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Environmental Effects on Mechanical Properties of Wet Lay-Up Fiber-Reinforced Polymer

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The demand for fiber-reinforced polymers (FRPs) in rehabilitation of infrastructure is increasing. New techniques use the light weight, high strength, and formability of FRP fabrics and laminates in various concrete retrofitting projects. This paper presents the results of studies on the long-term behavior of different types of FRP laminates produced using the wet lay-up technique. This technique is the most used in field application of FRPs on concrete structures. The scope of the paper is limited to only one mode of failure: laminate failure. It is noted that another form of failure is the bond at the interface. This mode of failure is currently under investigation at the University of Arizona.

A total of 525 specimens were prepared using one type of epoxy and seven different types of fabrics. Unidirectional and bidirectional fabrics made from glass, carbon, and aramid were used in this study. The samples were exposed to nine different environments. These environments were simulated using four different chemical solutions with a pH of 12.5, 10, 7, and 2.5 and substitute seawater. Additional FRP samples were exposed to ultraviolet (UV) radiation, temperatures of 60 and 50°C (140 and 122°F) with 95% relative humidity (RH), and soil with 25% moisture content and active microorganisms in specially constructed chambers. Uniaxial tension tests were performed on the samples after 6000, 12,000, and 20,000 hours of exposure as well as on control samples; and tensile properties were measured for each specimen. The results showed a significant loss of strength and ultimate strain for glass FRP (GFRP), especially in environments with high pH values, while carbon and hybrid glass-carbon laminates showed very little loss of mechanical properties.

Keywords: environmental effects; fabric; fiber-reinforced polymer; long-term durability; wet lay-up technique.

INTRODUCTION

Fiber-reinforced polymers (FRP) are increasingly attracting the attention of civil engineers because of their unique properties for retrofitting of structures. The excellent tensile strength, light weight, resistance to electrochemical corrosion, and formability of FRPs make them materials of choice for repair and retrofit of concrete structures. These materials have been used in other engineering fields, such as aerospace, automotive, marine, and chemical, for many years; and, in general, they have shown good long-term performance. The methods of fabrication and quality control in civil engineering projects, however, are quite different from those in the aerospace or defense industry. In this study, the authors attempted to simulate the process that is used to install FRP in civil-type structures to achieve realistic results of the long-term performance, as such performance is greatly affected by the manufacturing process. The purpose of this research was to look at the behavior of the wet lay-up technique of applying FRP to concrete structures, which is by far the most common method of application in construction. Due to the many sources of imperfection in hand application in the field, as compared to the machine application in controlled manufacturing facilities, the durability issues of the wet lay-up methods are quite different than those of FRP produced in factory settings.

In addition, the FRP used in civil engineering projects are exposed to different environments than those in other fields of engineering. Therefore, to address the rising concerns about the long-term performance of FRP in civil engineering projects, durability of these materials must be investigated according to the installation process and the unique civil engineering environments that they will be exposed to.

Several investigators have addressed the durability of FRP materials. Most of the research was concentrated on the effect of the moisture and temperature on FRP tendons, reinforcing bars, pultruded sections, and laminates made with standard vacuum bagging procedures under controlled temperature and curing cycles.[1-2] The results of such studies have been used initially to answer some of the concerns of structural engineers. Because the durability of FRP materials is significantly affected by their manufacturing process and quality control, however, studies are needed to address durability issues specifically for the type of projects involving the wet lay-up procedures as used in construction.

RESEARCH SIGNIFICANCE

During the past decade, FRPs have been used in numerous projects to increase the capacity of existing concrete bridges and buildings. Many investigations have shown the effectiveness of these materials for increasing the strength and ductility of existing concrete structures. There is significant concern in the industry, however, as to the long-term performance of these materials. This research addresses this important question by examining the environmental effects on the mechanical properties of FRPs that are produced in a manner typical of that used in construction and subjected to simulated civil engineering environments.

PREVIOUS WORKS

As previously explained, the existing database on the long-term durability of composite materials cannot address all the concerns of practicing civil engineers. The manufacturing processes of the composites used in those studies were different from that of the wet lay-up technique, which is the most common method used in civil engineering projects. The environments considered in most of those studies were not addressing all of civil engineering concerns either. In addition, most of the studies considered fairly short periods

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of exposure that may not satisfy the long-term performance issues. The published works on the durability of FRP structural elements can be categorized in three different groups.

Laminates

In a study conducted by Springer et al.,[3] environmental effects on glass FRP (GFRP) and vinylester composites were investigated. They exposed three different composite laminates to humid air (50 and 100% RH), saturated NaCl solution, diesel fuel, lubricating oil, antifreeze, and gasoline at two temperatures of 23 and 93°C (73.4 and 199.4°F) for 6 months. They obtained the tensile and shear properties of the laminates by conducting uniaxial tension and short-beam shear tests. The following conclusions were drawn from testing more than 600 specimens: specimens exposed at 93°C (199.4°F) showed the highest loss of mechanical properties (~19%) in solutions compared to those exposed at 23°C (73.4 °F) (~6%). The vinylester-based laminates showed less degradation (~9.5%) compared to the polyester-based laminates (~14.5%). Among all, on average, the losses for the environments of antifreeze, saturated salt, gasoline, and 100% RH after 6 months of exposure were 28%, 22%, 15%, and 13%, respectively.

