxy VE	**BPA based VE**
Styrene Content (%)	<35	30-40	**45**	45	50	**40-50**
Target Application	Marine	Marine	**Industrial**	Industrial	Industrial	**Industrial**
Viscosity (cps)	150-260	145	**370**	500	100	**100**
Initiator System	CHP only with cobalt	MEKP-9	**MEKP CoNap**	MEKP CoNap	MEKP CoNap	**MEKP**
Gel Time Min. (25C)	45-60	35	**30-60**	25-30	15-20	**35**
Tensile Strength	12,900 psi	11,500 psi	**12,000 psi**	11,600 psi	11,800 psi	**12,000 psi**
Tensile Modulus	330 Kpsi	500 Ksi	**460 Kpsi**	470 Kpsi	530 Kpsi	**540 Kpsi**
Tensile Elongation	4.90%	5.20%	**5-6%**	5%	4.50%	**5.50%**
Flexural Strength	21,900psi	21,600 psi	**22,000psi**	19,400 psi	21,200 psi	**22,000 psi**
Flexural Modulus	530 Kpsi	525 Ksi	**490 Ksi**	450 Kpsi	520 Kpsi	**500 Kpsi**
HDT deg. C	111	91	**105**	99	104	**108**
Barcol Hardness	44		**35**	30-38	30-38	**40**
Water Absop. 2 hrs 212F	0.65					
Water Absorp. 24hrs 73F	0.22					
Rec. Post Cure		24 hr 60C	**6 hr 80C**	6 hr 80C	6 hr 80C	**2hr 80C, 2 hr 120C**
CF Reference			**YES**	YES		**Yes**
			FRP present.	Graphite and Kevlar		

Vinyl Ester resin chemistry
With historical CF
Application data.

Carbon Fiber Designation

9/12/2018	Zoltek - Robert Faddis - "Our carbon fiber should be fine with a vinyl-ester resin and in the environment you described".
9/18/2018	Zoltek developing a specific VE sizing for their PX35 50K tow that they will supply us for our sub sea study
9/19/2018	Conference call with Kamesh, Robert and Paul - The VE sizing is now commercially available (1 other cust. In trials) and it called PX35-72 (Vs. standard PX35-13)
	Almost all of their data on VE and CF comparisons with epoxy are in Pultruded systems and products. They can supply a 600 gsm Uni fabric with the PX35-72
	We will need to sign an NDA with Zoltek in order for them to share their data regarding the performance of this new sizing product.
9/24/2018	Joe Fox of Ashland recommends the Zoltek PX-35-72 as an appropriate CF sized for VE
9/12/2018	Toray - Dr. Chet Moon Director -We do have a couple of fiber sizings that are compatible with vinyl ester chemistry.
	Type 5 size is our general purpose sizing and fabrics made with this sizing type are readily available.
	Type F0E sizing was developed specifically for vinyl ester resins, but no one is currently weaving this product, so availability would be problematic.
9/20/2018	Dr. Moon suggests talking with Dallas based sales for this project to obtain the -FOE sizing coated CF.
9/13/2018	Of all of our carbon fiber fabric products, the best performing with VE resin systems use the Toray T700SC-12K-50C input
	(mainly lower areal weight fabrics like C-BX 0600, C-BX 0900, C-LT 1100, C-QX 1800, & C-QX 2300).
	Regards,
	Trevor Gundberg, P.E.
	Director of Composites Engineering
	Vectorply Corporation
9/19/2018	Trevor Gundberg, P.E. - indicated that both Visby and the Zumwalt were made with Toray T700S Tow using the FOE sizing. He indicated that this sizing is more
	difficult to make and that the standard VE compatible sizing that Vectorply uses for the Toray based fabric is the 50C. The FOE has a better wet and laminar shear
	peroformance than the 50C. Vectorply has done a lot of work with Polynt and the compatability of their VE with the CF. He will send data.
9/24/2018	I liked the KF3202L, as it added toughness, and provided similar static properties as the RF1001L, but it does cost more (and I'm not sure how well it would work in hot/wet testing).
	Typically for carbon fiber in general, I'd recommend not infusing single ply FAW's about 600gsm without adjacent ply orientation changes or built in flow media (like our "Micromesh" monofilament Polyamide veils - standard is 17gsm -
	which work well when paired with 600gsm plies to increase permeability and not significantly effect mechanical properties). As long at the ply layers don't nest on themselves to a significant degree,
	infusion works pretty well (we have regularly infused ¾" thick laminates made from 800gsm quad fabrics made with the -50C input).
	I don't see any issues in hybridizing with glass fiber, as we do this regularly as well. I'd recommend hybridizing within the laminate (all single plies or lamina being a single fiber), even though interplay hybridizing is commonplace.
	. As a side note, we will be doing a VE infusion at CAMX on an automotive hood mold (3D printed mold) that will use the Vectorply carbon fiber,
	Polynt RF1001L-35 with a layer of Lantor's Soric TF 2mm as a core between two layers of carbon fiber. If you go to CAMX, please stop by our booth or the C-1 Demo zone.
9/17/2018	Rick Pauer - Polynt
	Regarding a 2 gallon sample. Of interest, I will be making the material next week in KC for our practice and again for the actual show, so my plan for you would
	be to ship you a part pail of RF1001L-35 for you to test with the VP carbon. Trevor is a great contact, but now that he has added engineering responsibility's at VP,
	our main contact has become Mike Ditzler. Either Trevor or Mike can answer your question on sizing nomenclature for VE resins.
	Rick Pauer of Polynt said that at CAMX 2018 he is working with Vectorply to do a demonstration of VE with CF in 3D printed Mold
	The VE resins match up well with the properly sized carbon fiber. We often work with Vectorply on demo's and with customers
	As a side note, we will be doing a VE infusion at CAMX on an automotive hood mold (3D printed) that will use the Vectorply carbon fiber,
	Polynt RF1001L-35 with a layer of Lontor's Soric TF 2mm as a core between two layers of Carbon Fiber.
9/24/2018	Michael Stevens Principle Scientist - Ashland
	DERAKANE 411-100 resin can be used for this application.
	The use of DERAKANE 510A-40 resin was used by the Navy because they also needed a fire retardant resin.
	If you do not need the fire retardant resin, then you will be better off using DERAKANE 411 resin

Carbon Fiber Reinforcement

- Zoltek standard carbon fiber is made with their -13 sizing. This is a multi-compatible sizing that is acceptable for epoxy and vinyl ester. Zoltek development sizing specifically for carbon fiber is the -72. This is now commercially available in limited fabrics. We would have to sign an NDA to get more information from Zoltek, but they are willing to generate the UD600 fabric if we want (for testing or for foils)
- Toray standard sizing for their carbon fiber is -50C. This is a multi-compatible sizing that is acceptable for epoxy and vinyl ester. Toray has a commercial product sizing –FOE that was used for the two destroyers, however it is not generally manufactured (somewhat more difficult to make). Toray indicated that based on the size of this project they may be willing to generate the TOW required with this sizing. We would purchase the fabrics from Vectorply

Vectorply CF / VE Resin Analysis

Fabric Manu.	Material	Fiber/Fabric Input	Laminate Schedule	Continuous Fiber by Axis	Test Date	Resin	Fab. Process	Wf (%)	Thickness (in)	Tension ASTM D 3039-00 (ASTM D 638)					Tension ASTM D 3039-00 (ASTM D 638)					Tension ASTM D 3039-00				
										0º					90º					45º				
										Strength (ksi)	S.D.	Modulus (Msi)	S.D.	Elongation %	Strength (ksi)	S.D.	Modulus (Msi)	S.D.	Elongation %	Strength (ksi)	S.D.	Modulus (Msi)	S.D.	Elongation %
Vectorply	C-BX 0900	T700SC-12K-50C	90 on inside	T700SC-12K-50C	12/29/2017	RF 1001	Infusion			136.73	5.500	8.11	0.200	1.65%	139.22	5.200	7.07							
Vectorply	C-BX 0600 / MM	T700SC-12K-50C, PA1800 Micromesh	(+45°/-45°)$_{4S}$	±45° - T700S	1/17/2014	VE: CCP Epovia KF3202L-00	Infusion	60.2	0.099											111.05	5.02	5.62	0.42	1.98%
Vectorply	C-BX 0600	T700SC-12K-50C	(+45°/-45°)$_{6S}$	±45° - T700S	1/17/2014	VE: CCP Epovia KF3202L-00	Infusion	72.2	0.095											162.92	7.38	9.55	0.25	1.71%
Vectorply	C-BX 1200 / MM	T700SC-12K-50C, PA1800 Micromesh	(+45°/-45°)$_{3S}$	±45° - T700S	1/17/2014	VE: CCP Epovia KF3202L-00	Infusion	62.9	0.116											147.03	5.28	6.98	0.19	2.11%
Vectorply	C-BX 1200	T700SC-12K-50C	(+45°/-45°)$_{3S}$	±45° - T700S	1/17/2014	VE: CCP Epovia KF3202L-00	Infusion	71.3	0.094											170.71	8.34	9.00	0.27	1.90%
Vectorply	C-BXi 0415	T700SC-12K-50C, PA1470 Spunfab	(+45°/-45°)$_{8S}$	±45° - T700S	1/17/2014	VE: CCP Epovia KF3202L-00	Infusion	71.6	0.093											157.65	7.40	9.56	0.13	1.65%
Vectorply	C-BXi 1220	T700SC-12K-50C, PA1470 Spunfab	(+45°/-45°)$_{3S}$	±45° - T700S	1/17/2014	VE: CCP Epovia KF3202L-00	Infusion	64.6	0.112											143.78	3.45	8.22	0.16	1.75%
Vectorply	C-BX 1200	T700SC-12K-50C	(+45°/-45°)$_{3S}$	±45° - T700S	8/13/2013	VE: CCP Epovia RF1001L00	Infusion	70.1												174.2	1.78% (CV)	10.70	7.83% (CV)	1.63%
Vectorply	C-BX 1200	T700SC-12K-50C	(+45°/-45°)$_{3S}$	±45° - T700S	8/13/2013	VE: CCP Epovia RF1001L00	Infusion	70.1												178.7	3.73% (CV)	8.90	3.00% (CV)	2.01%
Vectorply	C-BX 1200	T700SC-12K-50C	(+45°/-45°)$_{8S}$	±45° - T700S	8/13/2013	VE: CCP Epovia RF1001L00	Infusion	74.9																
Vectorply	C-LT 1800 /MM	T700SC-12K-50C	(0°/90°/MM)$_{2S}$	0° - T700S 90° - T700S	7/1/2013	VE: CCP KF3202L-00	Infusion	57.78	0.124	98.534	6.765	7.49	0.25	1.30%	131.434	8.747	7.37	0.20	1.71%					
Vectorply	C-BX 1200	T700SC-12K-50C, 0.5oz MM	±45°/±45°/±45°/±45°	±45° - T700S	9/10/2007	VE: Hexion 781-2140	Infusion	65.40	0.076											80.6	3.5203	8.36	0.194	0.96%
Vectorply	C-BX 1200 / MM	T700SC-12K-50C, 0.5oz MM	MM/±45°/MM/±45°/MM/±45°/MM/±45°	±45° - T700S	9/10/2007	VE: Hexion 781-2140	Infusion	52.50	0.083											92.4	4.109	7.65	0.3306	1.21%
Vectorply	C-BX 1200 / MM	T700SC-12K-50C, 0.5oz MM	MM/±45°/MM/±45°/MM/±45°/MM/±45°	±45° - T700S	7/24/2007	VE: Hexion 781-2140	Infusion		0.083															
Vectorply	C-BX 1200 / MM	T700SC-12K-50C, 0.5oz MM	MM/±45°/MM/±45°/MM/±45°/MM/±45°	±45° - T700S	7/24/2007	VE: Hexion 781-2140	Infusion		0.083															
Vectorply	C-BX 1200	T700SC-12K-50C	±45°/±45°/±45°/±45°	±45° - T700S	7/24/2007	VE: Hexion 781-2140	Infusion		0.076															
Vectorply	C-BX 1200	T700SC-12K-50C	±45°/±45°/±45°/±45°	±45° - T700S	7/24/2007	VE: Hexion 781-2140	Infusion		0.076															
Vectorply	C-BX 1200 / MM	T700SC-12K-50C, 0.5oz MM	±45°/±45°	±45° - T700S	6/18/2007	VE: Hexion 781-2140	Infusion		0.044											79.850	9.025	8.180	0.490	0.98%
Vectorply	C-BX 1200 / MM	T700SC-12K-50C, 0.5oz MM	±45°/±45°	±45° - T700S	6/18/2007	VE: Hexion 781-2140	Infusion		0.044											91.660	6.435	8.250	0.250	1.11%
Vectorply	C-BX 1200 / MM	T700SC-12K-50C, 0.5oz MM	±45°/±45°	±45° - T700S	6/18/2007	VE: Hexion 781-2140	Infusion		0.042											99.54	4.492	8.13	1.08	1.22%
Vectorply	C-LT 1800 / MM	T700SC-12K-50C, 0.5oz MM	(MM/0°/90°/MM/0°/90°)$_{5S}$	0° - T700S 90° - T700S	7/24/2007	VE: Hexion 781-2140	Infusion		0.301															
Vectorply	C-LT 1800 / MM	T700SC-12K-50C, 0.5oz MM	(MM/0°/90°/MM/0°/90°)$_{5S}$	0° - T700S 90° - T700S	7/24/2007	VE: Hexion 781-2140	Infusion		0.301															
Vectorply	C-LT 1800	T700SC-12K-50C	(0°/90°/0°/90°)$_{5S}$	0° - T700S 90° - T700S	7/24/2007	VE: Hexion 781-2140	Infusion		0.261															
Vectorply	C-LT 1800	T700SC-12K-50C	(0°/90°/0°/90°)$_{5S}$	0° - T700S 90° - T700S	7/24/2007	VE: Hexion 781-2140	Infusion		0.261															

Compression ASTM D 695-96 (ASTM D3410)				Flexural Properties ASTM D 790-00				Flexural Properties ASTM D 790-00				Flexural Properties ASTM D 790-00				ILSS ASTM D 2344						IP Shear ASTM D 4255 (D3518, D7078)								Notes
45º				0º				90º				45º				0º		90º		45º		0º				90º		45º		
Strength (ksi)	S.D.	Modulus (Msi)	S.D.	Strength (ksi)	S.D.	Modulus (Msi)	S.D.	Strength (ksi)	S.D.	Modulus (Msi)	S.D.	Strength (ksi)	S.D.	Modulus (Msi)	S.D.	Strength (ksi)	S.D.	Strength (ksi)	S.D.	Strength (ksi)	S.D.	Strength (ksi)	S.D.	Modulus (Msi)	S.D.	Strength (ksi)	S.D.	Strength (ksi)	S.D.	
												65.49		4.33																
												95.88		7.74																
												72.79		5.80																
												84.76		7.93																
												84.34		8.91																
												83.33		6.01																
85.5	6.02% (CV)	10	5.13% (CV)									96.2	5.32% (CV)	8.4	6.64% (CV)															
81.1	4.03% (CV)											84.3	3.15% (CV)	5.1	5.99% (CV)															
																				4.9 to 4.8	8.89% (CV) to 3.74% (CV)									
				84.261	2.612	6.72	0.15	71.475	6.843	4.13	0.24																			Tg (DMA) 134.3°C
58.000	6.371																													
61.600	6.825																													
												55.0		5.76																Micromesh side in tension
												62.9		5.83																carbon side in tension
												72.1		5.38																Tool side in tension
												80.7		4.78																Bag side in tension
53.540	11.566	8.230	1.240									49.495	13.322	5.84	1.83					3.08	0.364							11.01	N/A	
52.210	11.479											55.16	5.369	8.26	0.77					3.41	0.303							12.51	N/A	
45.890	9.324	8.380	1.050									42.255	9.433	7.43	0.88					3.13	0.378							15.57	N/A	
																4.08														Micromesh side in tension
																3.98														carbon side in tension
																3.80														Tool side in tension
																3.60														Bag side in tension

Pultrusion – Sizing / Vinyl Ester Resin

Product Feature	**Test Method**	**PX35-13**	**PX35-72**
Resin	-	Vinyl Ester	Vinyl Ester
Fiber volume fraction (mean)	ASTM D3171	62%	63%
Interlaminar Shear Strength (characteristic)	ISO14130	59 MPa	62 MPa
Transverse Flexural Strength (characteristic)	ASTM D790	40 MPa	72 MPa
Axial Tensile Modulus (mean)	ISO 527	137 GPa	141 GPa
Axial Compressive Modulus (mean)	ASTM D6641	128 GPa	133 GPa
Linear tensile strain to failure (characteristic)	ISO 527	1.08%	1.06 %
Linear compression strain to failure (characteristic)	ASTM D6641	0.77%	0.73%

Carbon Fiber Sizing For Vinyl Ester

Preliminary Technical Datasheet

ZOLTEK™ PX35 Vinyl Ester Compatible Tow

ZOLTEK Toray Group

Commercial Carbon Fiber for Industrial Applications

DESCRIPTION

Zoltek has developed a new product and sizing chemistry for use in vinyl ester resin systems. Introducing Zoltek's new PX35-72 product. This new product based on the proprietary -72 sizing chemistry exhibits excellent adhesion to and compatibility with vinyl ester resin systems.

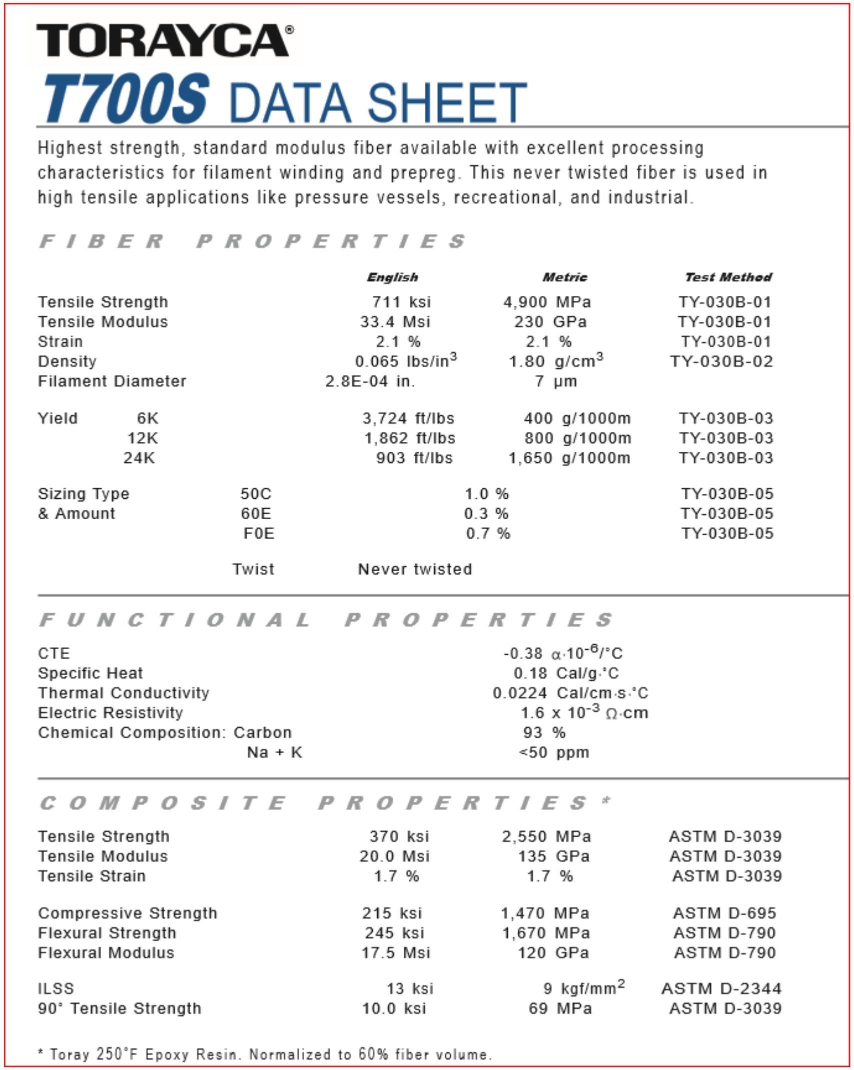
Most carbon fiber products are used to reinforce epoxy resin systems. Recently, the demand has grown for a product and sizing chemistry that can be used in vinyl ester resins whether cured thermally or via room temperature infusion.

