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DURABILITY DATA FOR FRP REHABILITATION SYSTEMS

by

VISTASP M. KARBHARI

Final Report Submitted to the California Department of Transportation Under Contract No. 59A0309.

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Huntsville, AL 35899

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16. Abstract

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1. Pull-off data from testing of materials
2. Long-term durability data on prefabricated systems

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ABSTRACT

The long-term durability of fiber reinforced polymer (FRP) composites is often stated as being the main reason for the use of these materials. However, their durability depends intrinsically on the choice of constituent materials, method and conditions of processing, and surrounding environmental conditions through their service lives. There is, today, a plethora of conflicting evidence related to the durability of composites resulting in an array of perceptions ranging from the absolute invincibility of these materials under terrestrial environments such that no maintenance would be required through their life to the extreme sensitivity of these same materials to environmental influences resulting in their rapid degradation within the first few months of use in a civil environment. Faced with these diverse and conflicting aspects it is no surprise that civil engineers, often with little knowledge of composites, treat the material and the entire technology with a great deal of caution. This report focuses on durability data related to FRP systems used for strengthening of concrete and consists of two sets of data, namely

1. Pull-off data from testing of materials
2. Long-term durability data on prefabricated systems

1. INTRODUCTION

Although FRP composites have been successfully used in the industrial, automotive, marine and aerospace sectors, there are critical differences in loading, environment and even the types of materials and processes used in these applications as compared to the materials-process-load combinations likely to be used in civil infrastructure. These materials have also a fairly successful record of use in pipelines, underground storage tanks, building facades, and architectural components. Anecdotal evidence provides substantial reason to believe that if appropriately designed and fabricated, these systems can provide longer lifetimes and lower maintenance costs than equivalent structures fabricated from conventional materials. However, actual data on durability is sparse, not well documented, and in cases where available – not easily accessible to the civil engineer.

The long-term durability of fiber reinforced polymer (FRP) composites is often stated as being the main reason for the use of these materials. However, their durability depends intrinsically on the choice of constituent materials, method and conditions of processing, and surrounding environmental conditions through their service lives. Although FRP composites do not corrode (as in rusting of steel) they do undergo physical and chemical changes, including oxidation. There is, today, a plethora of conflicting evidence related to the durability of composites resulting in an array of perceptions ranging from the absolute invincibility of these materials under terrestrial environments such that no maintenance would be required through their life to the extreme sensitivity of these same materials to environmental influences resulting in their rapid degradation within the first few months of use in a civil environment. Faced with these diverse and conflicting aspects it is no surprise that civil engineers, often with little knowledge of composites, treat the material and the entire technology with a great deal of caution.

It is important to point out, at the outset, that there are a number of myths regarding FRP composites, chief among which are that:

- Composites are a panacea for the deterioration of civil infrastructure;
- Composites do not degrade and are not affected by environmental influences;
- Performance attributes of FRP composites used in civil infrastructure, at present, are comparable to those of aerospace grade prepreg based autoclave cured composites;
- Due to stress-rupture considerations glass fiber reinforced composites should only be used in architectural applications;
- Carbon-fiber reinforced composites are not degradable and have infinite life;
- All composites have well documented data bases; and
- Variation in field conditions, incoming raw materials, or manufacturing processes do not cause any changes in properties and performance.

Rather than being a panacea for the current deterioration in civil infrastructure, FRP composites do provide alternatives for rehabilitation and renewal not possible with conventional materials. However, these materials can degrade at the level of the fiber, polymer, and/or interface under specific circumstances. It must be remembered that the

resin matrix allows moisture adsorption and this can lead to a variety of mechanisms, some of which result in deterioration of the polymer and, in some cases, of the reinforcing fiber. Although glass fiber reinforced composites are susceptible to creep- and stress-rupture, in general their use under sustained loads is possible as long as the stress levels do not exceed 25-30% of the ultimate. This has been shown to advantage in the resiliency of glass fiber reinforced pipes and underground storage tanks which have withstood very aggressive environments through the use of appropriate factors of safety (Karbhari and Li, 2001). Although carbon fibers are generally considered to be inert to most environmental influences likely to be faced in civil infrastructure applications the inertness does not apply to the fiber-matrix bond and the matrix itself, both of which can in fact be significantly deteriorated by environmental exposure. As emphasized in a previous benchmarking study (Karbhari et al, 2001) significant gaps exist in the durability data base for FRP composites used in civil infrastructure even for environmental conditions such as moisture and alkalinity due to reasons ranging from actual lack of data on specific systems to difficulty in accessing data from investigations conducted in industry and government laboratories. Based on the gap analysis conducted for each of the selected environmental conditions, it was emphasized that there was a substantial commonality of needs, which provides for the selection of a set of data/research requirements that is critical to the generic implementation of FRP composites in civil infrastructure. These needs, in no particular order of priority (since it is difficult to transition or compare the level of need within one category of environment to that in another), are (Karbhari et al, 2001):

- Collection, assessment, and appropriate documentation of available data in a form useable by the civil engineer/designer.
- Testing over extended (18+ months) time periods. Tests conducted over short time periods (less than 18 months) can yield misleading results due to effects of post-cure and slow interphase and fiber level degradation, and can provide an erroneous level of comfort in some cases.
- Testing under combined conditions (stress, moisture, solution, temperature, and/or other regimes) at both the materials and structural levels is critical.
- Assessment and characterization of the effects of incomplete cure and undercure, especially for ambient temperature cure systems, is essential.
- Development of standardized solutions and conditions for laboratory studies that closely simulate actual field conditions.
- Development of appropriate resin systems, gel coats, and coatings that would serve as protective layers for the bulk composite against external influences including environmental conditions, intended and accidental damage.

Further, it is important to understand that since FRP composites are formed through the combination of micron sized fibers in polymer matrices the actual performance of the materials is intrinsically controlled by the microstructure, which is in turn controlled by the choice of constituent materials and form, interphase development, and the processing route taken (Figure 1).

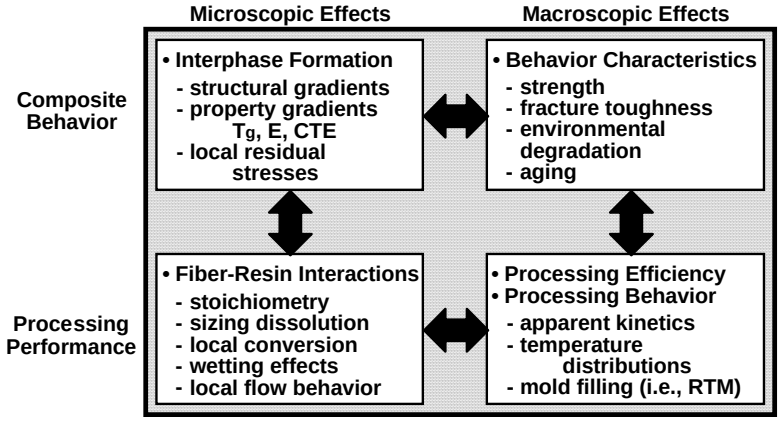


Figure 1: Interactions of Processing and Performance Through the Interphase

Minor changes in any of these aspects can result in significant changes, not just in short-term performance, but also in the overall durability of the FRP composite which depends on factors such as bonding, void content, degree of cure (Figure 2), and level of process induced residual stresses.

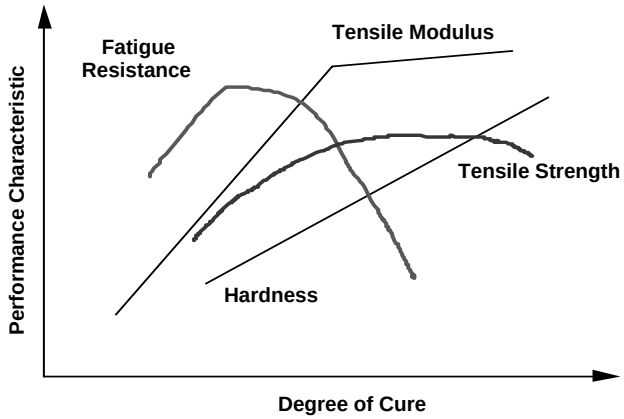


Figure 2: Schematic Showing Effect of Degree of Cure on Vinylester FRP Characteristics

Results from the aerospace industry are often used to argue that if composites could be accepted for use in such a high precision applications with very low tolerance for failure, then their use in civil infrastructure (often considered "low-tech" in comparison) should pose absolutely no problem. It should, however, be remembered that the use of composites in aerospace applications has been predicated on extensive materials testing for the purposes of qualification followed by strict adherence to prescribed specifications for autoclave based fabrication in highly controlled factory environments. These materials and processes are unlikely to find significant application in civil infrastructure due to cost and processing specific aspects. Civil applications are more likely to (a) use processes such as wet lay-up, pultrusion and resin infusion than autoclave molding, (b) fiber and resin as separate constituents rather than in the form of preimpregnated material, and (c) resin systems such as polyesters, vinylesters, phenolics and lower temperature cure epoxies rather than the higher temperature curable epoxies and thermoplastics. Further, in the cases of rehabilitation, there is likely to be extensive use of processes under ambient conditions in the field, rather than fabrication in factory controlled environments. Even in the case of prefabricated elements, adhesive bonding to

substrates has to be conducted under field conditions with little control, if any, of humidity and/or temperature. Thus, the civil engineering environment not only brings with it new challenges for the control of quality and uniformity of composites, but also makes it difficult (if not impossible) to use the well established databases generated by DoD (Department of Defense) sponsored research (such as those for AS4/3501-6 or T300/5208 based systems) for more than comparative baseline and trend analysis purposes. Further aerospace composites, are to a large degree extensively inspected at routine intervals within carefully controlled environments, whereas inspection and maintenance requirements in civil infrastructure are neither as regulated nor thorough.

Despite the significant changes in material specifications and process methods, FRP composites have been shown to have very good long-term response when used in applications such as underground storage tanks, pressure vessels, and in corrosion resistant equipment. In addition, their successful use in marine vessels over extended periods of time has been extensively documented. Yet, data from laboratory studies consistently shows significant levels of degradation in the same classes of materials when subjected to moisture/humidity, temperature, and stress. The mystery in the apparent dichotomy between "real-world" applications and laboratory data which is often forgotten in the discussion related to the use of composites in civil infrastructure can be explained in terms of the use of appropriate "knock-down" or safety factors.

Within the aerospace industry, composite materials usage is typically predicated through the establishment of design allowables through extensive programs of specification and qualification. This ensures that failure does not take place in unexpected periods of time and enables the use of a damage tolerance philosophy. The most commonly used basis levels are the A-basis, and the B-basis. The A-basis allowable is the level of mechanical property above which at least 99% of the population of values is expected to fall with a confidence level of 95%. A B-basis allowable, in comparison, is the level of mechanical property above which at least 90% of the population of values is expected to fall with a confidence level of 95%. Following procedures in MIL-HDBK-17, in order to obtain a reasonable evaluation of materials variability, the determination of these values is based on a minimum of 30 specimens from at least 5 batches of a material per environmental condition and direction. In some rare cases, S-basis allowables may be used wherein a minimum expected value is specified. Whereas the method for the establishment of the A- and B-basis values provides a very good method for the selection of materials allowables, it must be noted that qualification programs are extremely expensive and are based on the use of a limited number of materials, in carefully monitored applications wherein cost concerns (as related to qualification) are not the primary drivers. Further, due to the levels of safety factors used in the aerospace world (which can approach 1 in some cases, such as fairings) there is a need for a very high level of specification, qualification, and testing. Although very rigorous, the method does not allow for ease in replacement of materials constituents, and even minor modifications to qualified material systems can only be made after extensive testing. As an example, Table 1 shows factors of safety recommended for general use in the analysis and design of aerospace composites (NASA, 2000).

Table 1: Safety Factors for Aerospace Composites

Item	Ultimate Level	Minimum Test Factor		Acceptance Test Flight Units
		Qualification Unit	Flight Unit	
Nonprototype separate test unit	1.4	1.4		1.05
Nonprototype structure with stress riser or discontinuity	2			
Prototype test article	1.5		1.2	
Prototype structure	2			

The guide from the Civil Aviation Safety Authority of Australia states that a factor of 1.8 must be used for FRP composite primary structures subjected to hot-wet structural testing, and that a factor of 2.25 be used in the absence of specific consideration of these environmental conditions during testing. In a number of cases, however, others based on load environment, fatigue spectra, materials process conditions, and other uncertainty as shown in Table 2 replace these factors.

Table 2: Reduction Factors Based on Type of Uncertainty

Aspect	Basis for Factor of Safety (Uncertainty Factor)	Typical Value	Rationale
Critical Primary Load Bearing Structure	Limit to ultimate	1.5	Uncertainty in load (including eccentricity); manufacturing variability, variation in fasteners and joints, fit-up and residual stresses, part tolerances
	Fatigue life	4	Uncertainty in load spectrum, scatter in fatigue data
	Damage tolerance	2	Uncertainty in damage state, load spectra, inherent data scatter
	Material allowables	Determined statistically	Uncertainty in strength due to materials and process variation
Load combinations	Load cases and environments	Cascading factors	Uncertainty due to synergistic effects
Composites	Special allowables for material state	?	Uncertainty due to damage condition

Since FRP composites for most layups show linear-elastic response to failure, and in the case of carbon fiber reinforcements not only have fairly low strain levels (9000-10000 microstrain) but also are also very sensitive to defects, strain is often used as the controlling factor for determination of factors of safety rather than load or stress. Figure

3, which is based on the Joint Services guide handbook, schematically, shows the determination of the allowable strain level for design.

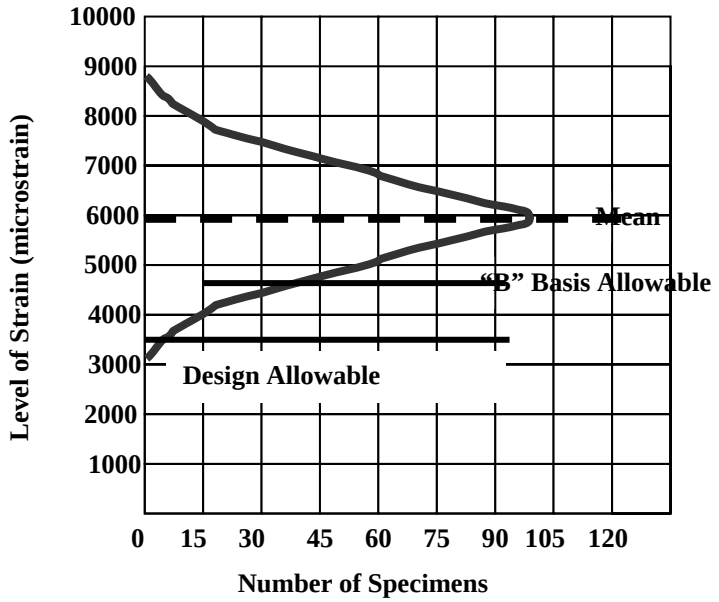


Figure 3: Determination of Allowable Strain Limit

The reduction from the "B" basis allowable level to the design allowable level in Figure 3 corresponds to an uncertainty factor of 1.5, which is generally applied related to layup, stacking sequence, and load variation. For the case of the material ultimate being about 9500 microstrain (i.e. 0.95%), a level of 4500 microstrain is generally taken to be the design limit with the drop from ultimate representing limitations for hole and defect tolerance. A factor of 1.5 when applied to the design ultimate would thus give a design allowable limit of 3000 microstrain with the factor of uncertainty representing load regime and path (as defined by layup and orientation).

Although FRP composites have been used extensively in naval and marine applications there is still a lack of design rules (Mouritz et al., 2001) and incomplete understanding of the complex scaling laws for anisotropic materials resulting in the use of very conservative safety factors that are often far higher than those used in similar applications using metals (Evans, et al, 1991). For the most part their use is predicated through the adoption of a factor of safety of 4-6 for strength (Puccini, 1993; Gibbs and Cox, 1960; Cable, 1991) based on combined effects of stress-rupture and fatigue. It should be noted that although hulls face a greater degree of loading than a number of thin skin composite elements in other application areas, hulls in general are not subjected to sustained loading, but rather to impact and slamming loads of short and intermittent duration (Puccini, 1993). If the structure has to be designed to carry impact loads safety factors as high as 10 are often used (Chalmers, 1988). In almost all cases, durability for long-term use is dependent on the use of an appropriate gel-coat without which there is a realistic fear of premature degradation through surface blistering which can lead to further deterioration and delamination of the FRP composites, especially those fabricated using orthophthalic polyesters.

FRP composites, primarily using glass fiber reinforcements, have a history of successful use in underground storage tanks, corrosion resistant equipment and pressure vessels. Because of a high level of regulatory activity this area has, perhaps, the highest development of standards for design and use. The U.S. standard – ASME RTP-1, for reinforced thermoset plastic corrosion resistant equipment provides for the use of factors based on whether design is conducted through the application of rules (Subpart 3A) or through stress analysis (Subpart 3B). When design rules are used a design factor of 10 is specified for the determination of minimum thickness of shells subject to internal pressure, and a factor of 5 is specified for determination of minimum moment of inertia for stiffening rings. In the case wherein design is done through the use of specific methods of stress analysis, minimum strength ratios between 8 and 10 for the inner surface and interior layer depending on the design method and type of non-destructive testing used (ASME-RTP-1, 1998). For vessels designated for critical service the factor is required to be multiplied by 1.25. For all other layers in the laminate the minimum strength ratio is required to be 1.6 for vessels not in critical service and 2 for vessels in critical service. The British standard, BS 4994 for the design and construction of vessels and tanks in reinforced plastics (BS4994, 1987) requires a minimum design factor of 8. It is noted that the forward explains that the factor was increased to 8 from the previous value of 6 specified in the 1973 edition "because experience has shown that the overall strain limitation does not permit lower values than 8." Under the provisions of the ASME Boiler and Pressure Vessel Code (ASME, 2001) two methods are allowable for qualification of design adequacy. Under Class-I design, which specifies qualification through pressure testing of a prototype the minimum qualification pressure is set at 6 times the design pressure. The maximum design pressure is limited to 1034 kPa (150 psi) for vessels fabricated using bag molding, centrifugal casting or contact molding, 10342 kPa (10342 psi) for filament wound vessels, and 20685 kPa (20685 psi) for filament wound vessels with polar boss openings. For the latter case only a 5:1 factor of safety is allowable. Specific conditions are also set for cycling and temperature conditions. Under Class-II design, stress analysis is required using either specific design rules or discontinuity analysis. If the specified design rules are used the membrane strains are restricted to 0.001 and the thickness is required to exceed 6 mm (0.25 in) with a design factor of 5 applied to the modulus parameter. In the case of discontinuity analysis the minimum buckling pressure is required to be at least 5 times the design external pressure and the average shear stress between the vessel and overlays/joints is restricted to 200 psi. Table 5 presents levels of factors of safety as prescribed by various codes for FRP pressure vessels and compares the values based on fiber type.

In all these examples of successful design it should be noted that stresses are kept to a very low level through the use of fairly high factors of safety, even in cases where inner metallic liners are used. This ensures a large part thickness with sufficient tolerance for some degradation and a very long period of time for moisture/solvent saturation or even through-thickness infiltration. It can thus be seen that through the use of an appropriate set of design allowables and the use of an appropriate design methodology, structures can be made such that durability is not a concern over the period of design service-life. The

use of very small factors of safety as espoused by some for civil infrastructure negates this very concept.

FRP composites have a long history of use in marine vessels, piping, corrosion equipment, and underground storage tanks, and anecdotal evidence and limited testing shows that they can be successfully engineered to have long service lives in contact with moisture and aqueous solutions. It is, however, a misnomer that FRP composites and polymers are "water-proof" since moisture diffuses into all organic polymers, leading to changes in thermophysical, mechanical and chemical characteristics. The primary effect of absorption is on the resin itself through hydrolysis, plasticization and saponification, which cause both reversible and irreversible changes in the polymer structure. At the minimum the absorption of moisture causes a depression in the glass transition temperature and hence it is critical that the FRP composite has a Tg a minimum of 30 degrees above the maximum service temperature to allow for this potential depression. In some cases the moisture wicks along the fiber-matrix interphase and has been shown to cause deleterious effects to the fiber-matrix bond resulting in loss of integrity at that level. Moisture and chemical solutions have also been shown to cause deterioration at the fiber level. In the case of glass fibers, degradation is initiated by the extraction of ions from the fiber by the water. These ions combine with water to form bases (alkaline solutions), which etch and pit the fiber surface, resulting in flaws that significantly degrade strength and can result in premature fracture and failure. Basic solutions, when in contact with glass fibers, can cause significant pitting and leaching, often resulting in the fiber loosing its core over a short period of time with the outer sheath being reactive, accelerating the leaching process. Notwithstanding these damage processes it is seen that in the presence of moisture the loss of strength in E-glass fiber composites is initially rapid followed by a slow asymptotic process which can be predicted if moisture absorption is measured.

Although there is a substantial body of literature related to aspects of moisture absorption in composites and there have been extensive studies of effects due to saltwater and marine environments there is a lack of information related to sea water effects on vinylesters and E-glass/Vinylester composites (Sagi-Mani et al, 1998), with most previous efforts being restricted to epoxy and unsaturated polyester based systems. The increasing consideration of E-glass/Vinylester composites in civil infrastructure systems such as piling, decking for piers and wharves, and fender systems, and in offshore applications such as risers, downhole tubing, and subsea flowlines, makes the lack of this information a severe drawback, since the use of very high factors of safety used conventionally for naval and marine vessels while ensuring durability also lead to increased costs. In the infrastructure world, acquisition has traditionally been on a lowest cost basis and hence the use of excessively high factors of safety will lead to FRP composite structures being uncompetitive. There is hence a need to develop a better understanding of the effects of sea water on such materials and structures fabricated thereof.

It is known that although moisture absorption in itself causes mechanisms of degradation, the actual effects are largely dependent on the type of aqueous solution being considered

with the presence of salts such as NaCl reducing saturation moisture content in some cases (Jones and Dickson, 1984; Soulier, 1988) and even causing substantial deviation from Fickian behavior in others including early onset of irreversibility. Penetration of aqueous solutions into thermoset composites is known to cause both plasticization over the short-term and hydrolysis through attack of the ester linkages. The chemical attack, hydrolysis, although primarily a phenomenon associated with long periods of exposure is also initiated by incomplete cure of the vinylester. Both plasticization and hydrolysis induce higher levels of molecular mobility resulting in a consequent drop in T_g, although the drop could be partially offset through the residual curing of the vinylester itself in the aqueous solution. Levels of T_g recorded over a range of exposure periods, including data taken after 18 months, and after drying at levels of 12 and 18 months are shown in Figure 4 for a E-Glass/Vinylester system (Wu et al, 2002). It can be seen that the maximum decrease in T_g, 14%, was seen after immersion in sea water for 18 months, whereas the minimum, 11.4%, was recorded for deionized water over the same period of time, which is in congruence with the results from thermal analysis. It is also seen that initially, till the 6 month level, there is very little change in T_g for specimens immersed in sea water and synthetic sea water, although results of DSC analysis conducted on the specimens shows a substantial decrease in levels of residual heat and hence an increase in degree of polymerization over the same period of time. This emphasizes the competition between two phenomena related to moisture sorption, hydrolysis causing an increase in molecular mobility resulting in a decrease in T_g, and residual curing causing an increase in cross-link density resulting in an increase in T_g. It should be noted that increases in T_g can also be due to the leaching of low molecular weight flexibilizing segments leading to the embrittlement of the network. Samples removed after 12 months and 18 months of immersion and then dried for 1 year at 23˚C and 55% RH do show some regain in T_g, but the levels, as shown in Figure 4, do not return to those prior to exposure, emphasizing irreversible changes due to chemical degradation.