Reinforcing bars and tendons

Several researchers have investigated durability and long-term performance of FRP reinforcing bars as reinforcement for concrete structures. Sen et al.,[4-6] Ceroni et al.,[7] Won and Park,[8] and Micelli and Nanni[9] have conducted extensive experimental and analytical studies on the long-term behavior of FRP reinforcing bars and tendons in seawater and other solutions simulating civil engineering environments.

As an example of this type of work, refer to a study conducted by Tannous and Saadatmanesh.[10] In that study, the effect of different environments on e-glass FRP reinforcing bars, pan-based carbon FRP tendons and aramid FRP tendons was investigated. They tested the specimens after exposure to seven different solutions, ultraviolet (UV) radiation, and freezing-and-thawing cycles. The solutions in the study consisted of fresh water at 25 and 65°C (77 and 149°F), alkaline (pH = 12 at 25 and 65°C [77 and 149°F]), acidic (pH = 3 at 25°C [77°F]), seawater (3.5% NaCl at 25°C [77°F]), and deicing salt (7% NaCl + $CaCl_2$ and NaCl + $MgCl_2$ at 25°C [77°F]). After 6 months of exposure, the specimens were tested in uniaxial tension. The results indicated higher strength loss in alkaline (~18%) and deicing salt (~17%) solutions compared to fresh water (4%), seawater (8%), and acidic (5%) solutions. In addition, they reported less degradation in vinylester-based reinforcing bars (~10%) in comparison to polyester-based ones (~16%). The loss of strength in smaller reinforcing bars (ϕ = 10 mm [0.39 in.]) (~16%) were much higher than the larger diameter reinforcing bars (ϕ = 25 mm [0.98 in.]) (~9%). Furthermore, they reported only a small change in the tensile modulus of the FRP reinforcing bars as a result of the exposure. Their test results after 1 year of exposure showed almost no degradation for carbon tendons. In the case of the aramid tendons, excellent freezing-and-thawing and fresh water immersion durability was observed. The acidic solution had the most effect on aramid tendons and caused an 8% drop in the strength, whereas for the rest of the environments, an average of 5% loss in tensile strength was reported.

Pultruded sections

Gomez and Casto[11] investigated freezing-and-thawing durability of pultruded fiber glass composites. They considered two different pultruded laminates with polyester and vinylester matrixes. They reported a reduction in flexural properties after 300 cycles of freezing and thawing, as follows: 24 and 22% reduction in flexural strength, 27 and 22% reduction in modulus of toughness, and 24 and 22% reduction in Young's modulus for laminates with polyester and vinylester matrixes, respectively.

In another study conducted by Bank et al.,[12] the accelerated aging of vinylester-based glass pultruded rods was addressed. For specimens immersed in water, they reported flexural strength losses of 14 to 45% for the temperatures of 40 to 80°C (104 to 176°F), respectively. The humid environment did not affect the properties.

EXPERIMENTAL STUDY

To investigate the effects of environmental exposure on the mechanical properties of FRP laminates as prepared in a typical civil engineering application, 525 coupon specimens were prepared, exposed to various environments and tested under uniaxial tension. Composite laminates made from fabrics of different materials with different weave patterns were tested after exposure to various simulated aggressive environments. Tensile properties such as the ultimate strength, modulus of elasticity, and the ultimate strain were measured for each sample after specific exposure time. By comparing the mechanical properties of the exposed specimens to those for the control specimens, the effect of different environments on the composite laminates was quantified.

Test variables

The effects of several parameters on the durability of FRP laminates were examined. Nine simulated aggressive environments were considered: 1) fresh water; 2) saturated calcium hydroxide, $Ca(OH)_2$, solution (pH = 12.5); 3) saturated $Ca(OH)_2$ solution (pH = 10.0); 4) hydrochloric acid, HCl, solution (pH = 2.5); 5) simulated seawater; 6) moist alkaline soil with micro organisms; 7) dry air at a temperature of 60°C (140°F); 8) air temperature of 50°C (122 °F) and RH of 95%; and 9) UV radiation. Seven different types of fabrics were used: 1) unidirectional loose glass, GL-U; 2) unidirectional glass, G-U; 3) unidirectional carbon, C-U; 4) unidirectional hybrid glass-carbon, GC-U; 5) bidirectional glass, B-G; 6) bidirectional hybrid glass-carbon, GC-B; and 7) bidirectional hybrid glass-aramid, GA-B, as shown in Fig. 1. For the designation of different fabrics, letters G, C, and A stand for E-glass, pan-based carbon, and aramid, respectively, whereas U and B represent unidirectional and bidirectional fiber pattern,

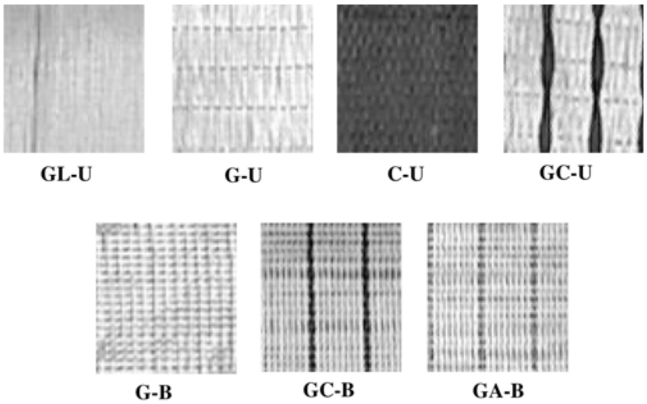

Fig. 1—Different types of fabric.

respectively. The exposure time plays an important role in the degradation process; therefore, three different exposure times of 6000, 12,000, and 20,000 hours were considered in the tests. Additional details on specimen types are given in the following.