When compared to Zoltek's standard carbon fiber product, PX35-13, the new vinyl ester compatible PX35-72 has significantly higher interlaminar shear strength (ILSS) and transverse flexural strength TFS, which both measure and indicate fiber to resin matrix compatibility and adhesion as well as composite performance.

Zoltek's PX35-72 continuous carbon fiber is manufactured from a polyacrylonitrile (PAN) precursor fiber. The consistency in yield and mechanical properties that are provided by large filament count strands gives the user flexibility to design and manufacture composite materials.

MARKET APPLICATIONS

Marine, wind energy, automotive



TORAYCA®

T700S DATA SHEET

Highest strength, standard modulus fiber available with excellent processing characteristics for filament winding and prepreg. This never twisted fiber is used in high tensile applications like pressure vessels, recreational, and industrial.

FIBER PROPERTIES

		English	Metric	Test Method
Tensile Strength		711 ksi	4,900 MPa	TY-030B-01
Tensile Modulus		33.4 Msi	230 GPa	TY-030B-01
Strain		2.1 %	2.1 %	TY-030B-01
Density		0.065 lbs/in^3	1.80 g/cm^3	TY-030B-02
Filament Diameter		2.8E-04 in.	7 µm	
Yield	6K	3,724 ft/lbs	400 g/1000m	TY-030B-03
	12K	1,862 ft/lbs	800 g/1000m	TY-030B-03
	24K	903 ft/lbs	1,650 g/1000m	TY-030B-03
Sizing Type & Amount	50C		1.0 %	TY-030B-05
	60E		0.3 %	TY-030B-05
	F0E		0.7 %	TY-030B-05
	Twist	Never twisted		

FUNCTIONAL PROPERTIES

CTE	-0.38 α·10^{-6}/°C
Specific Heat	0.18 Cal/g·°C
Thermal Conductivity	0.0224 Cal/cm·s·°C
Electric Resistivity	1.6 x 10^{-3} Ω·cm
Chemical Composition: Carbon	93 %
Na + K	<50 ppm

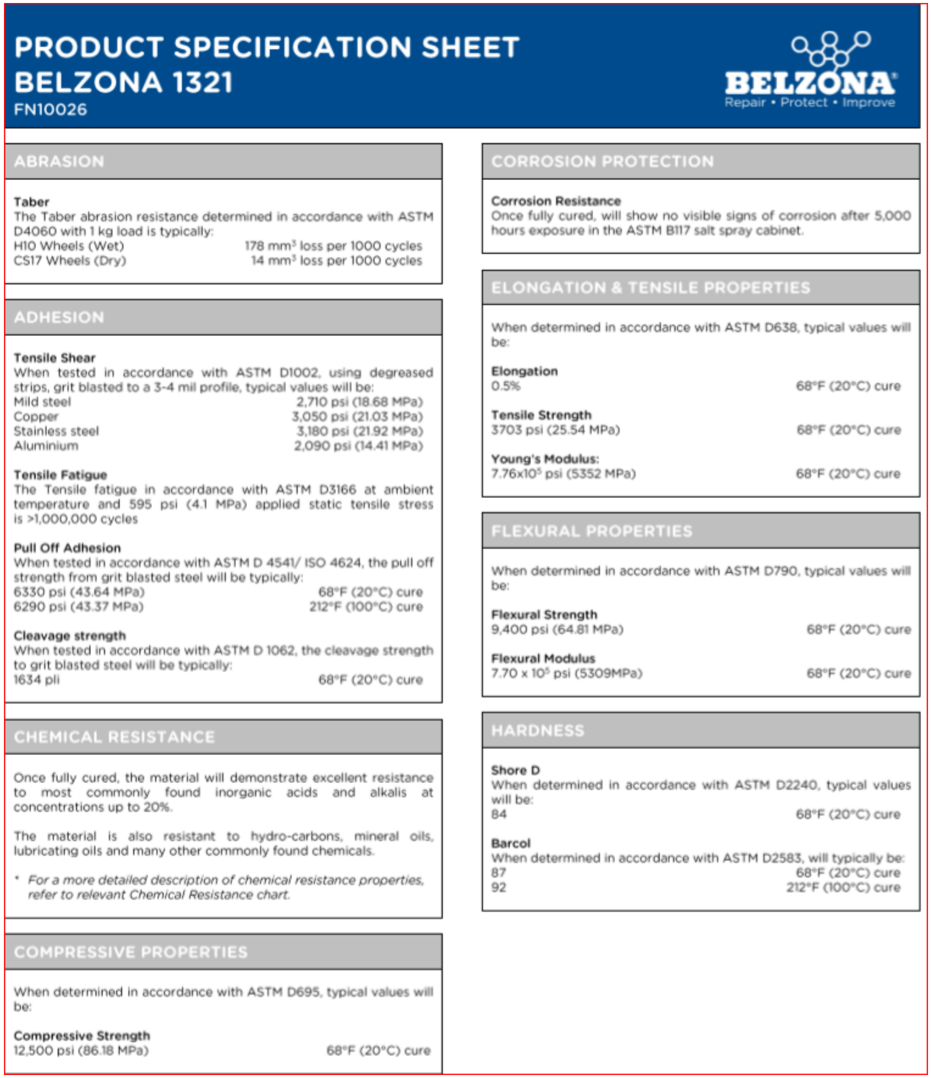
COMPOSITE PROPERTIES*

	English	Metric	Test Method
Tensile Strength	370 ksi	2,550 MPa	ASTM D-3039
Tensile Modulus	20.0 Msi	135 GPa	ASTM D-3039
Tensile Strain	1.7 %	1.7 %	ASTM D-3039
Compressive Strength	215 ksi	1,470 MPa	ASTM D-695
Flexural Strength	245 ksi	1,670 MPa	ASTM D-790
Flexural Modulus	17.5 Msi	120 GPa	ASTM D-790
ILSS	13 ksi	9 kgf/mm^2	ASTM D-2344
90° Tensile Strength	10.0 ksi	69 MPa	ASTM D-3039

* Toray 250°F Epoxy Resin. Normalized to 60% fiber volume.

POST MANUFACTURING COATING

Corrosion Coating



PRODUCT SPECIFICATION SHEET
BELZONA 1321
FN10026

BELZONA
Repair • Protect • Improve

ABRASION

Taber
The Taber abrasion resistance determined in accordance with ASTM D4060 with 1 kg load is typically:

H10 Wheels (Wet)	178 mm^3 loss per 1000 cycles
CS17 Wheels (Dry)	14 mm^3 loss per 1000 cycles

ADHESION

Tensile Shear
When tested in accordance with ASTM D1002, using degreased strips, grit blasted to a 3-4 mil profile, typical values will be:

Mild steel	2,710 psi (18.68 MPa)
Copper	3,050 psi (21.03 MPa)
Stainless steel	3,180 psi (21.92 MPa)
Aluminium	2,090 psi (14.41 MPa)

Tensile Fatigue
The Tensile fatigue in accordance with ASTM D3166 at ambient temperature and 595 psi (4.1 MPa) applied static tensile stress is >1,000,000 cycles

Pull Off Adhesion
When tested in accordance with ASTM D 4541/ ISO 4624, the pull off strength from grit blasted steel will be typically:

6330 psi (43.64 MPa)	68°F (20°C) cure
6290 psi (43.37 MPa)	212°F (100°C) cure

Cleavage strength
When tested in accordance with ASTM D 1062, the cleavage strength to grit blasted steel will be typically:
1634 pli 68°F (20°C) cure

CHEMICAL RESISTANCE

Once fully cured, the material will demonstrate excellent resistance to most commonly found inorganic acids and alkalis at concentrations up to 20%.

The material is also resistant to hydro-carbons, mineral oils, lubricating oils and many other commonly found chemicals.

* *For a more detailed description of chemical resistance properties, refer to relevant Chemical Resistance chart.*

COMPRESSIVE PROPERTIES

When determined in accordance with ASTM D695, typical values will be:

Compressive Strength
12,500 psi (86.18 MPa) 68°F (20°C) cure

CORROSION PROTECTION

Corrosion Resistance
Once fully cured, will show no visible signs of corrosion after 5,000 hours exposure in the ASTM B117 salt spray cabinet.

ELONGATION & TENSILE PROPERTIES

When determined in accordance with ASTM D638, typical values will be:

Elongation
0.5% 68°F (20°C) cure

Tensile Strength
3703 psi (25.54 MPa) 68°F (20°C) cure

Young's Modulus:
7.76x10^5 psi (5352 MPa) 68°F (20°C) cure

FLEXURAL PROPERTIES

When determined in accordance with ASTM D790, typical values will be:

Flexural Strength
9,400 psi (64.81 MPa) 68°F (20°C) cure

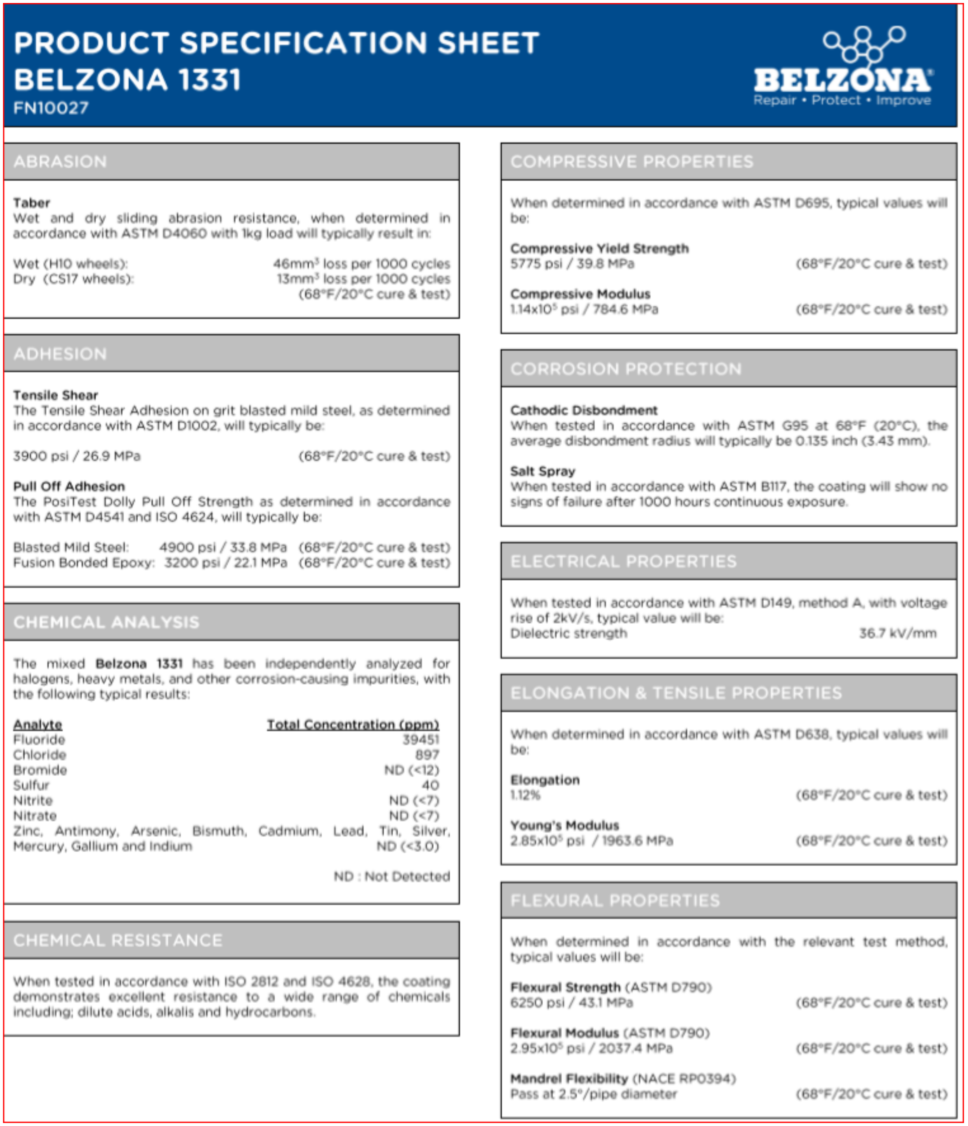
Flexural Modulus
7.70 x 10^5 psi (5309MPa) 68°F (20°C) cure

HARDNESS

Shore D
When determined in accordance with ASTM D2240, typical values will be:
84 68°F (20°C) cure

Barcol
When determined in accordance with ASTM D2583, will typically be:

87	68°F (20°C) cure
92	212°F (100°C) cure



PRODUCT SPECIFICATION SHEET
BELZONA 1331
FN10027

BELZONA
Repair • Protect • Improve

ABRASION

Taber
Wet and dry sliding abrasion resistance, when determined in accordance with ASTM D4060 with 1kg load will typically result in:

Wet (H10 wheels):	46mm^3 loss per 1000 cycles
Dry (CS17 wheels):	13mm^3 loss per 1000 cycles

(68°F/20°C cure & test)

ADHESION

Tensile Shear
The Tensile Shear Adhesion on grit blasted mild steel, as determined in accordance with ASTM D1002, will typically be:

3900 psi / 26.9 MPa (68°F/20°C cure & test)

Pull Off Adhesion
The PosiTest Dolly Pull Off Strength as determined in accordance with ASTM D4541 and ISO 4624, will typically be:

Blasted Mild Steel:	4900 psi / 33.8 MPa	(68°F/20°C cure & test)
Fusion Bonded Epoxy:	3200 psi / 22.1 MPa	(68°F/20°C cure & test)

CHEMICAL ANALYSIS

The mixed **Belzona 1331** has been independently analyzed for halogens, heavy metals, and other corrosion-causing impurities, with the following typical results:

Analyte	Total Concentration (ppm)
Fluoride	39451
Chloride	897
Bromide	ND (<12)
Sulfur	40
Nitrite	ND (<7)
Nitrate	ND (<7)
Zinc, Antimony, Arsenic, Bismuth, Cadmium, Lead, Tin, Silver, Mercury, Gallium and Indium	ND (<3.0)

ND : Not Detected

CHEMICAL RESISTANCE

When tested in accordance with ISO 2812 and ISO 4628, the coating demonstrates excellent resistance to a wide range of chemicals including; dilute acids, alkalis and hydrocarbons.

COMPRESSIVE PROPERTIES

When determined in accordance with ASTM D695, typical values will be:

Compressive Yield Strength
5775 psi / 39.8 MPa (68°F/20°C cure & test)

Compressive Modulus
1.14x10^5 psi / 784.6 MPa (68°F/20°C cure & test)

CORROSION PROTECTION

Cathodic Disbondment
When tested in accordance with ASTM G95 at 68°F (20°C), the average disbondment radius will typically be 0.135 inch (3.43 mm).

Salt Spray
When tested in accordance with ASTM B117, the coating will show no signs of failure after 1000 hours continuous exposure.

ELECTRICAL PROPERTIES

When tested in accordance with ASTM D149, method A, with voltage rise of 2kV/s, typical value will be:
Dielectric strength 36.7 kV/mm

ELONGATION & TENSILE PROPERTIES

When determined in accordance with ASTM D638, typical values will be:

Elongation
1.12% (68°F/20°C cure & test)

Young's Modulus
2.85x10^5 psi / 1963.6 MPa (68°F/20°C cure & test)

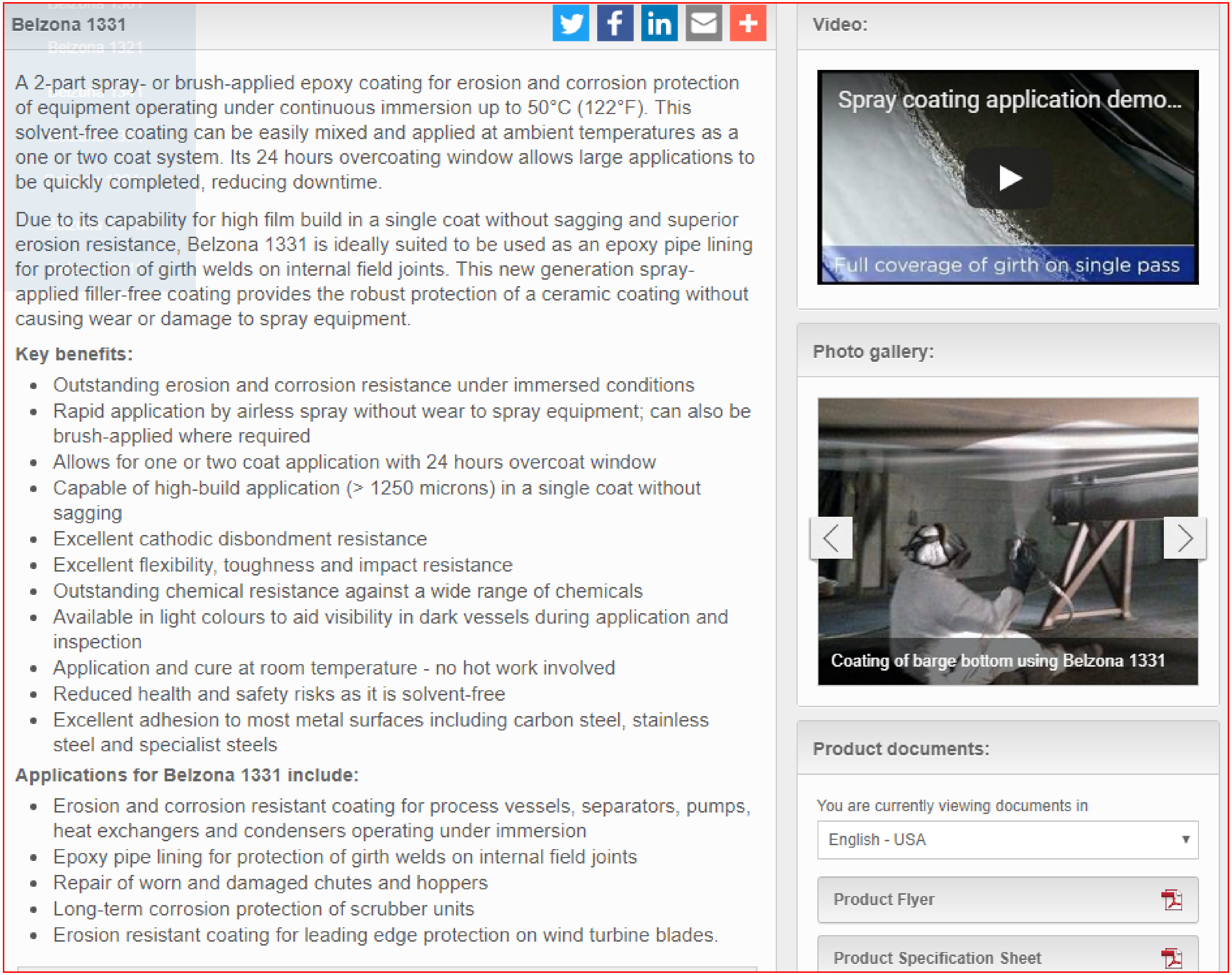
FLEXURAL PROPERTIES

When determined in accordance with the relevant test method, typical values will be:

Flexural Strength (ASTM D790)
6250 psi / 43.1 MPa (68°F/20°C cure & test)

Flexural Modulus (ASTM D790)
2.95x10^5 psi / 2037.4 MPa (68°F/20°C cure & test)

Mandrel Flexibility (NACE RP0394)
Pass at 2.5°/pipe diameter (68°F/20°C cure & test)



Belzona 1331

A 2-part spray- or brush-applied epoxy coating for erosion and corrosion protection of equipment operating under continuous immersion up to 50°C (122°F). This solvent-free coating can be easily mixed and applied at ambient temperatures as a one or two coat system. Its 24 hours overcoating window allows large applications to be quickly completed, reducing downtime.