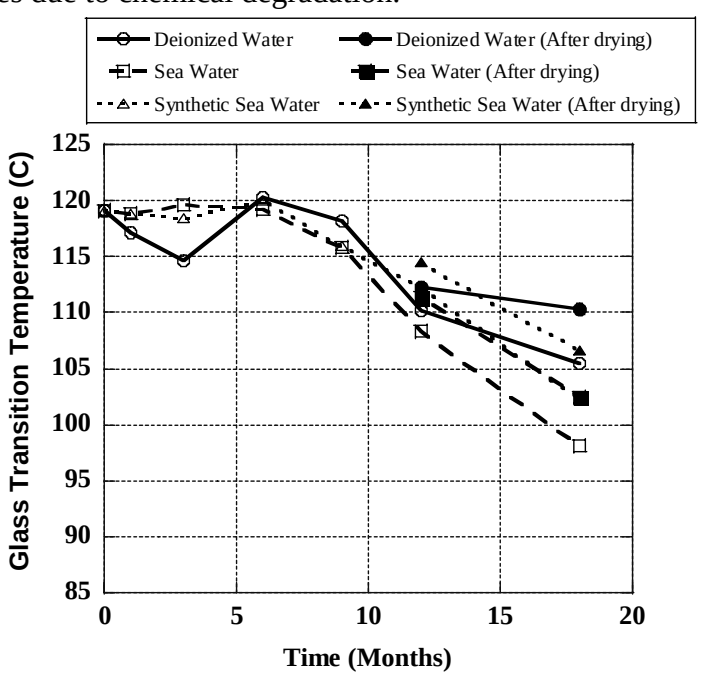


Figure 4: Change in T_g as a Function of Aqueous Solution and Period of Immersion

FRP composites are increasingly being accepted for use in the seismic retrofit and strengthening of columns. At the present time a variety of composite jacketing systems/techniques can be identified including (a) the use of the wet layup process using fabric or tape, (b) the wet-winding of tow, (c) the winding and elevated temperature cure of prepreg tape or tow, (d) the use of cables or prefabricated strips wound under tension in a spiral fashion and anchored at ends, (e) the adhesive bonding of prefabricated shell elements, and (f) the fabrication of the jacket in-situ using resin infusion. It should be noted that the seismic retrofit of columns is a fiber dominated application, emphasizing the effectiveness of a tailored anisotropic material, with the predominant role of the composite being to enable the application of constraint to the concrete core. It is in this sense that composites offer a substantial advantage over conventional materials since the fibers can be oriented primarily in the hoop direction to provide constraint without substantially increasing stiffness over the height. Considerable testing at 40% and full-scale levels has been conducted on a number of these systems, and a comprehensive set of design equations has been developed and validated based on scale and full-scale testing. A number of state departments of transportation in the US and various Japanese agencies have already published guidelines for determination of required thickness. Due to the potential for long term durability, ease and speed of application / installation without significant disruption of traffic, and overall cost-effectiveness, there is significant interest in the use of these systems by State Departments of Transportation, and by public and private agencies. Although detailed guidelines for the design of composite jackets for seismic retrofit have been prepared and specifications have been issued by the a number of agencies there currently exist a number of concerns including the lack of comprehensive databases for the selection, use and comparison of different methods both as related to structural effectiveness and overall durability. In order to provide a validated basis for characterization and comparison of these systems a detailed evaluation program was undertaken by the Civil Engineering Research Foundation (CERF) under the auspices of the Highway Innovative Technology Evaluation Center (HITEC) (Reynaud et al, 1999). Due to lower costs and greater overall familiarity E-glass reinforced epoxy systems are often used in preference to the others. Whereas both sustained load levels and environmental attack can be expected to be less severe in the case of seismic retrofit of columns as compared to storage tanks for corrosive media, the design of wraps/jackets still needs to consider aspects related to long-term durability. A number of studies conducted on flat coupon specimens of commercial systems have shown the degradation of these materials when exposed to water, as would be possible when columns are in a flood plain, raising significant concern related to the life-expectancy of the systems. Whereas moisture related degradation, especially in cases where there is either no protective coating/gel coat on the system, or the coating has been abraded off through accidental damage or scour, is likely it is possible to reduce the level of degradation through appropriate selection of materials and processes. An effective means of enhancing durability of these systems is through the use of appropriate sizings/finishes on the fibers themselves. Figure 5 shows the effect of using 3 different sizings on E-glass fibers for a commercially available E-glass/epoxy material system, for seismic retrofit, subjected to an accelerated exposure to water at 140˚F (60˚C).

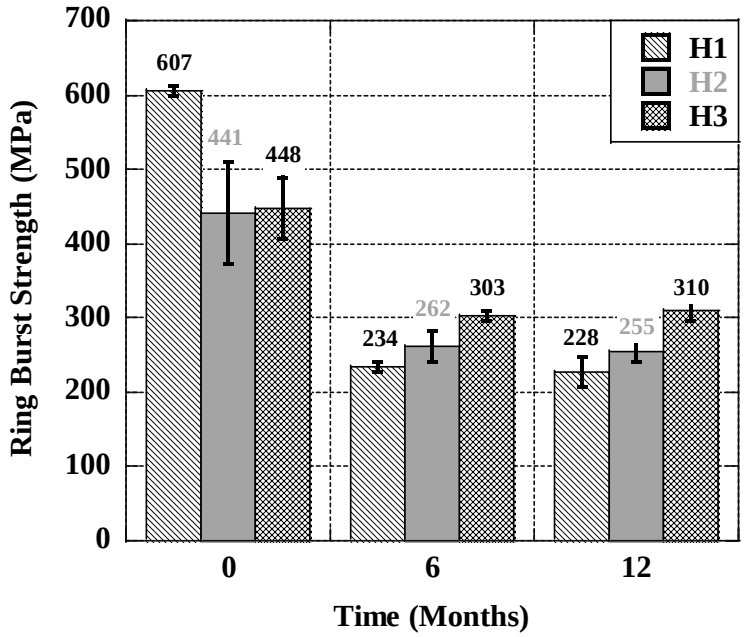


Figure 5: Change in Tensile Strength in the Hoop Direction as a Function of Exposure Time for the Three Differently Sized E-Glass/Epoxy Systems

The different sizes/finishes used were the 111A from Owens Corning, the 2022 from PPG, and the 61H11 from Vertrotex Certainteed, designated in composite form for the purposes of this study as H1, H2 and H3, respectively. All three use 250 yield direct wound E-glass roving supplied with bushing applied commercial finishes for multi-resin compatibility. The specimens were fabricated in the form of ring blanks following the protocol described by Reynaud et al (1999) and were then tested using a ring burst test to evaluate hoop direction properties. It is clearly seen that although the unexposed value of strength attained by set H1 is significantly higher than that of H2 and H3 respectively, the level and rate of degradation of strength are also significantly higher. At the end of the 12-month immersion periods, rings from set H1 show a 62.5% reduction from the original unexposed value whereas those from H2 and H3, both having different sizings, show a 42.19% and 30.77% reduction, respectively. It is noted that in all cases most of the loss in strength occurred in the first six months with subsequent deterioration being significantly less. Besides emphasizing the efficacy of tailoring of sizing to enhance durability of FRP composite systems, the results of the study suggest that it may be better to trade higher initial performance attributes for better long-term results. Further, based on the results presented it is also reasonable to conclude that the use of a tougher and higher elongation resin system would yield both higher initial and post-exposure results since a greater "stretch" or global strain would be required before local stress concentrations and notch effects would dominate. The combination of this with optimally tailored sizings is suggested as a means for achieving a durable and damage tolerant FRP system without sacrificing overall cost effectiveness.

In a number of cases in civil infrastructure composites are not just subject to environmental effects related to aqueous exposure, but also to freeze and Freeze-thaw

conditions. Based on an investigation of ambient cured E-glass/vinylester specimens of the type used in offshore and civil infrastructure applications the effect of exposure conditions on the tensile strength and modulus are shown in Figures 6(a) and (b) respectively.

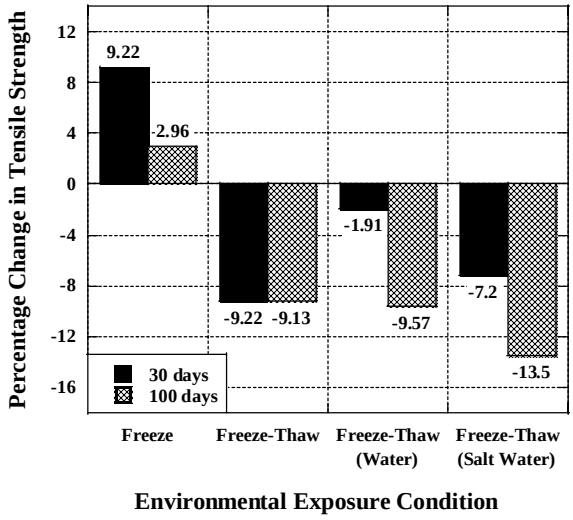


Figure 6(a): Effects of Exposure Conditions on Longitudinal Tensile Strength after 2400 Hours Exposure

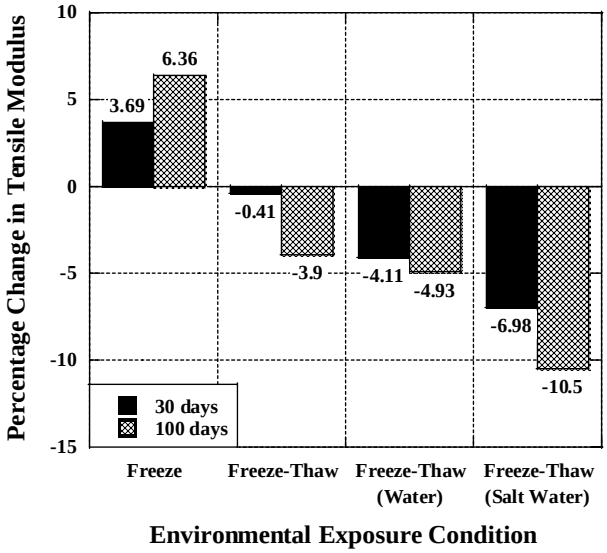


Figure 6(b): Effects of Exposure Conditions on Longitudinal Tensile Modulus After 2400 Hours Exposure

It is seen that exposure to the -10˚C conditions results in an increase in strength and modulus whereas both properties decrease as a result of the freeze-thaw exposure. It can be shown that the matrix stiffens with decrease in temperature resulting in an increase in modulus as determined by

$$E_{m(T)} = E_{m\,(To)} + K(T_0\text{-}T)$$

where $E_{m(To)}$ is the matrix modulus at temperature T_0, $E_{m(T)}$ is the matrix modulus at temperature T, wherein $T_0 > T$ and is measured in ˚C, and K is an empirical constant of the order of 20 MPa/˚C. Using this in conjunction with the rule of mixtures it is seen that the experimentally determined range of 34.8 GPa at 720 hours and 35.71 GPa at 2400 hours exposure to -10˚C compares reasonably with the predicted value of 35.19 GPa. Freeze-thaw exposures, especially in an aqueous environment cause fiber-matrix debonding and matrix microcracking resulting in a decrease in both tensile strength and modulus with the maximum degradation being seen to occur as a result of freeze-thaw in seawater. The diffusion and wicking of NaCl in solution is seen as the reason for this with the crystallization causing an increased level of interfacial debonding and crack opening during each freeze-thaw cycle. Again the effects of exposure are seen to increase through synergistic effects between different environments.

Despite the large body of literature that shows that synergistic environments can cause accelerated degradation in laboratory studies there is evidence that in the field, where synergism between a variety of environments is normal, the effects are not as severe. Figures 7(a) and (b) show results of field exposure on the properties of a E-glass/polyester adhesively bonded system, and an E-glass/epoxy wet layup system, respectively, used for seismic retrofit of columns after exposure for a period of 18 months in Seattle, Washington state adjacent to actual bridge columns and subject to the same environment as faced by the columns (Zhang et al, 2002).

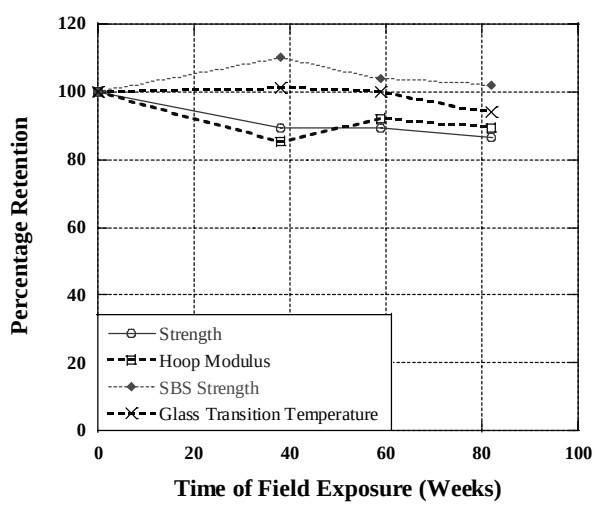


Figure 7(a): Percentage Retention of Jacket Properties After Field Exposure for a E-Glass/Polyester Adhesively Bonded Wrap System

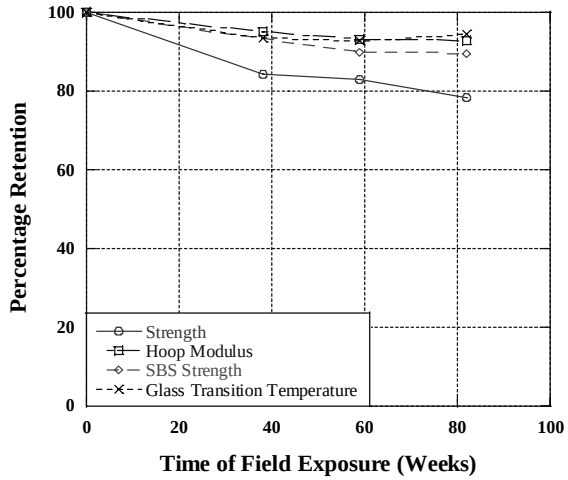


Figure 7(b): Percentage Retention of Jacket Properties After Field Exposure for a E-Glass/Epoxy Wet Layup Wrap System

Despite the large variation in field climate over the period of exposure the deterioration is seen to be lower than that expected from laboratory exposures, emphasizing the critical need to establish correlations between laboratory and field derived results of durability.

2. REPORT SCOPE

This report consists of two sets of data, namely

1. Pull-off data from testing of materials
2. Long-term durability data on prefabricated systems

3. PULL-OFF TESTING

Ten different FRP composite systems, supplied by five different manufacturers, were evaluated under the current program. The details of the composite systems are presented in Table 3. It should be noted that while S1 incorporates an E-glass fabric and S2 incorporates a carbon fabric the resin system used in both is the same. In contrast, systems S3 and S4 incorporate the same stabilized unidirectional carbon fabric with two different resin systems.

Table 3: Details of FRP Systems

System	Composite System	Fabric Weight (g/sq. m)	Matrix System	Process	Fiber Volume Fraction in Composite Layer
S1	Unidirectional E-glass fabric with hot melt adhesively bonded bicomponent thermoplastic thread in the transverse direction	913	High-tack, low VOC, 2 component 100% solids epoxy resin with a resin viscosity of 2500 cps at 23°C	Wet Layup	28%
S2	Unidirectional carbon fabric with hot melt adhesively bonded bicomponent thermoplastic thread in the transverse direction	618			33%
S3	Unidirectional tow based carbon fabric	300	Two component epoxy resin formulated for summer application (15-35°C) with a viscosity of 2700 cps at 23°C and a 120 minute pot life	Wet Layup	27%
S4			Two component epoxy resin formulated for winter application (5-15°C), by addition of acrylate, with a viscosity of 3500 cps at 23°C	Wet Layup	32%
S5	Unidirectional carbon fabric with aramid cross fibers	644	2 component epoxy resin with a viscosity of 600-700 cps at 23°C	Wet Layup	29%
S6	Prefabricated unidirectional carbon /epoxy pulformed strip		Paste form, two component, solvent free, epoxy adhesive	Adhesive Bonding	62%
S7	Unidirectional carbon fabric with stitch-bonded transverse epoxy coated glass yarn	300	Two component, 100% solids, epoxy resin with a viscosity of 700-900 cps at 23°C	Wet Layup	26%
S8		600			34%
S9	Prefabricated carbon pultruded strip		Paste form, two component epoxy adhesive	Adhesive Bonding	61%
S10	Prefabricated carbon pultruded strip		Two component, 100% solids, non sag paste form epoxy adhesive	Adhesive Bonding	69%

System S3 uses a base resin formulation designed for normal cure under ambient conditions whereas the resin in system S4 is a modification through the addition of an acrylate to enable faster curing in cold temperature regimes through development of a higher exotherm. Systems S7 and S8 use the same resin system and a stitch bonded unidirectional carbon fabric, with the only difference being that the fabric used in S8 has twice the aerial weight of that in S7 (600 gsm as compared to 300 gsm in S7). Systems S6, S9 and S10 all comprise of prefabricated carbon/epoxy strips designed to be bonded to the concrete substrate using 100% solids epoxy adhesive systems. In each case, only a single layer of FRP composite was bonded to the concrete substrate so as to remove any inter- and intra-laminar variables present in multilayered fabric systems and enable the focused study of the performance of the bond between concrete and the FRP composite.

In order to facilitate pull-off testing concrete blocks of size 305 mm x 178 mm x 76 mm (12 inches x 7 inches x 3 inches) were cast using Type V Portland cement having a slump of 76 mm with a 28 day compressive strength of 41.4 MPa design mix following specifications set for the HITEC evaluation process (Reynaud et al., 2001). The size was predicated by the requirement of having a minimum of three pull-off tests conducted per block, leaving enough space between test areas to ensure that there was no influence on one test from others conducted on the same block. Concrete cylinders were also cast at the same time for determination of the concrete compressive strength. After 28-day cure, the surface of the specimens were sandblasted to the level of aggregate with a rough surface and to free the concrete from any debris, grease, laitance, and loose material at the surface for proper bonding of the composite systems to concrete. All surfaces were prepared and primed following procedures for the specific systems under consideration. The carbon and glass fabrics were first cut into strips of 280 mm x 152 mm (11 inches x 6 inches) and a typical wet-layup procedure was followed for bonding the fabric systems to the concrete blocks using the appropriate resin systems. Special care was taken to ensure that the fabric was uniformly wet-out and a metallic roller was also used to compact the fabric and to drive out any air voids or excess resin. The prefabricated FRP strip systems came in widths of 152 mm (6 inches) for specimen S6 and in widths of 51 mm (2 inches) for specimens S9 and S10. A uniform layer of adhesive was first applied to both the prepared concrete surface and the prepared side of the FRP strip after which the strip was bonded to the specimens using a hard roller, which was used to drive out any excess adhesive or air voids.

Flat panels of the resin and adhesive were also cast at the same time for tensile and moisture uptake characterization. Once cured the panels were cut into square (25.4 mm x 25.4 mm) specimens for use in moisture uptake characterization, and dog-bone shaped specimens were cut from the resin and adhesive panels following ASTM D638 specifications using a water-jet for tensile characterization. A minimum of 5 specimens were used for each set (time period and exposure type). Fiber volume fraction of the FRP specimens was determined following ASTM D3171 (2004).

Specimens, prepared for pull-off testing, belonging to each set were exposed to 6 different environments, namely

(a) Immersion in deionized water at 22.8^{o}C (73°F);

(b) Immersion in salt water (5% NaCl solution) at 22.8°C (73°F);
(c) Ponding at 22.8°C (73°F); In this case the specimens were placed in a controlled environmental chamber at 22.8°C and 50% RH (relative humidity) supported at ends with the bonded face facing down and a dam built on the top face such that a depth of 5 mm of water could be renewed through the test period to simulate collection of water on top of strengthened decks wherein water would be transported through the porous concrete to the adhesive/resin-concrete interface;
(d) 95% RH at 37.8°C (100°F) with the same setup for ponding;
(e) Freeze conditions of -18°C (0°F); and
(f) Controlled room temperature conditions of 22.8°C (73°F) representing the unexposed condition and hereafter denoted as "Control" specimens.

A total of 25 concrete blocks were used for the evaluation of each system. Five of the 25 specimens were controls kept at room temperature and tested at the beginning of the durability assessment period as well as at the end of each 6-month exposure period up to two years. Of the other 20 specimens, 4 each were subjected to the five different exposure conditions and one specimen from each exposure was tested every 6 months for 2 years. Thus for the 10 composite systems studied, a total of 250 specimens were cast and tested.

Tensile coupons of each resin/adhesive were stored in the some of the same conditions, i.e.

(a) Immersion in deionized water at 22.8°C (73°F);
(b) Immersion in salt water (5% NaCl solution) at 22.8°C (73°F);
(c) Immersion in deionized water at 37.8°C (100°F). This environment was used to replicate as closely as possible the 95% RH at 37.8°C (100°F) ponding exposure used for the pull-off specimens;
(d) Immersion in concrete based alkali solution at 22.8°C (73°F). The solution was formed by allowing water to be transported through blocks of concrete thereby simulating a similar ionic content and concentration as would be seen in the case of ponding at 22.8°C (73°F) used for the pull-off tests, and
(e) Controlled room temperature conditions of 22.8°C (73°F) representing the unexposed condition and hereafter denoted as "Control" specimens.

5 specimens were tested at 6 month intervals over the 24 month test period for each exposure condition.

Moisture uptake was monitored through gravimetric means using a minimum of 10 specimens for each system and exposure period for the four exposure conditions used for tensile coupons. Moisture uptake, expressed as % weight change was determined as

$$\%\ Weight\ Change = \frac{(Exposed\ Weight)_t - (Initial\ Weight)_o}{(Initial\ Weight)_o} \ x\ 100 \qquad (1)$$

where $(Exposed\ Weight)_t$ is the weight of the specimen after exposure to the selected environmental condition for a period of time t, and $(Initial\ Weight)_o$ is the weight of the specimen prior to initiation of exposure. Specimens were removed for weighing at appropriate intervals and were then placed back into the appropriate environment. In

order to obtain values of activation energy specimens were also placed in deionized water at 37.8°C (100°F) and 60°C (140°F). The activation energy is determined using an Arrhenius type of relationship (Crank and Park, 1968)

$$\boldsymbol{D = D_0\, exp\left(\frac{-E_d}{RT}\right)} \qquad \text{..... (2)}$$

where D_o is a constant, R is the universal gas constant (8.3143 J/mol K), D is the diffusion coefficient, and T is the temperature expressed on the Kelvin scale. The activation energy, E_d, can be determined by plotting ln(D) versus (1/T).

Pull-off tests were conducted following each period of exposure by bonding three 50 mm (2") diameter aluminum disks to the top surface of the FRP composite system of each specimen using Sikadur Modular 31 two-component epoxy adhesive*. This adhesive was chosen since it had a significantly higher short-term, unexposed, bond strength as compared to the other adhesive/resin systems used for bonding the composites to the concrete surface and thus would ensure failure at the composite-concrete bondline or within the concrete rather than at the bond between the composite and the aluminum disk. A drill-press operated hole-saw was used to core around the disks through the composite and into the concrete for a depth of 15±5 mm to isolate the circular area of composite to be tested, following commonly used practice in concrete (Austin et al, 1995). A round-headed screw was used to connect the aluminum disk to the pull-off tester and the disk was then pulled out by cranking up the hand-operated lever, which applies a tension force normal to the surface of the composite. The average strength (computed by dividing the pull-off force by the area enclosed by the internal diameter of the core) from the three pull-off tests for each specimen was used to evaluate the bond performance corresponding to a particular environmental exposure for each system. It is noted that both the value of the strength and the mode of failure are necessary to assess bond. A true assessment of bond strength is only possible in the case when failure mobilizes, and is restricted to, the bond-line, in which case it provides a measure of the adhesion between the FRP and the concrete substrate. Failure within the concrete merely indicates that the bond strength is greater than the tensile strength of the concrete substrate. However, for the purposes of the current investigation the minimum tensile strength required of the concrete by ACI-440 (2002) will also be considered as a threshold for performance of the system.

Overall results for moisture uptake, tensile property retention and normalized pull-off strength are given in Tables 4, 5 and 6, respectively. For clarity, however, results are reported first for moisture uptake, followed by results for tensile characteristics of the resins and adhesives, after which pull-off results are discussed, since the first two offer some insights into overall response of the bonded system.

* The identification of commercial products is for purposes of specification only, and does not imply endorsement, nor does it necessarily imply that the products are the best available for the purpose.

Since the integrity of bond as well as the performance characteristics of the polymeric materials are likely to be affected by moisture uptake it is instructive to study both the maximum level of moisture absorbed by the materials as well as the resulting diffusion coefficients, and these are listed in Table 4. It should be noted that in the case of the systems fabricated using the wet layup process the resin used for the bond is essentially the same as that used for the impregnation of the fabric, whereas in the pultruded systems the resin used in the prefabricated strip is different from the adhesive used for bonding to concrete. Assuming square packing of reinforcement a relationship between the diffusion coefficients of the composite, D_c, and resin, D_m, can be developed as

$$D_c = \left(1 - 2\sqrt{\frac{V_f}{\Pi}}\right) D_m \qquad \text{..... (3)}$$

where V_f is the fiber volume of the composite. Ingress/uptake of aqueous solutions is known to cause fiber-matrix debonding and matrix microcracking in the resin in FRP composites, which can lead to higher uptake of these solutions in the FRP than would be expected on the basis of unreinforced resins. An assessment of the level of deterioration can be made by comparing the theoretically determined value of diffusion coefficient for the resin from equation (3), given the experimentally determined values of fiber volume fraction and FRP diffusion coefficient, with the experimentally determined values of diffusion coefficient for the unreinforced resin. A higher ratio of $(D_m)_{calculated}/(D_m)_{experimental}$ would indicate higher levels of resin and interface deterioration, and these ratios are also reported in Table 4.

While the levels of maximum moisture uptake and the diffusion coefficients provide an assessment of the saturation moisture content and rate of uptake, they do not provide any generic direct data regarding deterioration, or potential for deterioration, of the resins, adhesives and composites, since different systems are formulated to have different responses. However, comparisons can be made between sets, and a relative assessment of level of deterioration can be made using the resin diffusion coefficient ratio.

A comparison of response of systems S1 and S2, which have the same resin system, shows that the use of glass fiber reinforcement (S1) results in both higher diffusion coefficients and higher resin diffusion coefficient ratios than the carbon fiber reinforced system S2, across all four environments. This would indicate that the glass fiber reinforced system undergoes slightly greater moisture initiated deterioration than the carbon fiber reinforced system, which can be expected to translate to lower pull-off bond strengths. In fact, Table 6 shows that with the exception of the -18°C exposure condition, which does not involve transport of water molecules, this is borne out with the pull-off strengths measured at each time interval being higher in the case of system S2 than those measured for system S1.