Materials

Epoxy—A two-component epoxy was used as the matrix for preparing the coupons. The mixing ratio of the epoxy was two-part resin (bisphenal A-based) to one-part hardener (polyamine-based) by volume. The epoxy had a pot life of 45 minutes and full cure time of 7 days at 25°C (77°F).

Fabrics—Seven different unidirectional and bidirectional fabrics were used in the study. The fabrics were made of E-glass, pan-based carbon, and aramid fibers. Three sticky string unidirectional fabrics were used. These included glass, carbon, and glass-carbon hybrid fabrics. Another unidirectional glass fabric with loose fibers sandwiched between two layers of mat was also used. The three bidirectional fabrics included glass, glass-carbon hybrid, and glass-aramid hybrid. These fabrics were stitched to a glass mat on one side with a polyester thread. Various characteristics of these fabrics are listed in Table 1.

Environments

To expose the composite coupons to aggressive conditions similar to those in civil engineering applications, nine different environments were simulated using chemical solutions following ASTM specifications. These environments are listed in Table 2. More description on the characteristics of the selected environments is given in the following.

Solutions—Distilled water with a neutral pH of 7 was used to simulate exposure to fresh water. Saturated calcium hydroxide, $Ca(OH)_2$, solutions with a pH of 10 and 12.5 were used to simulate exposure to hydrating cement and other alkaline environments. The alkaline solutions were prepared by dissolving $Ca(OH)_2$ in distilled water until saturation. Then NaOH solution was added to control the pH as needed. An acidic solution was used to simulate exposure to low pH environments such as those encountered in sewer pipes and wastewater treatment facilities. The solution was prepared by the addition of diluted hydrochloric acid, HCl, to distilled water until reaching a pH of 2.5. Substitute ocean water with a pH of 7.25 was used to simulate exposure to a marine environment. The major ingredients of this solution were NaCl (24.53 g/L [3.2 oz/gal.]), $MgCl_2$ (5.20 g/L [0.7 oz/gal.]), Na_2SO_4 (4.09 g/L [0.54 oz/gal.]), $CaCl_2$ (1.16 g/L [0.15 oz/gal.]),

Table 1—Characteristics of different fabrics

Designation	Orientation	Fiber type	Style	Weight, g/m^2 (lb/ft^2)	Glass content, volume	Glass content, wt.
GL-U	Unidirectional	Glass	Loose between two mats	650 (0.133)	1	1
G-U	Unidirectional	Glass	Sticky string	400 (0.082)	1	1
C-U	Unidirectional	Carbon	Sticky string	350 (0.072)	0	0
GC-U	Unidirectional	Glass/ carbon	Sticky string	950 (0.195)	0.82	0.87
G-B	Bidirectional	Glass	Stitched to mat	350 (0.072)	1	1
GC-B	Bidirectional	Glass/ carbon	Stitched to mat	700 (0.143)	0.88	0.91
GA-B	Bidirectional	Glass/ aramid	Stitched to mat	600 (0.123)	0.94	0.96

Table 2—Properties of selected aggregate environments

Designation	Temperature	Humidity	pH	ASTM*
W-S- ALK	Ambient	NA	12.5	C581
W-W-ALK	Ambient	NA	10.0	C581
W- NEUT	Ambient	NA	7.0	C581
W-S-ACID	Ambient	NA	2.5	C581
OCIEN	Ambient	NA	7.25	D1141
SOIL†	Ambient	NA	10.5	D3083
HEAT-D	60°C	RH = 0 ~ 5 %	NA	D3045
HEAT-M	50°C	RH = 95%	NA	D4585
UV-RAD-D‡	Ambient	RH = 5 ~ 10 %	NA	G53

**Annual Book of ASTM Standards*, 1998.
†MC = 25 to 30%; MC = moisture content.
‡UV-A (340 nm).
Note: NA is not available.

KCl (0.695 g/L [0.09 oz/gal.]), and $NaHCO_3$ (0.201 g/L [0.03 oz/gal.]) in water according to ASTM D1141.[13] The pH of the solutions was monitored weekly with an electronic pH meter with a resolution of ±0.1. The adjustment to the solutions was made after ±0.2 deviations in pH. All solutions were replaced with new ones every 2 months to prevent contamination and change in their chemical composition.

Alkaline soil—To simulate exposure to alkaline soil containing microorganisms, compost soil was prepared using commercial potting soil and natural fertilizers. The moisture content of the mixture was kept between 25 to 30% (by weight) by adding water periodically. Lime was added to the soil to keep the approximate alkalinity pH of 10.5. Cotton strips were used to monitor the biological activity in the mixture. A 70% drop in the tensile strength of the cotton strips in 1 week was an indication of satisfactory biological activities. Soil samples were replaced every month to ensure the high level of biological activity.