Due to its capability for high film build in a single coat without sagging and superior erosion resistance, Belzona 1331 is ideally suited to be used as an epoxy pipe lining for protection of girth welds on internal field joints. This new generation spray-applied filler-free coating provides the robust protection of a ceramic coating without causing wear or damage to spray equipment.

Key benefits:

- Outstanding erosion and corrosion resistance under immersed conditions
- Rapid application by airless spray without wear to spray equipment; can also be brush-applied where required
- Allows for one or two coat application with 24 hours overcoat window
- Capable of high-build application (> 1250 microns) in a single coat without sagging
- Excellent cathodic disbondment resistance
- Excellent flexibility, toughness and impact resistance
- Outstanding chemical resistance against a wide range of chemicals
- Available in light colours to aid visibility in dark vessels during application and inspection
- Application and cure at room temperature - no hot work involved
- Reduced health and safety risks as it is solvent-free
- Excellent adhesion to most metal surfaces including carbon steel, stainless steel and specialist steels

Applications for Belzona 1331 include:

- Erosion and corrosion resistant coating for process vessels, separators, pumps, heat exchangers and condensers operating under immersion
- Epoxy pipe lining for protection of girth welds on internal field joints
- Repair of worn and damaged chutes and hoppers
- Long-term corrosion protection of scrubber units
- Erosion resistant coating for leading edge protection on wind turbine blades.

PROPOSED SHORT TERM TESTING

Proposed Short Term Testing

- Work with Zoltek to obtain PX35-72 and PX35-13 UD600 for test panels
- Work with Toray to obtain T700S-FOE and -50C for test panels
- Generate test panels with both Carbon Fiber supplies (standard and VE specific) using Polynt RF1001L and Derakane 411-100 for identification of permeability using MITS table and any other processing related issues
- Coat respective panels with Belzona 1321 and 1331 for processing considerations
- Work with MSU to get test panels into accelerated aging ASTM 1141 conditions for evaluation of performance with and without Belzona coatings
- Develop test plan for before and after laminate performance related to moisture absorption, fatigue, and interfacial bond performance.
- Work with Evisive to create testing protocol viability for microwave NDT.

11. APPENDIX C: MSU, ORPC TEST DATA V1.0, 11DEC2019

MONTANA
STATE UNIVERSITY
NORM ASBJORNSON
College of
ENGINEERING

Department of
Mechanical &
Industrial Engineering

December 4, 2019

Jarlath McEntee, PE
Senior Vice President and CTO
ORPC, Inc.
RE: Test Results from ORPC Immersion Coupons

Dear Jarlath and ORPC Engineering Staff,

Attached with this letter is a summary of the test coupon results from the immersion study on a collection of provided composite plates. The report details the coupons and materials that were provided to MSU, and the testing procedures and results from the immersion and mechanical testing performed at MSU.

A summary of the data collected, as well as individual coupon data sets, are included in the report. Data for the moisture uptake of each material set, short beam shear results, and notched beam shear tests were collected in the dry (as-received) and fully saturated conditions.

From these data, it is expected that a subset of materials will be identified as potential candidates for future developments. As these materials are identified, and as we have confirmed in conversation, MSU stands ready to perform additional testing. Additional tests will measure constitutive parameters that will enable ORPC to complete a more thorough mechanical and failure analysis of their composite systems.

It has been a pleasure, and a great opportunity, for MSU to contribute to this endeavor. We hope that ORPC finds this data beneficial, and we hope to continue aiding the project in the future.

Regards,

David A. Miller

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Mountains & Minds

Coupons and Materials

Coupons were created from the 14 delivered plates, detailed below in table 1. The coupons were cut using a diamond blade on a wet circular table saw. The short beam shear coupons were cut to a length of 50.8mm with a width of 12.7mm. The V-Notch coupons were cut to a length of 76mm, width of 19mm. The notches were cut to a 90-degree angle leaving a cross-sectional width of 11.4mm. Exact measurements of thickness and width were recorded for each coupon. Details on plates 17 and 18 were not provided with the rest of the plates, and need confirmation of materials.

Table 1: Details on each of the delivered plates

Panel #	Pattern	Resin	Process	Reinforcement	Coating	Coupon reference	Panel Sq in
1	−−−+	1	In Mold	CF 1	1	1S, 1V	576
2	+−−+	2	In Mold	CF 1	1	2S, 2V	576
3	−+−+	1	Post Mold	CF 1	1	3AS, 3AV	864
3	−+−−	1	Post Mold	CF 1	2	3BS, 3BV	864
4	++++	2	Post Mold	CF 2	1	4AS, 4AV	864
4	+++−	2	Post Mold	CF 2	2	4BS, 4BV	864
6	−+++	1	Post Mold	CF 2	1	6AS, 6AV	864
6	−++−	1	Post Mold	CF 2	2	6BS, 6BV	864
10	++−+	2	Post Mold	CF 1	1	10AS, 10AV	864
10	++−−	2	Post Mold	CF 1	2	10BS, 10BV	864
11	+−++	2	In Mold	CF 2	1	11S, 11V	576
12	−−++	1	In Mold	CF 2	1	12S, 12V	576
17							
18							

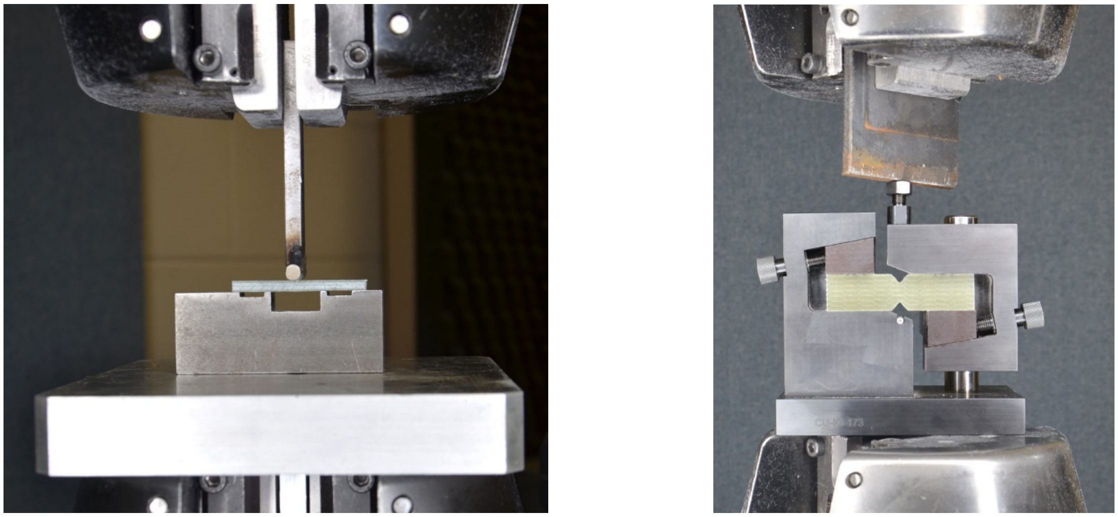
Testing Procedures

Hydrothermal Expansion conditioning

A representative sample of short beam shear and v-notch coupons were placed in a distilled water bath in an oven at 50 °C and allowed to absorb water. Mass measurements of the samples were taken and periodic intervals up until the time of testing. The short beam shear tests were performed first after a soak time of 2370 hours and the V-notched coupons were soaked for 3340 hours. Mass measurements were compared to the initial mass to find the percent uptake.

Short Beam Shear coupons for each material configuration are labeled with an S as shown in the Coupon Reference in Table 1, and were tested according to ASTM standard D2344. A generic test fixture, Figure 1, was loaded into an electromechanical test frame, and the max load was recorded for each coupon. The coupons were loaded with the gel coat side down, resulting in this face undergoing a tensile load. Incremental load and displacement values were recorded for the final test of each type. The standard load rate of .05 in/min was used, and the test was stopped at a load drop off of 30%.

V-Notched Shear coupons for each material configuration are labeled with a V as shown in the Coupon Reference in Table , and were tested following ASTM standard D5379 using a Wyoming Tests Fixtures device, Figure 1. The coupons were loaded with the Gel Coat facing the back of the fixture. The fixture was then placed into an electromechanical test frame, which was run under displacement control at .05 in/min. Max load values were recorded for each coupon. For 2 coupons of each unique resin, conditioning and reinforcement system, or 28 coupons in total, the Aramis 2018 Digital Image Correlation (DIC) strain measurement system was used to measure the complete 2-D shear strain.



a. b.

Figure 1 Testing fixtures for the a.) short beam shear and the b.) notched beam shear

Testing Results

The average percent mass uptake was calculated for each coupon. This number was averaged for each plate, and the results are plotted in Figure 2 below. The 3AS and 1s coupons absorbed the most water by mass, while the 17S and 18S coupons absorbed the least. The Short Beam Shear Coupons were tested after 2,370 hours of soaking, and the results are detailed in Table 2 below. To find the shear strength, the maximum force applied was multiplied by .75 and divided by the cross-sectional area, as per the ASTM standard. For each of the plates, except 6AS, coupons lost strength due to the conditioning process. For all other coupons, the materials lost between 6% and 27% shear strength, with an average loss of 13.9%. Since the gel coat was in tension, and has a lower strength than the composite, it generally failed first; however, on many of the coupons there was also crack propagation in the composite beginning at the load-head of the fixture.

For 1 out of every 10 tests, load displacement data for the entire test was recorded. The load stress values were calculated according to the same formula described above. Figure 3 shows the graph for the 1S coupons. The chart was truncated to a displacement value of 0.035 in. More data was recorded for each test, but since the coupons were taken to different final displacements, 0.035 in was chosen to avoid misrepresenting data. The charts for each of the other Coupons are contained in Appendix A. All data sets were similarly truncated to include only equivalent displacements.

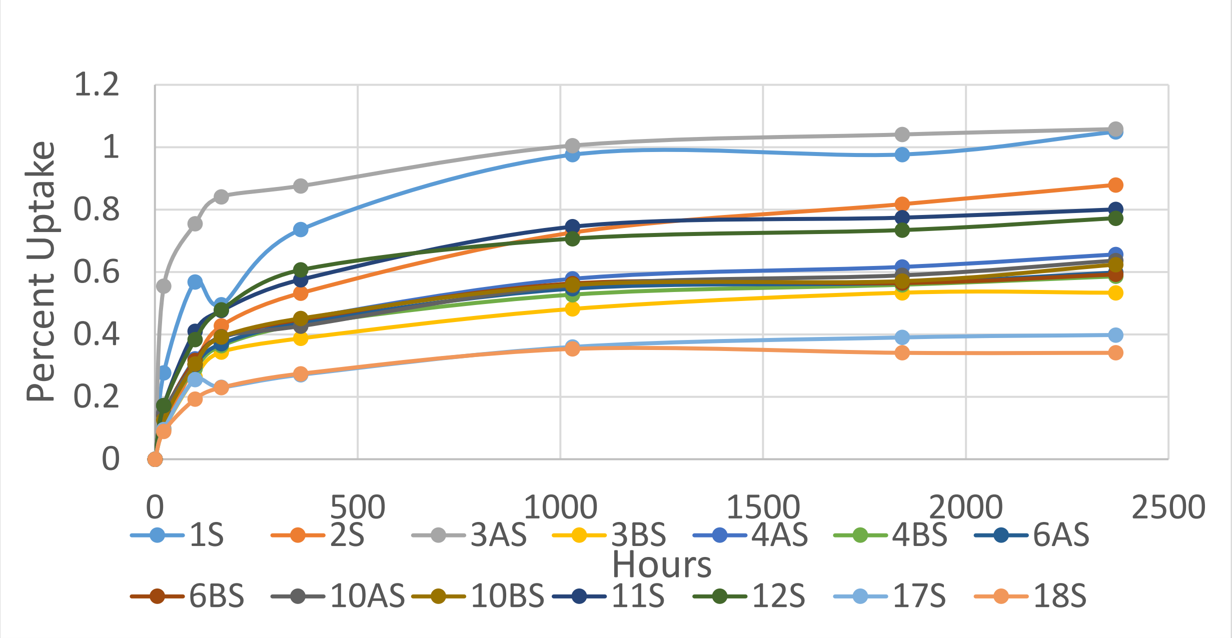


Figure 2: Short Beam Shear Uptake Chart

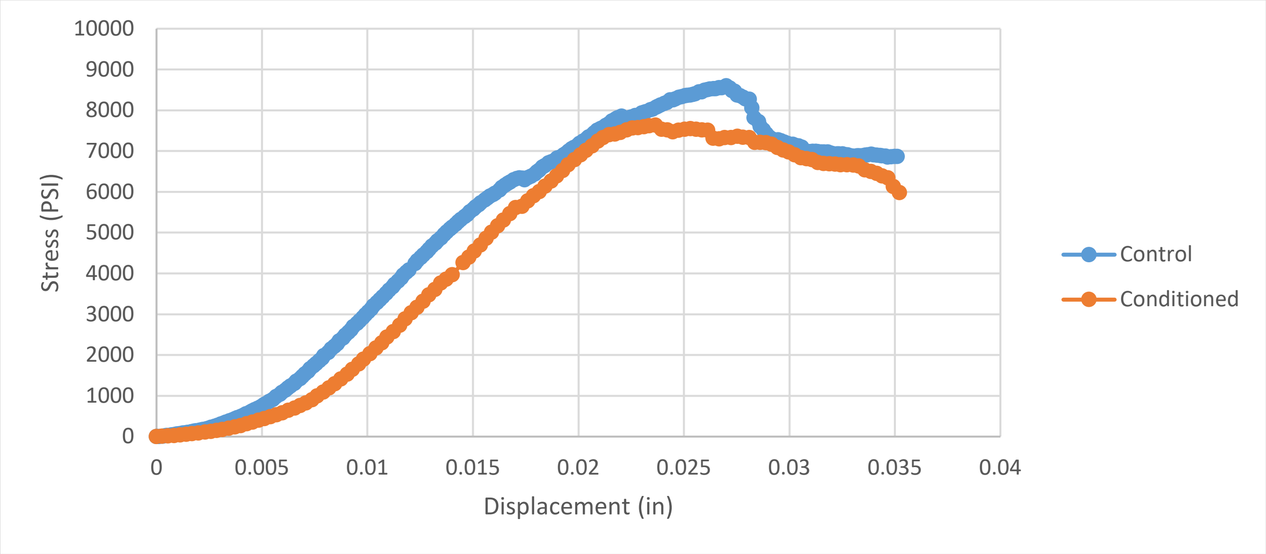


Figure 3: Stress Displacement chart for 1s coupons

Table 2: Results for Short Beam Shear Tests

Material System	# of Tests	Conditioning	Average Max Stress	Standard Deviation	Shear Strength Loss
		% Increase in Mass	(PSI)	(PSI)	%
1S-Dry	10	0.00	6019	754	
1S-Cond.	10	1.05	5320	497	11.6%
2S-Cond.	10	0.00	5931	479	
2S-Cond.	10	0.88	4337	406	26.9%
3AS-Dry	10	0.00	7040	789	
3AS-Cond.	10	1.06	6211	630	11.8%
3BS-Dry	10	0.00	6348	588	
3BS-Cond.	10	0.53	5533	677	12.8%
4AS-Dry	10	0.00	7662	582	
4AS-Cond.	10	0.66	7139	418	6.8%
4BS-Dry	10	0.00	7888	357	
4BS-Cond.	10	0.59	7143	424	9.4%
6AS-Dry	10	0.00	7749	595	
6AS-Cond.	10	0.60	8267	553	-6.7%
6BS-Dry	10	0.00	8265	734	
6BS-Cond.	10	0.59	7330	568	11.3%
10AS-Dry	10	0.00	6435	736	
10AS-Cond.	10	0.64	4637	516	27.9%
10BS-Dry	10	0.00	6939	528	
10BS-Cond.	10	0.62	5238	624	24.5%
11S-Dry	10	0.00	8297	893	
11S-Cond.	10	0.80	7670	399	7.6%
12S-Dry	10	0.00	7814	434	
12S-Cond.	10	0.77	7349	424	6.0%
17S-Dry	10	0.00	6490	515	
17S-Cond.	10	0.40	4814	316	25.8%
18S-Dry	10	0.00	8963	677	
18S-Cond.	10	0.34	7295	597	18.6%

For the v-notch coupons, the percent mass uptake was averaged for each plate, and the results are plotted in Figure 4 below. For this set of coupons, the 1V and 2V coupons absorbed the most water, while the 17V and 18V coupons absorbed the least. The V-Notch Coupons were tested after 3,340 hours of soaking, and the results are detailed in Table 3 below. Throughout all tests, coupons lost strength due to the conditioning process. The shear strength values were calculated following the standard, taking the maximum observed force and dividing by the cross-sectional area or the notch. The materials lost between 7.8% and 25.1% of their shear strength, with an average loss of 13.9% which is in line with what was observed in the Short Beam Shear tests.

