

Comparative Degradation of Pultruded E-Glass/Vinylester in Deionized Water, Alkaline Solution, and Concrete Leachate Solution

Wellington Chu, Lixin Wu, Vistasp M. Karbhari

Department of Structural Engineering, University of California, San Diego, La Jolla, California

Received 9 September 2003; accepted 19 February 2005

DOI 10.1002/app.22625

Published online in Wiley InterScience (www.interscience.wiley.com).

ABSTRACT: The use of E-glass/vinylester composites, fabricated by processes such as resin infusion and pultrusion involving low-moderate temperature cure regimes, in civil infrastructure applications is increasing. A major consideration in these applications is long-term durability in the presence of aqueous solutions ranging from water to alkaline environments such as would be seen from pore water of concrete in the case of a reinforcing bar in concrete, or from an alkaline rich concrete leachate due to water migrating through porous concrete to the surface of a composite over-

lay. This study characterizes mass uptake, tensile, and interlaminar shear response of a pultruded E-glass/vinylester immersed in deionized water, alkali solution, and concrete leachate solution for periods up to 75 weeks. The high pH solutions are seen to cause a greater degree of irreversible damage at the resin, interface, and fiber levels. © 2005 Wiley Periodicals, Inc. *J Appl Polym Sci* 99: 1405–1414, 2006

Key words: composite materials; alkali solution; concrete leachate; vinylester; E-glass; mechanical characterization

INTRODUCTION

E-Glass fiber reinforced polymer matrix composites are increasingly being used as replacements for steel rebar, tendons, cables, and even jackets for the seismic retrofit of columns. In some cases, bridge decks manufactured from E-glass reinforced vinylesters and polyesters have been used in preference to orthotropic steel decks. In all these cases, and others in civil infrastructure, E-glass reinforced composites are being considered because of their corrosion (as in rusting of steel) resistance, light weight, tailorability, and ease of placement in the field, all of which are anticipated to not only result in a systems-level savings in construction, but also in substantially lower maintenance cost over the structure's service life. However, there is still a lack of understanding of the physicochemical changes in the performance of these materials as a result of the outdoor environment and as a consequence of interaction with conventional materials such as concrete. A detailed understanding of these effects especially in terms of mechanisms of degradation is critical to the development of models capable of assessing service life of structures and components made of these composites. An ability to predict useful service life as well as rates of material deterioration as a function of environment is essential to the selection

of the appropriate material sets for use in a civil infrastructure application wherein service life can be expected to be fairly long, 75+ years for example, for a bridge, in conditions that are harsh and changing as a function of time.

Although the polymer is expected to serve as a form of protection to the fiber, in addition to being the matrix, polymers are known to be sensitive to moisture and alkaline solutions, undergoing plasticization, hydrolysis, and chain scission. An overview of moisture transport and its effect on glass fiber reinforced composites was given by Schutte¹ and the effect of concrete based alkali solutions was recently discussed by Karbhari et al.² In a series of publications, Chin and coworkers have also investigated the effects of water, salt solution, and simulated concrete pore solution on unreinforced resins, noting that effects ranged from plasticization to mass loss and hydrolytic deterioration.^{3,4} In particular, the effect of water and alkali on these materials is of concern, since in a civil environment such exposure would be commonly expected. Unfortunately, to date there is still a critical lack of understanding at the mechanistic level of the effect of these exposure conditions on composites fabricated using ambient and moderate temperature cure regimes (taken to represent processing above ambient conditions but below the temperature at which full progression of cure would take place) and processes such as wet layup, resin infusion, and pultrusion. Further, there is still need for development of an understanding of cure progression and ester hydrolysis

Correspondence to: V. M. Karbhari (vkarbhari@ucsd.edu).

in vinylesters, which are rapidly becoming the commercial resin of choice in these applications.

This study characterizes the response of pultruded E-glass/vinylester to hydrolytic aging in deionized water, concentrated alkali solution, and concrete leachate solution. It is expected that an understanding of moisture and degradation kinetics in these environments will lead to a further knowledge of the aging and service life of this class of materials.

EXPERIMENTAL

Unidirectional composites were pultruded in 1.6-mm thick strips of 1524-mm width using Hybon 2001 E-glass rovings of 23 m/kN yield with a Dow Derakane 441-400 vinylester. Fiber loading, assessed through burn-off procedures, was determined to be ~62%. To obviate differences in initial level of moisture-induced plasticization, the specimens were preconditioned at 23°C and 46% relative humidity for 28 days (at which point they showed a level of constancy in weight and glass transition temperature) prior to initiation of the test program.

To assess changes in material characteristics, the specimens were subjected to mechanical testing through tension (ASTM D3039) and short-beam-shear (ASTM D2344) modes. Dynamic mechanical thermal analysis was conducted at a frequency of 1 Hz between 25 and 200°C. Fourier transform infrared (FTIR) spectroscopy was also conducted to assess changes at the polymer level. Mass uptake through sorption pro-

cesses was tracked through gravimetric means. Both optical and scanning electron microscopies were used to characterize damage mechanisms and growth. Specimens were immersed in solutions of deionized water, concentrated calcium carbonate and calcium hydroxide based alkali solution, and concrete leachate for periods up to 75 weeks, with tests being conducted both immediately after removal from the solution and after reconditioning at 23°C and 46% RH for 28 days (equal to the original period of conditioning) to assess effects of "redrying" on property regain. It is noted that various researchers have attempted to simulate alkaline concrete pore water in the laboratory using a variety of solutions, each of which has a slightly different effect due to pH and ion concentration effects.² The simulated alkali solution used in the current investigation consists of 10.89 g/L of CaCO_3 and 5.95 g/L of $\text{Ca}(\text{OH})_2$ in deionized water to provide a saturated solution at pH 11.5, following Hawkins *et al.*⁵ with the calcium hydroxide being used as a reagent to maintain pH levels similar to that in concrete. However, since this does not exactly mimic concrete pore water and previous studies have indicated that these simulated solutions are actually less aggressive than KOH and NaOH containing pore water,⁶ it was decided to use a solution derived directly from concrete by allowing actual concrete cylinders to be in a deionized water bath, thereby enabling alkaline salts and other chemicals associated with the concrete to actually leach out or otherwise dissolve/diffuse into the solution. This solution also had a pH of about 11.5.