Chambers—The effects of hot-dry and hot-moist climates were measured in two separate chambers. In the first chamber, the temperature was kept at 60°C (140°F) with minimal moisture present. In the second chamber, the temperature was kept at 50°C (122°F) with an RH of 95%. The temperature was kept at ±1°C (±1,8°F) from the target value by using a heating element and a thermostat. The RH was kept at ±2% by providing an adequate evaporation

Table 3—Statistical characteristics of control specimens

Designation	Ultimate strength, MPa (ksi)			Modulus of elasticity, GPa (ksi)			Ultimate strain, %		Load/width, kN/mm (lb/in. × 10^3)	
	AVG	COV	COC	AVG	COV	COC	AVG	COV	AVG	COV
GL-U	286.4 (41.54)	0.22 (0.032)	–0.65 (–0.094)	18.9 (2741)	0.05 (7.25)	–0.83 (–120.4)	1.535	0.22	0.288 (1.65)	0.020 (0.12)
G-U	286.6 (41.53)	0.14 (0.020)	–0.72 (–0.10)	20.3 (2944)	0.08 (11.6)	–0.87 (–126.2)	1.470	0.20	0.367 (2.10)	0.014 (0.08)
C-U	564.3 (81.84)	0.10 (0.015)	–0.63 (–0.09)	56.1 (8137)	0.07 (10.2)	–0.97 (–140.7)	1.000	0.07	0.417 (2.38)	0.007 (0.04)
GC-U	317.0 (45.98)	0.16 (0.023)	–0.64 (–0.09)	31.0 (4496)	0.08 (11.6)	–0.78 (–113.1)	1.030	0.19	0.413 (2.36)	0.018 (0.10)
G-B	125.6 (18.22)	0.07 (0.010)	–0.65 (–0.09)	9.2 (1334)	0.08 (11.6)	–0.77 (–111.7)	1.432	0.11	0.095 (0.54)	0.008 (0.05)
GC-B	204.4 (29.65)	0.08 (0.012)	–0.80 (–0.12)	16.6 (2408)	0.09 (13.1)	–0.98 (–142.1)	1.248	0.05	0.222 (1.27)	0.006 (0.03)
GA-B	168.8 (24.48)	0.10 (0.015)	–0.86 (–0.13)	12.9 (1871)	0.10 (14.5)	–0.98 (–142.1)	1.355	0.07	0.182 (1.04)	0.007 (0.04)

Note: AVG = average value; COV = coefficient of variation; and COC = coefficient of correlation.

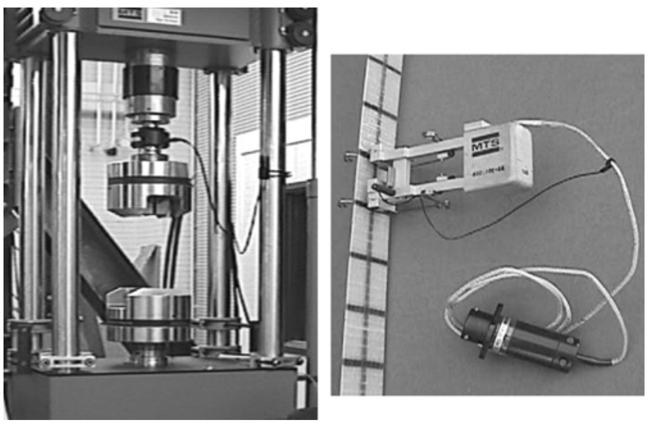

Fig. 2—Universal testing machine and extensometer mounted on typical specimen.

surface for water containers in the chamber. In the third chamber, the effect of sunlight exposure was studied. A series of 15 Watt black light fluorescent tubes was used to simulate UV radiation between 300 and 400 nm with a peak of 340 nm and intensity of 30×10^{-6} J/sec/cm^2. Tubes and specimens were 250 mm (9.84 in.) apart from each other. In all chambers, miniature fans were circulating air to achieve uniform environments.

Sample preparation

Seven different types of FRP laminates (coupons) were manufactured using the wet lay-up technique without heat and pressure treatments. The laminates, 250 mm (9.84 in.) wide by 500 mm (19.69 in.) long, were made of one layer of fabric. Fabrics, after saturation with epoxy, were placed between two layers of Mylar sheets. Excessive air bubbles were bled out of the laminate along with extra epoxy using a putty knife and a 120 mm (4.7 in.) wide roller. Laminates were then placed between two 2 mm (0.08 in.) thick glass plates on a level surface. The laminates were kept under 1 kPa pressure for 24 hours and then the Mylar sheets were peeled off. The laminates were kept inside the laboratory under ambient temperatures for 6 more days before being cut into strips with dimensions of 25 x 400 mm (0.98 x 15.75 in.). The edges of the coupons were smoothened using grid 100 sandpaper on a flat surface. The exact dimensions and weight of each coupon were measured using a caliper and a digital scale. The resolution of the caliper and scale were ±0.025 mm (±0.001 in.) and ±0.01 g (±0.00035 oz), respectively.

Experimental setup

Certain mechanical properties of the composite laminates were sensitive to their thicknesses. Considering the unavoidable variation in the thickness of the coupons made with this technique, 12 coupons were selected randomly as control specimens. The rest of the coupons were then placed in specified environments and their behaviors were monitored over time. A total of nine coupons for each laminate were placed in each environment to be tested at three different times. For each laminate, 12 control specimens were kept inside the laboratory under ambient conditions and were tested with the first batch of exposed coupons after 6000 hours. Each set of exposed coupons was washed with fresh water and kept inside the laboratory under ambient conditions for 7 days to dry out, and then their weights were measured. The uniaxial tension tests were performed following ASTM D3039 using an MTS test machine and MTS hydraulic wedge grips.