For 2 coupons of each unique resin, reinforcement, and conditioning system, Digital Image Correlation (DIC) was run to track shear strain in the coupons. Figure 5 shows the shear strain on coupon 1V-3 at the final point during the test. Crack propagation can be seen near the initial notch. Only one of these images was included, because all coupons closely resemble each other. Force throughout the test was also recorded, allowing for the calculation of stress and strain through the entire test. These tests allow for the shear modulus of the materials to be measured, and a stress-strain curve can be created for each test. The Stress-Strain curves for all tests for material system 1, can be seen below in figure 6. The values for modulus for each coupon are found in table 4. The remainder of the stress-strain curves can be found in Appendix B.

Finally, gathered data for each coupon has been included in Appendix C. Table C.1 contains short beam shear uptake data. Table C.2 contains short beam shear test data. Table C.3 and C.4 contain respective data for the v-notch shear tests.

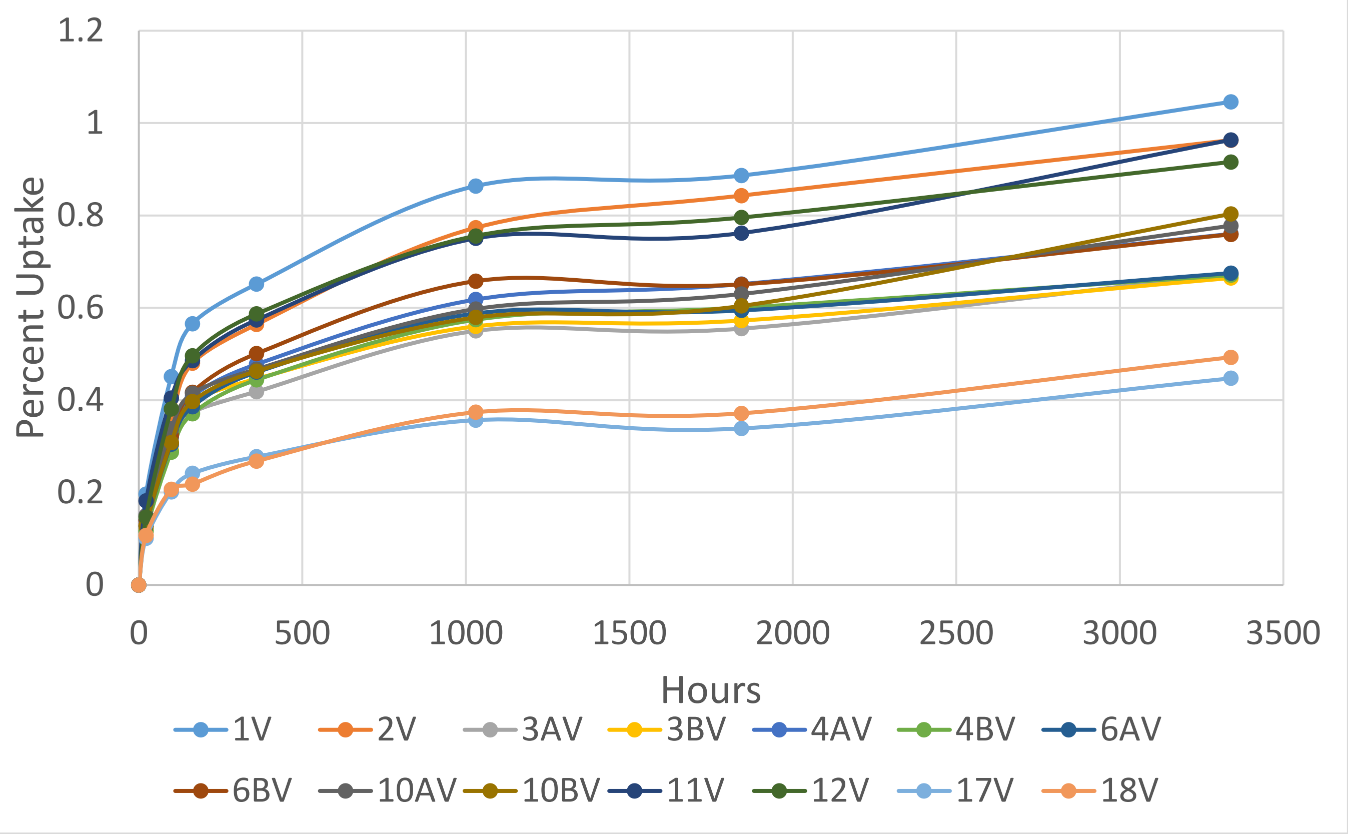


Figure 4: V-notch Shear Uptake Chart.

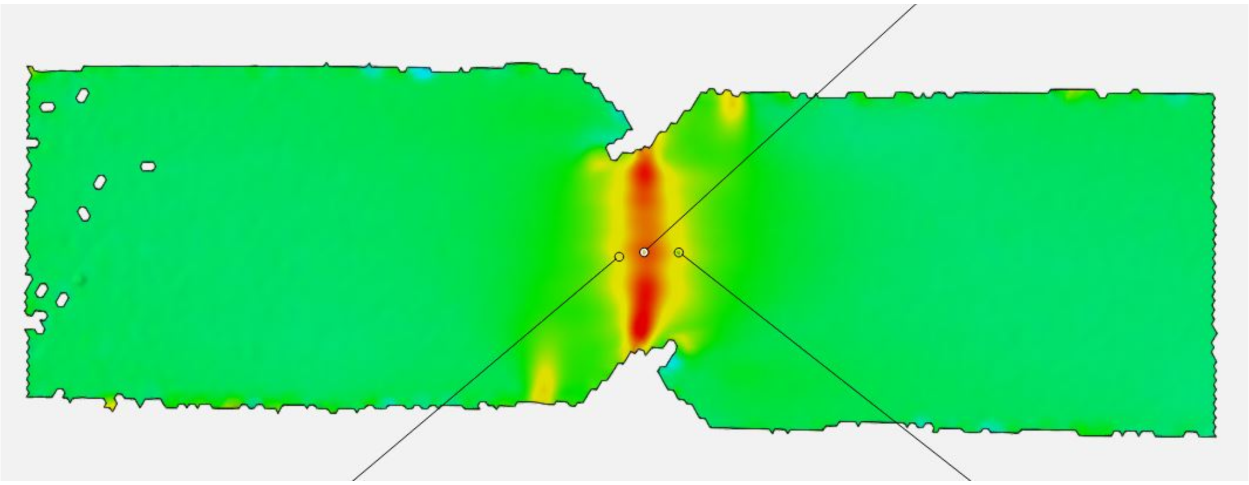


Figure 5: DIC snapshot showing Shear Strain at final deformation for Coupon 1V-3

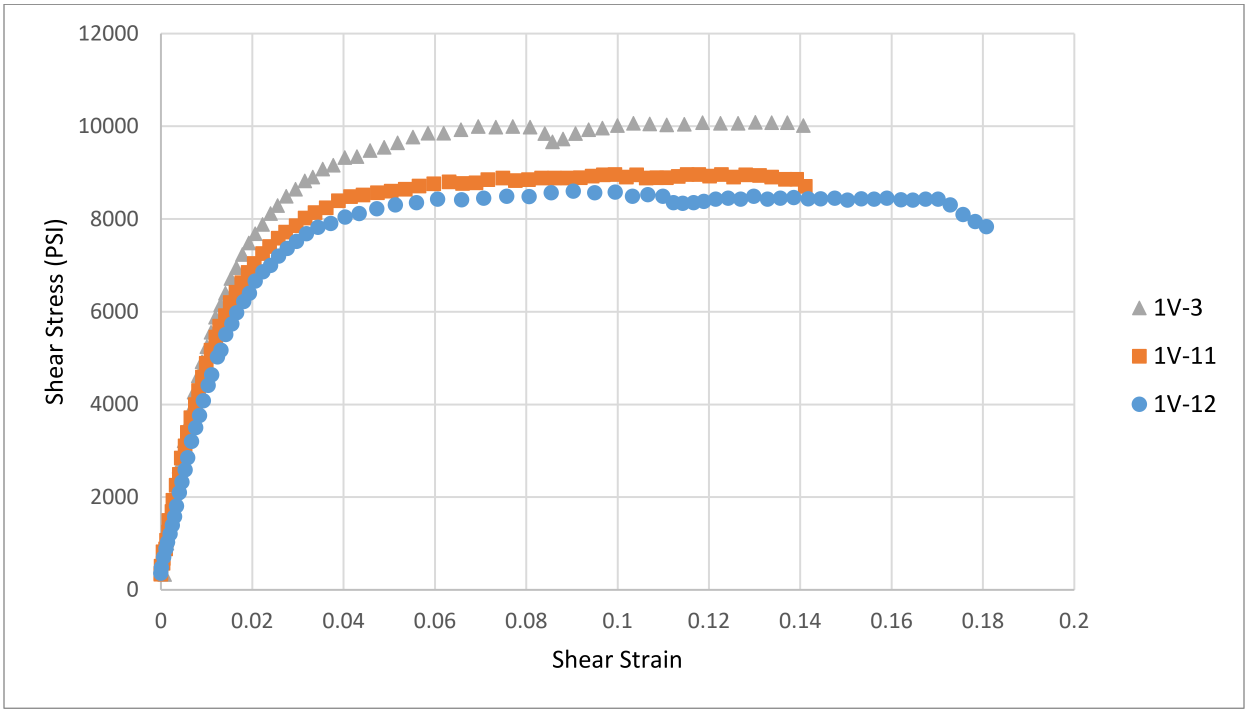


Figure 6: Stress Strain Curve for 1V coupons. Sample 3 is unsaturated control, and 11 and 12 are fully saturated

Table 3: Results for V-Notch Shear Tests

Material System	**# of Tests**	**Conditioning**	**Average Max Stress**	**Standard Deviation**	**Shear Strength Loss**
		% Increase in Mass	**(PSI)**	**(PSI)**	**%**
1V- Dry	10	0.00	9815	631	
1V- Cond.	10	1.05	8422	869	14.2%
2V- Dry	10	0.00	10134	868	
2V- Cond.	11	0.96	8136	453	19.7%
3AV- Dry	10	0.00	10040	433	
3AV- Cond.	10	0.67	8766	447	12.7%
3BV- Dry	10	0.00	9233	659	
3BV- Cond.	12	0.66	8259	422	10.6%
4AV- Dry	10	0.00	12387	709	
4AV- Cond.	12	0.76	10810	682	12.7%
4BV- Dry	10	0.00	11834	435	
4BV- Cond.	10	0.67	10363	651	12.4%
6AV- Dry	10	0.00	11874	768	
6AV- Cond.	10	0.68	10953	195	7.8%
6BV- Dry	10	0.00	11388	441	
6BV- Cond.	10	0.76	10032	359	11.9%
10AV- Dry	10	0.00	10001	555	
10AV- Cond.	11	0.78	7814	289	21.9%
10BV- Dry	10	0.00	9385	424	
10BV- Cond.	12	0.80	7027	323	25.1%
11V- Dry	10	0.00	12241	551	
11V- Cond.	13	0.96	10452	389	14.6%
12V- Dry	10	0.00	11807	498	
12V- Cond.	12	0.92	10346	263	12.4%
17V- Dry	10	0.00	12466	880	
17V- Cond.	12	0.45	10669	784	14.4%
18V- Dry	10	0.00	9450	816	
18V- Cond.	13	0.49	7686	525	18.7%

Table 4: Shear Modulus for V-Notch Coupons (G12)

Coupon	Shear Modulus (PSI)
1V-3	7.5E+05
1V-11	4.2E+05
1V-12	3.4E+05
2V-1	5.5E+05
2V-2	3.8E+05
2V-11	2.7E+05
2V-12	3.5E+05
3AV-1	4.0E+05
3AV-2	3.0E+05
3AV-11	2.5E+05
3AV-12	3.8E+05
4AV-1	5.1E+05
4AV-2	6.4E+05
4AV-11	4.0E+05
4AV-12	3.5E+05
6AV-1	4.0E+05
6AV-2	4.9E+05
6AV-11	4.5E+05
6AV-12	4.2E+05
17V-1	4.6E+05
17V-2	3.9E+05
17V-11	4.2E+05
17V-12	4.7E+05
18V-1	5.0E+05
18V-2	4.6E+05
18V-11	3.1E+05
18V-12	5.2E+05