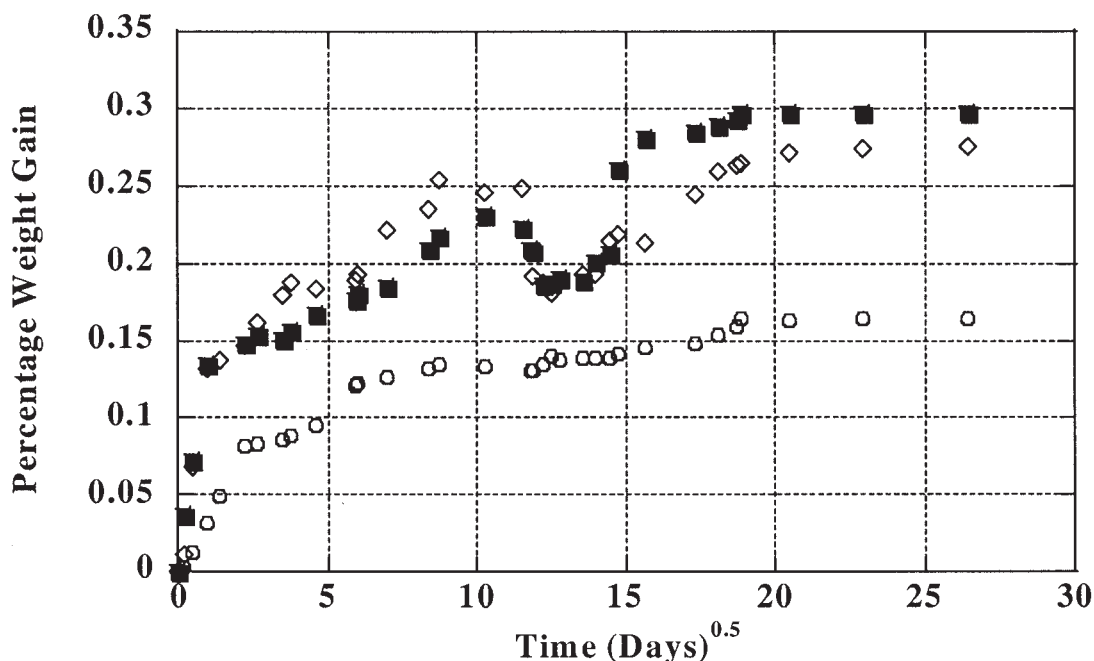


Figure 1 Mass uptake in the composite as a function of immersion times (O: deionized water, ■: alkali solution, ◇: concrete leachate).

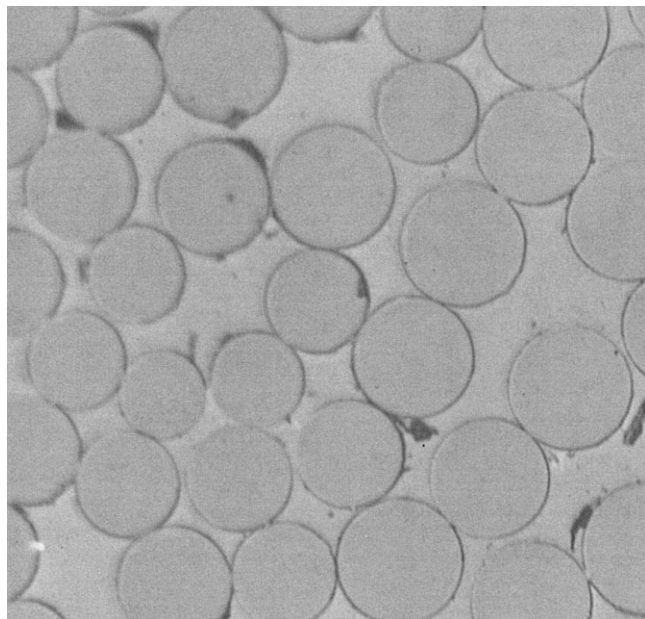


Figure 2 Debonding and interface degradation due to alkaline attack.

Further details on this and pH as well as element concentration are described by Karbhari et al.² All solutions were maintained at a constant temperature of 23°C.

RESULTS AND DISCUSSION

Mass uptake

Mass uptake plots for the composite in the three solutions is shown in Figure 1. It can be seen that initial mass uptake is much more rapid in the high pH solutions as is the maximum value of percentage weight gain. In deionized water the response shows the initial characteristic linear region, $\frac{M_t}{M_\infty} \approx 0.6$, followed by a slower increase and then an asymptote. The loss of weight can be traced to ester hydrolysis, leaching of low molecular weight flexibilizing segments of the polymer, and actual loss of material at both the interfacial and fiber levels (as shown in Fig. 2). Such degradation and mass-uptake response has

also been noted by Apicella et al.,⁷ albeit toward the end of their period of investigation, and this did not allow for study of further changes. The loss results in further space in the composite that results in increased wicking and uptake of solution resulting in increased mass uptake. As noted through mechanical characterization there is a marked transition in regain in this period as a result of reconditioning, indicating irreversible damage.

Although the uptake response cannot strictly be considered, Fickian characteristics of moisture kinetics can reasonably be approximated from the data in Figure 1 for purposes of relative assessment, since

1. Both uptake and desorption plots of $\frac{M_t}{M_\infty}$ versus $t^{0.5}$ are initially linear and
2. Above the linear region the curves are concave to the abscissa with the exception of a region wherein loss is seen.