Table 4: Moisture Uptake Characteristics (For ease of comparison the three pultruded systems – S6, S9 and S10, have been grouped together. For these systems $(M_m)_{resin}$ and D_m refer to the adhesive rather than the resin used in the pultruded FRP strip)

Exposure	**System**	**V_f** (%)	**Maximum Weight Gain**		**Diffusion Coefficients**		**Calculated Diffusion Coefficient for Resin – Eq (3)** (mm^2/s)	$\frac{(D_m)_{calculated}}{(D_m)_{experimental}}$
			$(M_m)_{resin}$ (%)	**$(M_m)_{FRP}$** (%)	**D_m** (mm^2/s)	**D_c** (mm^2/s)		
Immersion in Deionized Water at 22.8°C	S1	0.28	3.30	3.07	6.05×10^{-8}	4.26×10^{-8}	10.6×10^{-8}	1.75
	S2	0.33	3.30	2.80	6.05×10^{-8}	2.62×10^{-8}	7.45×10^{-8}	1.23
	S3	0.27	1.86	1.40	6.36×10^{-8}	3.00×10^{-8}	7.25×10^{-8}	1.14
	S4	0.32	3.34	2.42	6.11×10^{-8}	4.13×10^{-8}	11.42×10^{-8}	1.87
	S5	0.29	2.93	2.01	5.30×10^{-8}	3.77×10^{-8}	9.6×10^{-8}	1.81
	S7	0.26	4.06	2.51	4.60×10^{-8}	2.08×10^{-8}	4.89×10^{-8}	1.06
	S8	0.34	4.06	3.08	4.60×10^{-8}	2.45×10^{-8}	7.17×10^{-8}	1.56
	S6	0.62	2.44	0.52	1.75×10^{-7}	8.77×10^{-9}	-	-
	S9	0.61	3.99	0.30	2.96×10^{-8}	5.18×10^{-9}	-	-
	S10	0.69	0.86	1.09	3.24×10^{-8}	7.67×10^{-9}	-	-
Immersion in Salt Water (5% NaCl solution) at 22.8°C	S1	3.42	3.04	2.86	4.64×10^{-8}	3.09×10^{-7}	7.67×10^{-8}	1.65
	S2	0.33	3.04	2.66	4.64×10^{-8}	2.29×10^{-8}	6.51×10^{-8}	1.40
	S3	0.27	1.64	1.06	5.24×10^{-8}	4.45×10^{-8}	10.76×10^{-8}	2.05
	S4	0.32	2.92	1.83	4.75×10^{-8}	3.09×10^{-8}	8.55×10^{-8}	1.80
	S5	0.29	2.70	1.73	4.45×10^{-8}	3.57×10^{-8}	9.10×10^{-8}	2.05
	S7	0.26	3.92	2.37	4.87×10^{-8}	3.05×10^{-8}	7.19×10^{-8}	1.48
	S8	0.34	3.92	3.29	4.87×10^{-8}	2.95×10^{-8}	8.63×10^{-8}	1.77
	S6	0.62	2.16	0.36	1.69×10^{-7}	7.15×10^{-9}	-	-
	S9	0.61	3.55	0.31	3.52×10^{-8}	5.74×10^{-9}	-	-
	S10	0.69	0.21	0.55	2.78×10^{-8}	5.38×10^{-9}	-	-

Immersion in Deionized Water at 37.8°C	S1	0.28	3.42	3.77	1.47×10^{-7}	7.25×10^{-8}	1.80×10^{-7}	1.22
	S2	0.33	3.42	3.62	1.47×10^{-7}	5.20×10^{-8}	1.48×10^{-7}	1.01
	S3	0.27	1.98	1.38	1.83×10^{-7}	1.46×10^{-7}	3.53×10^{-7}	1.93
	S4	0.32	3.16	2.06	3.40×10^{-7}	2.91×10^{-7}	8.05×10^{-7}	2.37
	S5	0.29	2.74	2.14	1.60×10^{-7}	8.03×10^{-8}	2.05×10^{-7}	1.28
	S7	0.26	4.06	2.81	1.38×10^{-7}	6.93×10^{-8}	1.63×10^{-7}	1.18
	S8	0.34	4.06	3.32	1.38×10^{-7}	7.02×10^{-8}	2.05×10^{-7}	1.49
	S6	0.62	2.58	0.55	4.05×10^{-7}	2.26×10^{-8}	-	-
	S9	0.61	4.31	0.34	8.34×10^{-8}	3.69×10^{-8}	-	-
	S10	0.69	1.37	1.56	7.92×10^{-8}	3.49×10^{-8}	-	-

Immersion in Concrete Based Alkali Solution at 22.8°C	S1	0.28	3.78	3.24	6.17×10^{-8}	4.13×10^{-8}	1.03×10^{-7}	1.67
	S2	0.33	3.78	4.16	6.17×10^{-8}	2.42×10^{-8}	6.88×10^{-8}	1.12
	S3	0.27	1.83	1.25	5.65×10^{-8}	2.34×10^{-8}	5.66×10^{-8}	1.00
	S4	0.32	3.21	1.95	5.65×10^{-8}	3.33×10^{-8}	9.21×10^{-8}	1.63
	S5	0.29	3.22	2.24	6.23×10^{-8}	5.05×10^{-7}	1.29×10^{-8}	2.07
	S7	0.26	4.06	2.52	4.49×10^{-8}	3.77×10^{-8}	8.88×10^{-8}	1.24
	S8	0.34	4.06	3.24	4.49×10^{-8}	2.23×10^{-8}	6.52×10^{-8}	1.45
	S6	0.62	2.69	1.06	1.68×10^{-7}	9.03×10^{-9}	-	-
	S9	0.61	3.79	0.62	3.57×10^{-7}	1.52×10^{-8}	-	-
	S10	0.69	1.12	1.00	3.25×10^{-8}	8.81×10^{-9}	-	-

In the case of the prefabricated strip systems, S6, S9 and S10, all of which consisted of unidirectional carbon tows impregnated with epoxy, maximum moisture uptake was significantly lower than the levels attained in the wet layup based systems which is expected due to both the higher fiber volume fractions and use of elevated cure regimes in the prefabricated strips. It is noted that within the prefabricated group, system S10 showed a much higher level of moisture uptake than the other systems, under all exposure conditions except in the concrete based alkali solution. In contrast the adhesive used in system S10 had the lowest uptake level of all systems, including the resins used for wet layup.

Given that systems S3 and S4 used the same epoxy backbone with the formulation for S3 being modified through the use of an acrylate to enable better cure and performance in cold climates it is interesting to note that in all cases (resin and composite) the diffusion coefficients for system S4 were higher than those for S3, indicating that the modification was itself responsible for a greater propensity for moisture uptake. It is noted that the resin diffusion coefficient ratio for S4 was also higher than that of S3 indicating greater deterioration in 3 of the 4 environments considered (the exception being the salt water immersion). It could hence be expected that the pull-off strengths for S4 would be lower than those for S3 under these environmental conditions. As can be seen from Table 6, the pull-off strengths recorded for system S4 at the end of the 24 month period of exposure are, in fact, 10.4%, 7.5%, 11.25% and 7.5% lower than those attained with the use of system S3, for the cases of immersion in salt water at 22.8^{o}C, immersion in deionized water at 22.8^{o}C, ponding of water at 22.8^{o}C, and ponding of water under conditions of 95% RH at 37.8^{o}C, respectively. However, in the case of exposure to -18°C, the use of the specially formulated resin in system S4 results in a 27% increase in pull-off strength over that of the “summer” variation of the resin in system S3.

The use of higher aerial weight fabric is sometimes preferred so that a greater amount of fiber can be used through the layup of a single layer. A comparison of systems S7 and S8 which used the same resin and the same style of unidirectional stitch bonded carbon fabric clearly shows that the use of the higher basis weight fabric (600 gsm in the case of system S8 compared to the 300 gsm fabric in system S7) results in higher levels of moisture uptake as well as greater deterioration in the bulk resin as indicated through the use of the resin diffusion coefficient ratio. These characteristics again provide an expectation of pull-off strength being lower for S8 in comparison to S7, which is again borne out by the results in Table 6.

A summary of the level of retention of tensile modulus and strength at the end of the 24 month exposure period, for each of the resins and adhesives used, as a function of type of exposure is listed in Table 5.

Table 5: Normalized Retention of Tensile Characteristics After 24 Months Exposure

System	Type	Modulus				Strength			
		Immersion in Deionized Water at 22.8°C	Immersion in Deionized Water at 37.8°C	Immersion in Salt Water (5% NaCl solution) at 22.8°C	Immersion in Concrete Based Alkali Solution at 22.8°C	Immersion in Deionized Water at 22.8°C	Immersion in Deionized Water at 37.8°C	Immersion in Salt Water (5% NaCl solution) at 22.8°C	Immersion in Concrete Based Alkali Solution at 22.8°C
S1/S2	Resin	0.83	0.84	0.90	0.89	0.93	0.95	0.93	0.90
S3	Resin	0.88	0.75	0.9	0.88	0.86	0.82	0.86	0.86
S4	Resin	0.20	0.17	0.18	0.22	0.17	0.17	0.17	0.14
S5	Resin	0.78	0.77	0.75	0.77	0.87	0.84	0.84	0.86
S6	Adhesive	0.90	0.86	0.97	0.90	0.95	0.88	0.88	0.77
S7/S8	Resin	0.80	0.64	0.83	0.87	0.82	0.72	0.84	0.86
S9	Adhesive	0.59	0.49	0.66	0.62	0.61	0.53	0.62	0.59
S10	Adhesive	0.57	0.54	0.63	0.45	0.55	0.53	0.62	0.46

It should be noted that these characteristics pertain to response of the bulk resin and adhesive systems at thicknesses significantly larger than those which would be seen in the resin/adhesive bond line, and hence cannot be directly correlated to material in the actual pull-off specimens. The results, however, when used in conjunction with moisture uptake characteristics, can provide useful indicators of comparative potential systems level response. For example, a comparison of response clearly shows that the "summer" resin used in system S3 has significantly better retention characteristics than the "winter" system used in system S4, which further corroborates results from moisture uptake studies.

In completing all the pull-off tests six different failure modes were observed:

a) Failure inside the concrete through and around aggregates, indicating that the FRP-concrete bond strength was higher than the tensile cracking strength of concrete. This mode was noted in the "control" samples and in most of the early-age specimens;
b) Partial failure in the top layer of concrete at the composite-concrete interface and remaining failure into concrete through/around aggregates;
c) Failure in the top layer of concrete close to the FRP-concrete interface indicating the presence of defects within the concrete saturated with primer/resin or degradation of this region due to environmental exposure. In this case the entire bond-line remains intact and failure takes place in the region of concrete that is likely to be penetrated to an extent by primer/resin/adhesive. Diffusion of moisture into this region is likely to result in loss of bond in asperities as well as deterioration of the thin polymer-concrete region resulting in failure within this region;
d) Failure within the resin/adhesive bondline with concrete, indicating degradation of the bond line as a result of exposure. This mode clearly shows the deterioration of the resin/adhesive layer at the interface between the FRP and the concrete and is increasingly seen in specimens showing large resin diffusion ratios;
e) Intra-laminar failure within the prefabricated FRP strips. Such failures were observed in specimen S10 immersed in salt water indicating fiber-matrix bond degradation within the FRP;
f) Failure due to debonding of the aluminum disk from the composite. Such premature failures, though rare, can be attributed to improper bonding of the disk to the FRP and results were neglected in calculating the average pull-off strength of the specimens.

In order to provide a consistent base-line to enable a comparison of the results between different systems from exposure tests, results of all control tests (i.e. tests conducted on unexposed specimens) which represented failures within concrete were pooled providing a concrete strength of 4.07 MPa. This base-line value was then used as a normalizing factor such that a normalized pull-off ratio of 1 represent no deterioration as a result of exposure, and decreasing values, smaller than 1, would represent increasing levels of deterioration. A summary of overall results is given in Table 6.

Table 6: Normalized Pull-Off Strength Indices of Systems After Exposure

System #	Manufacturer ID	Exposure Condition	Time period (months)			
			6	12	18	24
S1	1	Immersion in Salt Water (5% NaCl solution) at 22.8°C	1.00	0.59	0.59	0.46
S2			1.00	0.93	0.87	0.74
S3	2		1.00	0.78	0.69	0.68
S4			1.00	0.69	0.60	0.61
S5	3		1.00	0.79	0.75	0.39
S6			0.93	0.57	0.57	0.50
S7	4		0.87	0.86	0.62	0.63
S8			0.71	-	0.57	0.54
S9			1.00	0.76	0.68	0.55
S10	5		1.00	0.27	0	0
S1	1	Immersion in Deionized Water at 22.8°C	0.90	0.85	0.87	0.77
S2			1.00	0.92	-	0.80
S3	2		1.00	0.96	0.81	0.80
S4			1.00	0.95	0.86	0.74
S5	3		0.91	0.80	0.78	0.72
S6			0.83	0.58	0.57	0.52
S7	4		0.87	0.80	0.65	0.42
S8			0.73	-	0.61	0.24
S9			0.81	0.76	0.62	0.61
S10	5		1.00	1.00	0.80	0.72

Table 6 (Contd.)

System #	Manufacturer ID	Exposure Condition	Time period (months)			
			6	12	18	24
S1	1	Ponding of Water at 22.8°C	1.00	0.76	0.70	0.66
S2			1.00	0.81	-	0.78
S3	2		1.00	0.92	0.82	0.80
S4			1.00	1.00	0.79	0.71
S5	3		0.91	0.87	0.82	0.78
S6			0.88	0.64	0.65	0.34
S7	4		0.90	0.89	0.67	0.58
S8			0.69	-	0.57	0.46
S9			0.81	-	0.74	0.39
S10	5		1.00	0.92	0.72	0.59
S1	1	Exposure to 95% RH at 37.8°C with ponding in an environmental chamber	0.90	0.70	0.66	0.63
S2			0.91	0.83	0.72	0.71
S3	2		0.94	0.92	0.86	0.81
S4			1.00	0.78	0.76	0.74
S5	3		1.00	0.66	0.64	0.63
S6			0.92	0.87	0.76	0.60
S7	4		0.82	0.71	0.71	0.66
S8			0.67	-	0.56	0.48
S9			0.92	0.62	0.65	0.66
S10	5		1.00	0.95	0.88	0.76
S1	1	Freeze condition at -18°C	0.60	0.62	0.61	0.59
S2			0.81	0.77	0.59	0.50
S3	2		0.78	0.65	0.59	0.52
S4			0.77	0.72	0.64	0.66
S5	3		0.55	0.52	0.51	0.51
S6			0.74	0.76	0.48	0.52
S7	4		0.78	0.68	0.60	0.57
S8			0.40	0.46	0.23	0.20
S9			0.68	0.59	0.57	0.53
S10	5		0.65	0.65	0.59	0.51

As can be seen from Table 6 immersion in deionized water for a period of 2 years resulted in roughly equivalent levels of deterioration in systems S1, S2, S3, S4, S5 and S10 with the level of deterioration being between 20 and 28%. The highest level of deterioration, 76%, was noted in system S8. The resin used in this system had the highest level of moisture uptake, 4.06%, of all systems. Although the same resin was also used in S7, the two had very different levels of resin level deterioration in the FRP composite layer as can be seen from the diffusion ratios in the last column in Table 4. System S7 shows a very small deviation in the value of the theoretical diffusion coefficient as compared to the actual, whereas system S8 has a 56% greater value, indicating substantial resin microcracking and fiber-matrix interface level debonding which led to higher than normal levels of moisture uptake in the resin. It is noted that beyond 12 months of exposure, failure surfaces of the pull-off samples from system S7 showed a combination of failure in the top layer of concrete and within the bond-line, whereas those for system S8 were at the level of the bond-line. Systems S9 which had the next highest levels of deterioration showed the next highest level of moisture uptake in the adhesive, 3.99%, whereas system S6 which showed a 48% deterioration in bond strength had the highest coefficient of diffusion of all adhesives used in the study. While these criteria help in assessing the reasons for low retention of strength, it is clear that final performance characteristics are due to a combination of phenomena and cannot be directly ascribed to only one aspect.

With the exception of systems S7 and S8, immersion in salt water caused a higher level of degradation in bond strength in all systems than that due to immersion in deionized water. While the exact reasons for this are unknown at present it is noted that Rege and Lakkad (1983) had indicated that at the molecular level NaCl could strain or rupture intermolecular bonds in the bulk matrix and at the level of the fiber-matrix interface, resulting in greater degradation of compressive, interlaminar and flexural strengths than through immersion in water. The least effect was noted in system S2, with a 26% deterioration at the end of the 24 month period, and the most drastic effect was seen on specimen S10 which showed almost a 100% deterioration in bond strength after 12 months of immersion. In this case the system was noted to fail within the FRP strip itself resulting in a brooming type configuration of fibers between the remnants of the system bonded to the aluminum disk and those bonded to the concrete substrate. Similar failure modes were observed in the tests at the 18 and 24 month level with the composite having no residual bond strength, resulting in intralaminar separation under very low applied pull-off force. It is noted that this mode was not seen in the other two prefabricated systems which had a lower fiber volume fraction (62% for system S6 and 61% for system S9 in comparison to 69% in system S10). The presence of locally high fiber volume fraction regions with accompanying resin-poor regions with microscopic dry spots between filaments in this particular system had been noted earlier to cause failure along horizontal surfaces through the strip when used as externally bonded reinforcement for the strengthening of slabs (Seim et al., 2001). Considerable degradation in bond strength after immersion in salt-water was also observed in specimens S1 and S5 with the normalized pull-off strength index falling to 0.46 and 0.39, respectively at the end of the 2 year exposure period. In both cases, the pull-off samples were observed to have failures

at the epoxy resin-concrete interface. System S5 had the highest value of diffusion index for the resin, 2.05, indicating substantial deterioration in the bulk which would provide additional paths for wicking of solution, as well as one of the highest values of diffusion coefficients for the FRP composite layer.

Ponding of water on the top surface of the concrete block, which results in transport of water through the concrete to the resin/adhesive bond-line with concrete, had the most significant adverse effect on the bond performance of systems S6 and S9, both of which were pultruded carbon/epoxy strip systems adhesively bonded to the concrete. The normalized pull-off strength indices for these two systems fell to 0.34 and 0.39, respectively, at the end of the 2 year exposure period. In the case of system S6 the failures of the pull-off samples were at the adhesive bondline whereas in the case of system S9 the failure surfaces were partially in the bond-line and partially in the top layer of concrete. Although diffusion coefficients for the adhesive under the specific mode of moisture transport (through concrete) are not available, tests were conducted to characterize moisture kinetics in an alkaline solution formed by diffusion of water through concrete specimens to provide a similar solution. As can be seen from Table 2, systems S6 and S9 had the highest diffusion coefficients of all the resins and adhesives studied in this investigation. It is noteworthy that the best performing systems, S2, S3 and, S5, which showed only a 20-22% deterioration in bond-strength at the end of the 24 month period of exposure had the lowest overall resin diffusion ratios (1.0) indicating negligible breakdown of the bulk resin.

The effect of subjecting the specimens to 95% RH at 37.8^{o}C with ponding was not as pronounced on the pull-off strength degradations as compared to the other exposure conditions. The normalized strength index was higher than 0.6 for all systems other than system S8 which showed a majority of the degradation (33% from a total of 52%) in the first 6 months of exposure. The failures of the pull-off samples for system S8 were observed to occur at the resin bondline with very little concrete adhesion as compared to the failures in the other systems which occurred either within the top layer of concrete or deeper within the concrete substrate.

The most severe overall degradation in bond strengths over the 2 year exposure period was observed as a result of exposure to freezing conditions at -18°C. All the systems, other than S4 (a carbon fabric system with an epoxy resin formulated specifically for winter applications), had normalized pull-off strength indices lower than 0.6, with system S8 having the most significant bond strength degradation with the normalized pull-off strength index falling to 0.2 at the end of the 2 year exposure period. This degradation of pull-off strengths for majority of composite systems can be attributed to the increasing brittleness of the resins and adhesives as a result of continued exposure to sub-zero environments, as well as the increased propensity for matrix cracking (Dutta, 1988; Lord and Dutta, 1988) initiating from pre-existing defects such as voids. The apparent increase in matrix brittleness and decrease in tensile strength was also noted by Gadke (1985). The loss in bond-strength leading to decreases in failure load levels of scale beams with externally bonded FRP after exposure to freeze conditions of -15.5^{o}C had been reported earlier by Karbhari and Engineer (1996b). It is noted that with the

exception of system S4 the failures of all the samples were at the bondline itself. However, in the case of system S4, which was specially formulated for cold weather use, failures were entirely within the concrete albeit with variation in depth between specimens.

The ACI-440 (2002) design guidelines for FRP strengthening identify the strength of the existing concrete substrate as an important parameter for bond critical applications and specify a minimum tensile strength of concrete of 1.38 MPa (200 psi). Considering this as the minimum threshold for performance, the minimum required normalized pull-off strength index after exposure can be expressed as the ratio of this level to the value of the average baseline pull-off strength, 4.07 MPa. This results in a normalized index of 0.33, indicating that a maximum of 67% degradation from the unexposed levels could be allowed before the minimum strength threshold was exceeded. Using this criterion the ten different systems are assessed and ranked in Table 7 using a scale from 1-10, with 1 representing the best performance and 10 representing the worst.

Table 7: Overall ranking of bond performance of FRP systems after 2 years of exposure (using a scale of 1-10, with 1 signifying the best performance, and 10 the worst)

System #	**Mfg. ID**	**Immersion in Salt water at 22.8°C**	**Immersion in Deionized Water at 22.8°C**	**Ponding of Water at 22.8°C**	**Exposure to 95% RH at 37.8°C With Ponding**	**Freeze Condition at -18°C**
S1	1	8	2	4	6	2
S2		1	1	2	4	7
S3	2	2	1	1	1	5
S4		4	3	3	3	1
S5	3	9	4	2	6	6
S6		7	6	Unacceptable	7	5
S7	4	3	7	6	5	3
S8		6	Unacceptable	7	8	Unacceptable
S9		5	5	8	5	4
S10	5	Unacceptable	4	5	2	6

Using this criteria and comparing the normalized pull-off strength indices of the composite systems at the end of the 2 year exposure period, as presented in Table 6, it can be seen that system S8 (which uses the highest aerial weight fabric) performs the poorest falling below the minimum threshold in two cases. Systems S6 and S10, both involving the use of prefabricated carbon/epoxy strips, fall below the threshold in the case of a single exposure each. It can also be noted that the overall performance of systems S3, S4 and S2 (in that order), performed the best overall. It is interesting to note that the wet layup systems, in general, performed better than the prefabricated systems. This is attributed to both a thinner bond line and the greater level of penetration into concrete, and hence a more durable mechanical bond, in the case of the lower viscosity resins systems. It is noted that the lower viscosity systems also penetrate the concrete to a greater extent enabling a stronger interphase and better shear transfer between the FRP and concrete. However, if the concrete surface is extremely rough and uneven and shows large irregularities the wet layup process efficiency could decrease significantly due to the formation of local radial stresses at irregularities and the greater proportion of load carried by the thicker regions of unreinforced resin resulting in local microcracking. Additionally, it should be pointed out that, the adhesive systems used have high filler content which results in lower reactivity and greater potential for local embrittlement and deterioration under specific environmental conditions.

Considering that 3 systems did not meet the minimum bond-strength threshold due to continued deterioration under specific conditions of environmental exposure (System S10 in salt water, system S8 in deionized water and freeze conditions, and system S6 under ponding conditions) it is crucial to note that system level failure (in a rehabilitated structure) could take place even if the FRP itself did not deteriorate. It is thus important to clearly incorporate criteria related to deterioration not just for the FRP systems used in rehabilitation, but also for the resin or adhesive, which provides the bond for the system to the concrete substrate.

While the pull-off test provides an efficient means of determining bond-strength, and of comparing the relative performance of different systems, the mode of loading – direct tension, does not accurately represent most actual applications, wherein the force between the FRP and concrete layer is transferred primarily through shear. It is thus useful to be able to relate results for bond strength derived from pull-off to those in shear or bending. Based on the study of test methods and quality of concrete on bond strength Horiguchi and Saeki (1997) reported empirical relationships between the bond-strength and concrete compressive strength of the form

$$f_b(shear) = 0.09 \times f_c^{'(2/3)} \qquad \text{.....(4)}$$

$$f_b(bending) = 0.22 \times f_c^{'(2/3)} \qquad \text{.....(5)}$$

and

$$f_b(tension) = 0.36 \times f_c^{'(2/3)} \qquad \text{.....(6)}$$

where $f_b(shear)$, $f_b(bending)$, and $f_b(tension)$ are the bond-strengths between FRP and concrete under shear, flexure, and direct-tension modes of loading, respectively, and $f_c^{'}$

is the compressive strength of concrete. Using equations (4)-(6) direct relations between the different forms of bond-strength can be determined as

$$f_b(shear) = 0.25 \times f_b(tension) \qquad \text{…...(7)}$$

and

$$f_b(bending) = 0.61 \times f_b(tension) \qquad \text{…...(8)}$$

Correlation of pull-off strengths with compression tests conducted as part of the current investigation, for control specimens, provided a relation very similar in form to equation (6) as

$$f_b(tension) = 0.3662 \times f_c^{'(2/3)} - 1.6285 \qquad \text{….(9)}$$

indicating that similar forms of (7) and (8) could be used. The results obtained in this study in terms of bond strength degradation of the 10 different composite systems subjected to the five exposure conditions as obtained from the pull-off tests (in tension) can thus be approximately correlated to the corresponding bond strengths in shear or bending, which can be more directly used in design. It is suggested that this approach be used in conjunction with method developed for predictions of FRP durability as determined for system S7 by Abanilla et al (2005), and Karbhari and Abanilla (2006) to enable a better assessment of the durability and reliability of FRP strengthened concrete structural elements and systems. The combined approach of the afore mentioned references is recommended for use.