Appendix A: Stress Displacement charts for Short Beam Shear Coupons

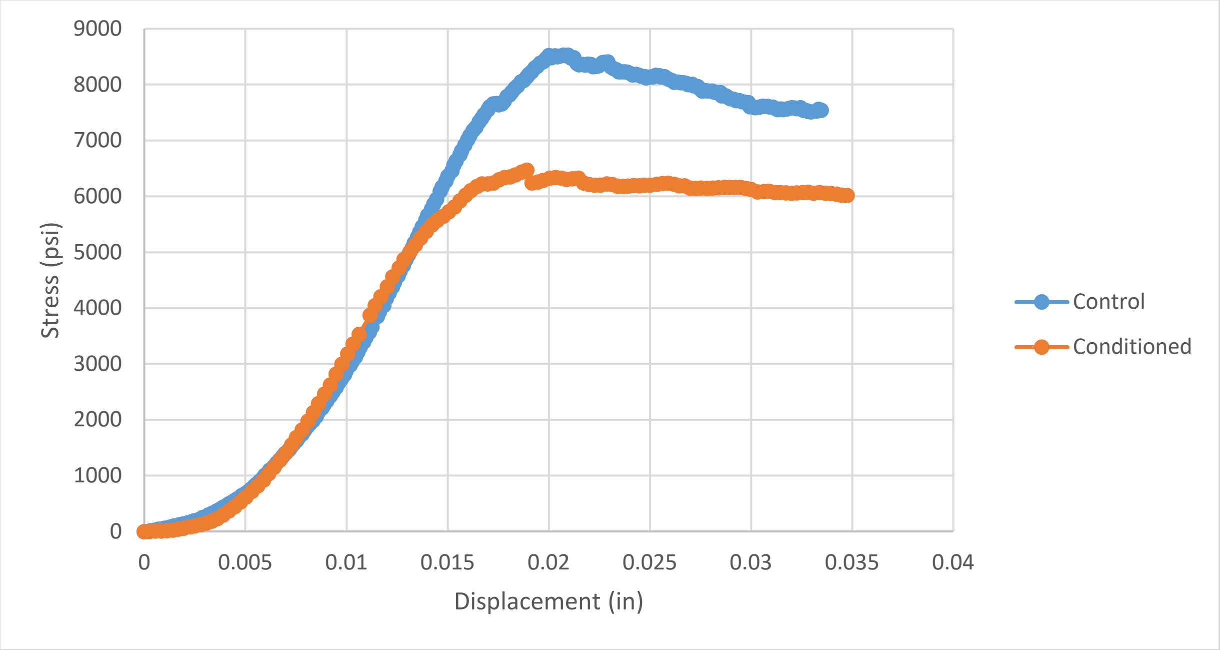


Figure A1: Stress Displacement chart for plate 2S

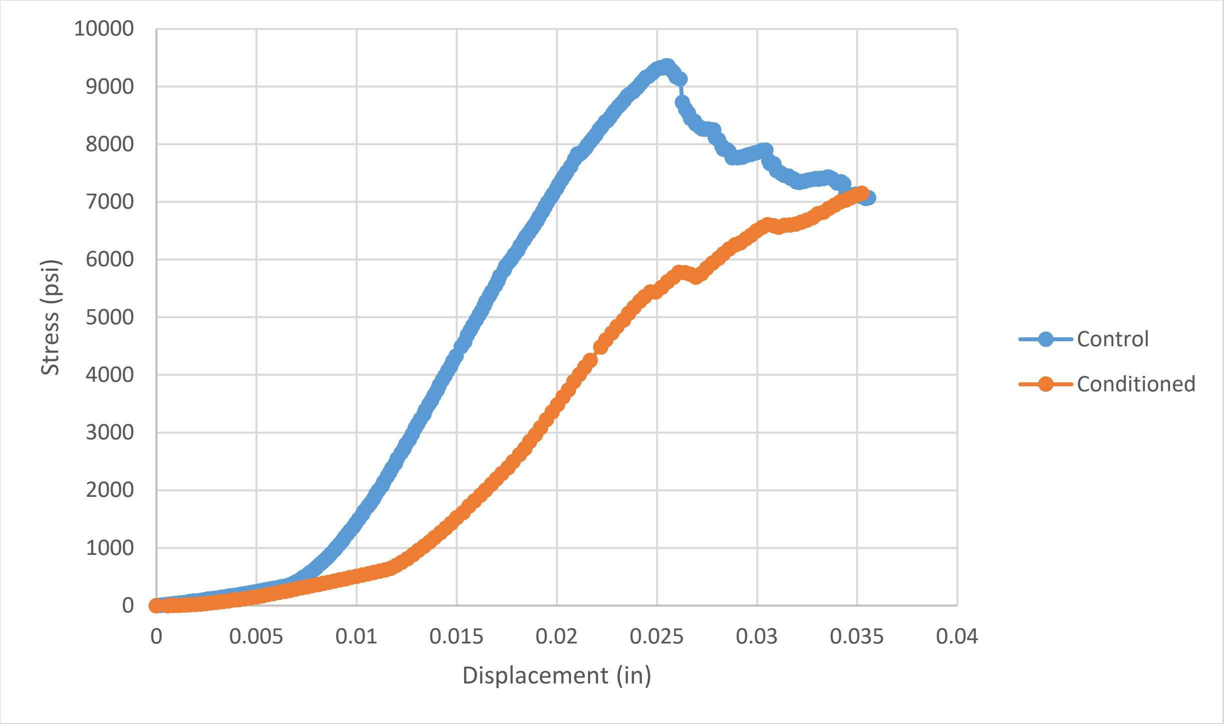


Figure A2: Stress Displacement chart for plate 3AS

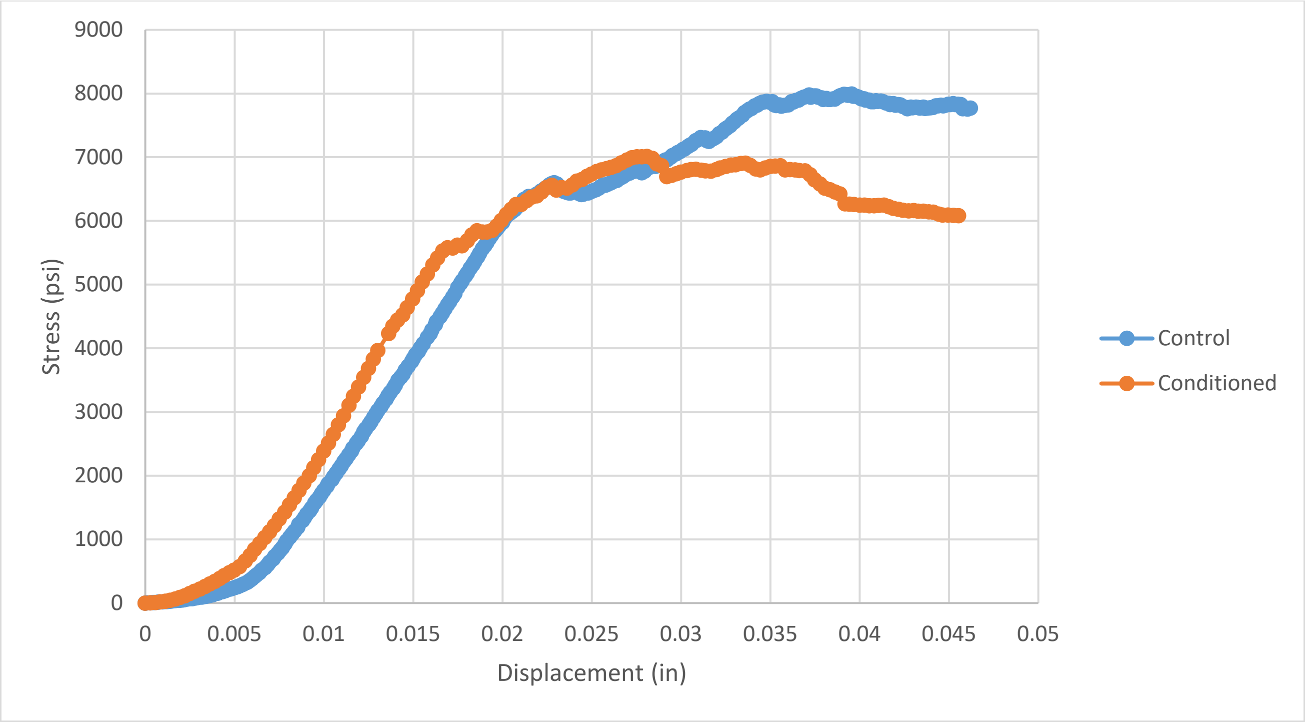


Figure A3: Stress Displacement chart for plate 3BS

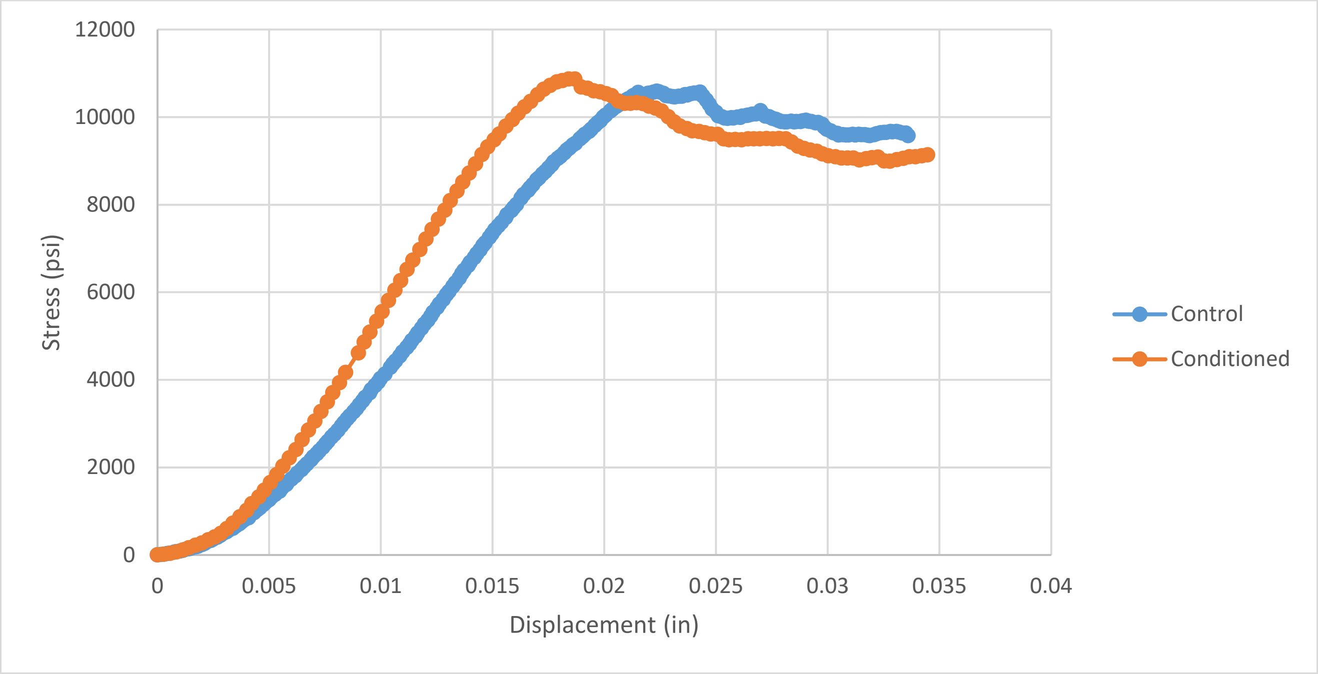


Figure A4: Stress Displacement chart for plate 4AS

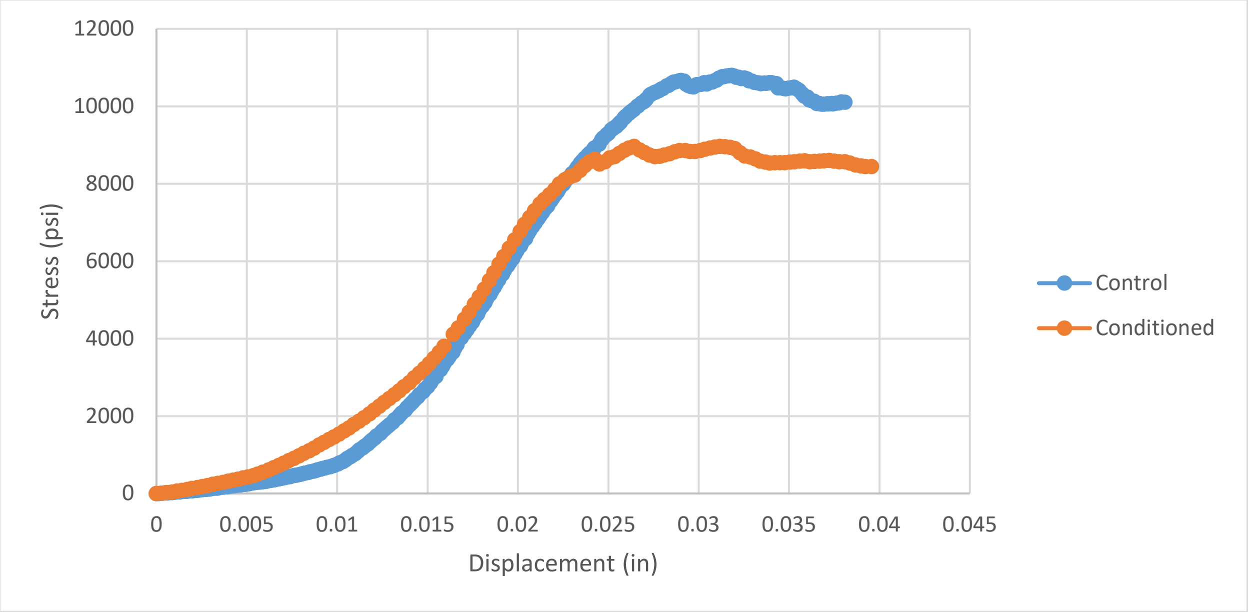


Figure A5: Stress Displacement chart for plate 4BS

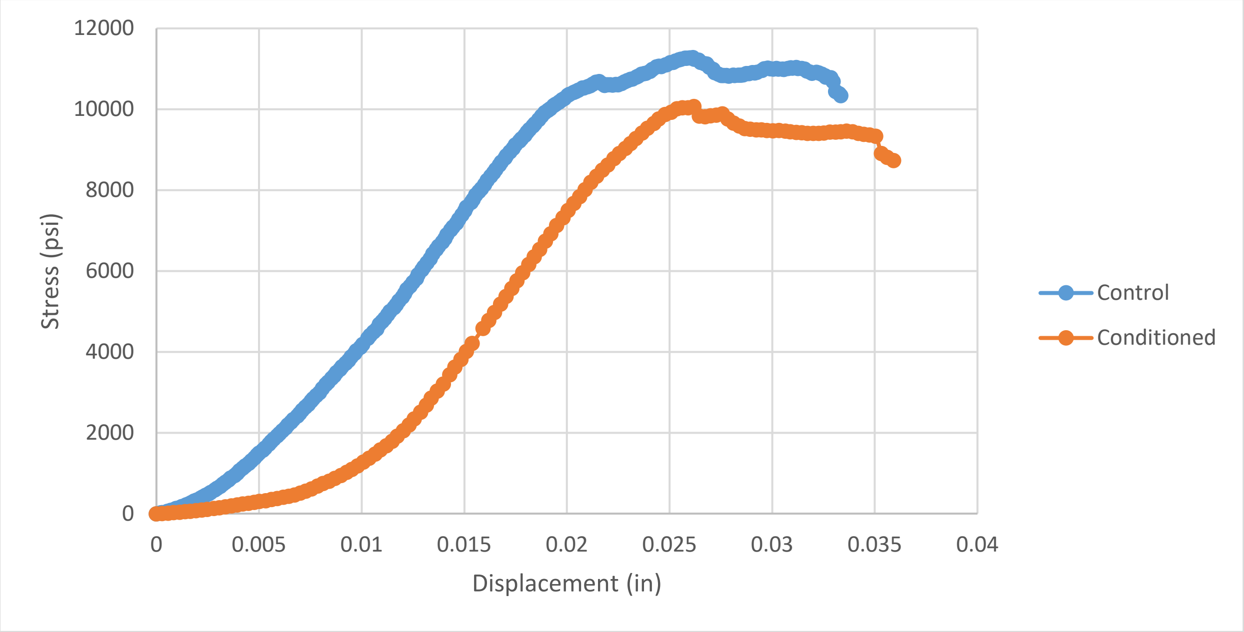


Figure A6: Stress Displacement chart for plate 6AS

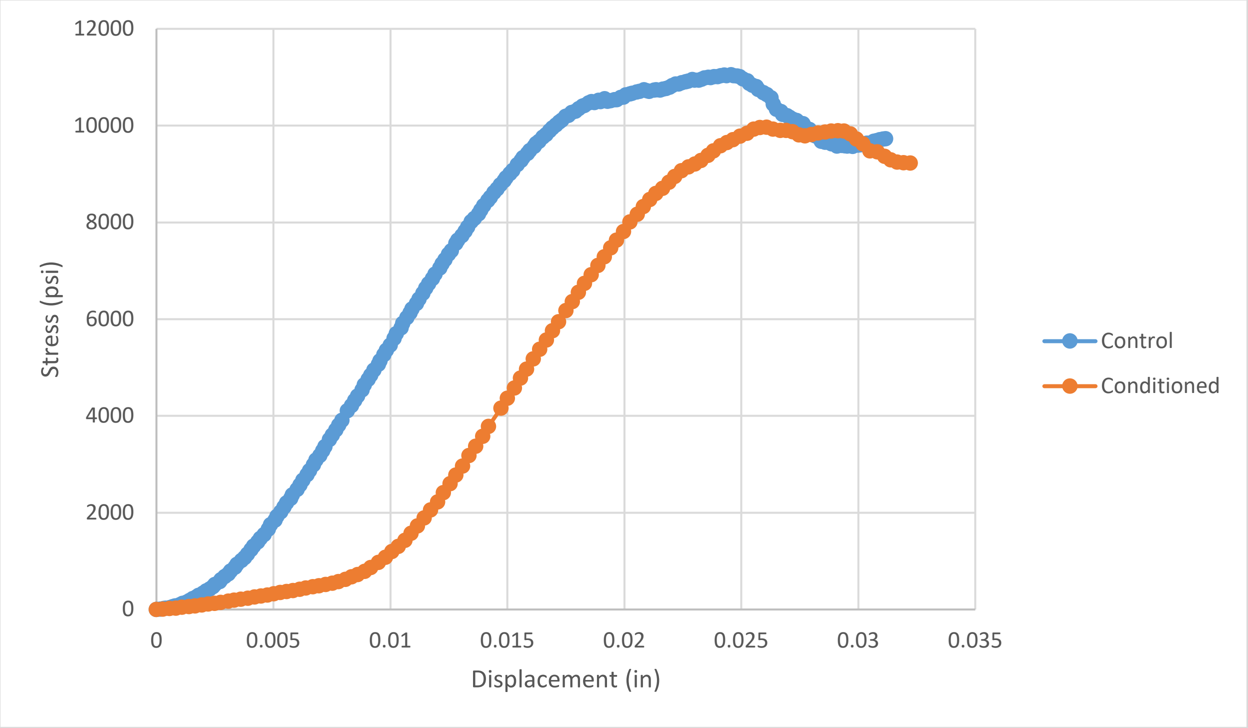


Figure A7: Stress Displacement chart for plate 6BS