During previous experiments, special Surf-Alloy flat wedges were used for gripping purposes to avoid using tabs on the coupons. This simplified the test setup considerably. The axial deformation was monitored using an MTS extensometer with a gauge length of 25.4 mm (1 in.) and an accuracy of 10 microstrains, as shown in Fig. 2. The load was measured by an MTS load cell with a capacity of 100 kN (22.5 kips). Displacement controlled loading was used with a rate of 0.025 mm/second (0.001 in./second). The values of the load and strain were recorded every second and the data were analyzed using a spreadsheet.

EVALUATION AND ANALYSIS OF RESULTS

The first step in analyzing the result was establishing an average value for the tensile properties of the control specimens. Initially, 12 values for each laminate were averaged and considered as the control values. After conducting a correlation analysis, it was observed that the values for the ultimate strength and the modulus of elasticity had a strong correlation with the thickness of the laminates. Therefore, a different approach for these two parameters was considered. A linear regression between the values of these two parameters and the laminate thickness was performed. In these cases, linear

Table 4—Weight change of laminates in different environments

Designation	Exposure time, h	W-S- ALK	W-W-ALK	W- NEUT	W-S-ACID	OCIEN	SOIL	HEAT-D	HEAT-M	UV-RAD-D
GL-U	20,000	–1.10	–0.04	–0.73	–0.52	–0.24	0.00	–1.42	–1.21	–0.62
	12,000	–1.06	–0.71	–1.87	–0.29	–0.33	–0.40	–1.24	–1.48	–0.46
	6000	–0.65	–0.46	–0.18	–0.28	–0.33	–0.30	–1.16	–1.46	–0.62
G-U	20,000	–0.40	–0.72	0.28	–0.54	–0.07	0.47	–1.14	–0.97	–0.42
	12,000	–0.59	–0.07	0.03	–0.17	–0.18	–0.06	–1.22	–0.70	–0.19
	6000	–0.22	–0.25	–0.09	–0.10	–0.02	0.00	–0.97	–0.76	–0.29
C-U	20,000	–0.65	–0.71	–1.32	–0.44	–1.22	–0.64	–2.30	–1.61	–0.39
	12,000	–0.97	–0.71	–0.25	–0.62	–0.86	–1.09	–2.04	–2.30	–0.92
	6000	–0.57	–0.39	–0.52	–0.21	–0.50	–0.40	–1.58	–1.61	–0.52
GC-U	20,000	–0.03	0.32	–0.07	–0.23	–0.10	0.28	–1.50	–1.23	–0.46
	12,000	–0.14	–0.07	–0.23	–0.33	0.03	–0.06	–0.91	–1.07	–0.44
	6000	0.70	0.09	–0.14	0.06	0.62	0.32	–1.02	–0.95	–0.23
G-B	20,000	–1.12	–0.47	–0.41	–0.79	–1.07	–0.33	–1.77	–1.30	–0.62
	12,000	–0.49	–0.62	–0.07	–0.41	–0.73	–0.46	–1.59	–1.62	–0.80
	6000	–0.23	–0.55	–0.23	–0.18	–0.67	–0.27	–1.14	–1.38	–0.68
GC-B	20,000	–1.24	–0.95	–0.47	–0.63	–0.58	–0.60	–1.94	–1.51	–0.42
	12,000	–1.14	–0.92	–0.64	–0.30	–0.57	–0.64	–1.59	–1.45	–0.39
	6000	–0.50	–0.61	–0.43	–0.68	–0.25	–0.37	–1.15	–1.30	–0.24
GA-B	20,000	–0.90	–0.92	–0.58	–0.63	–0.77	–0.66	–1.58	–2.30	–0.58
	12,000	–0.92	–1.03	–0.50	–0.68	–0.54	–0.77	–1.42	–1.34	–0.44
	6000	–0.37	–0.69	–0.12	0.00	–0.18	–0.32	–1.41	–1.10	–0.35

control functions replaced the control values. A summary of the averages (AVR), coefficients of variation (COV), and coefficients of correlation (COC) is presented in Table 3.

After establishing the control values and functions for different laminates, testing of coupons with 6000, 12,000, and 20,000 hours of exposure commenced. Three coupons were tested for each environment, exposure time, and composite type. The ultimate tensile strength, tensile strain and tensile modulus of elasticity were measured for each laminate. To simplify the analysis, all the values for exposed specimens were normalized with respect to their corresponding control values. The results for the normalized values of ultimate tensile strengths and strains are respectively presented in Fig. 3 and 4. The change in weight of the laminates in different environments was obtained by subtracting the dry weight of each coupon from the weight after exposure. The weight changes are given in Table 4.

It is noted in Fig. 3 and 4 that there is certain level of discrepancy in property changes with exposure time. This is partially due to the intrinsic nature of production of laminates and coupons using the plain hand wet lay-up technique, where quality control is not as high as FRP manufacturing under controlled factory circumstances. Constructing test samples in this manner was a primary focus in this study to simulate the potential inaccuracies in the field manufacturing process used in the FRP applications in construction environments.

A more detailed description and a discussion of the results are categorized as follows.