4. DURABILITY TESTING

Pursuant to discussions with the California Department of Transportation, results of the study are presented by system in a specifically determined format that follows that used in part by MIL-HDBK-17, while preserving the primary requirements of ease of use by the civil design and owner communities. Results are provided in the context of this report by system with the order as listed below:

Prefabricated Systems
- Sika
- SCCI
- Fyfe

Wet Layup Systems
- Fyfe

SIKA PREFABRICATED SYSTEM

GENERAL INFORMATION

Material: Adhesive, Sikadur 30
Manufacturer: SIKA
Resin Type: Two-component thixotropic mortar based on a solvent free epoxy resin (component A: aromatic hydrocarbon, component B: aliphatic amine, mixed in 3 : 1 ratio by volume).
Fiber Type: N/A
Fabric Type: N/A
Fabric Weight: N/A
Type of Cure: Ambient Temperature
Method of Manufacture: Casting
Density: 1.67 g/cm^3
Fiber Volume Fraction: N/A
Resin Volume Fraction: N/A
Void Volume Fraction: N/A
Configuration: N/A

PROPERTIES

A). Moisture Uptake (Data for a period of 218 weeks)

Material: Adhesive, Sikadur 30 Manufacturer: SIKA Test Method: Gravimetric, ASTM D 5229/D 5229M - 92 Nominal Specimen Size (Length × Width × Thickness): 25.4 mm × 25.4 mm × 5.9 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Curve shape		2-stage[1]	2-stage[1]	Sigmoidal[2]	2-stage[1]	2-stage[1]
M_{max} (%)	0.10	0.98	2.17	6.83	1.57	0.29
Time for M_{max}	At 154 week	At end	At end	At end	At end	At 121 week
M_∞						
M_∞ (%) in stage 1 [3]		0.76	0.78	0.86	0.67	0.20
D (mm^2/s) in stage 1		3.41×10^{-8}	1.12×10^{-7}	4.59×10^{-7}	4.40×10^{-8}	6.15×10^{-8}
k (1/s$^{0.5}$) in stage 2		2.00×10^{-5}	1.40×10^{-4}	5.50×10^{-4}	1.70×10^{-4}	4.00×10^{-5}
2-stage formula (details see Ref.1)	$M_t = M_\infty\left(1+k\sqrt{t}\right)\left\{1-\exp\left[-7.3\left(\frac{Dt}{h^2}\right)^{0.75}\right]\right\}$					

1. Following Bao, L.R., Yee, A.F. and Lee, C.Y.C., "Moisture Absorption and Hygrothermal Aging in a Bismaleimide Resin" *Polymer*, 42, 2001, pp. 7327-7333.
2. Use 2-stage model to curve fit the data.
3. M_∞ determined following the graphical method in Tsotsis, T. K. and Weitsman, Y., "A Simple Graphical-Method For Determining Diffusion Parameters For 2-Stage Sorption In Composites." *Journal Of Materials Science Letters*, 13[22], 1994, pp. 1635-1636.

B). Tensile Test

Material: Adhesive, Sikadur 30 Manufacturer: SIKA Test Method: ASTM D 638 - 99 Nominal Specimen Size: According to ASTM standard, Overall Length = 165 mm, Gage Length = 50 mm, Width of Narrow Section = 13 mm, Thickness = 6 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing	
Condition	After preconditioning
Strength	
Mean (MPa)	25.29
STD (MPa)	2.54
Max (MPa)	27.74
Min (MPa)	22.67
CV	0.10
No. specimens	3
Modulus	
Mean (GPa)	6.93
STD (GPa)	0.48
Max (GPa)	7.36
Min (GPa)	6.42
CV	0.07
No. specimens	3

B). Tensile Test (contd.)

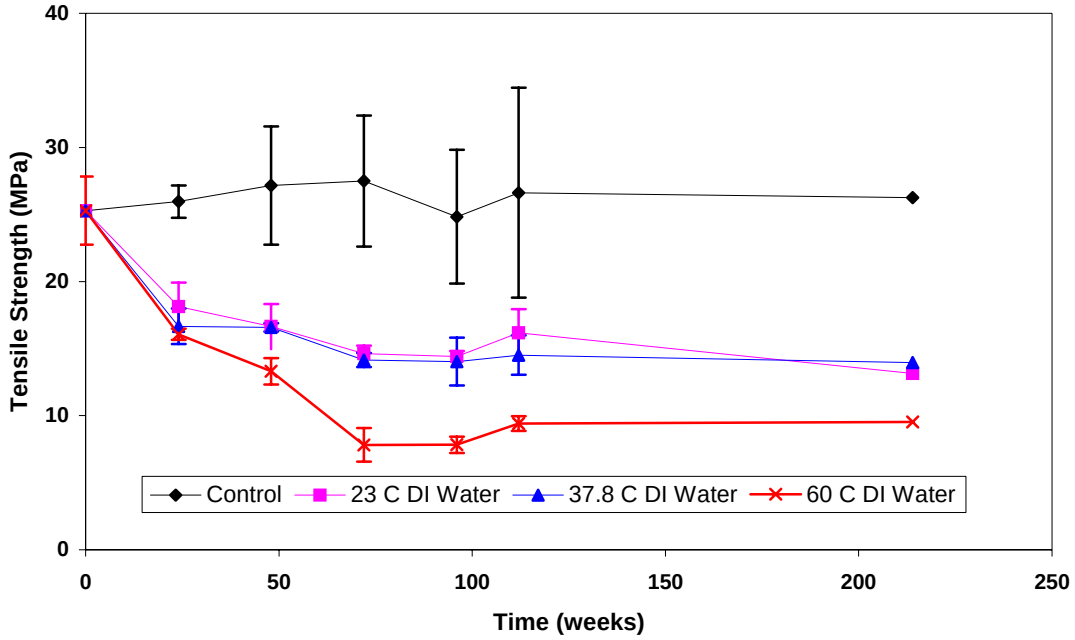
Material: Adhesive, Sikadur 30 Manufacturer: SIKA Test Method: ASTM D 638 - 99 Nominal Specimen Size: According to ASTM standard Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 24 weeks						
Strength						
Mean (MPa)	25.96	18.13	16.66	16.07	18.57	23.32
STD (MPa)	1.21	1.78	1.33	0.42	1.48	3.97
Max (MPa)	27.29	20.46	17.62	16.68	19.92	26.06
Min (MPa)	24.94	16.43	14.35	15.77	16.08	17.53
CV	0.05	0.10	0.08	0.03	0.08	0.17
No. specimens	3	5	5	4	5	4
Modulus						
Mean (GPa)	7.16	5.28	5.19	4.16	5.40	6.63
STD (GPa)	0.13	0.44	0.38	0.41	1.15	1.12
Max (GPa)	7.28	5.97	5.68	4.76	7.42	7.55
Min (GPa)	7.03	4.75	4.88	3.82	4.67	5.01
CV	0.02	0.08	0.07	0.10	0.21	0.17
No. specimens	3	4	5	4	5	4
Exposure period: 48 weeks						
Strength						
Mean (MPa)	27.16	16.65	16.58	13.31	17.34	18.26
STD (MPa)	4.42	1.67	0.30	0.99	1.80	5.05
Max (MPa)	31.97	18.41	16.95	14.23	20.52	25.78
Min (MPa)	19.99	14.31	16.26	12.18	16.26	11.65
CV	0.16	0.10	0.02	0.07	0.10	0.28
No. specimens	5	5	5	5	5	5
Modulus						
Mean (GPa)	8.38	5.17	5.10	3.93	4.76	5.18
STD (GPa)	1.09	0.98	0.38	1.02	0.41	0.79
Max (GPa)	9.55	6.41	5.71	5.72	4.99	6.15
Min (GPa)	7.25	4.10	4.68	3.17	4.03	4.24
CV	0.13	0.19	0.07	0.26	0.09	0.15
No. specimens	5	5	5	5	5	5

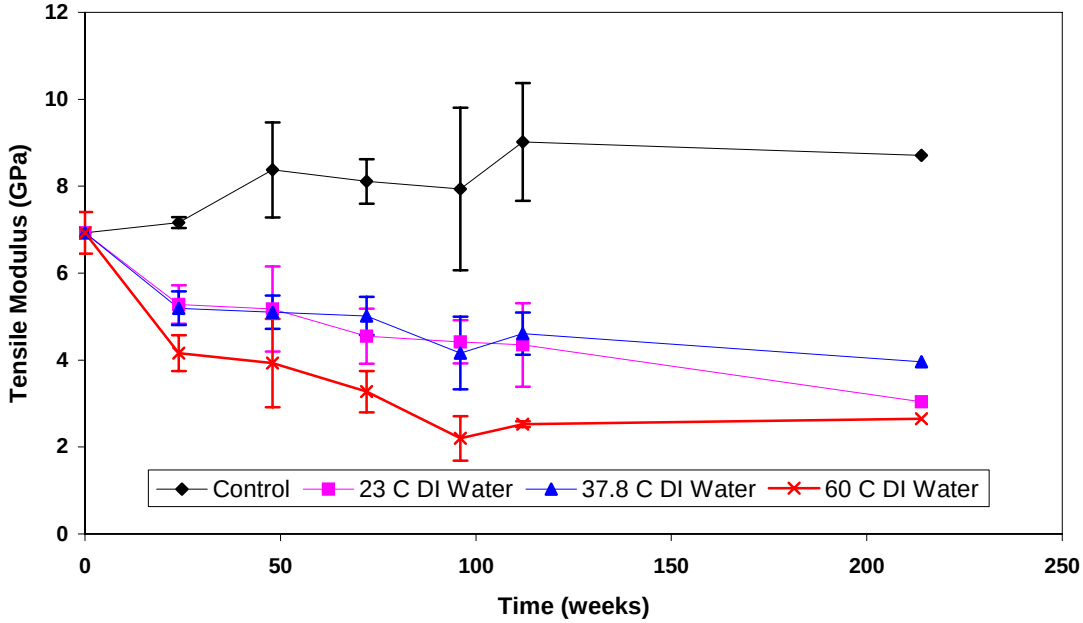
B). Tensile Test (contd.)

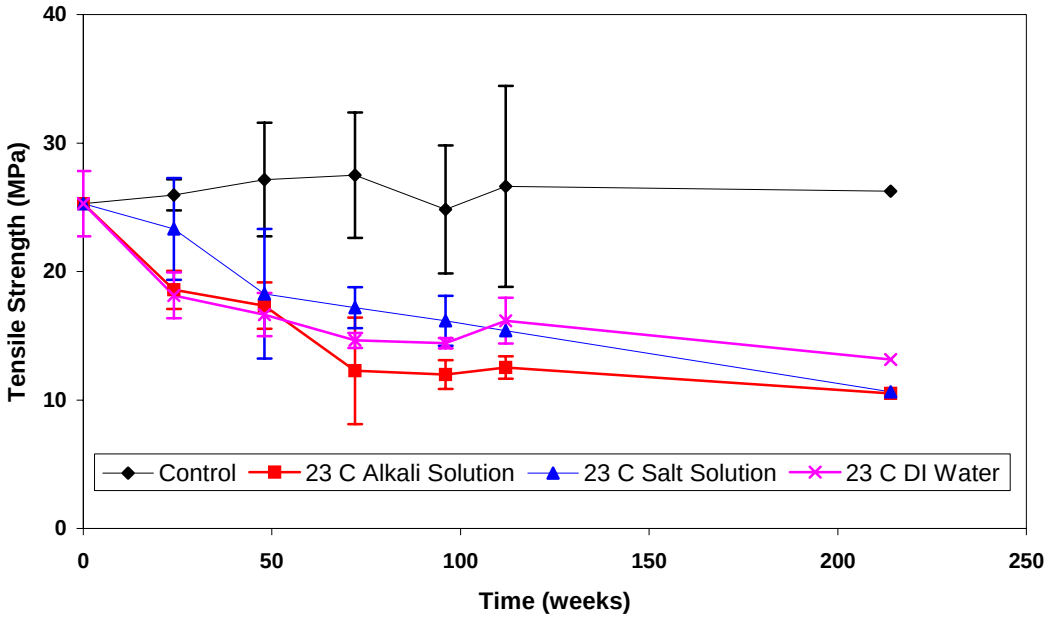
Material: Adhesive, Sikadur 30 Manufacturer: SIKA Test Method: ASTM D 638 - 99 Nominal Specimen Size: According to ASTM standard Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 72 weeks						
Strength						
Mean (MPa)	27.49	14.64	14.16	7.82	12.27	17.19
STD (MPa)	4.88	0.58	0.52	1.26	4.14	1.60
Max (MPa)	34.09	15.47	14.78	9.29	16.51	19.40
Min (MPa)	23.35	14.04	13.48	6.21	7.36	15.81
CV	0.18	0.04	0.04	0.16	0.34	0.09
No. specimens	4	5	5	4	5	4
Modulus						
Mean (GPa)	8.11	4.55	5.01	3.27	4.74	5.15
STD (GPa)	0.51	0.63	0.44	0.48	0.73	0.19
Max (GPa)	8.69	5.21	5.65	3.86	5.86	5.34
Min (GPa)	7.67	3.69	4.64	2.73	3.86	4.90
CV	0.06	0.14	0.09	0.15	0.15	0.04
No. specimens	4	5	5	4	5	4
Exposure period: 96 weeks						
Strength						
Mean (MPa)	24.84	14.42	14.03	7.83	11.99	16.16
STD (MPa)	4.98	0.40	1.78	0.61	1.12	1.95
Max (MPa)	33.23	14.86	16.26	8.45	12.74	18.05
Min (MPa)	20.28	14.08	12.32	7.23	10.32	14.40
CV	0.20	0.03	0.13	0.08	0.09	0.12
No. specimens	5	3	5	3	4	4
Modulus						
Mean (GPa)	7.94	4.42	4.16	2.20	3.48	4.85
STD (GPa)	1.87	0.50	0.84	0.51	0.81	0.73
Max (GPa)	10.83	4.74	5.14	2.74	4.68	5.90
Min (GPa)	6.30	3.85	3.03	1.72	2.97	4.26
CV	0.24	0.11	0.20	0.23	0.23	0.15
No. specimens	5	3	5	3	4	4

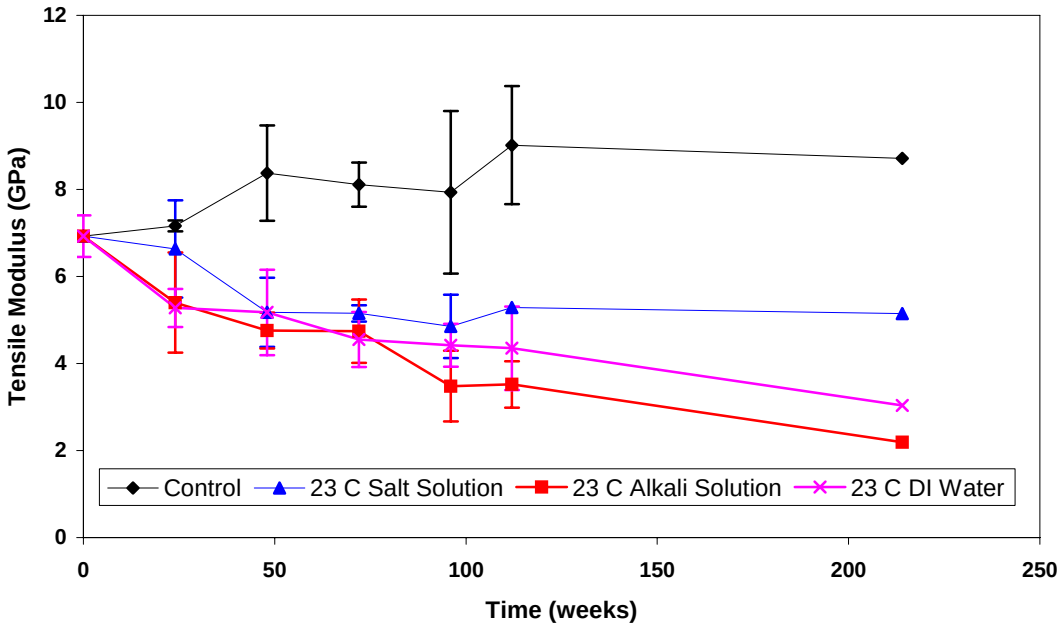
B). Tensile Test (contd.)

Material: Adhesive, Sikadur 30 Manufacturer: SIKA Test Method: ASTM D 638 - 99 Nominal Specimen Size: According to ASTM standard Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 112 weeks						
Strength						
Mean (MPa)	26.62	16.17	14.52	9.41	12.52	15.38
STD (MPa)	7.82	1.78	1.46	0.54	0.88	
Max (MPa)	35.37	18.04	16.06	10.03	13.96	15.70
Min (MPa)	20.30	13.29	12.53	9.09	11.56	15.06
CV	0.29	0.11	0.10	0.06	0.07	
No. specimens	3	5	5	3	5	2
Modulus						
Mean (GPa)	9.02	4.35	4.61	2.52	3.52	5.29
STD (GPa)	1.36	0.96	0.48	0.07	0.53	
Max (GPa)	10.35	5.64	5.34	2.60	4.10	6.65
Min (GPa)	7.64	3.48	4.15	2.48	2.77	3.93
CV	0.15	0.22	0.11	0.03	0.15	
No. specimens	3	5	5	3	5	2
Exposure period: 214 weeks						
Strength						
Mean (MPa)	26.25	13.15	13.96	9.54	10.50	10.63
STD (MPa)						
Max (MPa)	34.25	14.66	14.08	9.75	10.69	11.29
Min (MPa)	18.25	11.64	13.85	9.34	10.31	9.98
CV						
No. specimens	2	2	2	2	2	2
Modulus						
Mean (GPa)	8.71	3.04	3.96	2.65	2.19	5.15
STD (GPa)						
Max (GPa)	9.87	3.19	4.02	2.67	2.21	6.36
Min (GPa)	7.54	2.89	3.89	2.63	2.17	3.93
CV						
No. specimens	2	2	2	2	2	2


Tensile Strength (MPa)
40
30
20
10
0
0
50
100
150
200
250
Time (weeks)
Control
23 C DI Water
37.8 C DI Water
60 C DI Water


Tensile Modulus (GPa)
12
10
8
6
4
2
0
0
50
100
150
200
250
Time (weeks)
Control
23 C DI Water
37.8 C DI Water
60 C DI Water


Tensile Strength (MPa)
40
30
20
10
0
0
50
100
150
200
250
Time (weeks)
Control
23 C Alkali Solution
23 C Salt Solution
23 C DI Water


Tensile Modulus (GPa)
12
10
8
6
4
2
0
0
50
100
150
200
250
Time (weeks)
Control
23 C Salt Solution
23 C Alkali Solution
23 C DI Water

C). Dynamic Mechanical Thermal Analysis

Material: Adhesive, Sikadur 30 Manufacturer: SIKA Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 25 °C and 150 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 5.9 mm, span = 28 mm Precondition: All specimens were preconditioned for 7 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing	
Condition	After preconditioning
T_g by tanδ	80.87 °C [$\pm^{0.94}_{0.63}$] *
tanδ height	0.81 [$\pm^{0.03}_{0.03}$]
T_g by E''	73.67 °C [$\pm^{0.51}_{0.73}$]
T_g by E'	71.85 °C [$\pm^{0.53}_{0.33}$]
E' at T_g – 40 °C	3.63×10^9 Pa [$\pm^{1.69\times10^9\ \mathrm{Pa}}_{1.40\times10^9\ \mathrm{Pa}}$]
E' at T_g + 40 °C	5.72×10^7 Pa [$\pm^{1.49\times10^7\ \mathrm{Pa}}_{7.59\times10^6\ \mathrm{Pa}}$]
No. specimens	3

* Data is reported as Mean [± Bounds]

C). Dynamic Mechanical Thermal Analysis (contd.)

Material: Adhesive, Sikadur 30 Manufacturer: SIKA Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 25 °C and 150 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 5.9 mm Precondition: All specimens were preconditioned for 7 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 24 weeks						
T_g by tanδ	84.12 °C [$\pm^{0.43}_{0.43}$]	76.89 °C [$\pm^{1.00}_{1.39}$]	88.35 °C [$\pm^{1.68}_{1.58}$]	86.19 °C [$\pm^{0.87}_{1.74}$]	76.51 °C [$\pm^{1.38}_{1.38}$]	77.52 °C [$\pm^{0.76}_{1.17}$]
tanδ height	0.77 [$\pm^{0.02}_{0.02}$]	0.68 [$\pm^{0.02}_{0.02}$]	0.41 [$\pm^{0.02}_{0.03}$]	0.49 [$\pm^{0.01}_{0.02}$]	0.75 [$\pm^{0.02}_{0.02}$]	0.70 [$\pm^{0.01}_{0.02}$]
T_g by E''	77.49 °C [$\pm^{0.44}_{0.44}$]	71.02 °C [$\pm^{0.52}_{0.34}$]	82.39 °C [$\pm^{0.66}_{0.48}$]	81.42 °C [$\pm^{0.83}_{1.16}$]	68.70 °C [$\pm^{1.09}_{1.09}$]	71.55 °C [$\pm^{2.08}_{1.45}$]
T_g by E'	75.17 °C [$\pm^{0.21}_{0.21}$]	68.36 °C [$\pm^{0.94}_{1.40}$]	80.13 °C [$\pm^{0.56}_{0.58}$]	79.39 °C [$\pm^{0.22}_{0.18}$]	65.48 °C [$\pm^{0.40}_{0.40}$]	70.47 °C [$\pm^{2.93}_{1.61}$]
E' at T_g – 40 °C (Pa)	2.27×10^9 [$\pm^{7.18\times10^8}_{7.18\times10^8}$]	2.12×10^9 [$\pm^{4.10\times10^7}_{3.64\times10^7}$]	2.16×10^9 [$\pm^{1.31\times10^9}_{8.55\times10^8}$]	1.84×10^9 [$\pm^{4.66\times10^8}_{6.81\times10^8}$]	4.33×10^9 [$\pm^{5.97\times10^7}_{5.97\times10^7}$]	1.77×10^9 [$\pm^{3.83\times10^8}_{5.19\times10^8}$]
E' at T_g + 40 °C (Pa)	4.85×10^7 [$\pm^{7.47\times10^6}_{7.47\times10^6}$]	5.77×10^7 [$\pm^{8.55\times10^6}_{6.74\times10^6}$]	4.89×10^7 [$\pm^{3.48\times10^6}_{5.77\times10^6}$]	5.18×10^7 [$\pm^{1.00\times10^7}_{7.05\times10^6}$]	6.37×10^7 [$\pm^{4.43\times10^6}_{4.43\times10^6}$]	6.65×10^7 [$\pm^{8.44\times10^6}_{8.37\times10^6}$]
No. specimens	2	3	3	3	2	3

C). Dynamic Mechanical Thermal Analysis (contd.)

Material: Adhesive, Sikadur 30 Manufacturer: SIKA Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 25 °C and 150 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 5.9 mm Precondition: All specimens were preconditioned for 7 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 48 weeks						
T_g by tanδ	85.66 °C [$\pm^{0.05}_{0.05}$]	78.60 °C [$\pm^{0.14}_{0.14}$]	88.30 °C [$\pm^{1.55}_{1.55}$]	85.98 °C [$\pm^{2.57}_{2.57}$]	77.87 °C [$\pm^{0.09}_{0.09}$]	79.25 °C [$\pm^{0.38}_{0.38}$]
tanδ height	0.78 [$\pm^{0.01}_{0.01}$]	0.66 [$\pm^{0.01}_{0.01}$]	0.40 [$\pm^{0.00}_{0.00}$]	0.41 [$\pm^{0.02}_{0.02}$]	0.75 [$\pm^{0.00}_{0.00}$]	0.61 [$\pm^{0.01}_{0.01}$]
T_g by E''	78.10 °C [$\pm^{0.49}_{0.49}$]	73.86 °C [$\pm^{0.99}_{0.99}$]	83.43 °C [$\pm^{0.57}_{0.57}$]	81.66 °C [$\pm^{2.17}_{2.17}$]	70.63 °C [$\pm^{0.08}_{0.08}$]	72.85 °C [$\pm^{0.21}_{0.21}$]
T_g by E'	75.42 °C [$\pm^{0.23}_{0.23}$]	70.38 °C [$\pm^{0.08}_{0.08}$]	81.47 °C [$\pm^{0.28}_{0.28}$]	79.03 °C [$\pm^{1.93}_{1.93}$]	69.49 °C [$\pm^{0.67}_{0.67}$]	70.63 °C [$\pm^{0.42}_{0.42}$]
E' at T_g – 40 °C (Pa)	5.70×10^9 [$\pm^{4.85\times10^8}_{4.85\times10^8}$]	2.82×10^9 [$\pm^{1.01\times10^9}_{1.01\times10^9}$]	3.36×10^9 [$\pm^{8.48\times10^8}_{8.48\times10^8}$]	2.24×10^9 [$\pm^{4.01\times10^7}_{4.01\times10^7}$]	3.60×10^9 [$\pm^{2.53\times10^8}_{2.53\times10^8}$]	2.02×10^9 [$\pm^{3.11\times10^8}_{3.11\times10^8}$]
E' at T_g + 40 °C (Pa)	7.26×10^7 [$\pm^{1.34\times10^7}_{1.34\times10^7}$]	5.17×10^7 [$\pm^{1.45\times10^7}_{1.45\times10^7}$]	6.41×10^7 [$\pm^{9.24\times10^6}_{9.24\times10^6}$]	6.72×10^7 [$\pm^{1.25\times10^7}_{1.25\times10^7}$]	7.32×10^7 [$\pm^{1.27\times10^7}_{1.27\times10^7}$]	4.85×10^7 [$\pm^{3.27\times10^6}_{3.27\times10^6}$]
No. specimens	2	2	2	2	2	2

C). Dynamic Mechanical Thermal Analysis (contd.)