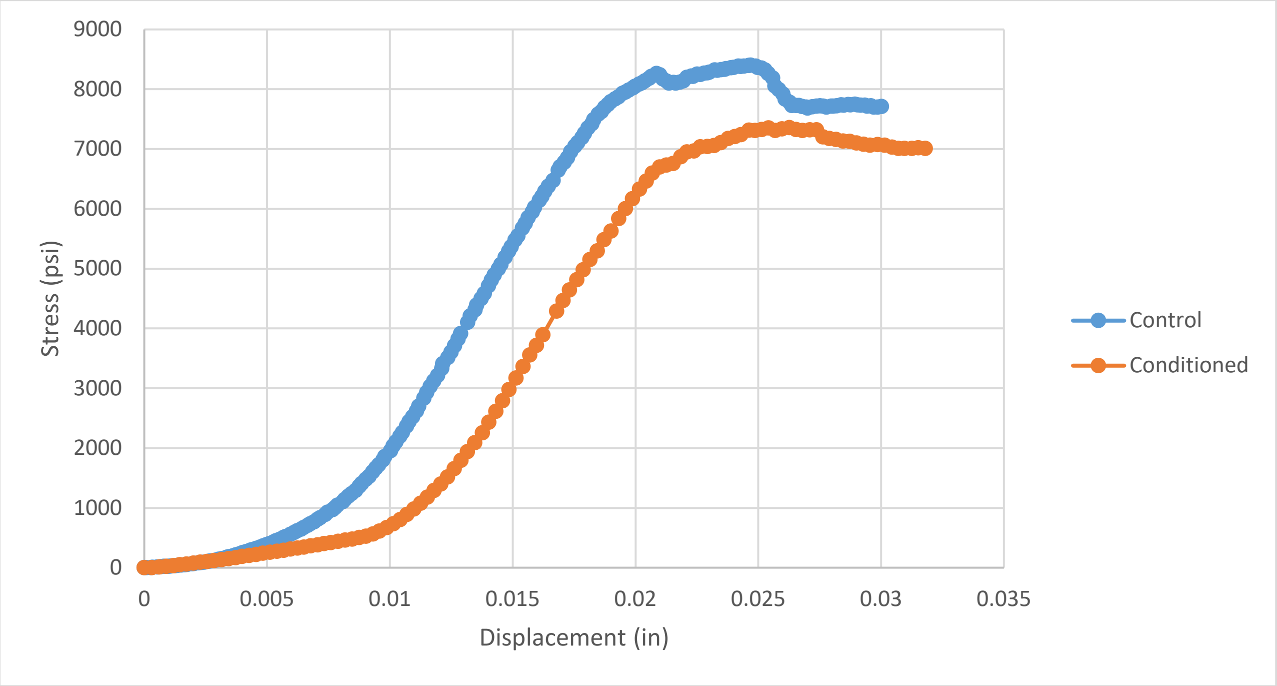


Figure A8: Stress Displacement chart for plate 10AS

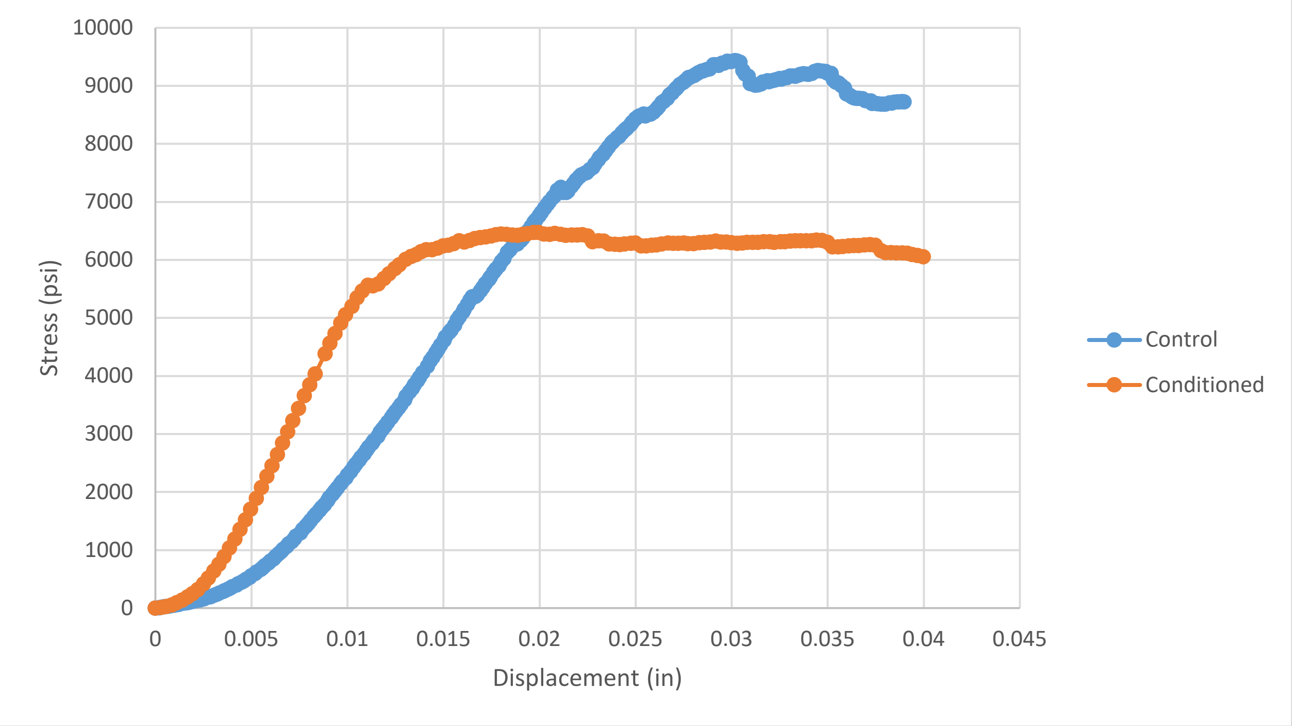


Figure A9: Stress Displacement chart for plate 10BS

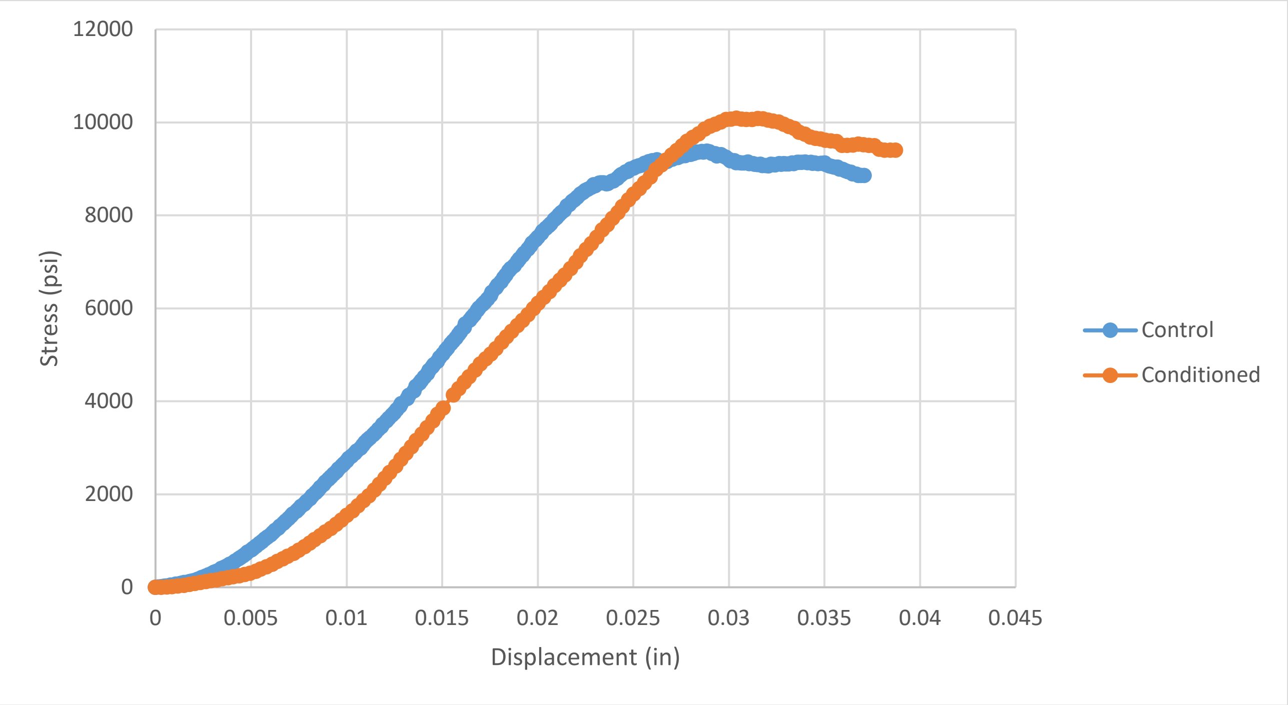


Figure A10: Stress Displacement chart for plate 11S

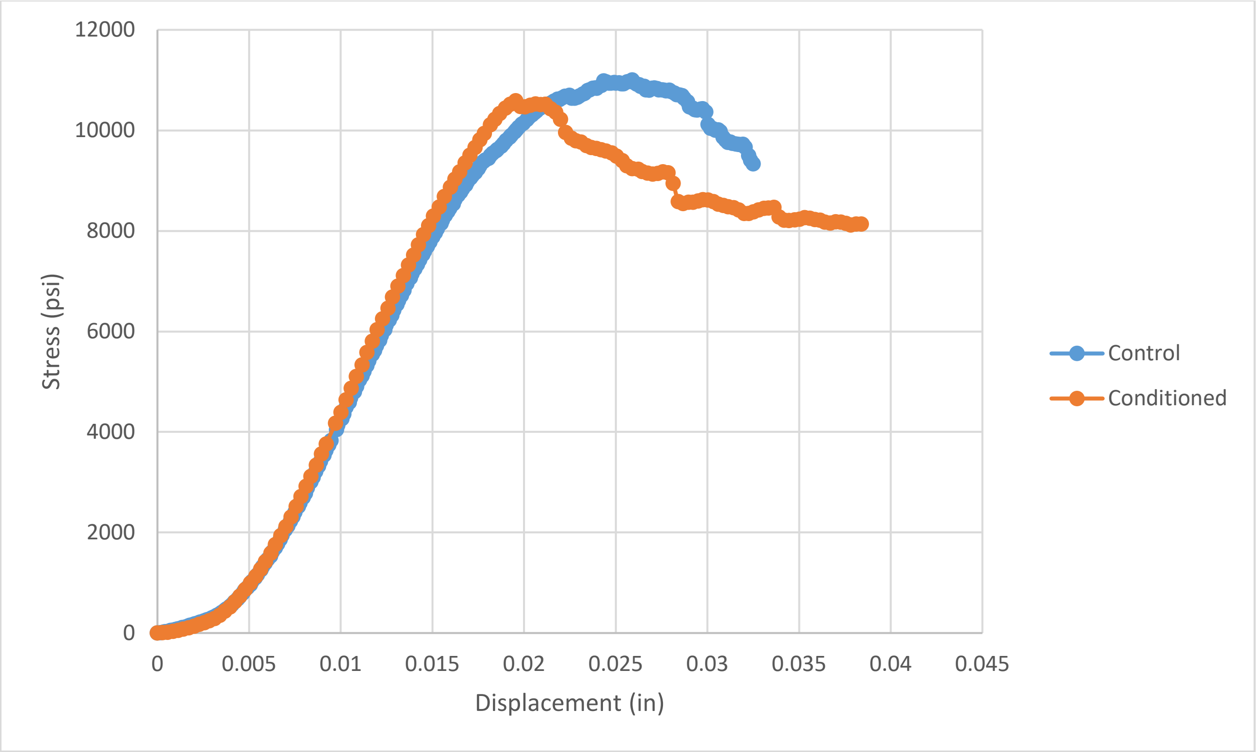


Figure A11: Stress Displacement chart for plate 12S

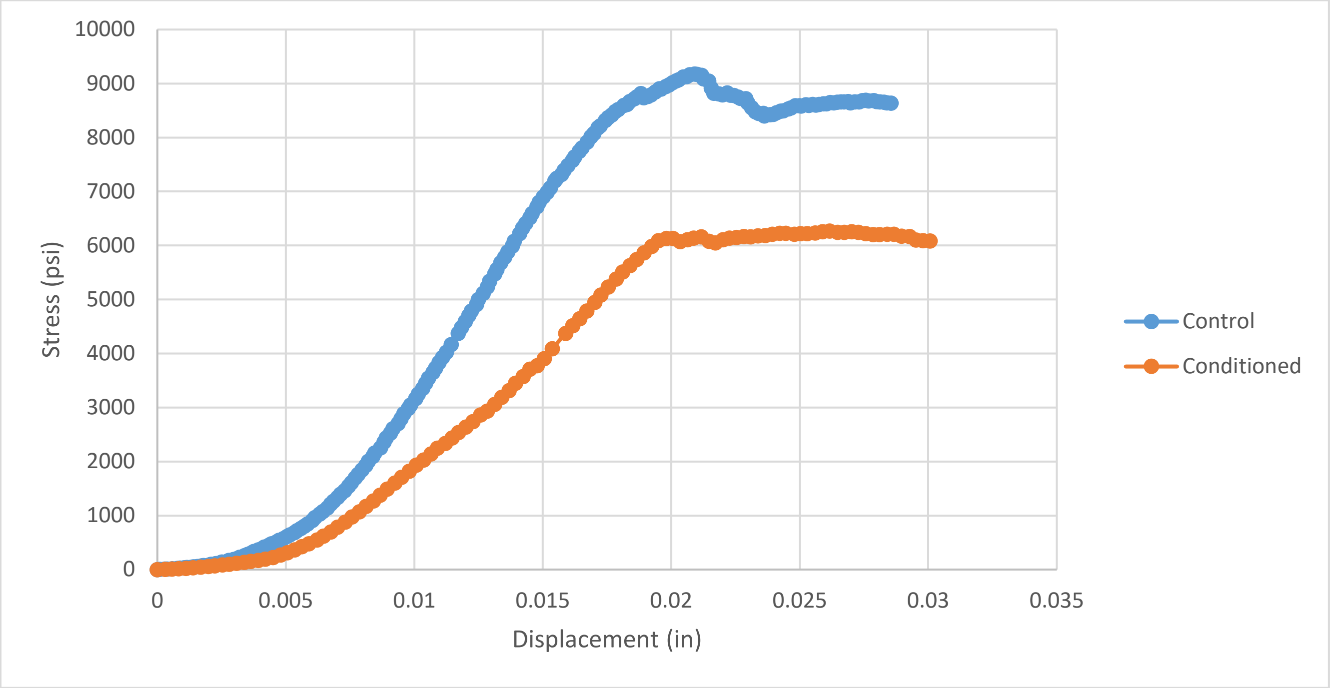


Figure A12: Stress Displacement chart for plate 17S

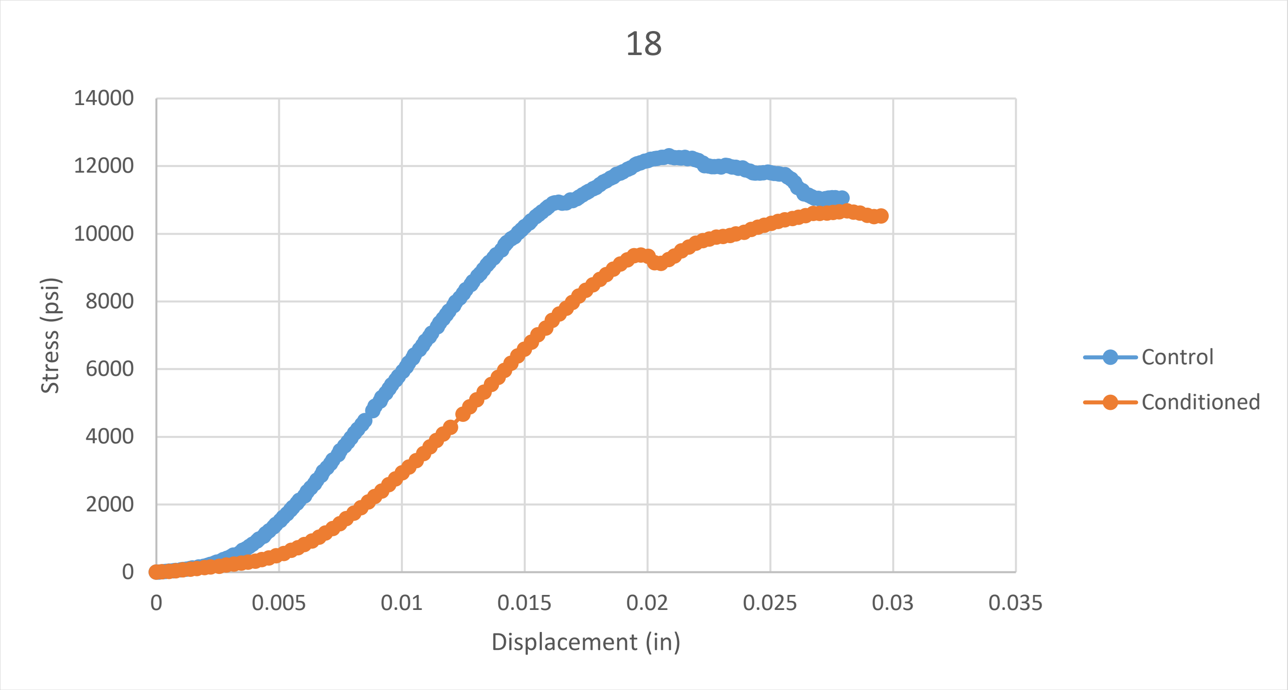


Figure A13: Stress Displacement chart for plate 18S

Appendix B: DIC Shear Strain Distribution, and Shear Stress-Strain Charts for V-Notch Coupons

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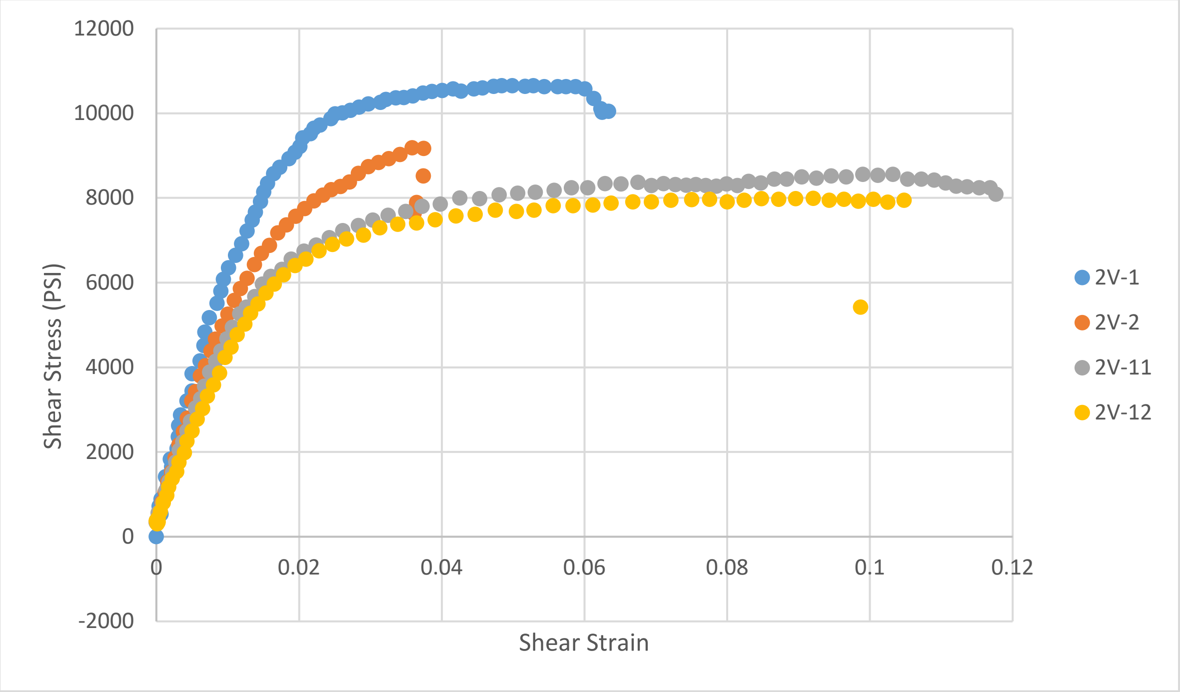