Fresh water (pH = 7.0)

Fresh water, with a neutral pH, did not show any significant effect on the modulus of elasticity of the laminates. After 20,000 hours of exposure, however, the following reductions in the properties of different coupons were observed. The ultimate strength and strain of GL-U laminates decreased by 48% and 46%, respectively. For the G-U laminates, the ultimate strength and strain reduced by 26% and 32%, respectively, after the 20,000 hours of exposure time,

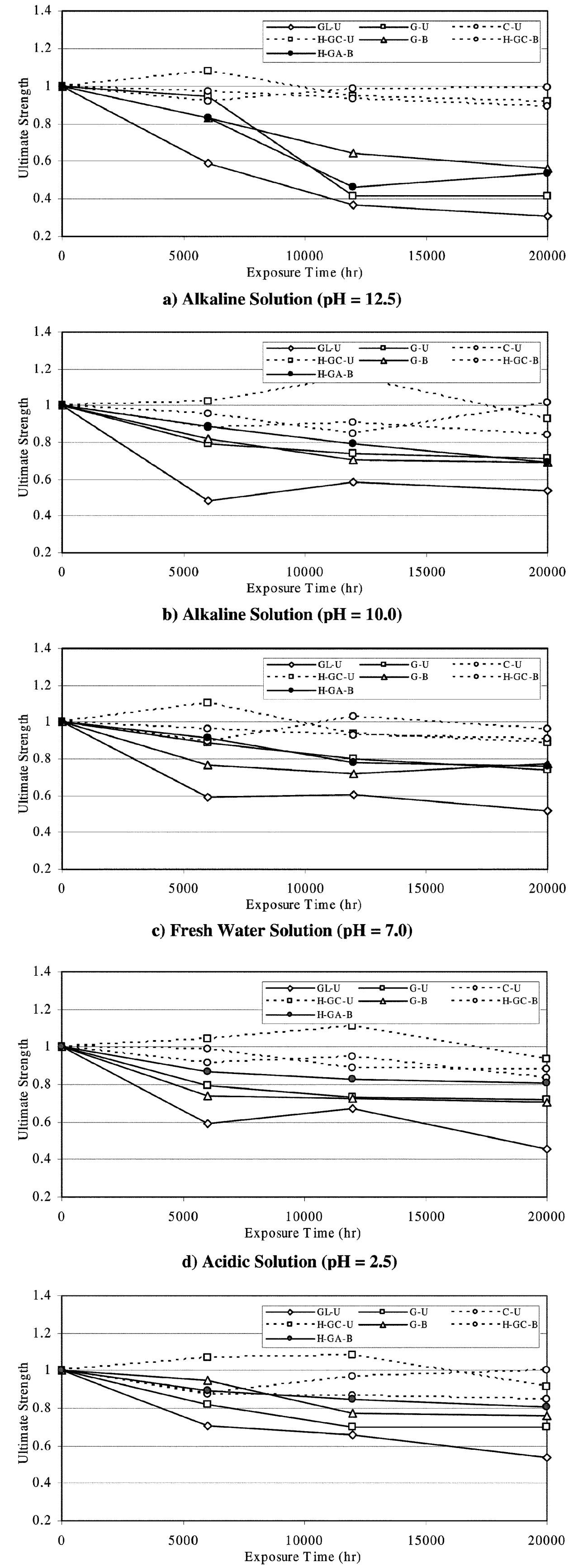

Fig. 3—Normalized values of ultimate tensile strengths versus exposure time for laminates in different environments.

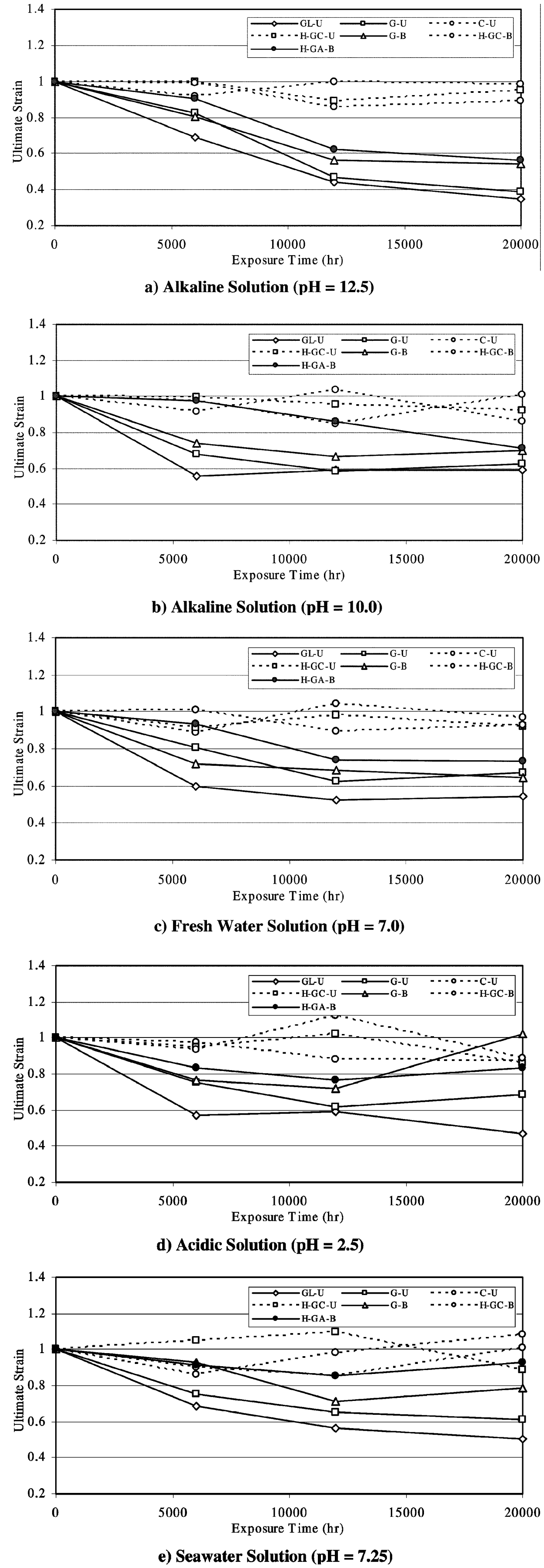

Fig. 4—Normalized values of ultimate strains at failure versus exposure time for laminates in different environments.