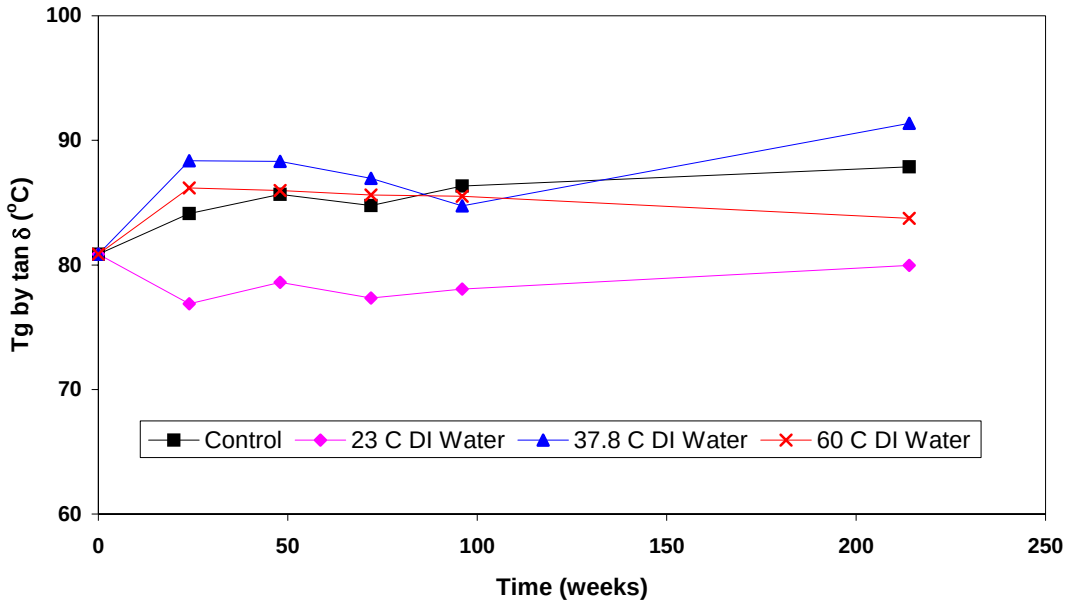
Material: Adhesive, Sikadur 30 Manufacturer: SIKA Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 25 °C and 150 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 5.9 mm Precondition: All specimens were preconditioned for 7 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 72 weeks						
T_g by tanδ	84.77 °C [$\pm^{0.19}_{0.19}$]	77.34 °C [$\pm^{0.06}_{0.06}$]	86.96 °C [$\pm^{4.10}_{4.10}$]	85.61 °C		78.49 °C
tanδ height	0.78 [$\pm^{0.00}_{0.00}$]	0.60 [$\pm^{0.01}_{0.01}$]	0.41 [$\pm^{0.04}_{0.04}$]	0.36		0.59
T_g by E''	76.07 °C [$\pm^{0.43}_{0.43}$]	72.41 °C [$\pm^{0.44}_{0.44}$]	81.32 °C [$\pm^{3.51}_{3.51}$]	78.62 °C		70.34 °C
T_g by E'	71.77 °C [$\pm^{1.10}_{1.10}$]	68.88 °C [$\pm^{1.36}_{1.36}$]	79.38 °C [$\pm^{3.49}_{3.49}$]	77.82 °C		65.16 °C
E' at T_g – 40 °C (Pa)	5.17×10^9 [$\pm^{4.68\times10^8}_{4.68\times10^8}$]	1.91×10^9 [$\pm^{7.63\times10^8}_{7.63\times10^8}$]	2.86×10^9 [$\pm^{2.34\times10^8}_{2.34\times10^8}$]	2.16×10^9		3.72×10^9
E' at T_g + 40 °C (Pa)	7.06×10^7 [$\pm^{1.26\times10^7}_{1.26\times10^7}$]	4.98×10^7 [$\pm^{1.64\times10^6}_{1.64\times10^6}$]	6.09×10^7 [$\pm^{2.29\times10^6}_{2.29\times10^6}$]	6.25×10^7		7.60×10^7
No. specimens	2	2	2	1		1

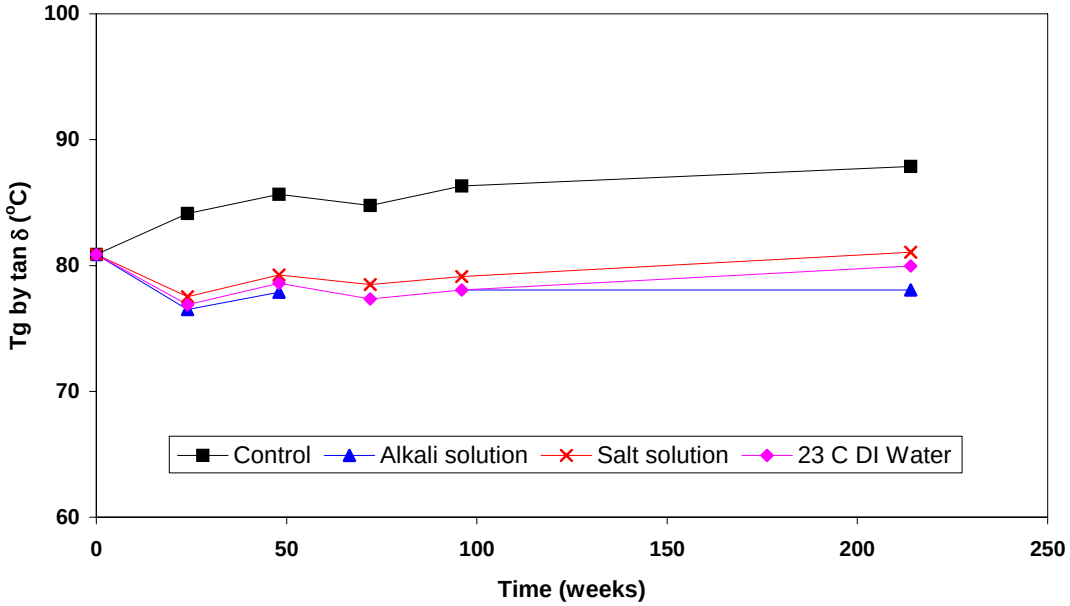
C). Dynamic Mechanical Thermal Analysis (contd.)

Material: Adhesive, Sikadur 30 Manufacturer: SIKA Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 25 °C and 150 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 5.9 mm Precondition: All specimens were preconditioned for 7 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 96 weeks						
T_g by tanδ	86.33 °C [$\pm^{0.39}_{0.46}$]	78.07 °C [$\pm^{0.25}_{0.27}$]	84.74 °C [$\pm^{0.31}_{0.52}$]	85.51 °C [$\pm^{1.02}_{1.48}$]	78.06 °C [$\pm^{0.67}_{0.40}$]	79.13 °C [$\pm^{0.43}_{0.38}$]
tanδ height	0.76 [$\pm^{0.05}_{0.05}$]	0.60 [$\pm^{0.02}_{0.02}$]	0.37 [$\pm^{0.03}_{0.02}$]	0.40 [$\pm^{0.03}_{0.01}$]	0.70 [$\pm^{0.02}_{0.02}$]	0.52 [$\pm^{0.01}_{0.01}$]
T_g by E''	78.90 °C [$\pm^{0.48}_{0.28}$]	71.85 °C [$\pm^{0.62}_{0.62}$]	79.66 °C [$\pm^{0.56}_{0.45}$]	78.69 °C [$\pm^{0.09}_{0.13}$]	71.10 °C [$\pm^{0.65}_{0.44}$]	72.29 °C [$\pm^{1.77}_{2.07}$]
T_g by E'	76.32 °C [$\pm^{0.50}_{0.42}$]	68.36 °C [$\pm^{0.57}_{0.87}$]	77.17 °C [$\pm^{0.30}_{0.23}$]	75.65 °C [$\pm^{0.78}_{1.21}$]	68.07 °C [$\pm^{0.48}_{0.25}$]	69.62 °C [$\pm^{2.57}_{2.30}$]
E' at T_g – 40 °C (Pa)	3.45×10^9 [$\pm^{1.82\times10^9}_{1.38\times10^9}$]	3.23×10^9 [$\pm^{7.00\times10^8}_{8.67\times10^8}$]	3.54×10^9 [$\pm^{5.07\times10^7}_{5.10\times10^7}$]	2.19×10^9 [$\pm^{3.24\times10^8}_{2.58\times10^8}$]	2.46×10^9 [$\pm^{1.11\times10^9}_{8.31\times10^8}$]	2.29×10^9 [$\pm^{5.66\times10^8}_{7.58\times10^8}$]
E' at T_g + 40 °C (Pa)	7.39×10^7 [$\pm^{3.63\times10^7}_{1.95\times10^7}$]	5.87×10^7 [$\pm^{1.23\times10^7}_{9.89\times10^6}$]	7.57×10^7 [$\pm^{3.13\times10^6}_{4.22\times10^6}$]	5.17×10^7 [$\pm^{7.98\times10^6}_{4.92\times10^6}$]	5.08×10^7 [$\pm^{1.23\times10^7}_{6.32\times10^6}$]	6.55×10^7 [$\pm^{9.00\times10^6}_{1.51\times10^7}$]
No. specimens	3	3	3	3	3	3

C). Dynamic Mechanical Thermal Analysis (contd.)

Material: Adhesive, Sikadur 30 Manufacturer: SIKA Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 25 °C and 150 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 5.9 mm Precondition: All specimens were preconditioned for 7 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 214 weeks						
T_g by tanδ	87.88 °C	79.96 °C	91.36 °C	83.75 °C	78.05 °C	81.60 °C
tanδ height	0.73	0.50	0.39	0.43	0.66	0.38
T_g by E''	82.05 °C	74.02 °C	84.17 °C	78.12 °C	71.08 °C	75.02 °C
T_g by E'	78.62 °C	70.88 °C	82.97 °C	73.69 °C	68.22 °C	68.50 °C
E' at T_g – 40 °C (Pa)	2.33×10^9	2.45×10^9	4.21×10^9	3.11×10^9	3.46×10^9	1.04×10^9
E' at T_g + 40 °C (Pa)	6.04×10^7	3.77×10^7	6.88×10^7	6.61×10^7	7.03×10^7	1.79×10^7
No. specimens	1	1	1	1	1	1


100
90
80
70
60
Tg by tan δ (°C)
0
50
100
150
200
250
Time (weeks)
Control
23 C DI Water
37.8 C DI Water
60 C DI Water


100
90
80
70
60
Tg by tan δ (°C)
0
50
100
150
200
250
Time (weeks)
Control
Alkali solution
Salt solution
23 C DI Water

GENERAL INFORMATION

Material: Carbon fiber reinforced epoxy, prefabricated strip
Manufacturer: SIKA
Resin Type: BisA epoxy with anhydride curing agent
Fiber Type: T700 Carbon
Fabric Type: N/A
Fabric Weight: N/A
Type of Cure: Elevated Temperature
Method of Manufacture: Pultrusion
Density: 1.59 g/cm^3
Fiber Volume Fraction: 0.69 (determined by acid digestion test)
Resin Volume Fraction: 0.29
Void Volume Fraction: 0.02
Configuration: Strip 50.0 mm wide × 1.3 mm thick

PROPERTIES

A). Moisture Uptake (Data for a period of 257 weeks)

Material: Carbon fiber reinforced epoxy produced by pultrusion Manufacturer: SIKA Test Method: Gravimetric, ASTM D 5229/D 5229M - 92 Nominal Specimen Size (Length × Width × Thickness): 25.4 mm × 25.4 mm × 1.3 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Curve shape	Flat	2-stage[1]	2-stage[1]	2-stage[1]	Sigmoidal[2]	2-stage[1]
M_{max} (%)	0.01	1.26	1.51	1.89	2.84	0.84
Time for M_{max}	At 77 weeks	At end of 154 weeks	At end of 154 weeks	At end of 154 weeks	At end	At end
M_∞	0.00					
M_∞ (%) in stage 1 [3]		1.02	1.02	1.02	0.66	0.41
D (mm^2/s) in stage 1		7.49×10^{-9}	2.01×10^{-8}	1.00×10^{-7}	3.28×10^{-8}	1.09×10^{-8}
k ($1/s^{0.5}$) in stage 2		1.26×10^{-5}	4.13×10^{-5}	6.22×10^{-5}	3.95×10^{-5}	5.87×10^{-5}
2-stage formula (details see Ref.1)	$M_t = M_\infty\left(1+k\sqrt{t}\right)\left\{1-\exp\left[-7.3\left(\frac{Dt}{h^2}\right)^{0.75}\right]\right\}$					

4. Following Bao, L.R., Yee, A.F. and Lee, C.Y.C., "Moisture Absorption and Hygrothermal Aging in a Bismaleimide Resin" *Polymer*, 42, 2001, pp. 7327-7333.
5. Use 2-stage model to curve fit the data.
6. M_∞ determined following the graphical method in Tsotsis, T. K. and Weitsman, Y., "A Simple Graphical-Method For Determining Diffusion Parameters For 2-Stage Sorption In Composites." *Journal Of Materials Science Letters*, 13[22], 1994, pp. 1635-1636.

B). Tensile Test

Material: Carbon fiber reinforced epoxy produced by pultrusion Manufacturer: SIKA Test Method: ASTM D 3039/D 3039M - 00 Nominal Specimen Size (Length × Width × Thickness): 254 mm × 12.7 mm × 1.3 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing	
Condition	After preconditioning
Strength	
Mean (MPa)	2833.87
STD (MPa)	71.98
Max (MPa)	2901.05
Min (MPa)	2733.63
CV	0.03
No. specimens	4
Modulus	
Mean (GPa)	168.62
STD (GPa)	5.98
Max (GPa)	176.33
Min (GPa)	161.74
CV	0.04
No. specimens	4

B). Tensile Test (contd.)

Material: Carbon fiber reinforced epoxy produced by pultrusion Manufacturer: SIKA Test Method: ASTM D 3039/D 3039M - 00 Nominal Specimen Size (Length × Width × Thickness): 254 mm × 12.7 mm × 1.3 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 8 weeks						
Strength						
Mean (MPa)		2693.99	2406.85	2236.87	2170.09	2437.17
STD (MPa)		198.22	61.53	185.55	34.02	222.31
Max (MPa)		2814.98	2489.67	2535.23	2209.59	2666.12
Min (MPa)		2347.70	2344.27	2083.67	2126.32	2204.65
CV		0.07	0.03	0.08	0.02	0.09
No. specimens		5	5	5	5	5
Modulus						
Mean (GPa)		167.28	167.84	166.14	166.15	167.03
STD (GPa)		5.27	4.37	2.23	7.36	4.29
Max (GPa)		173.03	171.29	169.85	173.11	172.84
Min (GPa)		160.61	162.70	164.00	155.87	162.84
CV		0.03	0.03	0.01	0.04	0.03
No. specimens		5	5	5	5	5
Exposure period: 24 weeks						
Strength						
Mean (MPa)	2748.58	2671.56	2397.23	2164.40	2189.21	2430.91
STD (MPa)	110.40	155.95	198.86	201.72	90.56	310.19
Max (MPa)	2888.39	2849.29	2690.10	2496.92	2279.45	2726.75
Min (MPa)	2588.53	2557.60	2209.28	2001.59	2039.03	1999.93
CV	0.04	0.06	0.08	0.09	0.04	0.13
No. specimens	5	3	5	5	5	5
Modulus						
Mean (GPa)	168.29	160.40	160.84	157.23	161.51	165.23
STD (GPa)	4.50	14.90	10.076	2.24	10.35	8.47
Max (GPa)	171.38	169.56	176.35	160.01	177.61	178.15
Min (GPa)	160.75	143.21	150.98	155.03	151.91	154.79
CV	0.03	0.09	0.06	0.01	0.06	0.05
No. specimens	5	3	5	5	5	5

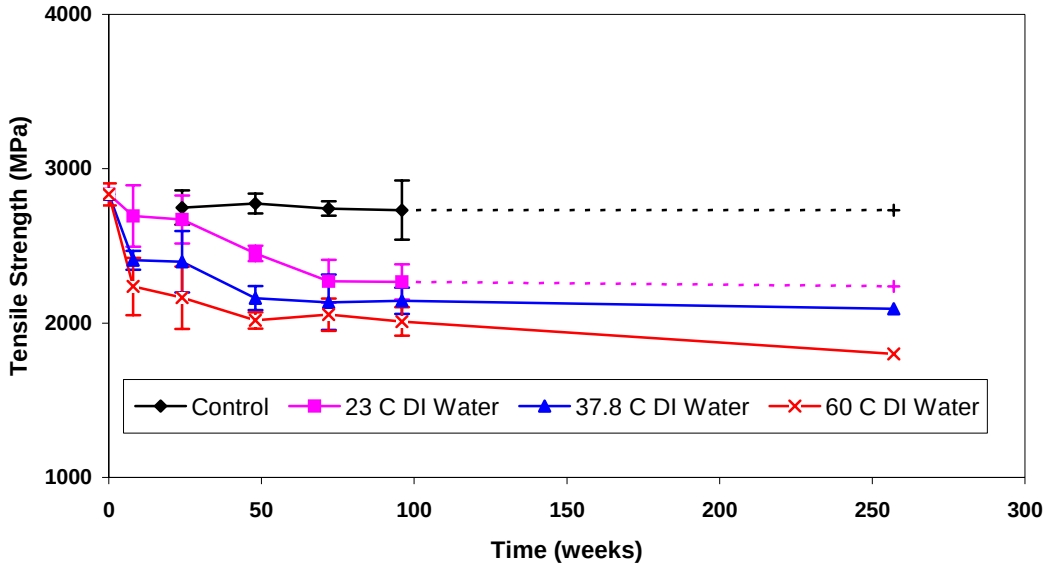
B). Tensile Test (contd.)

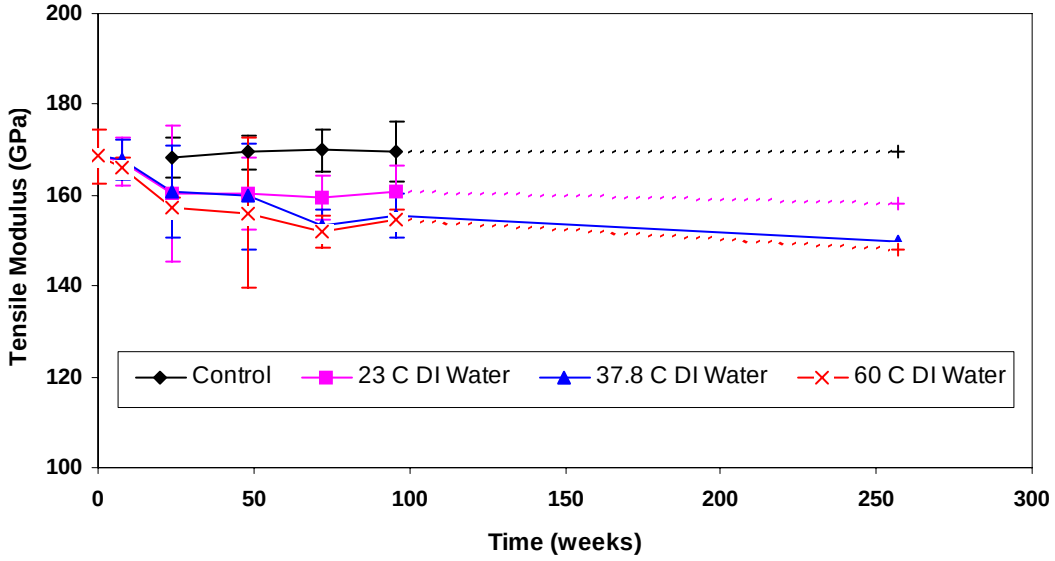
Material: Carbon fiber reinforced epoxy produced by pultrusion Manufacturer: SIKA Test Method: ASTM D 3039/D 3039M - 00 Nominal Specimen Size (Length × Width × Thickness): 254 mm × 12.7 mm × 1.3 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 48 weeks						
Strength						
Mean (MPa)	2774.28	2451.22	2161.33	2017.46	2001.44	2335.09
STD (MPa)	64.00	50.06	77.62	52.68	65.24	35.97
Max (MPa)	2873.83	2525.52	2240.32	2073.36	2059.18	2376.92
Min (MPa)	2696.80	2403.70	2037.40	1943.18	1911.56	2305.67
CV	0.02	0.02	0.04	0.03	0.03	0.02
No. specimens	5	5	5	5	4	5
Modulus						
Mean (GPa)	169.39	160.32	159.74	156.05	157.17	164.64
STD (GPa)	3.67	7.76	11.79	16.58	20.75	14.78
Max (GPa)	173.63	171.07	169.86	181.64	180.49	180.45
Min (GPa)	164.29	149.18	140.97	141.80	137.01	140.70
CV	0.02	0.05	0.07	0.11	0.13	0.09
No. specimens	5	5	5	5	4	5
Exposure period: 72 weeks						
Strength						
Mean (MPa)	2742.41	2271.35	2134.92	2054.64	2079.80	2225.00
STD (MPa)	47.28	138.78	178.62	104.92	97.91	150.81
Max (MPa)	2816.29	2458.01	2264.01	2207.44	2191.91	2370.40
Min (MPa)	2697.38	2111.36	1821.92	1924.38	1966.29	2061.75
CV	0.02	0.06	0.08	0.05	0.05	0.07
No. specimens	5	5	5	5	5	5
Modulus						
Mean (GPa)	169.85	159.53	153.30	152.04	158.53	158.95
STD (GPa)	4.47	4.74	3.51	3.61	6.58	6.75
Max (GPa)	173.90	164.87	158.43	158.25	164.22	167.68
Min (GPa)	164.12	152.96	149.59	149.23	147.37	152.47
CV	0.03	0.03	0.02	0.02	0.04	0.04
No. specimens	5	5	5	5	5	5

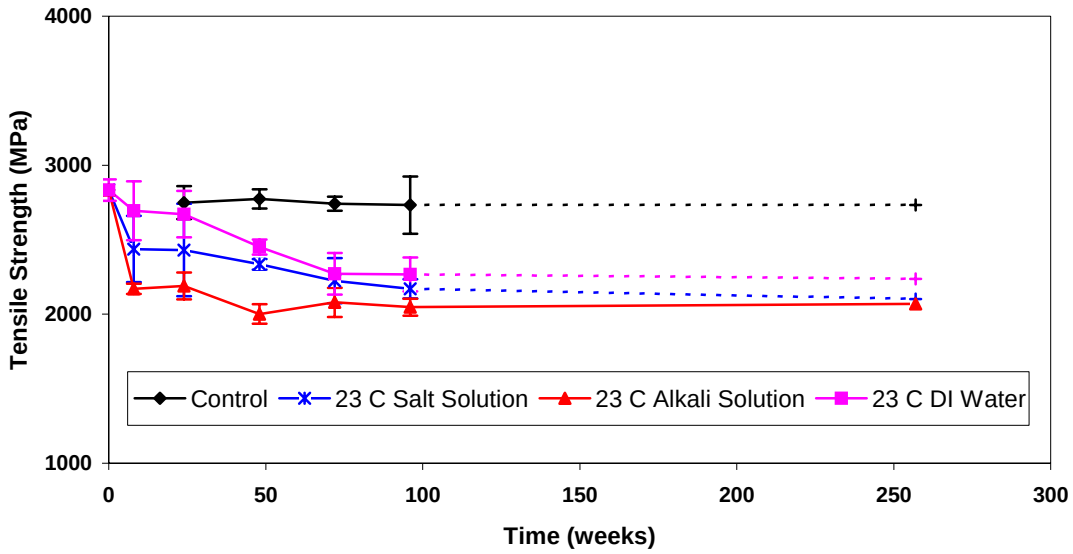
B). Tensile Test (contd.)