Figure B1: Stress Strain Chart for 2V coupons

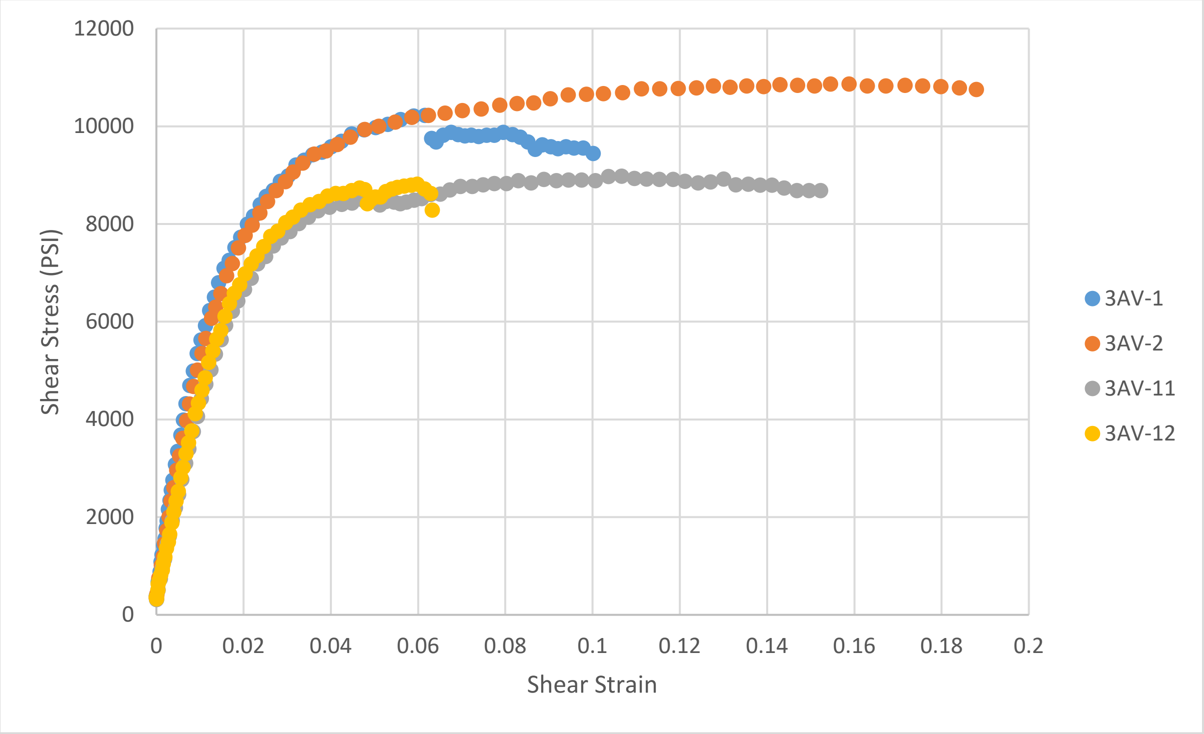

Figure B2: Stress Strain Chart for 3AV coupons

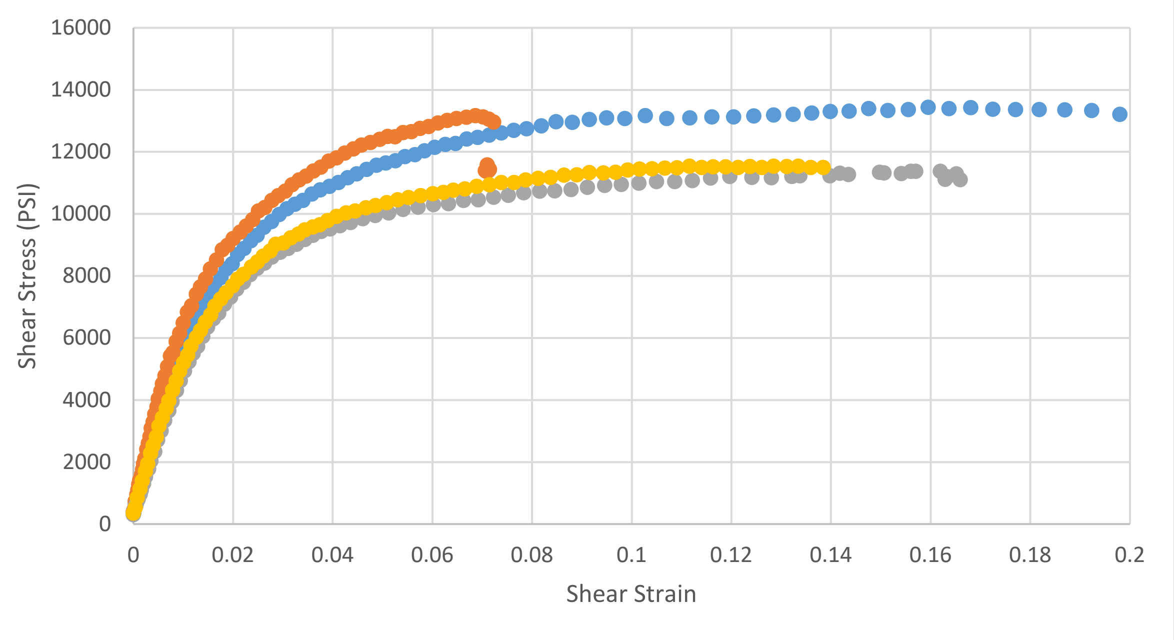

Figure B3: Stress Strain Chart for 4AV coupons

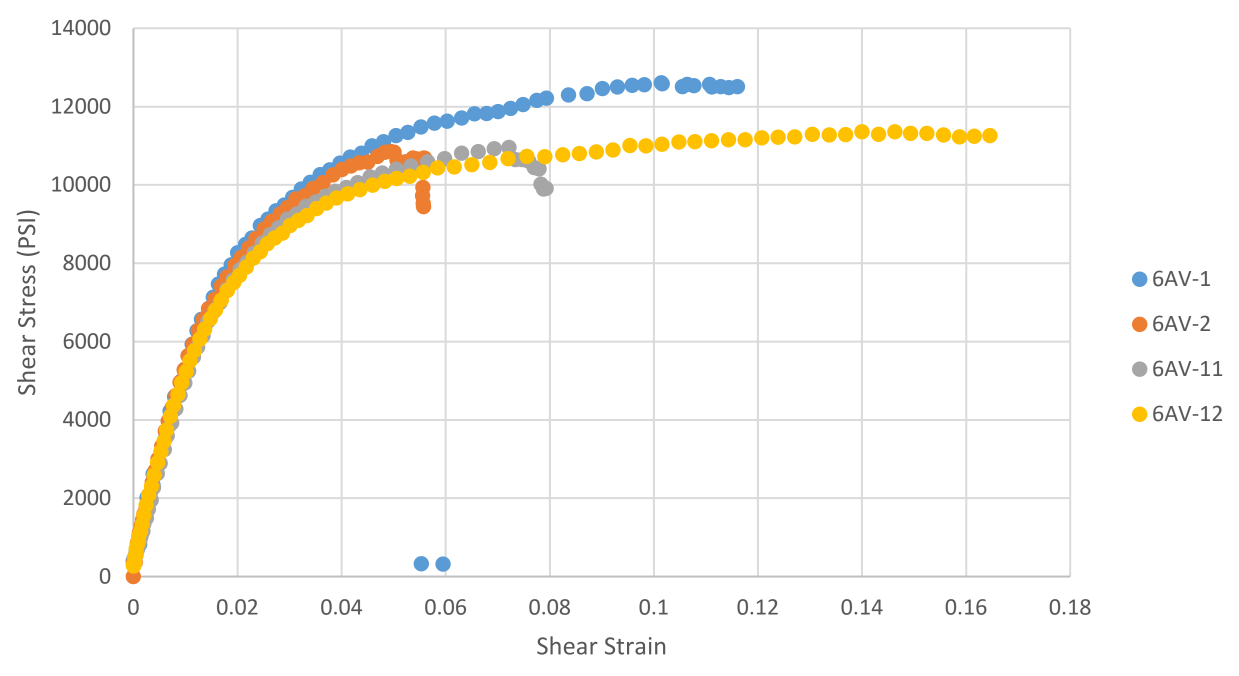

Figure B4: Stress Strain Chart for 6AV coupons

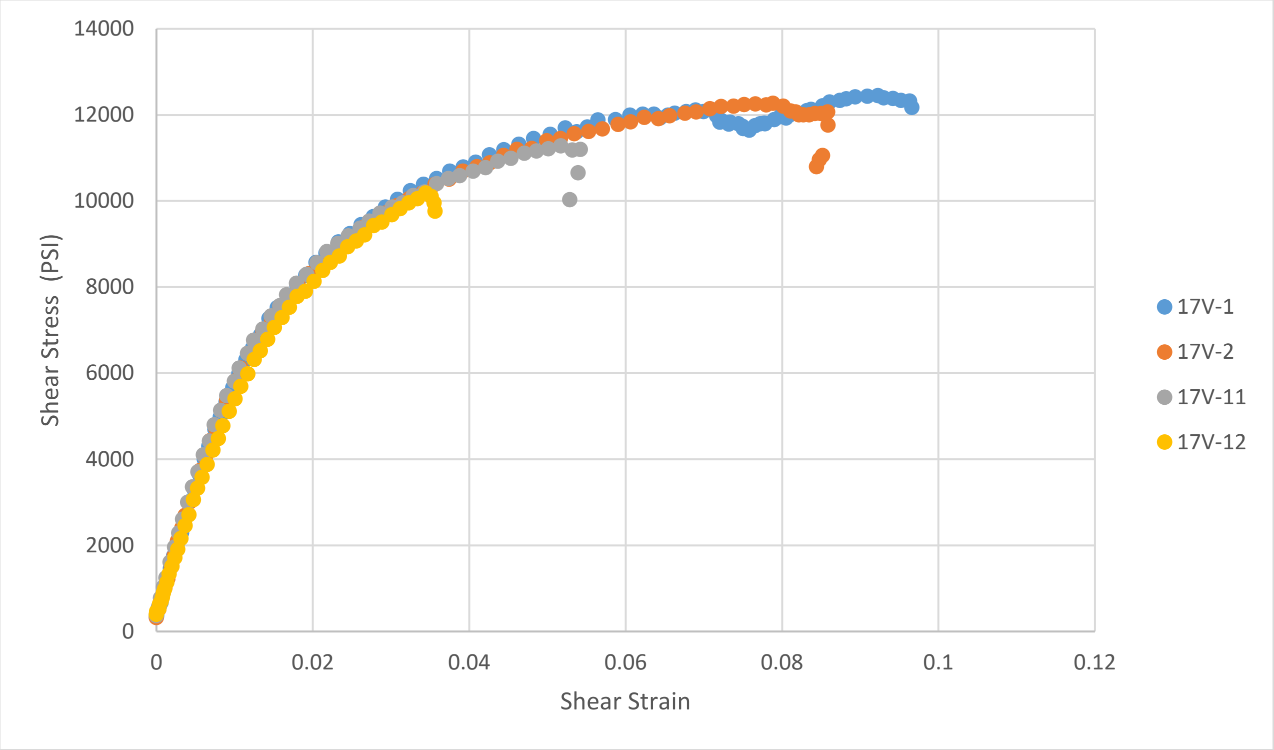

Figure B5: Stress Strain Chart for 17V coupons

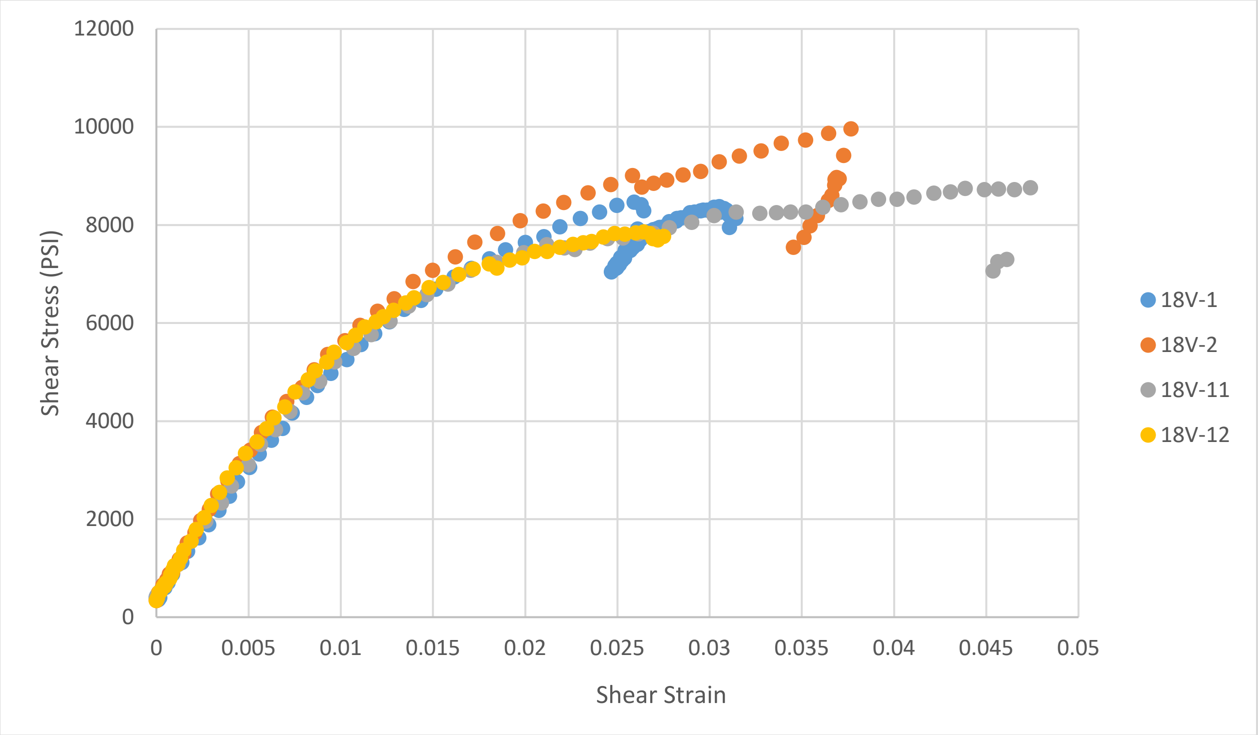

Figure B6: Stress Strain Chart for 18V coupons

Appendix C: Values for Each Test

Table C1: Measured Shear Values for Each Short Beam Shear Coupon

			max load	**width**	**thickness**	**shear strength**
			pound force	in	in	psi
1S	Control	1	471	0.511811	0.12126	5691.88
		2	513	0.511811	0.12126	6199.43
		3	514	0.511811	0.12126	6211.52
		4	583	0.511811	0.12126	7045.36
		5	560	0.511811	0.12126	6767.41
		6	534	0.511811	0.12126	6453.21
		7	452	0.511811	0.12126	5462.27
		8	380	0.511811	0.12126	4592.17
		9	436	0.511811	0.12126	5268.91
		10	538	0.511811	0.12126	6501.55
	Conditioned	11	355	0.511811	0.12126	4290.06
		12	416	0.511811	0.12126	5027.22
		13	458	0.511811	0.12126	5534.78
		14	469	0.511811	0.12126	5667.71
		15	471	0.511811	0.12126	5691.88
		16	406	0.511811	0.12126	4906.37
		17	484	0.511811	0.12126	5848.98
		18	413	0.511811	0.12126	4990.97
		19	454	0.511811	0.12126	5486.44
		20	476	0.511811	0.12126	5752.30
2S	Control	1	510	0.511811	0.135827	5502.20
		2	593	0.511811	0.135827	6397.66
		3	529	0.511811	0.135827	5707.18
		4	471	0.511811	0.135827	5081.44
		5	501	0.511811	0.135827	5405.10
		6	562	0.511811	0.135827	6063.21
		7	564	0.511811	0.135827	6084.79
		8	575	0.511811	0.135827	6203.46
		9	597	0.511811	0.135827	6440.81
		10	595	0.511811	0.135827	6419.23
	Conditioned	11	364	0.511811	0.135827	3927.06
		12	330	0.511811	0.135827	3560.25
		13	428	0.511811	0.135827	4617.53
		14	386	0.511811	0.135827	4164.41
		15	426	0.511811	0.135827	4595.96
		16	411	0.511811	0.135827	4434.13
		17	379	0.511811	0.135827	4088.89

		18	403	0.511811	0.135827	4347.82
		19	441	0.511811	0.135827	4757.79
		20	452	0.511811	0.135827	4876.46
3AS	Control	1	691	0.511811	0.115748	8748.15
		2	575	0.511811	0.115748	7279.57
		3	589	0.511811	0.115748	7456.81
		4	562	0.511811	0.115748	7114.99
		5	536	0.511811	0.115748	6785.83
		6	479	0.511811	0.115748	6064.20
		7	585	0.511811	0.115748	7406.17
		8	501	0.511811	0.115748	6342.72
		9	485	0.511811	0.115748	6140.16
		10	558	0.511811	0.115748	7064.35
	Conditioned	11	486	0.511811	0.115748	6152.82
		12	547	0.511811	0.115748	6925.09
		13	493	0.511811	0.115748	6241.44
		14	533	0.511811	0.115748	6747.85
		15	528	0.511811	0.115748	6684.55
		16	508	0.511811	0.115748	6431.34
		17	415	0.511811	0.115748	5253.95
		18	429	0.511811	0.115748	5431.19
		19	538	0.511811	0.115748	6811.15
		20	429	0.511811	0.115748	5431.19
3BS	Control	1	534	0.511811	0.122835	6370.48
		2	514	0.511811	0.122835	6131.88
		3	501	0.511811	0.122835	5976.80
		4	503	0.511811	0.122835	6000.66
		5	547	0.511811	0.122835	6525.56
		6	625	0.511811	0.122835	7456.08
		7	582	0.511811	0.122835	6943.11
		8	560	0.511811	0.122835	6680.65
		9	449	0.511811	0.122835	5356.45
		10	506	0.511811	0.122835	6036.45
	Conditioned	11	498	0.511811	0.122835	5941.01
		12	422	0.511811	0.122835	5034.35
		13	432	0.511811	0.122835	5153.64
		14	439	0.511811	0.122835	5237.15
		15	461	0.511811	0.122835	5499.61
		16	459	0.511811	0.122835	5475.75

		17	582	0.511811	0.122835	6943.11
		18	521	0.511811	0.122835	6215.39
		19	382	0.511811	0.122835	4557.16
		20	442	0.511811	0.122835	5272.94
4AS	Control	1	683	0.511811	0.119685	8362.43
		2	601	0.511811	0.119685	7358.45
		3	681	0.511811	0.119685	8337.94
		4	680	0.511811	0.119685	8325.70
		5	625	0.511811	0.119685	7652.30
		6	618	0.511811	0.119685	7566.59
		7	591	0.511811	0.119685	7236.01
		8	544	0.511811	0.119685	6660.56
		9	583	0.511811	0.119685	7138.06
		10	652	0.511811	0.119685	7982.88
	Conditioned	11	602	0.511811	0.119685	7370.69
		12	607	0.511811	0.119685	7431.91
		13	664	0.511811	0.119685	8129.80
		14	686	0.511811	0.119685	8399.16
		15	651	0.511811	0.119685	7970.63
		17	634	0.511811	0.119685	7762.49
		18	621	0.511811	0.119685	7603.32
		19	698	0.511811	0.119685	8546.08
		20	668	0.511811	0.119685	8178.77
4BS	Control	1	655	0.511811	0.129528	7410.21
		2	717	0.511811	0.129528	8111.64
		3	685	0.511811	0.129528	7749.61
		4	711	0.511811	0.129528	8043.76
		5	683	0.511811	0.129528	7726.99
		6	679	0.511811	0.129528	7681.73
		7	672	0.511811	0.129528	7602.54
		8	766	0.511811	0.129528	8665.99
		9	686	0.511811	0.129528	7760.93
		10	718	0.511811	0.129528	8122.95
	Conditioned	11	659	0.511811	0.129528	7455.47
		12	686	0.511811	0.129528	7760.93
		13	645	0.511811	0.129528	7297.08
		14	641	0.511811	0.129528	7251.83
		15	607	0.511811	0.129528	6867.18
		16	636	0.511811	0.129528	7195.26

		17	641	0.511811	0.129528	7251.83
		18	552	0.511811	0.129528	6244.94
		19	651	0.511811	0.129528	7364.96
		20	596	0.511811	0.129528	6742.73
6AS	Control	1	656	0.511811	0.11811	8138.94
		2	700	0.511811	0.11811	8684.85
		3	620	0.511811	0.11811	7692.29
		4	647	0.511811	0.11811	8027.28
		5	729	0.511811	0.11811	9044.65
		6	697	0.511811	0.11811	8647.63
		7	750	0.511811	0.11811	9305.19
		8	763	0.511811	0.11811	9466.48
		10	684	0.511811	0.11811	8486.34
	Conditioned	11	664	0.511811	0.11811	8238.20
		12	643	0.511811	0.11811	7977.65
		13	658	0.511811	0.11811	8163.76
		14	685	0.511811	0.11811	8498.74
		15	615	0.511811	0.11811	7630.26
		16	654	0.511811	0.11811	8114.13
		17	760	0.511811	0.11811	9429.26
		18	713	0.511811	0.11811	8846.14
		19	661	0.511811	0.11811	8200.98
		20	610	0.511811	0.11811	7568.22
6BS	Control	1	817	0.511811	0.127953	9356.73
		2	789	0.511811	0.127953	9036.06
		3	634	0.511811	0.127953	7260.91
		4	621	0.511811	0.127953	7112.03
		5	773	0.511811	0.127953	8852.82
		6	693	0.511811	0.127953	7936.61
		7	686	0.511811	0.127953	7856.45
		8	729	0.511811	0.127953	8348.90
		9	749	0.511811	0.127953	8577.96
		10	726	0.511811	0.127953	8314.55
	Conditioned	11	675	0.511811	0.127953	7730.47
		12	615	0.511811	0.127953	7043.31
		13	683	0.511811	0.127953	7822.09
		14	588	0.511811	0.127953	6734.10
		15	673	0.511811	0.127953	7707.56
		16	531	0.511811	0.127953	6081.30

		17	678	0.511811	0.127953	7764.83
		18	672	0.511811	0.127953	7696.11
		19	631	0.511811	0.127953	7226.56
		20	654	0.511811	0.127953	7489.96
10AS	Control	1	582	0.511811	0.127165	6706.65
		2	552	0.511811	0.127165	6360.95
		3	718	0.511811	0.127165	8273.84
		4	486	0.511811	0.127165	5600.40
		5	513	0.511811	0.127165	5911.53
		6	515	0.511811	0.127165	5934.58
		7	575	0.511811	0.127165	6625.99
		8	568	0.511811	0.127165	6545.32
		9	526	0.511811	0.127165	6061.34
		10	549	0.511811	0.127165	6326.38
	Conditioned	11	347	0.511811	0.127165	3998.64
		12	416	0.511811	0.127165	4793.76
		13	373	0.511811	0.127165	4298.25
		14	436	0.511811	0.127165	5024.23
		15	352	0.511811	0.127165	4056.26
		16	382	0.511811	0.127165	4401.96
		17	367	0.511811	0.127165	4229.11
		18	422	0.511811	0.127165	4862.90
		19	449	0.511811	0.127165	5174.03
		20	480	0.511811	0.127165	5531.26
10BS	Control	1	589	0.511811	0.122441	7049.21
		2	551	0.511811	0.122441	6594.42
		3	625	0.511811	0.122441	7480.06
		4	495	0.511811	0.122441	5924.21
		5	611	0.511811	0.122441	7312.50
		6	634	0.511811	0.122441	7587.77
		7	532	0.511811	0.122441	6367.03
		8	606	0.511811	0.122441	7252.66
		10	593	0.511811	0.122441	7097.08
	Conditioned	11	562	0.511811	0.122441	6726.07
		12	446	0.511811	0.122441	5337.77
		13	397	0.511811	0.122441	4751.33
		14	409	0.511811	0.122441	4894.95
		15	403	0.511811	0.122441	4823.14
		16	409	0.511811	0.122441	4894.95