Results for maximum mass uptake and apparent coefficients of diffusion for the composite and the neat resin are listed in Table I. In the case of the neat resin samples, characteristic Fickian response was seen till the end of the period of investigation. It is noted that the diffusion coefficient for the resin in deionized water closely matches the value of 6.88×10^{-7} mm²/s reported by Chin et al.³ for a 411–350PA vinylester in distilled water, whereas the values for the composite in both the alkali and concrete leachate solutions are lower than previously reported values of 4.13×10^{-7} mm²/s to 6.45×10^{-7} mm²/s for a E-glass/CORVE8121 vinylester in a variety of concrete leachate solutions.² It should be noted, however, that the higher values of diffusion coefficient can be explained through both the lower volume fraction, i.e. 41.7%, and the processing method—resin infusion with ambient cure, which were used in that study.²

Verification for the hypothesis regarding the transient anomalous behavior of the specimens immersed in the alkali and concrete leachate solutions can be partially derived through FTIR spectroscopy. The ester carbonyl peak at 1730 cm⁻¹ was seen to decrease in both the cases in a fashion similar to that reported by

TABLE I
Moisture Uptake Characteristics

Solution type	Resin		Composite	
	Maximum uptake (wt %)	Coefficient of diffusion (10 ⁻⁷ mm ² /s)	Maximum uptake (wt %)	Coefficient of diffusion (10 ⁻⁷ mm ² /s)
Deionized water	0.64	6.25	0.164	1.39
Alkali	0.73	9.43	0.298	2.17
Concrete leachate	0.66	9.75	0.274	2.05

TABLE II
Changes in Glass Transition Temperature

Time period (weeks)	Deionized water (°C)	Saturated alkali solution (°C)	Concrete leachate solution (°C)
0	148.2 ± 0.18	148.2 ± 0.18	148.2 ± 0.18
5	138.7 ± 2.59	141.8 ± 2.76	140.8 ± 2.64
10	146.6 ± 0.81	141.6 ± 3.14	141.0 ± 2.22
15	144.1 ± 1.32	143.3 ± 2.97	133.5 ± 0.35
20	139.4 ± 1.70	141.2 ± 0.42	132.4 ± 4.9
30	129.2 ± 2.71	137.2 ± 1.07	130.7 ± 3.00
50	115.7 ± 0.45	130.6 ± 2.81	130.6 ± 3.33
75	114.5 ± 0.61	130.6 ± 1.85	129.3 ± 3.17

Chin et al.⁸ and Ghorbel and Valentin,⁹ with the decrease being about 15% greater for the case of the alkaline solution. Using the C—H aromatic stretch peak at 3027 cm⁻¹ as the base, the normalized intensity of the O—H stretching peak at 3475 cm⁻¹ was seen to increase by 17 and 23% for the case of the alkali and the concrete leachate solutions, respectively. These changes are consistent with ester hydrolysis, in which the ester-carbonyl functionality is transformed to carboxylic acids and hydroxyl functional groups, indicating resin deterioration. The exact reason for the changes occurring at the specific time period of immersion and the subsequent return to conventional uptake response is not known at this point in time.

Assuming a direct relationship between moisture uptake in the unreinforced polymer and its composite as

$$\frac{(M_m\%)_{\text{composite}}}{(M_m\%)_{\text{resin}}} = \frac{\rho_m}{\rho_c}(1 - V_f)$$

where $M_m\%$ is the level of maximum uptake, ρ_m is the density of the resin (1.136 g/cm³ in the current case),

ρ_c is the density of the composite (1.982 g/cm³ in this case), and V_f is the fiber volume fraction (0.62 in this case), the maximum theoretical expected uptake in the composite can be determined to be 0.139%, 0.159%, and 0.144%, from immersion in deionized water, alkali solution, and concrete leachate solution, respectively. It is noted that, with the exception of the deionized water case, the experimentally determined values of uptake are substantially higher than the theoretical ones. This is due to activation of damage at the interface and bulk resin level resulting in formation of new paths for wicking along debonds and cracks. It is noted that, in addition to diffusion, solution sorption in the composite can take place by mechanisms related to capillarity- and microcrack-induced transport. Both these mechanisms are direct consequences of initial solution related deterioration. Capillarity results in wicking along debonded fiber-matrix interfaces, whereas solution migration through microcracks involves both flow and storage. Often, in addition to paths formed through microcrack coalescence, debonds will coalesce to provide additional pathways

TABLE III
Comparison of Tensile Strength in the "Wet" and "Dry" States

Time period (weeks)	Deionized water			Saturated alkali solution			Concrete leachate solution		
	"Wet" (MPa)	"Dry" (MPa)	% Regain	"Wet" (MPa)	"Dry" (MPa)	% Regain	"Wet" (MPa)	"Dry" (MPa)	% Regain
0	923.34 [50.73]			923.34 [50.73]			923.34 [50.73]		
5	864.05 [88.23]	900.99 [62.55]	62.30	833.67 [56.66]	847.13 [48.75]	15.01	786.19 [44.74]	840.67 [61.65]	39.72
10	842.66 [34.75]	896.76 [65.92]	62.39	797.16 [65.61]	846.18 [28.72]	38.85	777.22 [52.04]	830.77 [54.91]	36.65
15	843.26 [78.26]	869.97 [59.91]	33.35	768.17 [56.58]	845.67 [63.33]	49.95	761.32 [58.82]	823.22 [53.13]	38.21
20	816.08 [84.10]	825.87 [32.25]	9.13	726.81 [61.10]	829.29 [23.20]	52.15	748.06 [33.83]	776.09 [19.45]	15.99
30	807.98 [36.31]	813.99 [44.77]	5.21	708.48 [56.86]	789.28 [53.26]	37.61	717.67 [41.07]	747.32 [68.55]	14.42
50	671.08 [23.44]	739.96 [81.03]	27.31	612.67 [67.18]	648.10 [69.56]	11.40	560.33 [67.05]	598.61 [55.48]	10.55
75	602.21 [22.64]	708.54 [43.21]	33.11	537.75 [53.46]	556.72 [48.67]	4.92	465.32 [42.61]	481.63 [55.37]	3.46

Standard deviation values are given in square brackets.