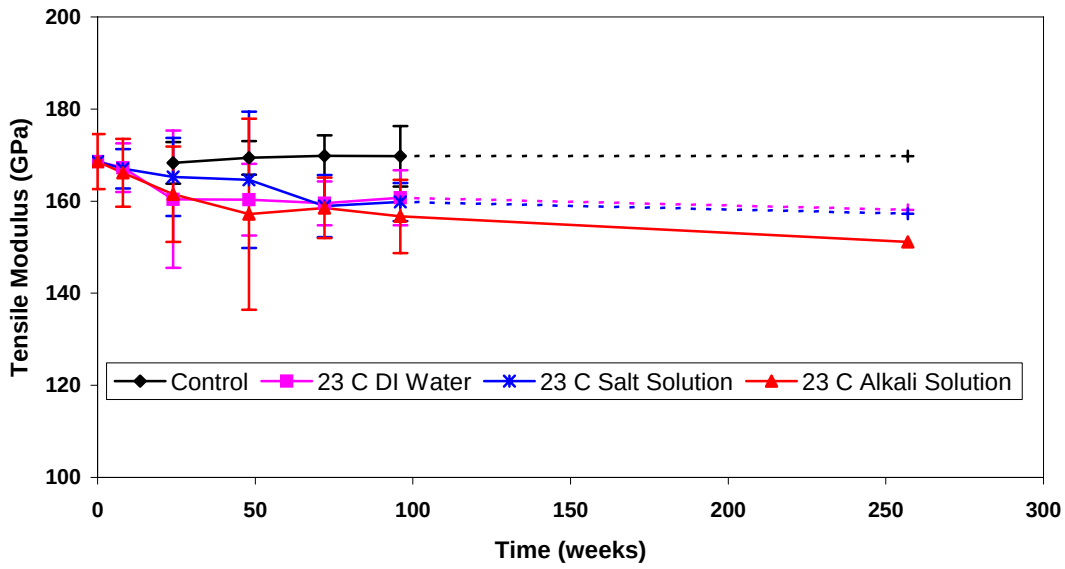
Material: Carbon fiber reinforced epoxy produced by pultrusion Manufacturer: SIKA Test Method: ASTM D 3039/D 3039M - 00 Nominal Specimen Size (Length × Width × Thickness): 254 mm × 12.7 mm × 1.3 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 96 weeks						
Strength						
Mean (MPa)	2732.16	2266.99	2144.96	2010.15	2047.11	2169.99
STD (MPa)	192.03	114.33	84.92	91.85	57.48	64.63
Max (MPa)	2899.27	2441.57	2276.09	2121.17	2097.37	2227.86
Min (MPa)	2500.81	2156.28	2054.39	1867.80	1951.10	2071.20
CV	0.07	0.05	0.04	0.05	0.03	0.03
No. specimens	5	5	5	5	5	5
Modulus						
Mean (GPa)	169.76	160.73	155.47	154.75	156.68	159.80
STD (GPa)	6.57	6.00	4.75	1.88	7.98	4.11
Max (GPa)	177.37	166.50	161.60	156.75	165.83	163.55
Min (GPa)	159.20	152.92	150.24	151.94	146.15	154.73
CV	0.04	0.04	0.03	0.01	0.05	0.03
No. specimens	5	5	5	5	5	5
Exposure period: 257 weeks						
Strength						
Mean (MPa)	2732.16	2237.69	2093.34	1799.48	2068.92	2102.33
STD (MPa)						
Max (MPa)			2145.89	1944.49	2150.36	
Min (MPa)			2040.78	1654.47	1987.48	
CV						
No. specimens	+	+	2	2	2	+
Modulus						
Mean (GPa)	169.76	158.12	149.77	147.85	151.15	157.25
STD (GPa)						
Max (GPa)			152.86		156.54	
Min (GPa)			146.67		145.75	
CV						
No. specimens	+	+	2	+	2	+

+ : Not statistically sufficient


4000
3000
2000
1000
Tensile Strength (MPa)
0
50
100
150
200
250
300
Time (weeks)
Control
23 C DI Water
37.8 C DI Water
60 C DI Water


200
180
160
140
120
100
Tensile Modulus (GPa)
0
50
100
150
200
250
300
Time (weeks)
Control
23 C DI Water
37.8 C DI Water
60 C DI Water


4000
3000
2000
1000
Tensile Strength (MPa)
0
50
100
150
200
250
300
Time (weeks)
Control
23 C Salt Solution
23 C Alkali Solution
23 C DI Water


200
180
160
140
120
100
Tensile Modulus (GPa)
0
50
100
150
200
250
300
Time (weeks)
Control
23 C DI Water
23 C Salt Solution
23 C Alkali Solution

C). Flexural Test

Material: Carbon fiber reinforced epoxy produced by pultrusion Manufacturer: SIKA Test Method: ASTM D 790 - 03 (3 point bending) Nominal Specimen Size (Length × Width × Thickness): 68.6 mm × 12.7 mm × 1.3 mm Span: 21 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing	
Condition	After preconditioning
Strength	
Mean (MPa)	1414.54
STD (MPa)	115.06
Max (MPa)	1541.38
Min (MPa)	1243.45
CV	0.08
No. specimens	5

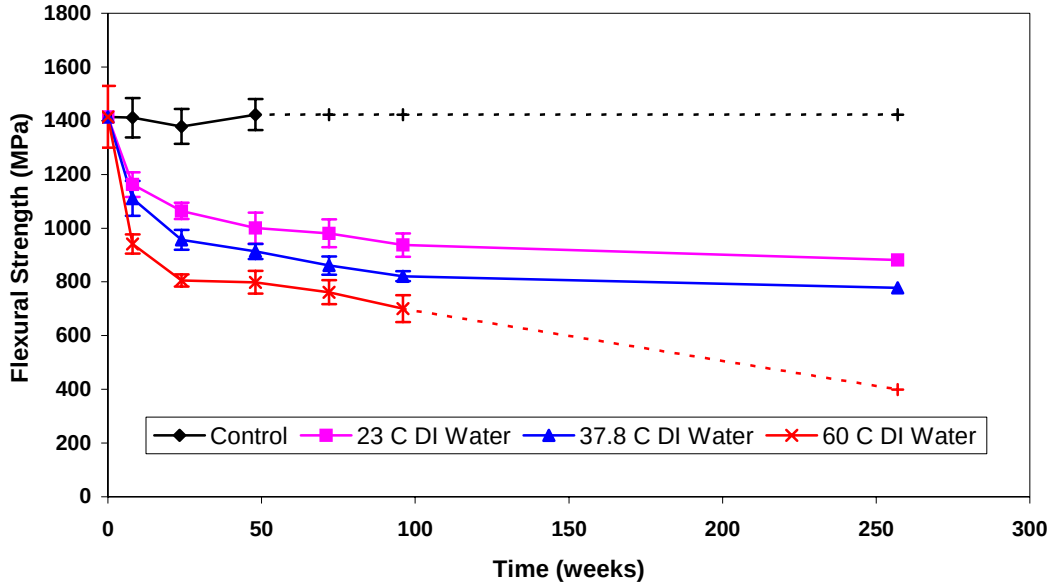
C). Flexural Test (contd.)

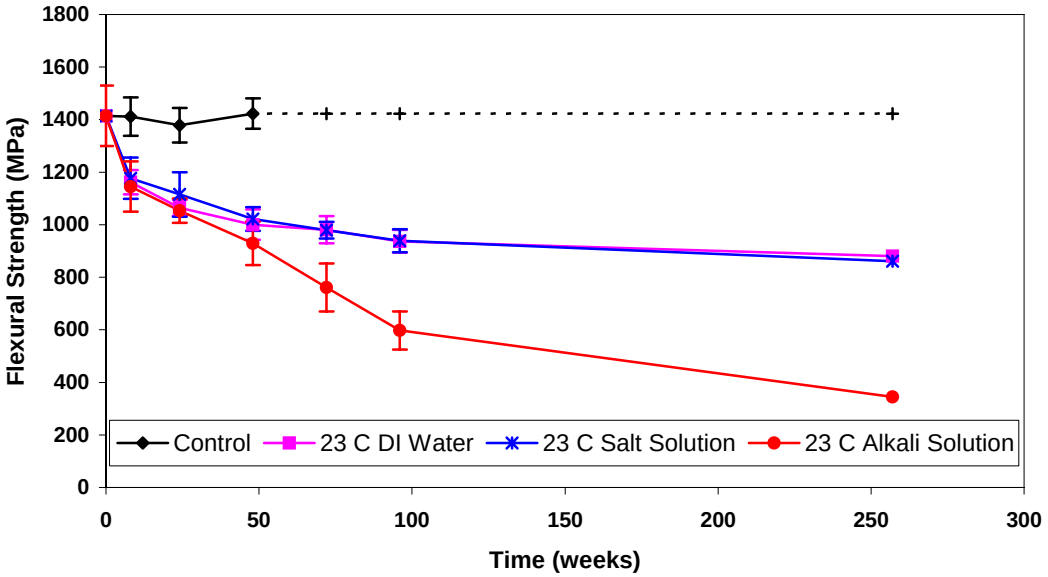
Material: Carbon fiber reinforced epoxy produced by pultrusion Manufacturer: SIKA Test Method: ASTM D 790 - 03 (3 point bending) Nominal Specimen Size (Length × Width × Thickness): 68.6 mm × 12.7 mm × 1.3 mm Span: 21 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 8 weeks						
Strength						
Mean (MPa)	1411.50	1162.21	1110.77	941.00	1145.36	1176.78
STD (MPa)	73.33	46.14	64.74	36.20	95.12	78.31
Max (MPa)	1513.38	1212.08	1204.59	981.72	1300.34	1295.71
Min (MPa)	1314.10	1116.59	1049.37	901.70	1039.69	1090.48
CV	0.05	0.04	0.06	0.04	0.08	0.07
No. specimens	5	5	4	5	5	5
Exposure period: 24 weeks						
Strength						
Mean (MPa)	1378.74	1064.36	956.92	805.58	1053.08	1115.25
STD (MPa)	65.28	29.96	36.83	22.62	46.26	84.70
Max (MPa)	1436.89	1111.47	988.73	834.93	1096.02	1233.32
Min (MPa)	1280.04	1036.96	915.08	777.86	983.65	1005.26
CV	0.05	0.03	0.04	0.03	0.04	0.08
No. specimens	5	5	5	5	5	5
Exposure period: 48 weeks						
Strength						
Mean (MPa)	1422.53	1000.27	913.40	798.47	929.22	1021.71
STD (MPa)	57.88	57.99	27.96	42.33	83.13	44.74
Max (MPa)	1492.49	1054.41	936.55	831.41	1023.65	1054.81
Min (MPa)	1334.25	935.10	866.17	740.47	816.09	948.20
CV	0.04	0.06	0.03	0.05	0.09	0.04
No. specimens	5	5	5	5	5	5

C). Flexural Test (contd.)

Material: Carbon fiber reinforced epoxy produced by pultrusion Manufacturer: SIKA Test Method: ASTM D 790 – 03 (3 point bending) Nominal Specimen Size (Length × Width × Thickness): 68.6 mm × 12.7 mm × 1.3 mm Span: 21 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 72 weeks						
Strength						
Mean (MPa)	1422.53	980.82	861.00	761.62	761.59	979.47
STD (MPa)		51.47	33.96	44.82	91.29	31.40
Max (MPa)		1032.67	908.04	823.86	887.24	1013.17
Min (MPa)		914.66	816.29	715.58	646.06	943.56
CV		0.05	0.04	0.06	0.12	0.03
No. specimens	+	5	5	5	5	5
Exposure period: 96 weeks						
Strength						
Mean (MPa)	1422.53	936.95	821.01	699.94	597.40	938.89
STD (MPa)		43.21	18.62	50.07	72.94	43.91
Max (MPa)		987.55	843.11	775.77	686.16	996.06
Min (MPa)		892.76	792.98	644.49	540.83	885.00
CV		0.05	0.02	0.07	0.12	0.05
No. specimens	+	5	5	5	5	5
Exposure period: 257 weeks						
Strength						
Mean (MPa)	1422.53	881.04	777.86	398.67	345.24	860.47
STD (MPa)						
Max (MPa)		886.23	793.87		366.40	879.44
Min (MPa)		875.85	761.84		324.08	841.50
CV						
No. specimens	+	2	2	+	2	2

+ : Not statistically sufficient


1800
1600
1400
1200
1000
800
600
400
200
0
Flexural Strength (MPa)
0
50
100
150
200
250
300
Time (weeks)
Control
23 C DI Water
37.8 C DI Water
60 C DI Water


1800
1600
1400
1200
1000
800
600
400
200
0
Flexural Strength (MPa)
0
50
100
150
200
250
300
Time (weeks)
Control
23 C DI Water
23 C Salt Solution
23 C Alkali Solution

D). Short Beam Shear Test

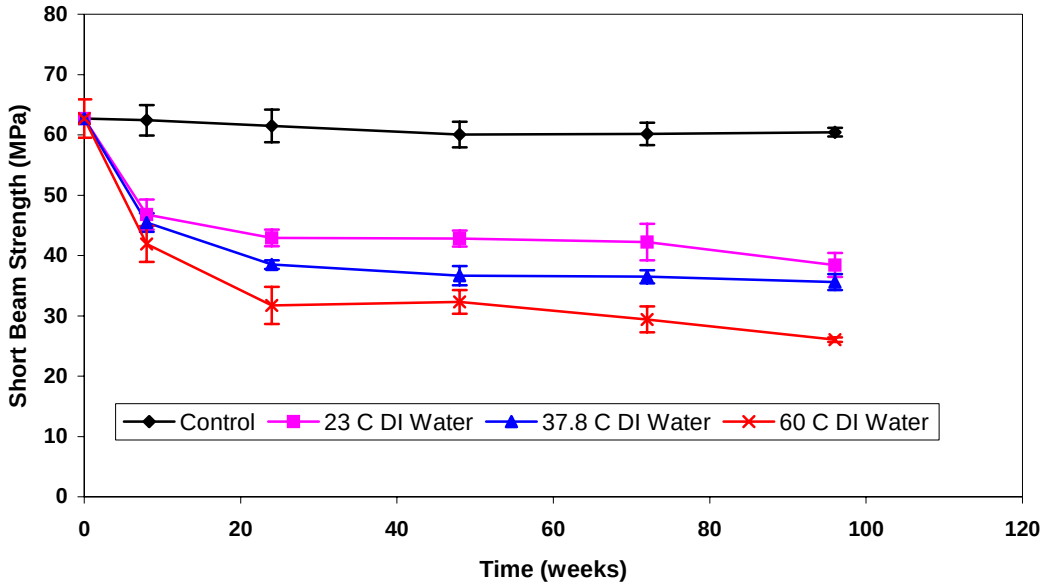
Material: Carbon fiber reinforced epoxy produced by pultrusion Manufacturer: SIKA Test Method: ASTM D 2344/D 2344M - 00 Nominal Specimen Size (Length × Width × Thickness): 12.7 mm × 4.0 mm × 1.3 mm Span: 7.0 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing	
Condition	After preconditioning
Strength	
Mean (MPa)	62.72
STD (MPa)	3.17
Max (MPa)	66.87
Min (MPa)	59.15
CV	0.05
No. specimens	5

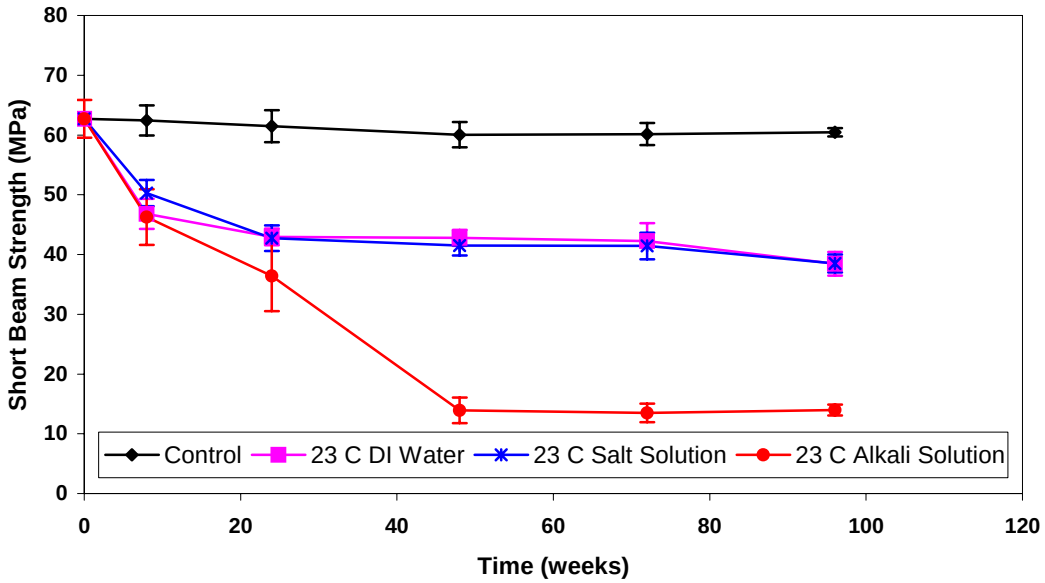
D). Short Beam Shear Test (contd.)

Material: Carbon fiber reinforced epoxy produced by pultrusion Manufacturer: SIKA Test Method: ASTM D 2344/D 2344M - 00 Nominal Specimen Size (Length × Width × Thickness): 12.7 mm × 4.0 mm × 1.3 mm Span: 7.0 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 8 weeks						
Strength						
Mean (MPa)	62.43	46.78	45.46	41.90	46.27	50.28
STD (MPa)	2.51	2.51	1.53	2.97	4.64	2.20
Max (MPa)	65.85	49.15	47.41	45.41	49.95	54.06
Min (MPa)	59.81	42.60	43.49	39.11	38.42	48.65
CV	0.04	0.05	0.03	0.07	0.10	0.04
No. specimens	5	5	5	5	5	5
Exposure period: 24 weeks						
Strength						
Mean (MPa)	61.47	42.94	38.49	31.72	36.42	42.75
STD (MPa)	2.70	1.38	0.70	3.07	5.91	2.14
Max (MPa)	65.21	44.66	39.16	35.15	44.76	45.73
Min (MPa)	57.72	41.06	37.33	29.09	28.54	39.85
CV	0.04	0.03	0.02	0.10	0.16	0.05
No. specimens	5	5	5	5	5	5
Exposure period: 48 weeks						
Strength						
Mean (MPa)	60.03	42.79	36.65	32.33	13.92	41.50
STD (MPa)	2.12	1.33	1.59	1.96	2.16	1.68
Max (MPa)	63.12	44.86	39.10	35.01	17.45	43.83
Min (MPa)	57.81	41.49	35.23	30.42	11.92	39.66
CV	0.04	0.03	0.04	0.06	0.15	0.04
No. specimens	5	5	5	5	5	5

D). Short Beam Shear Test (contd.)

Material: Carbon fiber reinforced epoxy produced by pultrusion Manufacturer: SIKA Test Method: ASTM D 2344/D 2344M - 00 Nominal Specimen Size (Length × Width × Thickness): 12.7 mm × 4.0 mm × 1.3 mm Span: 7.0 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 72 weeks						
Strength						
Mean (MPa)	60.16	42.23	36.49	29.42	13.48	41.42
STD (MPa)	1.86	3.02	1.09	2.13	1.56	2.22
Max (MPa)	62.64	46.34	37.56	32.95	14.41	43.16
Min (MPa)	58.17	38.40	35.22	27.97	11.68	37.72
CV	0.03	0.07	1.09	0.07	0.12	0.05
No. specimens	5	5	5	5	3	5
Exposure period: 96 weeks						
Strength						
Mean (MPa)	60.45	38.43	35.61	26.06	13.99	38.48
STD (MPa)	0.70	1.98	1.33	0.37	0.90	1.50
Max (MPa)	61.04	40.39	37.37	26.49	14.85	40.32
Min (MPa)	59.62	35.69	33.69	25.76	13.05	36.47
CV	0.01	0.05	0.04	0.01	0.06	0.04
No. specimens	5	5	5	5	3	5


Short Beam Strength (MPa)
Time (weeks)
Control
23 C DI Water
37.8 C DI Water
60 C DI Water


Short Beam Strength (MPa)
Time (weeks)
Control
23 C DI Water
23 C Salt Solution
23 C Alkali Solution

E). Dynamic Mechanical Thermal Analysis

Material: Carbon fiber reinforced epoxy produced by pultrusion Manufacturer: SIKA Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 25 °C and 250 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 1.3 mm, span = 28 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing	
Condition	After preconditioning
T_g by tanδ	156.33 °C $[\pm^{1.23}_{1.77}]$ *
tanδ height	0.10 $[\pm^{0.01}_{0.01}]$
T_g by E''	149.36 °C $[\pm^{1.78}_{1.06}]$
T_g by E'	136.50 °C $[\pm^{0.57}_{0.54}]$
E' at T_g – 40 °C	6.32×10^{10} Pa $[\pm^{2.15\times10^9\ \mathrm{Pa}}_{1.35\times10^9\ \mathrm{Pa}}]$
E' at T_g + 40 °C	3.24×10^{10} Pa $[\pm^{2.87\times10^9\ \mathrm{Pa}}_{2.53\times10^9\ \mathrm{Pa}}]$
No. specimens	3

* Data is reported as Mean [± Bounds]

E). Dynamic Mechanical Thermal Analysis (contd.)

Material: Carbon fiber reinforced epoxy produced by pultrusion Manufacturer: SIKA Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 25 °C and 250 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 1.3 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 8 weeks						
T_g by tanδ	157.90 °C [$\pm^{0.59}_{0.58}$]	155.36 °C [$\pm^{5.12}_{2.89}$]	147.90 °C [$\pm^{1.77}_{2.49}$]	150.84 °C [$\pm^{1.99}_{2.98}$]	150.92 °C [$\pm^{1.22}_{0.86}$]	153.48 °C [$\pm^{4.26}_{7.59}$]
tanδ height	0.09 [$\pm^{0.00}_{0.00}$]	0.09 [$\pm^{0.00}_{0.00}$]	0.08 [$\pm^{0.00}_{0.00}$]	0.09 [$\pm^{0.01}_{0.00}$]	0.08 [$\pm^{0.00}_{0.01}$]	0.08 [$\pm^{0.01}_{0.00}$]
T_g by E''	155.54 °C [$\pm^{0.44}_{0.44}$]	148.67 °C [$\pm^{5.32}_{2.95}$]	137.96 °C [$\pm^{2.51}_{2.98}$]	138.43 °C [$\pm^{2.21}_{1.17}$]	141.23 °C [$\pm^{2.09}_{1.83}$]	145.24 °C [$\pm^{3.70}_{5.43}$]
T_g by E'	142.65 °C [$\pm^{3.74}_{3.74}$]	129.15 °C [$\pm^{2.97}_{5.08}$]	121.47 °C [$\pm^{0.72}_{0.80}$]	127.59 °C [$\pm^{0.49}_{0.72}$]	125.30 °C [$\pm^{0.95}_{0.61}$]	128.61 °C [$\pm^{0.43}_{0.23}$]
E' at T_g – 40 °C (Pa)	6.63×10^{10} [$\pm^{1.09\times10^{9}}_{1.09\times10^{9}}$]	6.93×10^{10} [$\pm^{7.10\times10^{9}}_{8.57\times10^{9}}$]	6.24×10^{10} [$\pm^{5.43\times10^{9}}_{2.85\times10^{9}}$]	2.58×10^{11} [$\pm^{3.86\times10^{11}}_{1.93\times10^{11}}$]	6.81×10^{10} [$\pm^{2.98\times10^{9}}_{1.64\times10^{9}}$]	7.19×10^{10} [$\pm^{6.22\times10^{9}}_{4.87\times10^{9}}$]
E' at T_g + 40 °C (Pa)	3.60×10^{10} [$\pm^{1.21\times10^{9}}_{1.21\times10^{9}}$]	4.30×10^{10} [$\pm^{2.26\times10^{9}}_{1.70\times10^{9}}$]	3.52×10^{10} [$\pm^{2.75\times10^{9}}_{3.71\times10^{9}}$]	1.40×10^{11} [$\pm^{2.11\times10^{11}}_{1.07\times10^{11}}$]	3.72×10^{10} [$\pm^{3.16\times10^{9}}_{2.14\times10^{9}}$]	4.00×10^{10} [$\pm^{4.85\times10^{9}}_{3.74\times10^{9}}$]
No. specimens	2	3	3	3	3	3

E). Dynamic Mechanical Thermal Analysis (contd.)

Material: Carbon fiber reinforced epoxy produced by pultrusion Manufacturer: SIKA Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 25 °C and 250 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 1.3 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 24 weeks						
T_g by tanδ	150.21 °C [$\pm^{3.07}_{1.83}$]	139.27 °C [$\pm^{4.61}_{5.23}$]	140.55 °C [$\pm^{1.35}_{1.36}$]	144.05 °C	150.73 °C [$\pm^{2.58}_{4.08}$]	147.06 °C [$\pm^{2.59}_{3.02}$]
tanδ height	0.08 [$\pm^{0.01}_{0.00}$]	0.09 [$\pm^{0.00}_{0.00}$]	0.10 [$\pm^{0.01}_{0.01}$]	0.10	0.10 [$\pm^{0.00}_{0.00}$]	0.09 [$\pm^{0.01}_{0.01}$]
T_g by E''	145.16 °C [$\pm^{5.46}_{2.85}$]	135.81 °C [$\pm^{1.43}_{1.77}$]	133.26 °C [$\pm^{3.23}_{3.29}$]	137.29 °C	143.83 °C [$\pm^{6.09}_{3.44}$]	144.15 °C [$\pm^{5.50}_{4.72}$]
T_g by E'	130.88 °C [$\pm^{5.78}_{4.19}$]	119.33 °C [$\pm^{3.74}_{2.62}$]	121.57 °C [$\pm^{3.40}_{5.55}$]	133.94 °C	116.87 °C [$\pm^{3.18}_{3.02}$]	130.40 °C [$\pm^{11.08}_{6.86}$]
E' at T_g – 40 °C (Pa)	7.66×10^{10} [$\pm^{4.57\times10^{9}}_{8.79\times10^{9}}$]	7.41×10^{10} [$\pm^{1.71\times10^{10}}_{1.25\times10^{10}}$]	7.07×10^{10} [$\pm^{1.18\times10^{10}}_{1.55\times10^{10}}$]	6.43×10^{10}	6.32×10^{10} [$\pm^{2.91\times10^{9}}_{4.76\times10^{9}}$]	8.89×10^{10} [$\pm^{1.46\times10^{10}}_{1.29\times10^{10}}$]
E' at T_g + 40 °C (Pa)	4.43×10^{10} [$\pm^{6.82\times10^{9}}_{7.48\times10^{9}}$]	5.23×10^{10} [$\pm^{5.89\times10^{9}}_{9.43\times10^{9}}$]	4.20×10^{10} [$\pm^{1.27\times10^{10}}_{2.26\times10^{10}}$]	5.65×10^{10}	3.24×10^{10} [$\pm^{2.10\times10^{9}}_{2.56\times10^{9}}$]	6.01×10^{10} [$\pm^{1.59\times10^{9}}_{8.04\times10^{8}}$]
No. specimens	3	3	3	1	3	3

E). Dynamic Mechanical Thermal Analysis (contd.)

Material: Carbon fiber reinforced epoxy produced by pultrusion Manufacturer: SIKA Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 25 °C and 250 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 1.3 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 48 weeks						
T_g by tanδ	148.60 °C [$\pm^{6.32}_{7.85}$]	140.08 °C [$\pm^{5.56}_{6.70}$]	140.18 °C [$\pm^{2.53}_{3.14}$]	146.42 °C [$\pm^{6.83}_{7.01}$]	150.62 °C	145.56 °C [$\pm^{0.41}_{0.42}$]
tanδ height	0.10 [$\pm^{0.01}_{0.01}$]	0.12 [$\pm^{0.03}_{0.02}$]	0.11 [$\pm^{0.03}_{0.02}$]	0.10 [$\pm^{0.00}_{0.00}$]	0.12	0.10 [$\pm^{0.00}_{0.00}$]
T_g by E''	142.83 °C [$\pm^{2.65}_{3.44}$]	134.53 °C [$\pm^{1.26}_{2.47}$]	135.75 °C [$\pm^{2.33}_{2.06}$]	139.85 °C [$\pm^{8.60}_{9.89}$]	143.17 °C	141.01 °C [$\pm^{4.97}_{4.97}$]
T_g by E'	128.59 °C [$\pm^{2.17}_{2.79}$]	124.93 °C [$\pm^{7.04}_{6.64}$]	132.23 °C [$\pm^{3.31}_{3.43}$]	133.38 °C [$\pm^{5.70}_{7.46}$]	138.37 °C	119.37 °C [$\pm^{0.25}_{0.26}$]
E' at T_g – 40 °C (Pa)	4.81×10^{10} [$\pm^{8.26\times10^9}_{5.19\times10^9}$]	5.75×10^{10} [$\pm^{7.18\times10^9}_{3.91\times10^9}$]	5.58×10^{10} [$\pm^{2.45\times10^9}_{2.42\times10^9}$]	5.66×10^{10} [$\pm^{3.90\times10^9}_{2.38\times10^9}$]	5.37×10^{10}	6.33×10^{10} [$\pm^{5.37\times10^9}_{5.37\times10^9}$]
E' at T_g + 40 °C (Pa)	2.55×10^{10} [$\pm^{2.98\times10^9}_{2.83\times10^9}$]	4.51×10^{10} [$\pm^{2.44\times10^9}_{3.02\times10^9}$]	4.92×10^{10} [$\pm^{5.31\times10^9}_{5.13\times10^9}$]	4.53×10^{10} [$\pm^{4.12\times10^9}_{2.73\times10^9}$]	4.42×10^{10}	4.49×10^{10} [$\pm^{2.47\times10^9}_{2.47\times10^9}$]
No. specimens	3	3	3	3	1	2

E). Dynamic Mechanical Thermal Analysis (contd.)