		17	466	0.511811	0.122441	5577.13
		18	476	0.511811	0.122441	5696.81
		19	403	0.511811	0.122441	4823.14
		20	406	0.511811	0.122441	4859.05
11S	Control	1	766	0.511811	0.125984	8909.72
		2	777	0.511811	0.125984	9037.67
		3	729	0.511811	0.125984	8479.36
		4	843	0.511811	0.125984	9805.35
		5	644	0.511811	0.125984	7490.68
		6	761	0.511811	0.125984	8851.56
		7	647	0.511811	0.125984	7525.57
		8	633	0.511811	0.125984	7362.73
		9	725	0.511811	0.125984	8432.83
		10	608	0.511811	0.125984	7071.95
	Conditioned	11	605	0.511811	0.125984	7037.05
		12	737	0.511811	0.125984	8572.41
		13	678	0.511811	0.125984	7886.15
		14	636	0.511811	0.125984	7397.63
		15	659	0.511811	0.125984	7665.15
		16	654	0.511811	0.125984	7606.99
		17	678	0.511811	0.125984	7886.15
		18	646	0.511811	0.125984	7513.94
		19	649	0.511811	0.125984	7548.84
		20	652	0.511811	0.125984	7583.73
12S	Control	1	668	0.511811	0.127559	7673.91
		2	649	0.511811	0.127559	7455.64
		3	723	0.511811	0.127559	8305.75
		4	612	0.511811	0.127559	7030.59
		5	647	0.511811	0.127559	7432.67
		6	666	0.511811	0.127559	7650.94
		7	713	0.511811	0.127559	8190.87
		8	690	0.511811	0.127559	7926.65
		9	712	0.511811	0.127559	8179.38
		10	722	0.511811	0.127559	8294.26
	Conditioned	11	603	0.511811	0.127559	6927.20
		12	645	0.511811	0.127559	7409.69
		13	631	0.511811	0.127559	7248.86
		14	597	0.511811	0.127559	6858.27
		15	695	0.511811	0.127559	7984.08

		16	664	0.511811	0.127559	7627.96
		17	593	0.511811	0.127559	6812.32
		18	625	0.511811	0.127559	7179.93
		19	651	0.511811	0.127559	7478.62
		20	693	0.511811	0.127559	7961.11
17S	Control	1	478	0.511811	0.119685	5852.48
		2	532	0.511811	0.119685	6513.63
		3	475	0.511811	0.119685	5815.75
		4	509	0.511811	0.119685	6232.03
		5	571	0.511811	0.119685	6991.14
		6	596	0.511811	0.119685	7297.23
		7	506	0.511811	0.119685	6195.30
		8	504	0.511811	0.119685	6170.81
		9	566	0.511811	0.119685	6929.92
		10	564	0.511811	0.119685	6905.43
	Conditioned	11	370	0.511811	0.119685	4530.16
		12	398	0.511811	0.119685	4872.98
		13	445	0.511811	0.119685	5448.43
		14	414	0.511811	0.119685	5068.88
		15	380	0.511811	0.119685	4652.60
		16	414	0.511811	0.119685	5068.88
		17	360	0.511811	0.119685	4407.72
		18	370	0.511811	0.119685	4530.16
		19	396	0.511811	0.119685	4848.49
		20	385	0.511811	0.119685	4713.81
18S	Control	1	722	0.511811	0.111811	9462.46
		2	753	0.511811	0.111811	9868.75
		3	624	0.511811	0.111811	8178.08
		4	714	0.511811	0.111811	9357.62
		5	675	0.511811	0.111811	8846.49
		6	591	0.511811	0.111811	7745.59
		7	734	0.511811	0.111811	9619.73
		8	646	0.511811	0.111811	8466.41
		9	673	0.511811	0.111811	8820.27
		10	707	0.511811	0.111811	9265.87
	Conditioned	11	526	0.511811	0.111811	6893.71
		12	609	0.511811	0.111811	7981.50
		13	603	0.511811	0.111811	7902.86
		14	546	0.511811	0.111811	7155.82

		15	473	0.511811	0.111811	6199.09
		16	567	0.511811	0.111811	7431.05
		17	567	0.511811	0.111811	7431.05
		18	556	0.511811	0.111811	7286.88
		19	507	0.511811	0.111811	6644.69
		20	612	0.511811	0.111811	8020.81

Table C2: Measured Values for Each V-Notch Shear Coupon

			max load	**width**	**thickness**	**shear strength**
			pound force	in	in	psi
1V	Control	1	492	0.459	0.1115	9613.41
		2	570	0.45635	0.128	9758.14
		3	527	0.4585	0.115	9994.78
		4	509	0.4545	0.124	9031.55
		5	604	0.461	0.126	10398.37
		6	560	0.478	0.1215	9642.37
		7	606	0.461	0.127	10350.66
		8	435	0.461	0.11	8578.19
		9	575	0.4565	0.1195	10540.45
		10	591	0.469	0.123	10244.94
	Conditioned	11	528	0.464	0.131	8686.50
		12	519	0.458	0.1365	8301.74
		13	482	0.46	0.121	8659.72
		14	512	0.459	0.131	8515.03
		15	543	0.4605	0.127	9284.67
		16	411	0.4575	0.101	8894.66
		17	439	0.4635	0.112	8456.62
		18	341	0.461	0.1215	6088.04
		19	481	0.4565	0.125	8429.35
		20	527	0.4605	0.1285	8905.90
2V	Control	1	582	0.4355	0.127	10522.79
		2	504	0.4555	0.127	8712.41
		3	571	0.463	0.1235	8901.64
		4	656	0.465	0.121	11659.11
		5	601	0.4655	0.123	10496.62
		6	641	0.48	0.132	10116.79
		7	495	0.4075	0.121	10039.04
		8	615	0.426	0.134	10773.60
		9	547	0.434	0.1215	10373.40
		10	570	0.415	0.141	9741.09
	Conditioned	11	441	0.4705	0.116	8080.18
		12	454	0.481	0.123	7673.71
		13	477	0.4585	0.1235	8423.88
		14	476	0.462	0.1285	8017.92
		15	395	0.445	0.116	7652.07

		16	501	0.458	0.136	8043.28
		17	411	0.468	0.119	7379.88
		18	397	0.406	0.115	8502.89
		19	471	0.399	0.1325	8909.07
		26	513	0.46	0.135	8260.87
		27	471	0.422	0.1305	8552.60
3AV	Control	1	481	0.447	0.112	9607.70
		2	584	0.447	0.1265	10327.97
		3	597	0.448	0.1395	9552.61
		4	597	0.4745	0.119	10572.83
		5	576	0.4785	0.1285	9367.80
		6	550	0.452	0.1205	10098.04
		7	559	0.475	0.116	10145.19
		8	594	0.466	0.123	10363.24
		9	684	0.462	0.151	9804.76
		10	613	0.457	0.127	10561.86
	Conditioned	11	500	0.443	0.133	8486.23
		12	524	0.4605	0.136	8366.86
		13	448	0.4645	0.122	7905.56
		14	517	0.468	0.1275	8664.32
		15	529	0.4705	0.128	8783.87
		16	544	0.452	0.132	9117.73
		17	485	0.468	0.116	8933.83
		18	525	0.4555	0.125	9220.64
		19	496	0.467	0.1215	8741.55
		21	557	0.4665	0.1265	9438.72
3BV	Control	1	540	0.451	0.119	10061.67
		2	561	0.4565	0.134	9171.01
		3	485	0.461	0.1215	8658.94
		4	523	0.4605	0.1205	9425.08
		5	578	0.4565	0.155	8168.75
		6	573	0.4665	0.136	9031.59
		7	583	0.468	0.121	10295.26
		8	501	0.4535	0.1265	8733.13
		9	600	0.463	0.133	9743.58
		10	615	0.491	0.1385	9043.65
	Conditioned	11	441	0.4655	0.119	7961.08
		12	497	0.476	0.1275	8189.16
		13	427	0.458	0.1185	7867.63

		14	439	0.4605	0.115	8289.67
		15	502	0.459	0.1275	8577.90
		16	454	0.4615	0.119	8266.80
		17	491	0.457	0.117	9182.89
		18	491	0.4645	0.126	8389.29
		19	496	0.4715	0.126	8348.90
		20	482	0.449	0.126	8519.81
		21	485	0.4605	0.131	8039.72
		22	441	0.472	0.125	7474.58
4AV	Control	1	728	0.476	0.119	12852.20
		2	678	0.4665	0.1155	12583.34
		3	703	0.4575	0.127	12099.31
		4	576	0.464	0.1145	10841.74
		5	669	0.456	0.1245	11783.98
		6	745	0.468	0.1275	12485.34
		7	762	0.467	0.1305	12503.38
		8	736	0.4565	0.123	13107.86
		9	748	0.4545	0.1235	13326.03
		10	738	0.462	0.13	12287.71
	Conditioned	11	705	0.4855	0.133	10918.13
		12	669	0.4715	0.128	11084.97
		13	646	0.4435	0.124	11746.74
		14	615	0.472	0.132	9870.96
		15	651	0.472	0.123	11213.31
		16	518	0.4495	0.12	9603.26
		17	577	0.462	0.1235	10112.69
		18	666	0.468	0.1335	10659.75
		19	715	0.471	0.1355	11203.30
		20	654	0.462	0.1265	11190.39
		21	703	0.4605	0.131	11653.45
		22	617	0.472	0.125	10457.63
4BV	Control	1	690	0.4785	0.126	11444.49
		2	689	0.441	0.1375	11362.61
		4	711	0.457	0.131	11876.33
		5	671	0.46	0.12	12155.80
		6	738	0.4565	0.1355	11930.98
		7	706	0.4665	0.133	11378.93
		8	699	0.472	0.129	11480.09
		9	737	0.478	0.1315	11725.03

		10	746	0.4525	0.1315	12537.02
		11	731	0.4625	0.127	12445.20
	Conditioned	12	571	0.4655	0.1245	9852.51
		13	645	0.4685	0.128	10755.74
		14	624	0.4525	0.1285	10731.56
		15	635	0.448	0.1265	11204.83
		16	555	0.465	0.1295	9216.59
		17	656	0.473	0.1385	10013.66
		18	640	0.4385	0.133	10973.84
		19	590	0.45	0.1365	9605.21
		20	619	0.461	0.125	10741.87
		21	633	0.4805	0.125	10539.02
6AV	Control	1	713	0.472	0.125	12084.75
		2	584	0.4785	0.118	10343.06
		3	782	0.477	0.1325	12372.93
		4	615	0.4695	0.1115	11748.02
		5	722	0.454	0.1225	12982.11
		6	689	0.458	0.1205	12484.37
		7	710	0.4705	0.124	12169.62
		8	691	0.478	0.1325	10910.24
		9	684	0.4665	0.1255	11683.17
		10	704	0.4785	0.123	11961.50
	Conditioned	11	708	0.467	0.132	11485.30
		12	724	0.4685	0.142	10882.80
		13	656	0.4705	0.125	11154.09
		14	594	0.4665	0.1155	11024.35
		15	621	0.463	0.119	11271.03
		16	547	0.473	0.1085	10658.51
		17	671	0.474	0.13	10889.32
		18	607	0.4785	0.117	10842.29
		19	646	0.476	0.1225	11078.72
		20	706	0.4855	0.135	10771.64
6BV	Control	1	661	0.4645	0.1285	11074.21
		2	761	0.467	0.1435	11355.75
		3	729	0.465	0.144	10887.10
		4	693	0.465	0.1305	11420.10
		5	751	0.467	0.1345	11956.41
		6	679	0.462	0.1195	12298.72
		7	731	0.4735	0.1385	11146.73

		8	667	0.4725	0.125	11293.12
		9	725	0.4645	0.136	11476.60
		10	727	0.475	0.1395	10971.51
	Conditioned	11	723	0.473	0.148	10327.98
		12	596	0.474	0.1295	9709.53
		13	651	0.483	0.132	10210.80
		14	625	0.469	0.126	10576.37
		15	655	0.466	0.1405	10004.12
		16	676	0.4695	0.144	9998.82
		17	650	0.4795	0.134	10116.26
		18	646	0.4615	0.141	9927.54
		19	615	0.476	0.1395	9261.77
		20	705	0.4855	0.1425	10190.25
10AV	Control	1	578	0.476	0.1125	10793.65
		2	698	0.4615	0.1445	10466.85
		3	479	0.459	0.1135	9194.48
		4	600	0.471	0.13	9799.12
		5	590	0.471	0.131	9562.24
		6	549	0.4855	0.1205	9384.17
		7	632	0.468	0.128	10550.21
		8	478	0.4695	0.1055	9650.28
		9	599	0.483	0.1185	10465.53
		10	601	0.4575	0.1295	10144.10
	Conditioned	11	439	0.4848	0.114	7943.23
		12	471	0.4775	0.132	7472.63
		13	455	0.4705	0.1155	8372.78
		14	456	0.4585	0.127	7831.08
		15	498	0.4705	0.1345	7869.51
		16	465	0.4725	0.1225	8033.69
		17	442	0.4785	0.121	7634.05
		18	521	0.4615	0.1405	8035.07
		19	461	0.489	0.1285	7336.50
		20	461	0.471	0.126	7768.00
		21	480	0.486	0.129	7656.24
10BV	Control	1	519	0.475	0.124	8811.54
		2	563	0.484	0.126	9231.93
		3	546	0.475	0.1275	9015.48
		4	576	0.4825	0.121	9865.97
		5	565	0.4805	0.1275	9222.42

		6	523	0.4785	0.1135	9629.95
		7	615	0.484	0.124	10247.27
		8	589	0.471	0.1365	9161.40
		9	542	0.478	0.1205	9409.89
		10	557	0.4795	0.1255	9255.99
	Conditioned	11	473	0.465	0.148	6873.00
		12	460	0.4645	0.1315	7530.89
		13	463	0.4665	0.1305	7605.34
		14	486	0.4825	0.1455	6922.71
		15	409	0.474	0.122	7072.70
		16	453	0.5075	0.1275	7000.87
		17	461	0.485	0.143	6646.96
		18	428	0.4785	0.124	7213.40
		19	473	0.49	0.1365	7071.84
		20	411	0.4835	0.1295	6564.11
		21	441	0.485	0.1275	7131.59
		22	479	0.476	0.1505	6686.40
11V	Control	1	715	0.4625	0.123	12568.67
		2	815	0.4825	0.14	12065.14
		3	783	0.494	0.131	12099.39
		4	707	0.4855	0.1235	11791.34
		5	656	0.4875	0.121	11121.00
		6	739	0.4995	0.1215	12176.79
		7	735	0.4825	0.1155	13188.88
		8	755	0.496	0.1215	12528.21
		9	809	0.4935	0.13	12610.08
		10	768	0.4875	0.1285	12259.80
	Conditioned	11	664	0.498	0.127	10498.69
		12	645	0.4885	0.133	9927.58
		13	706	0.4905	0.1355	10622.49
		14	668	0.484	0.13	10616.66
		15	626	0.484	0.124	10430.55
		16	586	0.487	0.1175	10240.73
		17	662	0.485	0.1215	11234.14
		18	650	0.4805	0.131	10326.39
		19	703	0.4855	0.136	10647.00
		20	674	0.4995	0.13	10379.61
		21	704	0.5015	0.1315	10675.20
		22	686	0.4965	0.1435	9628.37
		23	645	0.4985	0.1215	10649.23

12V	Control	1	721	0.4915	0.134	10947.30
		2	764	0.4755	0.136	11814.19
		3	738	0.4975	0.1325	11195.60
		4	795	0.4885	0.1365	11922.57
		5	751	0.4795	0.1345	11644.72
		6	793	0.5015	0.1235	12803.69
		7	801	0.4635	0.144	12001.08
		8	768	0.4695	0.137	11940.02
		9	756	0.477	0.134	11827.65
		10	776	0.475	0.1365	11968.38
	Conditioned	11	728	0.4855	0.149	10063.66
		12	697	0.4895	0.1385	10280.88
		13	696	0.487	0.136	10508.52
		14	685	0.4865	0.1355	10391.27
		15	660	0.4735	0.1355	10286.90
		16	668	0.485	0.133	10355.79
		17	641	0.4625	0.136	10190.78
		18	690	0.477	0.1335	10835.51
		19	672	0.4815	0.1305	10694.55
		20	660	0.4885	0.1335	10120.41
		21	590	0.474	0.1185	10504.01
		22	655	0.477	0.1385	9914.55
17V	Control	1	677	0.49	0.116	11910.63
		2	652	0.494	0.112	11784.27
		3	562	0.43	0.1225	10669.20
		4	561	0.4165	0.1035	13013.90
		5	558	0.443	0.102	12348.96
		6	597	0.4455	0.1045	12823.61
		7	682	0.4655	0.1145	12795.56
		8	661	0.4675	0.109	12971.59
		9	663	0.4575	0.104	13934.43
		10	665	0.47	0.114	12411.35
	Conditioned	11	567	0.492	0.107	10770.46
		12	562	0.498	0.1165	9686.82
		13	506	0.4895	0.093	11115.14
		14	567	0.5115	0.0935	11855.66
		15	483	0.4875	0.1105	8966.24
		16	621	0.511	0.113	10754.55
		17	612	0.486	0.112	11243.39

		18	513	0.4685	0.103	10630.91
		19	565	0.493	0.109	10514.17
		20	624	0.459	0.125	10875.82
		21	489	0.4935	0.0975	10162.89
		22	621	0.4905	0.1105	11457.51
18V	Control	1	434	0.493	0.11	8002.95
		2	499	0.499	0.106	9433.96
		3	526	0.503	0.0995	10509.81
		4	518	0.506	0.119	8602.65
		5	522	0.501	0.1055	9875.98
		6	542	0.4845	0.104	10756.53
		7	498	0.483	0.11	9373.24
		8	466	0.471	0.1075	9203.57
		9	500	0.4965	0.11	9154.99
		10	506	0.4935	0.107	9582.52
	Conditioned	11	418	0.4605	0.1095	8289.58
		12	461	0.507	0.1175	7738.47
		13	424	0.5055	0.1115	7522.63
		14	444	0.4825	0.1065	8640.44
		15	395	0.498	0.1015	7814.51
		16	382	0.4875	0.1045	7498.47
		17	369	0.478	0.098	7877.21
		18	341	0.4875	0.102	6857.72
		19	439	0.502	0.106	8250.02
		20	405	0.507	0.1025	7793.33
		21	334	0.4995	0.0965	6929.21
		22	399	0.498	0.1055	7594.36
		23	379	0.5	0.1065	7117.37