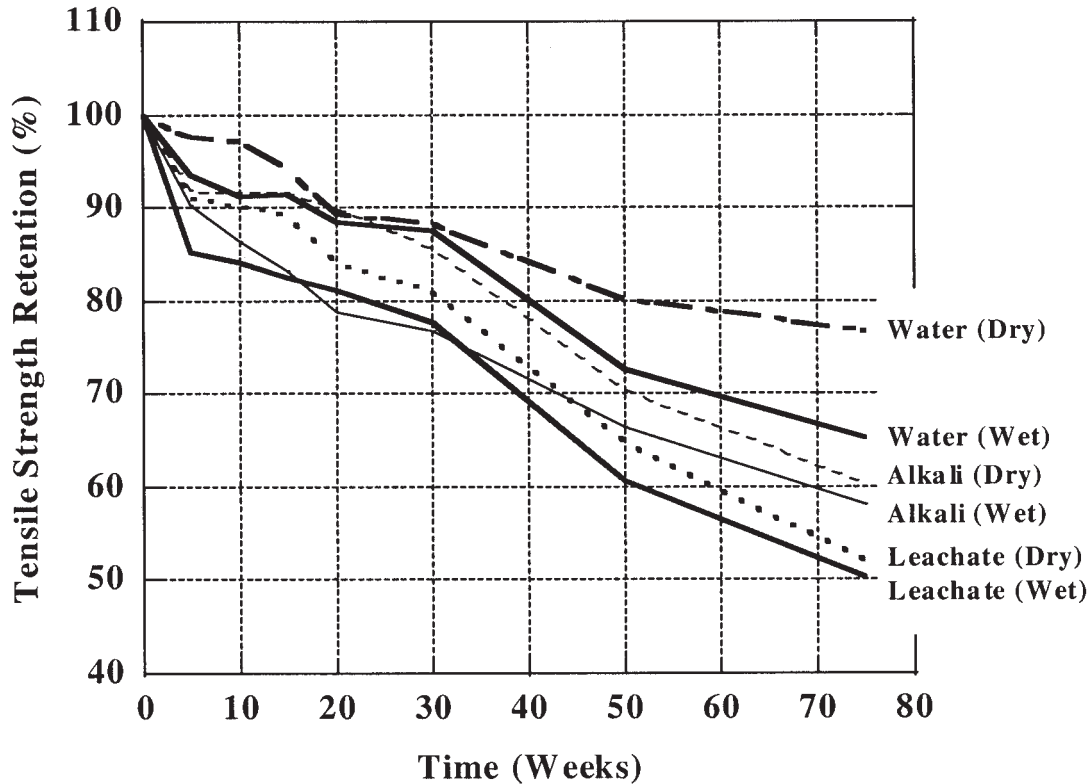


Figure 3 Percentage retention in tensile strength as a function of time and aqueous medium.

as in Figure 2, connecting the partial circumference fiber-matrix debonds around one fiber with the debonds around an adjacent fiber. The combination of these mechanisms is both an increased rate of uptake and an overall weight gain.

For a unidirectional composite, a coefficient of diffusion for the composite can be theoretically determined from the coefficient of diffusion of the neat polymer, D_m , and the fiber loading, V_f as

$$D_c = (1 - 2\sqrt{V_f/\pi})D_m$$

The use of this equation in the current case leads to values of $0.697 \times 10^{-7} \text{ mm}^2/\text{s}$, $1.05 \times 10^{-7} \text{ mm}^2/\text{s}$, and $1.09 \times 10^{-7} \text{ mm}^2/\text{s}$ for the cases of immersion in deionized water, alkali solution, and concrete leachate solution, respectively. A comparison of these values with the experimentally determined coefficients listed in Table I shows that the experimental coefficients are roughly twice those predicted theoretically, which is in line with the results reported by Marom and Broutman,¹⁰ ascribing the higher rates to the experimentally observed debonding that allows an increase in uptake through wicking in addition to diffusion.

Dynamic mechanical thermal analysis

Changes in glass transition temperature, T_g , determined from the peak of the $\tan \delta$ curve, with time of

immersion in the three solutions, are listed in Table II. As it can be seen, there is an overall decrease in the glass transition temperature with a maximum decrease of 7.99% (determined per convention in °K) being noted in deionized water. Levels of decrease due to immersion in the alkali and concrete leachate solutions are almost the same after 50 weeks, although the initial rate of decrease is more rapid in the concrete leachate solution. These decreases are in congruence with the effects of moisture uptake and hydrolysis, which is further borne out by decreases in E' over the same period of time. Values of storage modulus measured at the end of the 75-week period of immersion indicate a decrease of 16.2%, 8.5%, and 13.7% for the specimens in deionized water, alkali solution, and concrete leachate solution, respectively. The decrease in the bending modulus implies a loss of bond between the fibers and matrix, which can be readily seen in Figure 2. Since there is both a decrease in E' and T_g with time, hydrolytic degradation would appear to dominate over any residual postcure, which would be indicated by an increase in E' due to the increase in crosslink density. It is noted, however, that initial effects of postcure cannot be ruled out since the specimens in deionized water and concrete leachate solution do show a slight increase in T_g after 10 weeks of immersion, followed by a decrease, whereas a similar change is seen in the alkali solu-