Material: Carbon fiber reinforced epoxy produced by pultrusion Manufacturer: SIKA Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 25 °C and 250 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 1.3 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 72 weeks						
T_g by tanδ	156.71 °C [$\pm^{0.30}_{0.30}$]	143.36 °C [$\pm^{3.20}_{3.20}$]	139.82 °C [$\pm^{11.81}_{8.47}$]	145.51 °C [$\pm^{4.14}_{6.96}$]	151.81 °C [$\pm^{2.74}_{2.82}$]	148.01 °C [$\pm^{1.87}_{1.32}$]
tanδ height	0.10 [$\pm^{0.00}_{0.00}$]	0.10 [$\pm^{0.02}_{0.02}$]	0.08 [$\pm^{0.00}_{0.00}$]	0.08 [$\pm^{0.01}_{0.01}$]	0.09 [$\pm^{0.01}_{0.00}$]	0.07 [$\pm^{0.00}_{0.00}$]
T_g by E''	152.08 °C [$\pm^{0.38}_{0.38}$]	134.23 °C [$\pm^{4.51}_{4.51}$]	132.18 °C [$\pm^{1.29}_{0.83}$]	133.79 °C [$\pm^{7.07}_{4.04}$]	129.41 °C [$\pm^{1.14}_{0.85}$]	139.21 °C [$\pm^{2.77}_{3.19}$]
T_g by E'	137.45 °C [$\pm^{1.66}_{1.66}$]	122.82 °C [$\pm^{0.31}_{0.31}$]	120.85 °C [$\pm^{0.65}_{0.37}$]	128.48 °C [$\pm^{9.15}_{8.88}$]	121.76 °C [$\pm^{3.00}_{2.34}$]	122.86 °C [$\pm^{0.88}_{0.50}$]
E' at T_g – 40 °C (Pa)	7.84×10^{10} [$\pm^{7.55\times10^{9}}_{7.55\times10^{9}}$]	5.40×10^{10} [$\pm^{4.70\times10^{9}}_{4.70\times10^{9}}$]	7.42×10^{10} [$\pm^{6.37\times10^{9}}_{1.19\times10^{10}}$]	6.69×10^{10} [$\pm^{1.26\times10^{10}}_{7.33\times10^{9}}$]	1.04×10^{11} [$\pm^{1.15\times10^{10}}_{8.01\times10^{9}}$]	1.00×10^{11} [$\pm^{1.68\times10^{9}}_{2.00\times10^{9}}$]
E' at T_g + 40 °C (Pa)	5.00×10^{10} [$\pm^{1.03\times10^{9}}_{1.03\times10^{9}}$]	2.39×10^{10} [$\pm^{7.48\times10^{9}}_{7.48\times10^{9}}$]	4.93×10^{10} [$\pm^{1.45\times10^{10}}_{1.33\times10^{10}}$]	4.88×10^{10} [$\pm^{5.25\times10^{9}}_{5.79\times10^{9}}$]	5.52×10^{10} [$\pm^{8.53\times10^{9}}_{7.43\times10^{9}}$]	5.31×10^{10} [$\pm^{2.39\times10^{9}}_{2.95\times10^{9}}$]
No. specimens	2	2	3	3	3	3

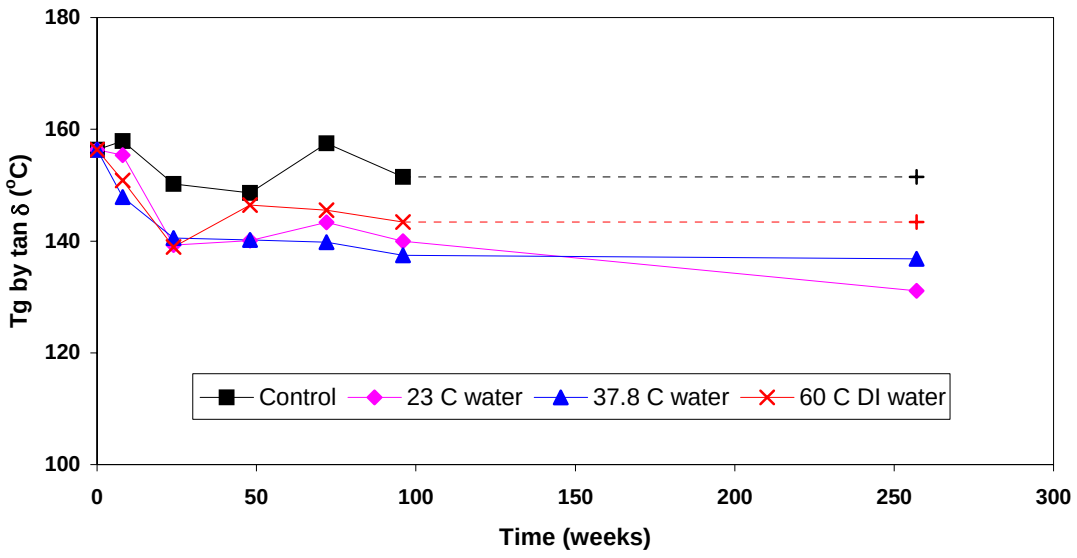
E). Dynamic Mechanical Thermal Analysis (contd.)

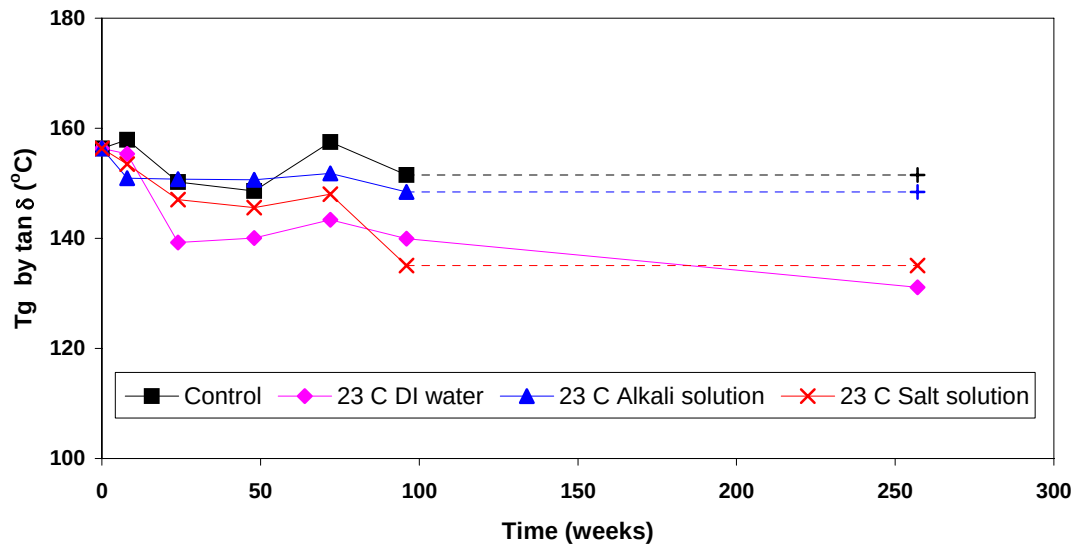
Material: Carbon fiber reinforced epoxy produced by pultrusion Manufacturer: SIKA Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 25 °C and 250 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 1.3 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 96 weeks						
T_g by tanδ	151.49 °C [$\pm^{4.39}_{6.53}$]	139.94 °C [$\pm^{3.28}_{2.88}$]	137.44 °C [$\pm^{1.93}_{2.95}$]	143.42 °C [$\pm^{5.26}_{7.98}$]	148.45 °C [$\pm^{5.04}_{4.46}$]	135.03 °C [$\pm^{4.61}_{4.30}$]
tanδ height	0.11 [$\pm^{0.01}_{0.02}$]	0.09 [$\pm^{0.01}_{0.00}$]	0.09 [$\pm^{0.01}_{0.01}$]	0.10 [$\pm^{0.01}_{0.01}$]	0.10 [$\pm^{0.01}_{0.02}$]	0.09 [$\pm^{0.01}_{0.01}$]
T_g by E''	148.56 °C [$\pm^{3.07}_{4.93}$]	130.41 °C [$\pm^{3.96}_{3.25}$]	130.70 °C [$\pm^{2.63}_{2.98}$]	130.67 °C [$\pm^{2.97}_{2.56}$]	129.17 °C [$\pm^{1.63}_{1.49}$]	131.67 °C [$\pm^{3.05}_{2.12}$]
T_g by E'	135.59 °C [$\pm^{4.44}_{8.78}$]	113.85 °C [$\pm^{4.28}_{4.84}$]	123.43 °C [$\pm^{1.77}_{2.54}$]	121.91 °C [$\pm^{9.71}_{10.57}$]	123.13 °C [$\pm^{1.16}_{0.79}$]	120.83 °C [$\pm^{3.92}_{5.82}$]
E' at T_g – 40 °C (Pa)	5.70×10^{10} [$\pm^{5.50\times10^{9}}_{3.05\times10^{9}}$]	5.92×10^{10} [$\pm^{4.84\times10^{9}}_{2.58\times10^{9}}$]	6.00×10^{10} [$\pm^{1.04\times10^{10}}_{6.95\times10^{9}}$]	6.46×10^{10} [$\pm^{1.29\times10^{10}}_{1.01\times10^{10}}$]	5.86×10^{10} [$\pm^{6.80\times10^{9}}_{1.27\times10^{10}}$]	6.20×10^{10} [$\pm^{1.00\times10^{10}}_{6.47\times10^{9}}$]
E' at T_g + 40 °C (Pa)	4.93×10^{10} [$\pm^{5.23\times10^{9}}_{4.06\times10^{9}}$]	4.03×10^{10} [$\pm^{1.33\times10^{10}}_{8.82\times10^{9}}$]	3.57×10^{10} [$\pm^{2.24\times10^{9}}_{3.45\times10^{9}}$]	3.17×10^{10} [$\pm^{1.32\times10^{10}}_{8.55\times10^{9}}$]	3.86×10^{10} [$\pm^{2.63\times10^{10}}_{1.75\times10^{10}}$]	4.83×10^{10} [$\pm^{7.34\times10^{9}}_{1.41\times10^{10}}$]
No. specimens	3	3	3	3	3	3

E). Dynamic Mechanical Thermal Analysis (contd.)

Material: Carbon fiber reinforced epoxy produced by pultrusion Manufacturer: SIKA Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 25 °C and 250 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 1.3 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 257 weeks						
T_g by tanδ	151.49 °C	131.11 °C	136.81 °C	143.42 °C	148.45 °C	135.03 °C
tanδ height		0.08	0.09			
T_g by E''		129.07 °C	128.22 °C			
T_g by E'		120.76 °C	115.43 °C			
E' at $T_g - 40$ °C (Pa)		7.49×10^{10}	7.05×10^{10}			
E' at $T_g + 40$ °C (Pa)		3.84×10^{10}	2.85×10^{10}			
No. specimens	+	1	1	+	+	+

+ : Not statistically sufficient


180
160
140
120
100
Tg by tan δ (°C)
0
50
100
150
200
250
300
Time (weeks)
Control
23 C water
37.8 C water
60 C DI water


180
160
140
120
100
Tg by tan δ (°C)
0
50
100
150
200
250
300
Time (weeks)
Control
23 C DI water
23 C Alkali solution
23 C Salt solution

SCCI PREFABRICATED SYSTEM

GENERAL INFORMATION

Material: Adhesive
Manufacturer: SCCI
Resin Type: Epoxy
Fiber Type: N/A
Fabric Type: N/A
Fabric Weight: N/A
Type of Cure: Ambient Temperature
Method of Manufacture: Cast
Density: 1.45 g/cm^3
Fiber Volume Fraction: N/A
Resin Volume Fraction: N/A
Void Volume Fraction: N/A
Configuration: N/A

PROPERTIES

A). Moisture Uptake (Data for a period of 227 weeks)

Material: Adhesive Manufacturer: SCCI Test Method: Gravimetric, ASTM D 5229/D 5229M - 92 Nominal Specimen Size (Length × Width × Thickness): 25.4 mm × 25.4 mm × 4.1 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Curve shape		2-stage[1]	2-stage[1]	Sigmoidal[2]	2-stage[1]	2-stage[1]
M_{max} (%)	0.32	4.16	5.81	20.62	3.72	3.38
Time for M_{max}	At end	At end	At end	At end	At end	At end
M_∞						
M_∞ (%) in stage 1 [3]		3.00	2.70	2.20	3.30	3.00
D (mm^2/s) in stage 1		4.19×10^{-8}	1.82×10^{-7}	8.97×10^{-7}	4.39×10^{-8}	4.59×10^{-8}
k (1/s$^{0.5}$) in stage 2		3.00×10^{-5}	9.00×10^{-5}	4.10×10^{-4}	1.00×10^{-5}	1.00×10^{-5}
2-stage formula (details see Ref.1)	$M_t = M_\infty\left(1+k\sqrt{t}\right)\left\{1-\exp\left[-7.3\left(\frac{Dt}{h^2}\right)^{0.75}\right]\right\}$					

1. Following Bao, L.R., Yee, A.F. and Lee, C.Y.C., "Moisture Absorption and Hygrothermal Aging in a Bismaleimide Resin" *Polymer*, 42, 2001, pp. 7327-7333.
2. Use 2-stage model to curve fit the data.
3. M_∞ determined following the graphical method in Tsotsis, T. K. and Weitsman, Y., "A Simple Graphical-Method For Determining Diffusion Parameters For 2-Stage Sorption In Composites." *Journal Of Materials Science Letters*, 13[22], 1994, pp. 1635-1636.

B). Tensile Test

Material: Adhesive Manufacturer: SCCI Test Method: ASTM D 638 - 99 Nominal Specimen Size: According to ASTM standard, Overall Length = 165 mm, Gage Length = 50 mm, Width of Narrow Section = 13 mm, Thickness = 4 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing	
Condition	After preconditioning
Strength	
Mean (MPa)	27.76
STD (MPa)	2.06
Max (MPa)	30.60
Min (MPa)	26.05
CV	0.07
No. specimens	4
Modulus	
Mean (GPa)	5.19
STD (GPa)	0.35
Max (GPa)	5.67
Min (GPa)	4.90
CV	0.07
No. specimens	4

B). Tensile Test (contd.)

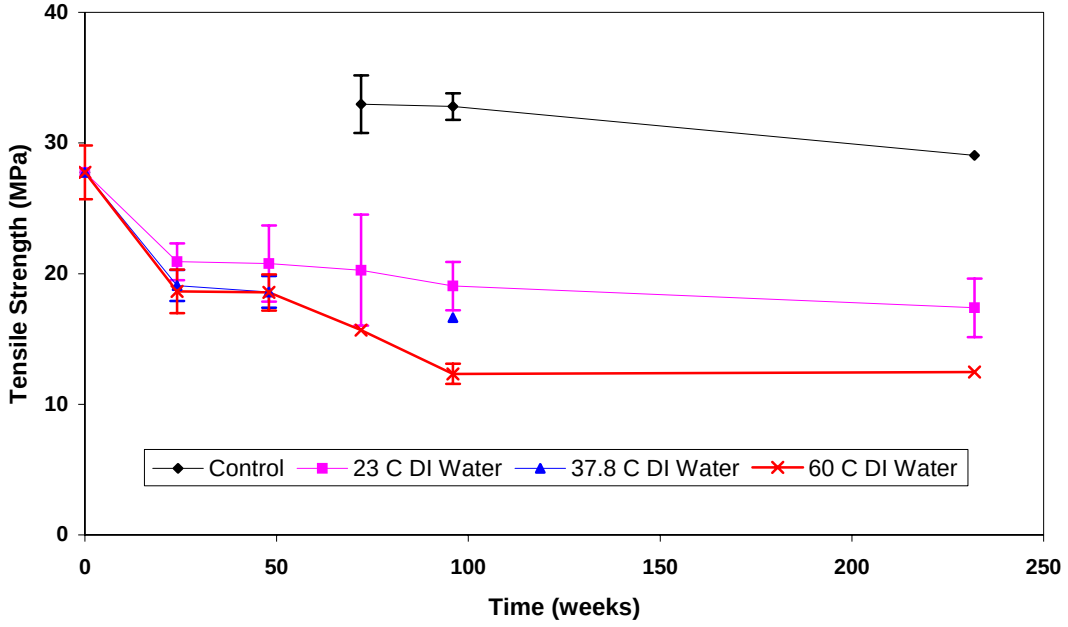
Material: Adhesive Manufacturer: SCCI Test Method: ASTM D 638 - 99 Nominal Specimen Size: According to ASTM standard Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 24 weeks						
Strength						
Mean (MPa)		20.92	19.09	18.65	18.02	19.86
STD (MPa)		1.41	1.18	1.67	0.91	0.93
Max (MPa)		22.36	20.11	20.49	18.80	21.07
Min (MPa)		19.38	17.72	16.46	16.99	18.90
CV		0.07	0.06	0.09	0.05	0.05
No. specimens		4	5	5	4	4
Modulus						
Mean (GPa)		3.78	3.46	3.03	3.21	3.62
STD (GPa)		0.35	0.21	0.33	0.18	0.39
Max (GPa)		4.11	3.71	3.48	3.39	3.85
Min (GPa)		3.29	3.26	2.70	3.01	3.03
CV		0.09	0.06	0.11	0.06	0.11
No. specimens		4	5	5	4	4
Exposure period: 48 weeks						
Strength						
Mean (MPa)		20.78	18.60	18.56	20.12	19.67
STD (MPa)		2.92	1.21	1.38	3.44	3.22
Max (MPa)		22.78	19.96	20.12	23.38	24.28
Min (MPa)		15.67	17.62	16.81	16.53	17.27
CV		0.14	0.07	0.07	0.17	0.16
No. specimens		5	3	5	3	4
Modulus						
Mean (GPa)		3.23	2.78	2.18	3.39	3.60
STD (GPa)		0.19	0.25	0.13	0.40	0.25
Max (GPa)		3.52	3.04	2.38	3.64	3.94
Min (GPa)		3.05	2.54	2.00	2.93	3.41
CV		0.06	0.09	0.06	0.12	0.07
No. specimens		5	3	5	3	4

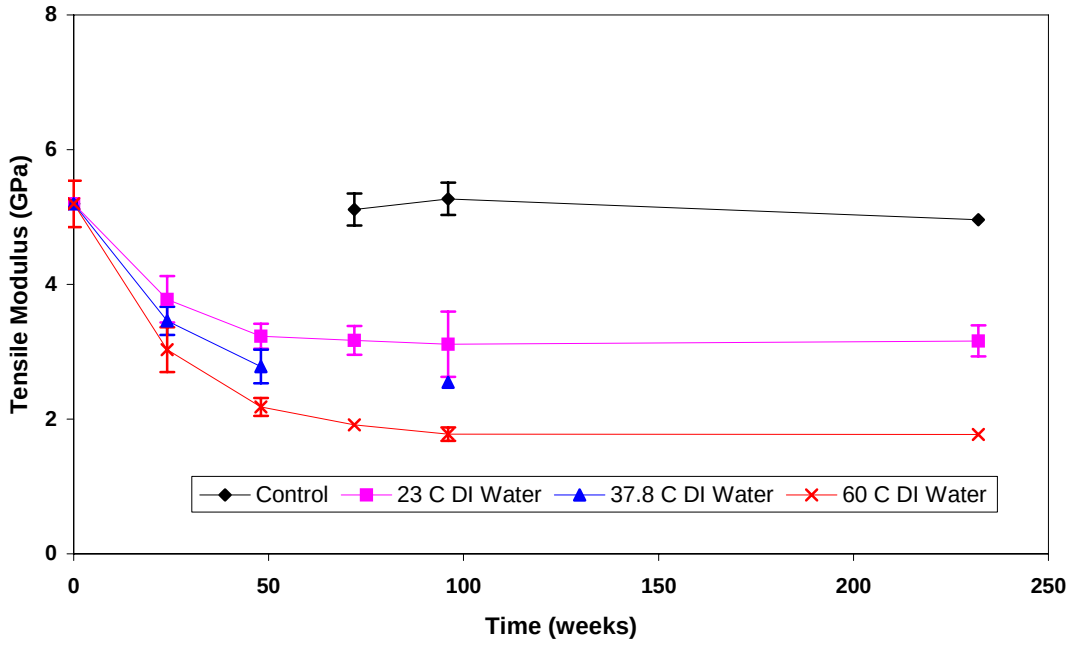
B). Tensile Test (contd.)

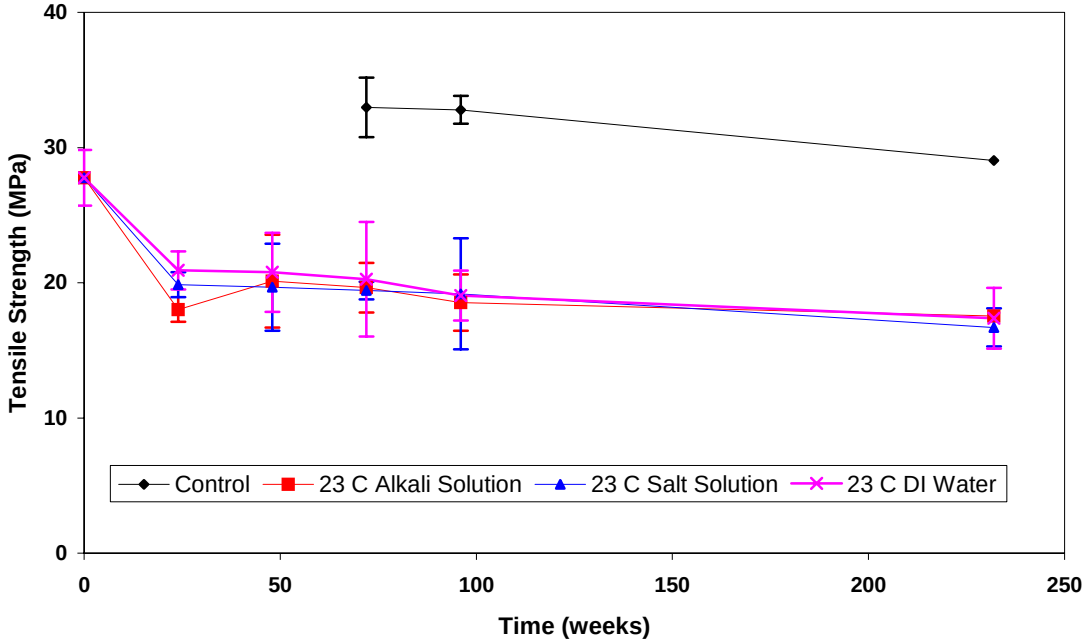
Material: Adhesive Manufacturer: SCCI Test Method: ASTM D 638 - 99 Nominal Specimen Size: According to ASTM standard Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 72 weeks						
Strength						
Mean (MPa)	32.96	20.26		15.67	19.64	19.42
STD (MPa)	2.20	4.25			1.83	0.65
Max (MPa)	35.40	24.18		16.64	21.75	19.81
Min (MPa)	30.91	16.34		14.70	18.47	18.67
CV	0.07	0.21			0.09	0.03
No. specimens	4	4		2	3	3
Modulus						
Mean (GPa)	5.11	3.17		1.91	3.34	3.53
STD (GPa)	0.24	0.21			0.61	0.41
Max (GPa)	5.29	3.41		2.20	3.99	3.83
Min (GPa)	4.78	2.94		1.63	2.79	3.07
CV	0.05	0.07			0.18	0.12
No. specimens	4	4		2	3	3
Exposure period: 96 weeks						
Strength						
Mean (MPa)	32.79	19.05	16.64	12.33	18.53	19.18
STD (MPa)	1.02	1.85		0.78	2.08	4.11
Max (MPa)	33.98	20.81	18.36	12.97	20.86	23.68
Min (MPa)	31.49	17.13	14.91	11.23	16.86	15.63
CV	0.03	0.10		0.06	0.11	0.21
No. specimens	4	3	2	4	3	3
Modulus						
Mean (GPa)	5.27	3.11	2.55	1.78	3.27	3.44
STD (GPa)	0.24	0.49		0.10	0.17	0.70
Max (GPa)	5.58	3.67	2.65	1.91	3.44	4.22
Min (GPa)	4.99	2.79	2.44	1.70	3.10	2.86
CV	0.05	0.16		0.06	0.05	0.20
No. specimens	4	3	2	4	3	3

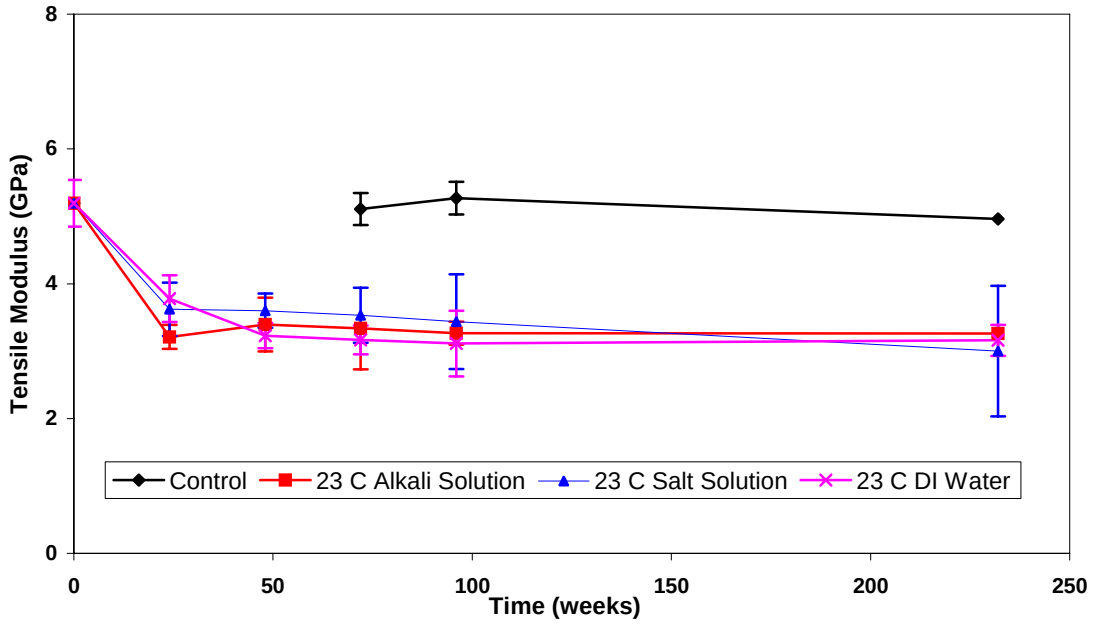
B). Tensile Test (contd.)