whereas for the G-B laminates, the reduction in the properties were 35%. The ultimate strength of GA-B laminates decreased 24%, whereas their strain at failure reduced by 27%. The carbon and the hybrid glass-carbon laminates displayed an insignificant decrease in their ultimate strength and strain at failure.

Alkaline solutions (pH = 10.0 and 12.5)

Alkaline solutions did not affect the modulus of elasticity of the laminates. The effect of these solutions on the other tensile properties of carbon-based laminates was also insignificant. Glass-based laminates, however, lost a significant portion of their tensile properties when subjected to alkaline solutions.

The following is a reduction of various laminate properties after 20,000 hours of exposure to alkaline environments. The strength of GL-U laminates decreased by 46% while the strain at failure dropped by 45%, 41%, and 41% after 6000, 12,000, and 20,000 hours, respectively. The ultimate strength of G-U laminates reduced by 29% and their ultimate strain reduced by 38%. The ultimate strength of G-B laminates fell by 31% while the strain at failure dropped by 30%. The ultimate strength and strain of GA-B laminates fell by approximately 30%.

At a pH of 12.5, the strength of GL-U laminates decreased by 69% while the strain at failure dropped by 65% after 20,000 hours of exposure. The ultimate strength and strain of G-U laminates reduced by 58% and 61%, respectively, for the same period of exposure. The ultimate strength of G-B laminates fell by 44%, whereas their ultimate strain dropped by 46%. The ultimate strength and strain of GA-B laminates dropped by 46 and 44%, respectively, after 20,000 hours of exposure.

Acidic solution (pH = 2.5)

Acidic solution did not affect the modulus of the elasticity of the laminates. The effect of this solution on other tensile properties of carbon-based laminates was relatively small. Exposed to the pH of 2.50, the strength of GL-U laminates decreased by 55%, whereas their strain at failure dropped by 53% after 20,000 hours of exposure. The ultimate strength of G-U laminates reduced by 28%, whereas the strain at failure dropped by 31% for the same exposure period. The ultimate strength and strain of G-B laminates dropped by 29 and 27%, respectively, after 20,000 hours of exposure. For the GA-B laminates, the reductions in the ultimate strength and strain were observed to be 19% and 17%, respectively.

Seawater (pH = 7.25)

Similar to the other solutions, seawater did not alter the modulus of elasticity of the laminates and its influence on the other tensile properties of the laminates containing carbon fibers was not significant. The glass laminates, however, were affected to a much higher level as a result of exposure to seawater. For example, the ultimate strength of GL-U laminates fell by 46%, whereas their ultimate strain dropped by 50% after the 20,000 hours of exposure time. The drops for the G-U laminates in the same periods were 30% and 39%, respectively. The ultimate strength of G-B laminates fell by 24% and the reduction in the strain at failure was 22%. The ultimate strength and strain of GA-B laminates both degraded by 7%.

Moist soil with microorganism

All but one laminate in this environment displayed minor changes in their tensile properties. The ultimate strength of

GL-U laminates decreased by 14%, whereas its ultimate tensile strain dropped by 25% after 20,000 hours of exposure.

Effect of dry heat (60°C [140°F])

When laminates were exposed to dry heat, their mechanical properties were affected by a smaller percentage compared to the other environments. The ultimate strength of G-U and G-B coupons declined by 12% and 11% after 12,000 hours of exposure, respectively. The strains at failure of GL-U, G-U, and G-B declined by 6%, 18%, and 16% after 12,000 hours of exposure, respectively. This reduction perhaps could be attributed to the differences in the coefficient of thermal expansion in the fiber and matrix, resulting in fiber slippage and matrix cracking.

Heat and moisture (50°C [122°F] and 95% RH)

For the laminates exposed to heat and moisture, G-B and G-U laminates displayed the only apparent changes. The ultimate strength of G-U and G-B degraded by approximately 16% after 20,000 hours of exposure. The strain at failure of GL-U, G-U, and G-B fell by 7%, 15%, and 18% after 20,000 hours of exposure, respectively.

Ultraviolet radiation

Similar to other environments, UV radiation did not cause any change in the values of the modulus of elasticity of the laminates. With regard to other tensile properties, the laminate did not degrade after exposure. In fact, some showed even a slight increase in their mechanical properties. This slight increase can be due to either the randomness in the specimens' properties, or it can possibly be due to UV exposure helping with the curing of the composites.

COMPARISON OF DIFFERENT LAMINATES

Glass coupons

Loose glass fiber laminates, GL-U, showed the lowest durability in the solutions. With the exception of the modulus of elasticity that did not change, the other tensile properties of the loose glass fiber laminates showed continued degradation, especially in alkaline solutions. After 20,000 hours of exposure, the ultimate strength and strain at failure decreased by 69 and 65% in strong alkaline solution, 55 and 53% in acidic solution, 48 and 46% in fresh water, 46 and 50% in seawater, and 46 and 41% in weak alkaline solution.