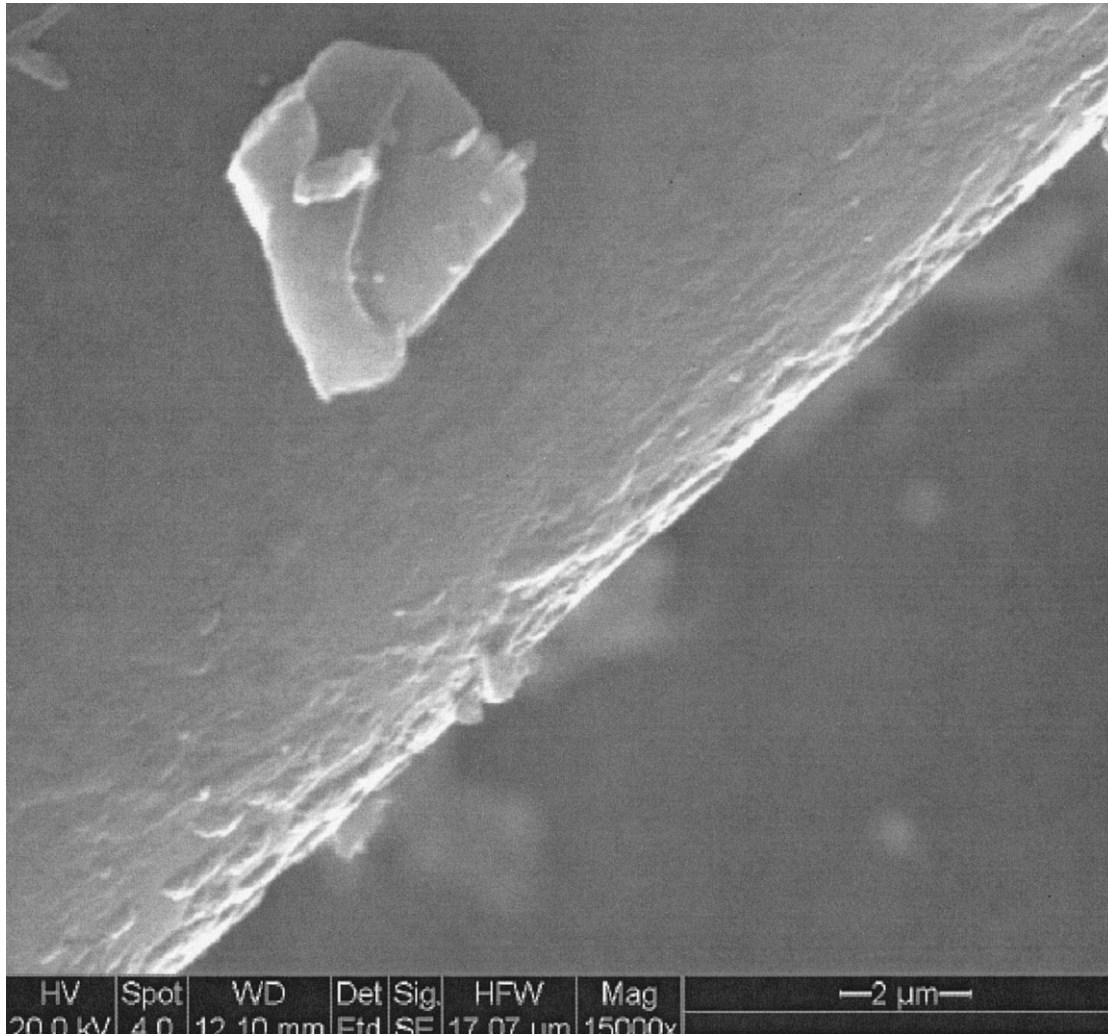


Figure 4 Surface degradation and pitting of a fiber after alkali attack.

tion at the 15-week level. From Figure 1 it can be seen that this period also marks a transition to a short-term anomalous behavior in moisture uptake which when coupled with the increase in T_g and E' in this local time period especially for the alkali and concrete leachate solutions could lend further validation for induced dissolution of low molecular weight flexibilizing segments of monomer that causes embrittlement. However, these effects are largely overcome by the effects of hydrolysis and chain scission over the 75-week period. Further studies are ongoing to assess changes in dynamic mechanical properties as a means of characterizing solution-induced degradation, and of developing mechanism-based service-life prediction methodologies.

Effects of tensile strength

Tensile tests were conducted on specimens, both immediately after periods of immersion in the three so-

lutions and after a period of reconditioning after removal. This was done to assess the regain in properties on removal of moisture sorbed during the period of immersion, and thus to gain an understanding of mechanisms, both reversible and irreversible, that accrue in the composites. In this study, the specimens tested immediately after their removal from the solution were referred to as "wet" whereas those tested immediately after reconditioning were referred as "dry". Overall results for tensile strength, including standard deviations, in the "wet" and "dry" states as well as the percentage regain in properties determined as

$$\% \text{ Regain} = \left[\frac{(\sigma_{\text{dry}})_t - (\sigma_{\text{wet}})_t}{\sigma_0 - (\sigma_{\text{wet}})_t} \right] \times 100$$

are given in Table III and plots for percentage retention are shown in Figure 3. In the definition of % regain, $(\sigma_{\text{dry}})_t$ is the strength determined after reconditioning after a period of immersion t , $(\sigma_{\text{wet}})_t$ is the

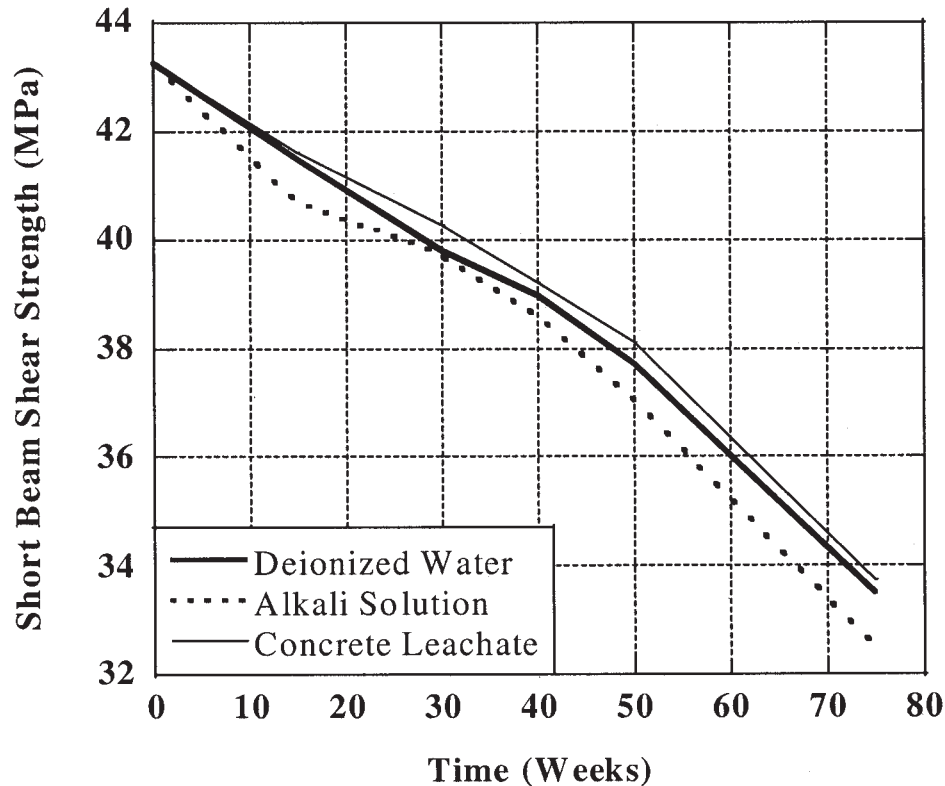


Figure 5 Change in short-beam-shear strength as a function of time and immersion solution.

strength determined from testing immediately after the same period of immersion t , and σ_0 is the strength determined prior to initiation of the immersion. The maximum decrease in tensile strength, 47.8%, as well as the minimum regain, 3.46%, occurs at the end of the 75-week period of immersion in the concrete leachate solution. This is due to the occurrence of both fiber- and interface-level degradation. Fiber level degradation is due to pitting and cracking in the fiber itself because of alkali ion assisted moisture attack on the fiber, with details similar to those reported earlier.² Fiber-level pitting and roughness due to degradation is clearly seen in Figure 4. Cleavage of silicon-oxygen bonds is followed by conversion to hydroxysilane, which in itself is an autocatalytic reaction that causes increasing fiber surface leaching and degradation, with formation of pits and flaws that further degrade strength. The presence of additional ions in the concrete leachate solution also causes increasing brittleness of the matrix itself (as seen in Fig. 5), but also aid in the migration of calcium hydroxide to the fiber surface, causing nucleation of these crystals (identified through energy dispersive X-ray spectroscopic analysis) on the fiber leading to embrittlement through leaching. Cleavage cracks in the crystal extend into the fiber, with hydroxylation causing fiber surface pitting and erosion of material, causing further flaw sites, with again severely reduced fiber properties in the

presence of moisture. Fiber-level pitting and roughness due to the the concrete-based alkaline salts aggravate the well-known degradation of glass fibers when the pH of the solution exceeds 9, wherein Si—O—Si bonds in the glass network are broken by hydroxyl ions.^{11,12} The extreme level of fiber surface degradation is shown in Figure 6.

Although such surface deterioration and pitting have been noted earlier because of moisture effects, these were not noted in the specimens immersed in deionized water, with the degradation being restricted to fiber-matrix debonding and changes in the resin because of hydrolysis. It should, however, be noted that the lack of such deteriorative mechanisms does not indicate that these are not operative in deionized water; rather that they may take a longer period of immersion or higher temperatures than those considered in this investigation.

In general short-term environmental exposures have not been reported to cause significant deterioration in tensile modulus and this is the case in this investigation as well. All samples show a fairly rapid loss of about 10–11% over the first 5 weeks from the unexposed modulus of 52.24 GPa (with a standard deviation of 4.01 GPa). This is followed by a period of increase in modulus due to residual cure effects. The residual cure resulted in an increase of 3.7%, 3.3%, and 4.8% for the specimens in deionized water, alkali so-

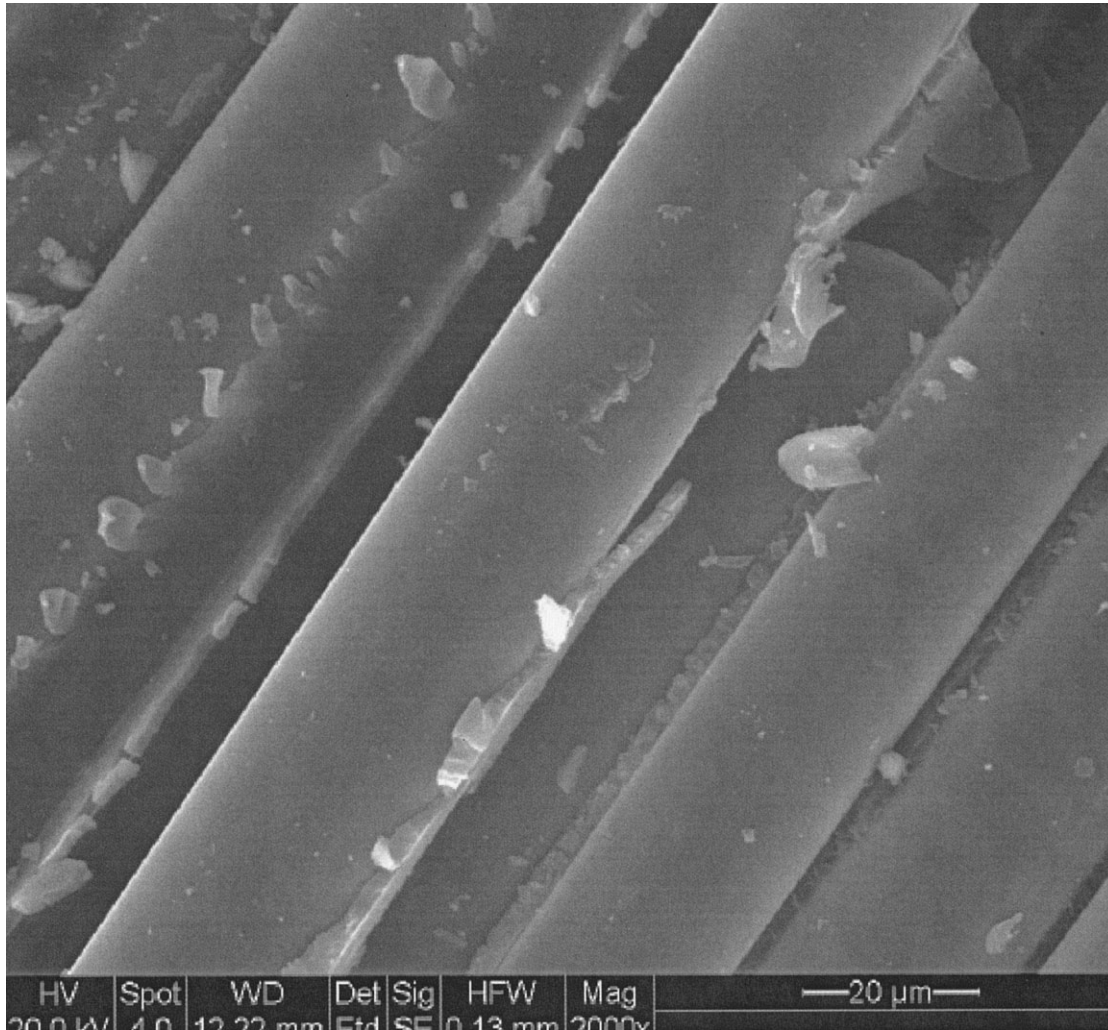


Figure 6 Scanning electron microscope image at $\times 2000$ showing fiber–matrix bond state and increasing brittleness of a resin as a result of immersion in concrete leachate.

lution, and concrete leachate solution, respectively, over the 5-week levels, with the peaks occurring at 15, 20, and 15 weeks, respectively. Further degradation is very small in the case of deionized water, whereas it is slightly more pronounced, although still not very significant for the other two solutions. The decrease in modulus at the end of the 75-week period was 9.1% (to a level of 47.5 GPa) for the specimens immersed in deionized water, 11.3% (to a level of 46.3 GPa) for the specimens immersed in the alkali solution, and 11.9% (to a level of 46.0 GPa) for the specimens immersed in the concrete leachate. Although there is some regain noted after reconditioning, in most cases it is within scatter bounds of the specimens, and is only 0.2%, 0.5%, and 0.3% for the specimens immersed in deionized water, alkali solution, and concrete leachate solution, respectively, at the end of the 75-week period of investigation. These results are not unexpected since the deterioration, as described earlier, is dominated by resin- and interface-level effects.