Bundled glass fiber laminates (unidirectional) performed better in the solutions compared to loose fibers. After 20,000 hours of exposure, the ultimate strength and strain at failure, respectively, decreased by 58% and 61% in strong alkaline solution, 30% and 39% in seawater, 2% and 38% in weak alkaline solution, 28% and 31% in acidic solution, and 26% and 32% in fresh water. Bundled fibers performed better than the loose fibers due to smaller penetration of the solution within the matrix around the fibers.

Bundled glass fiber laminates (bidirectional) performed better in the solutions compared to the other two. After 20,000 hours of exposure, their ultimate strength and strain decreased by approximately 45% in strong alkaline solution, approximately 31% in weak alkaline solution, approximately 28% in acidic solution, approximately 23% in seawater, and 22 and 35% in fresh water. The woven bidirectional fibers provided more resistance to solution penetration and, therefore, performed best.

Carbon coupons

None of tensile properties of laminates made from carbon fibers was affected significantly, even after 20,000 hours of exposure. The exposure time did not show any significant effect on the properties, except in the acidic solution where the properties reduced by approximately 10%, most likely due to matrix damage.

Hybrid coupons

Glass-carbon laminates (unidirectional and bidirectional) showed excellent durability similar to carbon laminates. The exposure time did not show any significant effect on the properties. The glass-aramid laminates showed continued degradation with time. Except for their modulus that remained unchanged, the ultimate strength and strain at failure for these laminates, respectively, decreased by 46% and 44% in strong alkaline solution, 30% and 29% in weak alkaline solution, 24% and 26% in fresh water, 19% and 17% in acidic solution, and 19% and 7% in seawater. Both aramid and glass fibers are more prone to environmental degradation compared to carbon fibers, consequently resulting in more reduction in the mechanical properties.

Fiber orientation of FRP

Comparison between the results of G-U and G-B laminates showed that unidirectional laminates had a higher degradation of approximately 7% and 2% in ultimate strength, and 5% and 2% in strain at failure after 6000 and 12,000 hours of exposure, respectively. The comparison between the results of GC-U and GC-B laminates showed higher degradation of approximately 14% and 10% in ultimate strength, and 8% and 3% in strain at failure for unidirectional laminates after 12,000 and 20,000 hours of exposure, respectively. This is due to the fact that, in bidirectional fabrics, the matrix dominates properties more than that in unidirectional fabrics. This further indicates that matrix materials are more affected by the environment than the fibers.

Weight change for FRP coupons

The weight change of the coupons in different chambers was analyzed. The specimens exposed to UV radiation displayed an average weight loss of 0.42%, 0.52%, and 0.50% after 6000, 12,000, and 20,000 hours of exposure, respectively. The exposed samples to the dry heat showed continuing weight loss for an average of 1.2%, 1.43%, and 1.66% after 6000, 12,000 and 20,000 hours of exposure, respectively. Samples exposed to the moist heat displayed a lower weight loss of 1.22%, 1.42%, and 1.45% after 6000, 12,000, and 20,000 hours of exposure, respectively, due to partial moisture absorption. The samples buried under soil displayed a minimal weight loss of approximately 0.25%.

The weight changes of the coupons as a result of exposure to different solutions were also analyzed. The exposed specimens were weighed after air-drying in room temperature for 7 days. Specimens submerged in alkaline solution with a pH of 12.5 displayed the highest weight loss of 0.26%, 0.76%, and 0.78% after 6000, 12,000, and 20,000 hours of exposure, respectively. The alkaline solution with a pH of 10.0 produced a weight loss of 0.41%, 0.57%, and 0.52% after 6000, 12,000, and 20,000 hours of exposure, respectively, whereas the specimens in fresh water showed the least weight loss of 0.24%, 0.50%, and 0.47% after 6000, 12,000, and 20,000 hours of exposure, respectively. Seawater and acidic solutions, respectively, caused a weight loss of 0.19%, 0.45%, and 0.58%, and 0.20%, 0.40%, and 0.54% after 6000, 12,000, and 20,000 hours of exposure.

CONCLUSIONS

The effects of different aggressive environments on tensile properties of seven different FRP coupons were investigated. FRP coupons were immersed in five different solutions and kept in four different chambers, which simulated typical harsh environments encountered in the field. Following the analysis of the results from the experiments, these conclusions can be made:

1. Carbon FRP laminates have excellent durability when they are exposed to hot and humid weather, UV radiation, or moist and biologically active alkaline soil. After more than 27 months of exposure, the mechanical properties of most coupons in tension were minimally affected by these environments, though for glass coupons, this effect was significantly more pronounced.

2. Laminates that are made from or contain carbon fibers have superb durability and remain completely unaffected, even after a long period of exposure to solutions with a variety of pHs and ionic compounds.

3. Glass fiber-reinforced polymer coupons are most vulnerable to immersion in solutions. High alkaline solution has the most effect on the coupons. Laminates made of glass fibers are not recommended for application in aggressive environments, especially when the composite is made of loose glass fibers.

4. The findings of this study show that unidirectional laminates tend to degrade at a slightly lower rate than bidirectional fabrics do. This is due to more matrix dominance in the bidirectional fabrics.

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