Effects on interlaminar shear strength

Interlaminar shear strength as measured by the SBS test provides a powerful tool for characterization of interface degradation effects. As can be seen from Figure 7, the drop in SBS strength with time is almost linear with very little actual difference between the deterioration due to the three different solutions. Regain in SBS strengths, as a result of reconditioning, are summarized in Table IV. It can be seen that the percentage regain decreases with increase in time period of immersion, with the level of regain decrease being very fast and severe for the two solutions with high pH (alkali and concrete leachate) for which regain at the end of 75 weeks was only 0.4%, whereas the regain for samples in deionized water was 23.7%. This clearly indicates a much higher degree of irreversible degradation due to exposure to the alkali and concrete leachate solutions as compared with the specimens in deion-

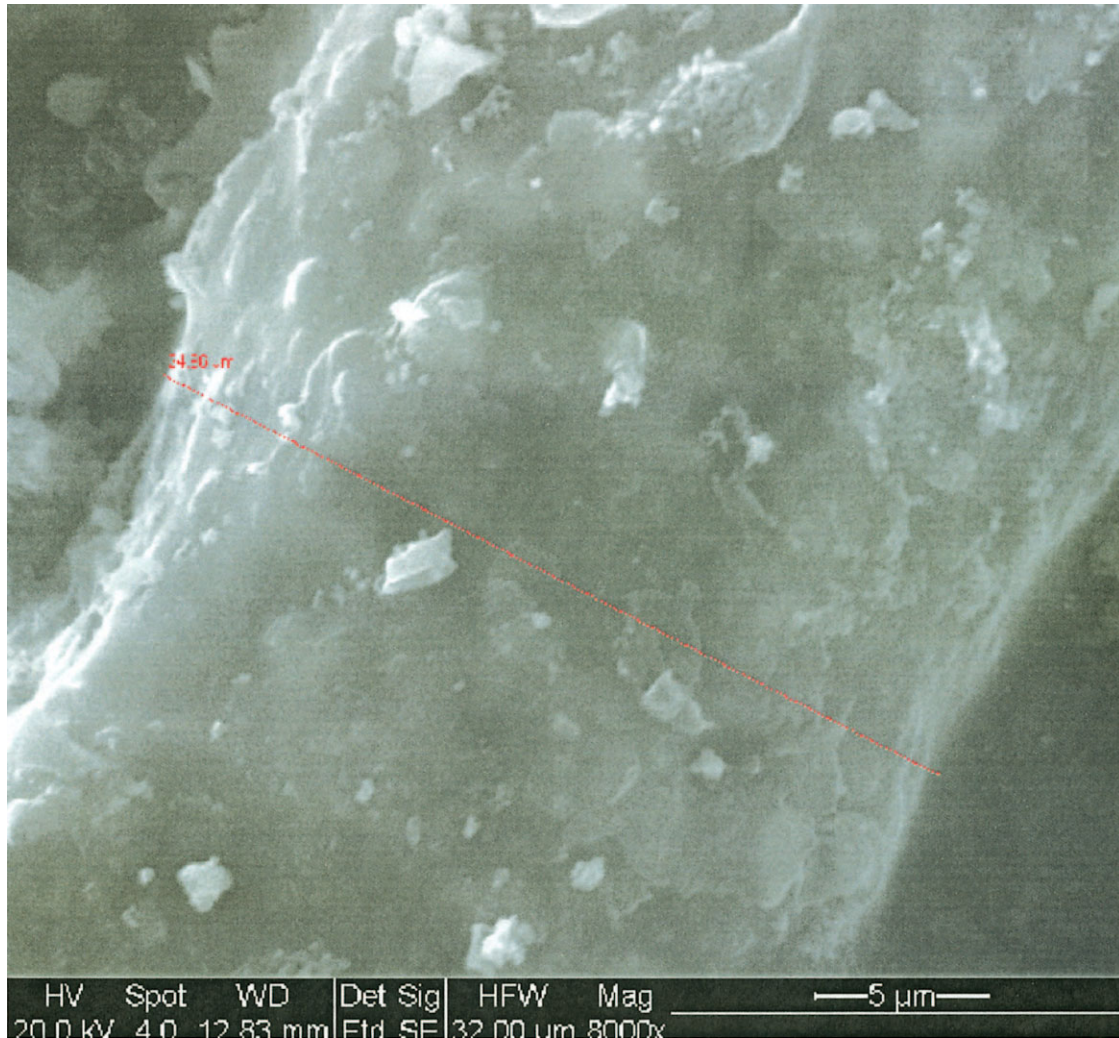


Figure 7 Scanning electron microscope image at $\times 8000$ showing fiber surface level degradation as a result of immersion of the composite in concrete leachate solution for 50 weeks. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

ized water. The exposure to deionized water causes plasticization of the resin with some interface-level degradation. In comparison, the higher pH accelerates hydrolysis, resulting in irreversible changes at both the resin and interface levels in addition to fiber-level degradation, as can be seen on compari-

TABLE IV
Percentage Regain as a Function of Time and Solution Type

Time period (weeks)	Deionized water (%)	Alkali solution (%)	Concrete leachate (%)
15	70.6	20.2	39.2
30	52.0	6.1	36.2
40	43.4	4.7	2.5
50	20.5	1.9	2.7
75	23.7	0.4	0.4

son of micrographs of specimens after immersion in deionized water [Fig. 8(a)] and alkali solution [Fig. 8(b)]. In the former, debonding is associated with very clean fiber surfaces, whereas in the latter, surface roughness can be noted on the fiber itself. The difference in damage modes, especially in light of the apparent similarity in SBS strength reduction from testing in the "wet" state, underlines the greater long-term deleterious effects of high pH solutions. This is even more critical in cases where thermal cycling occurs, such as those seen in a civil infrastructure environment, where column retrofit jackets that are partially submerged in a flood plain for part of the year are followed by exposure to a hot and dry climate for the rest of the year, or structures in arid desert regions that are subject to flash floods, because of which there can arise substantial changes in moisture content over time, ranging from near saturation to significantly lower levels.

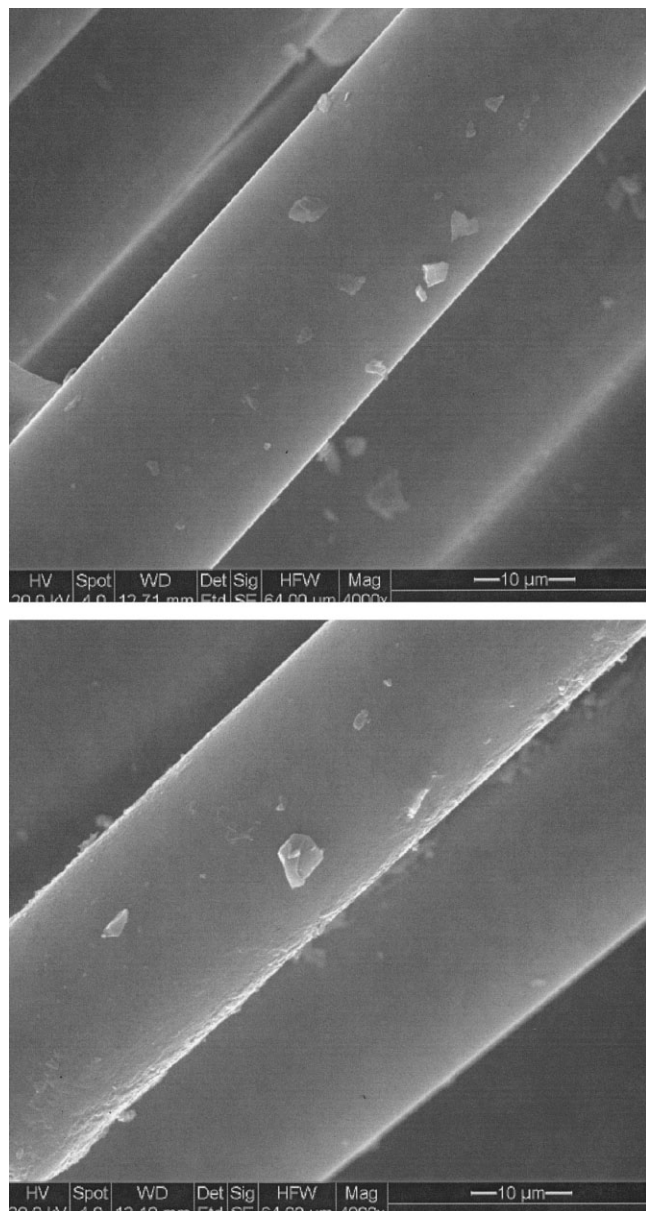


Figure 8 (a) Debond between fiber and matrix as a result of immersion in deionized water for 50 weeks (SEM image at $\times 4000$). (b) Debonding and fiber-level degradation as a result of immersion in alkaline solution for 50 weeks. (SEM image at $\times 4000$)

Summary

The moisture sorption and subsequent degradation of an E-glass/vinylester composite immersed in deion-

ized water, alkali solution, and concrete leachate solution is studied. Diffusion, with the exception of short-term anomalous behavior in the high pH solutions, is seen to follow Fick's law. Maximum uptake and diffusion coefficients measured experimentally are noted to be significantly higher than values predicted on the basis of unreinforced resin response indicating interface-level damage mechanisms that promote wicking of solution. Plasticization is noted in all specimens, with levels of hydrolytic degradation being enhanced because of the higher pH and presence of alkaline salts, which also cause fiber-level surface degradation and pitting. The level of fiber degradation is the highest when exposed to the concrete leachate solution, which not only has the high pH and Ca ions, but also other ions such as Na and K from cement, all of which accelerate leaching and pitting in the silica structure of the glass fiber. Levels of regain in properties—tensile as well as interlaminar shear—are significantly lower because of high pH exposures, emphasizing the criticality of studying the long-term effects of concrete-based alkali solutions, in the form of leachate and even pore water on composites used in civil infrastructure applications.

The authors gratefully acknowledge the support of the California Department of Transportation (C. Sikorsky, Program Manager).

References

1. Schutte, C. L. *Mater Sci Eng* 1994, R13, 265.
2. Karbhari, V. M.; Murphy, K.; Zhang, S. *J Compos Mater* 2002, 36, 2101.
3. Chin, J. W.; Nguyen, T.; Aouadi, K. *J Appl Polym Sci* 1999, 71, 483.
4. Chin, J. W.; Aouadi, K.; Haight, M. R.; Hughes, W. L.; Nguyen, T. *Polym Compos* 2001, 22, 282.
5. Hawkins, G. F.; Steckel, G. L.; Bauer, J. L., Jr.; Sultan, M. In *Proceedings of CDCC '98*, Sherbrooke, Canada 1998; p 25.
6. Gerritse, A. In *Proceedings of the 1st International Conference on Advanced Composite Materials in Bridges and Structures*, Sherbrooke, Canada 1992; p 129.
7. Apicella, A.; Migliaresi, C. Nicolais, L.; Iaccarino, L.; Roccotelli, S. *Composites* 1983, 14, 387.
8. Chin, J. W.; Hughes, W. L.; Signor, A. In *Proceedings of the 16th American Society of Composites Conference*, Blacksburg, VA 2001, 12 pp.
9. Ghorbel, I.; Valentin, D. *Polyester Compos* 1993, 14, 324.
10. Marom, G.; Broutman, L. J. *Polym Compos* 1981, 2, 132.
11. Paul, A. *Chemistry of Glasses*; Chapman & Hall: London, 1982.
12. Yilmaz, V. T. *J Non-Cryst Solids* 1992, 151, 236.