Material: Adhesive Manufacturer: SCCI Test Method: ASTM D 638 - 99 Nominal Specimen Size: According to ASTM standard Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 232 weeks						
Strength						
Mean (MPa)	29.05	17.38		12.46	17.53	16.69
STD (MPa)		2.25				1.41
Max (MPa)	30.57	19.40			17.77	17.58
Min (MPa)	27.52	14.96			17.28	15.06
CV		0.13				0.08
No. specimens	2	3		1	2	3
Modulus						
Mean (GPa)	4.96	3.16		1.77	3.26	3.00
STD (GPa)		0.23				0.97
Max (GPa)	4.98	3.39			3.33	3.70
Min (GPa)	4.94	2.93			3.18	1.89
CV		0.07				0.32
No. specimens	2	3		1	2	3


Tensile Strength (MPa)
40
30
20
10
0
0
50
100
150
200
250
Time (weeks)
Control
23 C DI Water
37.8 C DI Water
60 C DI Water


Tensile Modulus (GPa)
8
6
4
2
0
0
50
100
150
200
250
Time (weeks)
Control
23 C DI Water
37.8 C DI Water
60 C DI Water


Tensile Strength (MPa)
40
30
20
10
0
0
50
100
150
200
250
Time (weeks)
Control
23 C Alkali Solution
23 C Salt Solution
23 C DI Water


Tensile Modulus (GPa)
8
6
4
2
0
0
50
100
150
200
250
Time (weeks)
Control
23 C Alkali Solution
23 C Salt Solution
23 C DI Water

C). Dynamic Mechanical Thermal Analysis

Material: Adhesive Manufacturer: SCCI Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 25 °C and 140 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 4.1 mm, span = 28 mm Precondition: All specimens were preconditioned for 7 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing	
Condition	After preconditioning
T_g by tanδ (Mean)	87.29 °C $[\pm^{1.32}_{0.93}]$ *
tanδ height (Mean)	0.60 $[\pm^{0.05}_{0.09}]$
T_g by E''(Mean)	75.14 °C $[\pm^{0.43}_{0.81}]$
T_g by E'(Mean)	70.59 °C $[\pm^{1.77}_{2.26}]$
E' at T_g – 40 °C (Mean)	1.59×10^9 Pa $[\pm^{3.51\times10^8\ \mathrm{Pa}}_{2.12\times10^8\ \mathrm{Pa}}]$
E' at T_g + 40 °C (Mean)	2.45×10^7 Pa $[\pm^{2.41\times10^6\ \mathrm{Pa}}_{3.08\times10^6\ \mathrm{Pa}}]$
No. specimens	3

* Data is reported as Mean [± Bounds]

C). Dynamic Mechanical Thermal Analysis (contd.)

Material: Adhesive Manufacturer: SCCI Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 25 °C and 140 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 4.1 mm Precondition: All specimens were preconditioned for 7 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 24 weeks						
T_g by tanδ (Mean)	91.70 °C [$\pm^{3.30}_{1.72}$]	73.11 °C [$\pm^{2.25}_{3.91}$]	75.14 °C [$\pm^{3.04}_{3.36}$]	72.05 °C [$\pm^{1.00}_{1.24}$]	71.32 °C [$\pm^{3.84}_{3.63}$]	76.23 °C [$\pm^{3.05}_{1.95}$]
tanδ height (Mean)	0.65 [$\pm^{0.09}_{0.15}$]	0.43 [$\pm^{0.07}_{0.04}$]	0.37 [$\pm^{0.01}_{0.01}$]	0.40 [$\pm^{0.01}_{0.01}$]	0.43 [$\pm^{0.08}_{0.04}$]	0.38 [$\pm^{0.01}_{0.01}$]
T_g by E''(Mean)	80.13 °C [$\pm^{1.59}_{1.26}$]	60.18 °C [$\pm^{3.31}_{2.10}$]	48.83 °C [$\pm^{1.17}_{1.27}$]	49.89 °C [$\pm^{1.58}_{1.14}$]	59.77 °C [$\pm^{3.34}_{2.59}$]	60.36 °C [$\pm^{0.95}_{1.86}$]
T_g by E'(Mean)	74.02 °C [$\pm^{0.67}_{0.82}$]	53.42 °C [$\pm^{2.02}_{3.20}$]	43.75 °C [$\pm^{1.37}_{1.86}$]	45.70 °C [$\pm^{1.27}_{1.71}$]	54.20 °C [$\pm^{0.51}_{0.63}$]	53.58 °C [$\pm^{1.06}_{2.09}$]
E' at T_g – 40 °C (Mean, Pa)	1.77×10^9 [$\pm^{1.85\times10^8}_{3.67\times10^8}$]	1.13×10^9 [$\pm^{1.65\times10^8}_{1.22\times10^8}$]	9.19×10^8 [$\pm^{1.22\times10^8}_{6.84\times10^7}$]	1.12×10^9 [$\pm^{3.69\times10^7}_{4.73\times10^7}$]	9.36×10^8 [$\pm^{2.68\times10^8}_{2.03\times10^8}$]	1.62×10^9 [$\pm^{4.90\times10^8}_{5.06\times10^8}$]
E' at T_g + 40 °C (Mean, Pa)	3.30×10^7 [$\pm^{6.53\times10^6}_{5.62\times10^6}$]	3.13×10^7 [$\pm^{5.30\times10^6}_{7.86\times10^6}$]	2.33×10^7 [$\pm^{1.09\times10^7}_{6.63\times10^6}$]	3.55×10^7 [$\pm^{2.53\times10^6}_{2.19\times10^6}$]	2.77×10^7 [$\pm^{7.96\times10^6}_{5.50\times10^6}$]	4.73×10^7 [$\pm^{4.00\times10^6}_{7.72\times10^6}$]
No. specimens	3	3	3	3	3	3

C). Dynamic Mechanical Thermal Analysis (contd.)

Material: Adhesive Manufacturer: SCCI Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 25 °C and 140 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 4.1 mm Precondition: All specimens were preconditioned for 7 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 48 weeks						
T_g by tanδ (Mean)	90.41 °C [$\pm^{5.53}_{4.13}$]	68.90 °C [$\pm^{2.27}_{2.41}$]		65.71 °C	64.66 °C [$\pm^{3.33}_{4.45}$]	68.92 °C [$\pm^{1.09}_{1.09}$]
tanδ height (Mean)	0.54 [$\pm^{0.13}_{0.10}$]	0.55 [$\pm^{0.03}_{0.04}$]		0.46	0.49 [$\pm^{0.04}_{0.03}$]	0.43 [$\pm^{0.02}_{0.02}$]
T_g by E''(Mean)	76.98 °C [$\pm^{2.19}_{1.25}$]	59.06 °C [$\pm^{2.97}_{1.68}$]		47.51 °C	51.81 °C [$\pm^{5.80}_{3.18}$]	44.65 °C [$\pm^{5.62}_{5.62}$]
T_g by E'(Mean)	71.76 °C [$\pm^{1.49}_{1.19}$]	56.16 °C [$\pm^{2.09}_{1.71}$]		40.67 °C	50.41 °C [$\pm^{6.23}_{3.94}$]	41.62 °C [$\pm^{2.04}_{2.04}$]
E' at T_g – 40 °C (Mean, Pa)	2.70×10^9 [$\pm^{4.89\times10^8}_{4.71\times10^8}$]	1.51×10^9 [$\pm^{4.33\times10^8}_{5.42\times10^8}$]		1.05×10^9	1.38×10^9 [$\pm^{4.51\times10^8}_{2.73\times10^8}$]	1.26×10^9 [$\pm^{3.75\times10^8}_{3.75\times10^8}$]
E' at T_g + 40 °C (Mean, Pa)	3.72×10^7 [$\pm^{6.74\times10^6}_{6.86\times10^6}$]	4.07×10^7 [$\pm^{3.81\times10^6}_{6.12\times10^6}$]		3.25×10^7	2.86×10^7 [$\pm^{5.21\times10^6}_{6.16\times10^6}$]	5.51×10^7 [$\pm^{7.74\times10^6}_{7.74\times10^6}$]
No. specimens	3	3		1	3	2

C). Dynamic Mechanical Thermal Analysis (contd.)

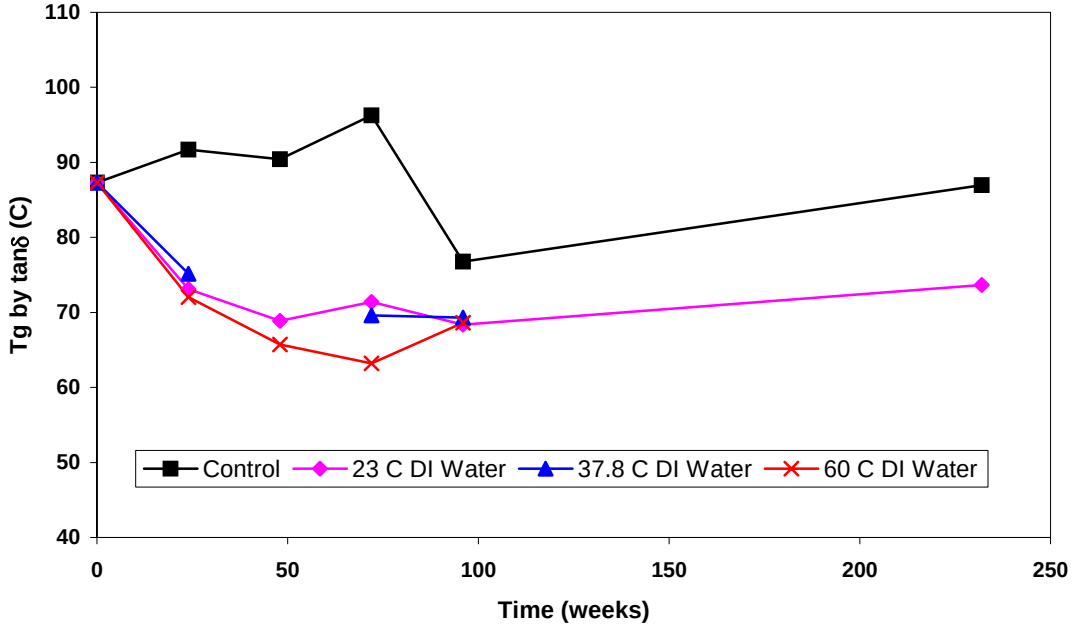
Material: Adhesive Manufacturer: SCCI Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 25 °C and 140 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 4.1 mm Precondition: All specimens were preconditioned for 7 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 72 weeks						
T_g by tanδ (Mean)	96.25 °C [$\pm^{0.01}_{0.01}$]	71.38 °C	69.60 °C [$\pm^{4.67}_{4.67}$]	63.19 °C [$\pm^{0.15}_{0.15}$]	67.51 °C [$\pm^{0.67}_{0.67}$]	72.30 °C [$\pm^{0.50}_{0.50}$]
tanδ height (Mean)	0.47 [$\pm^{0.00}_{0.00}$]	0.45	0.42 [$\pm^{0.07}_{0.07}$]	0.56 [$\pm^{0.03}_{0.03}$]	0.48 [$\pm^{0.02}_{0.02}$]	0.44 [$\pm^{0.03}_{0.03}$]
T_g by E''(Mean)	78.00 °C [$\pm^{1.04}_{1.04}$]	52.86 °C	52.18 °C [$\pm^{3.09}_{3.09}$]	53.30 °C [$\pm^{1.12}_{1.12}$]	57.38 °C [$\pm^{0.85}_{0.85}$]	66.05 °C [$\pm^{5.74}_{5.74}$]
T_g by E'(Mean)	71.04 °C [$\pm^{0.18}_{0.18}$]	51.10 °C	51.66 °C [$\pm^{2.02}_{2.02}$]	50.22 °C [$\pm^{0.22}_{0.22}$]	54.86 °C [$\pm^{0.80}_{0.80}$]	58.12 °C [$\pm^{4.20}_{4.20}$]
E' at T_g – 40 °C (Mean, Pa)	3.18×10^9 [$\pm^{3.95\times10^7}_{3.95\times10^7}$]	1.13×10^9	6.15×10^8 [$\pm^{8.72\times10^7}_{8.72\times10^7}$]	9.68×10^8 [$\pm^{6.49\times10^6}_{6.49\times10^6}$]	1.59×10^9 [$\pm^{1.26\times10^7}_{1.26\times10^7}$]	7.46×10^8 [$\pm^{5.64\times10^8}_{5.64\times10^8}$]
E' at T_g + 40 °C (Mean, Pa)	4.66×10^7 [$\pm^{2.47\times10^6}_{2.47\times10^6}$]	3.09×10^7	2.08×10^7 [$\pm^{3.17\times10^6}_{3.17\times10^6}$]	3.61×10^7 [$\pm^{4.62\times10^6}_{4.62\times10^6}$]	2.52×10^7 [$\pm^{1.11\times10^7}_{1.11\times10^7}$]	3.84×10^7 [$\pm^{1.53\times10^7}_{1.53\times10^7}$]
No. specimens	2	1	2	2	2	2

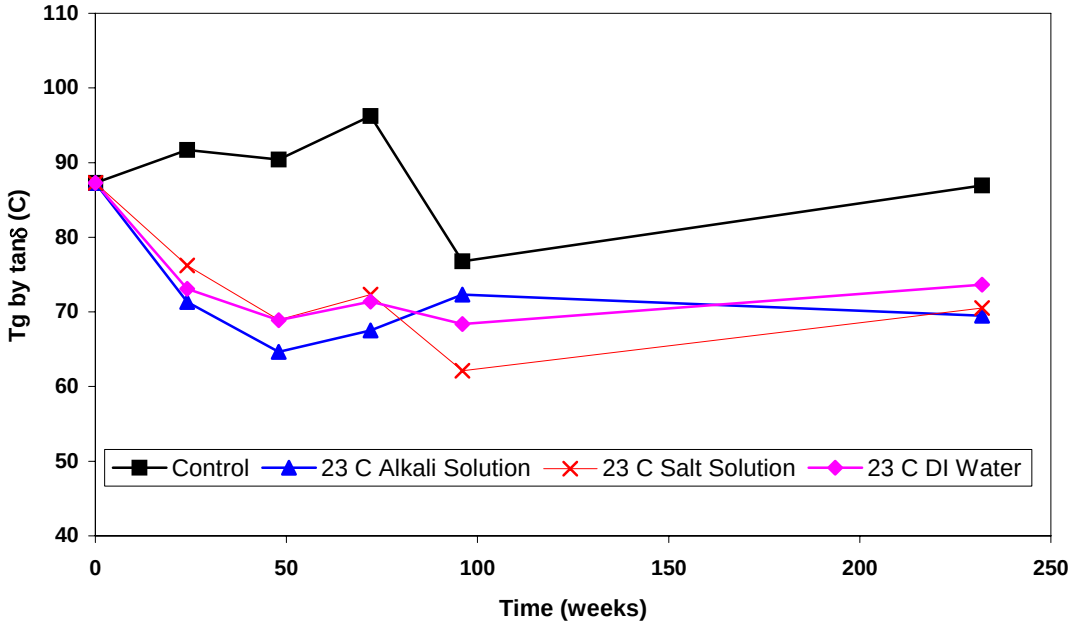
C). Dynamic Mechanical Thermal Analysis (contd.)

Material: Adhesive Manufacturer: SCCI Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 25 °C and 140 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 4.1 mm Precondition: All specimens were preconditioned for 7 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 96 weeks						
T_g by tanδ (Mean)	76.77 °C	68.36 °C	69.29 °C	68.62 °C	72.33 °C	62.12 °C
tanδ height (Mean)	0.62	0.59	0.37	0.43	0.39	0.44
T_g by E''(Mean)	64.99 °C	59.24 °C	61.22 °C	52.66 °C	60.03 °C	54.29 °C
T_g by E'(Mean)	61.29 °C	55.12 °C	40.04 °C	45.96 °C	53.34 °C	52.90 °C
E' at T_g – 40 °C (Mean, Pa)	3.66×10^9	1.02×10^9	1.02×10^9	7.68×10^8	1.94×10^9	6.94×10^8
E' at T_g + 40 °C (Mean, Pa)	5.23×10^7	6.47×10^7	2.86×10^7	3.02×10^7	5.26×10^7	1.11×10^7
No. specimens	1	1	1	1	1	1

C). Dynamic Mechanical Thermal Analysis (contd.)

Material: Adhesive Manufacturer: SCCI Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 25 °C and 140 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 4.1 mm Precondition: All specimens were preconditioned for 7 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 232 weeks						
T_g by tanδ (Mean)	86.95 °C [$\pm^{0.38}_{0.38}$]	73.65 °C [$\pm^{1.36}_{1.36}$]			69.49 °C	70.54 °C [$\pm^{1.20}_{1.20}$]
tanδ height (Mean)	0.48 [$\pm^{0.01}_{0.01}$]	0.39 [$\pm^{0.00}_{0.00}$]			0.34	0.38 [$\pm^{0.01}_{0.01}$]
T_g by E''(Mean)	74.27 °C [$\pm^{0.41}_{0.41}$]	61.15 °C [$\pm^{0.63}_{0.63}$]			56.68 °C	60.26 °C [$\pm^{0.97}_{0.97}$]
T_g by E'(Mean)	68.37 °C [$\pm^{0.44}_{0.44}$]	55.20 °C [$\pm^{1.54}_{1.54}$]			52.82 °C	54.51 °C [$\pm^{0.79}_{0.79}$]
E' at T_g – 40 °C (Mean, Pa)	1.92×10^9 [$\pm^{7.55\times10^7}_{7.55\times10^7}$]	1.96×10^9 [$\pm^{5.28\times10^7}_{5.28\times10^7}$]			1.21×10^9	1.28×10^9 [$\pm^{1.15\times10^8}_{1.15\times10^8}$]
E' at T_g + 40 °C (Mean, Pa)	3.41×10^7 [$\pm^{2.30\times10^6}_{2.30\times10^6}$]	4.21×10^7 [$\pm^{8.46\times10^5}_{8.46\times10^5}$]			3.72×10^7	4.32×10^7 [$\pm^{9.67\times10^6}_{9.67\times10^6}$]
No. specimens	2	2			1	2


110
100
90
80
70
60
50
40
Tg by tanδ (C)
0
50
100
150
200
250
Time (weeks)
Control
23 C DI Water
37.8 C DI Water
60 C DI Water


110
100
90
80
70
60
50
40
Tg by tanδ (C)
0
50
100
150
200
250
Time (weeks)
Control
23 C Alkali Solution
23 C Salt Solution
23 C DI Water

GENERAL INFORMATION

Material: Carbon fiber reinforced epoxy, prefabricated strip
Manufacturer: SCCI
Resin Type: Epoxy
Fiber Type: T700 Carbon
Fabric Type:
Fabric Weight:
Type of Cure: Elevated Temperature
Method of Manufacture: Pultrusion
Density: 1.55 g/cm^3
Fiber Volume Fraction: 0.61 (determined by acid digestion test)
Resin Volume Fraction: 0.38
Void Volume Fraction: 0.01
Configuration: Strip 51.0 mm wide × 1.3 mm thick

PROPERTIES

A). Moisture Uptake (Data for a period of 252 weeks)

Material: Carbon fiber reinforced epoxy produced by pultrusion
Manufacturer: SCCI
Test Method: Gravimetric, ASTM D 5229/D 5229M - 92
Nominal Specimen Size (Length × Width × Thickness): 25.4 mm × 25.4 mm × 1.3 mm
Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing

Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Curve shape	Fluctuate	2-stage[1]	2-stage[1]	2-stage[1]	Sigmoidal[2]	2-stage[1]
M_{max} (%)	0.09	0.32	0.42	0.63	1.35	0.33
Time for M_{max}	At end	At end	At end	At end	At end	At end
M_∞	0.09					
M_∞ (%) in stage 1 [3]		0.22	0.24	0.30	0.43	0.23
D (mm^2/s) in stage 1		3.55×10^{-8}	9.59×10^{-8}	3.18×10^{-7}	2.44×10^{-8}	4.76×10^{-8}
k (1/s$^{0.5}$) in stage 2		4.00×10^{-5}	6.00×10^{-5}	9.00×10^{-5}	8.00×10^{-5}	4.00×10^{-5}
2-stage formula (details see Ref.1)	$M_t = M_\infty\left(1+k\sqrt{t}\right)\left\{1-\exp\left[-7.3\left(\frac{Dt}{h^2}\right)^{0.75}\right]\right\}$					

1. Following Bao, L.R., Yee, A.F. and Lee, C.Y.C., "Moisture Absorption and Hygrothermal Aging in a Bismaleimide Resin" *Polymer*, 42, 2001, pp. 7327-7333.
2. Use 2-stage model to curve fit the data.
3. M_∞ determined following the graphical method in Tsotsis, T. K. and Weitsman, Y., "A Simple Graphical-Method For Determining Diffusion Parameters For 2-Stage Sorption In Composites." *Journal Of Materials Science Letters*, 13[22], 1994, pp. 1635-1636.

B). Tensile Test

Material: Carbon fiber reinforced epoxy produced by pultrusion Manufacturer: SCCI Test Method: ASTM D 3039/D 3039M - 00 Nominal Specimen Size (Length × Width × Thickness): 254 mm × 12.7 mm × 1.3 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing	
Condition	After preconditioning
Strength	
Mean (MPa)	2767.58
STD (MPa)	103.77
Max (MPa)	2861.07
Min (MPa)	2603.10
CV	0.04
No. specimens	5
Modulus	
Mean (GPa)	140.79
STD (GPa)	9.84
Max (GPa)	155.95
Min (GPa)	130.45
CV	0.07
No. specimens	5

B). Tensile Test (contd.)

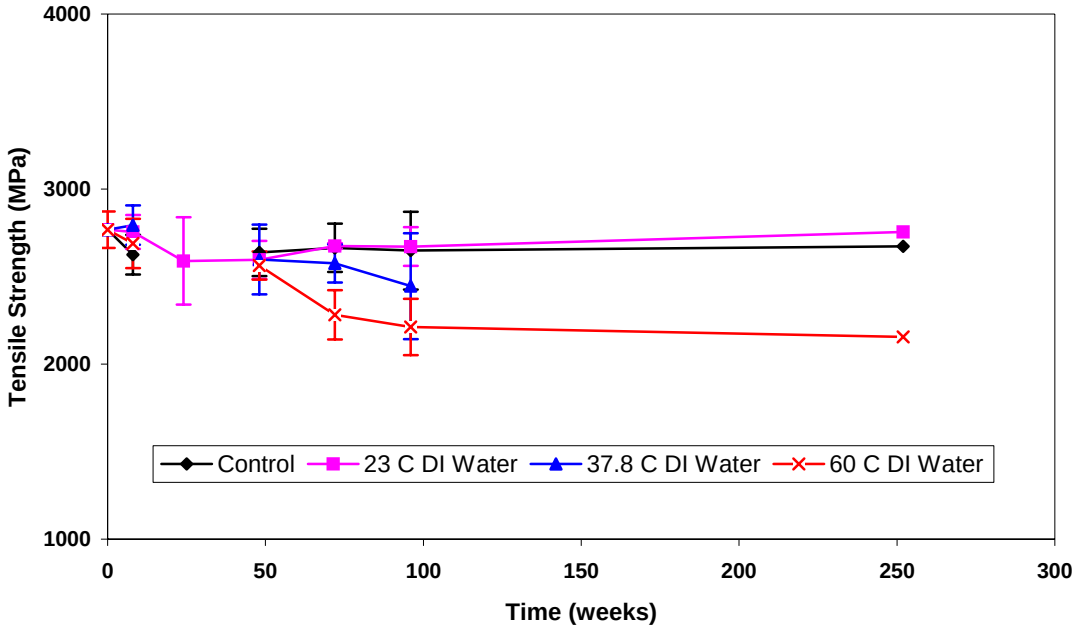
Material: Carbon fiber reinforced epoxy produced by pultrusion Manufacturer: SCCI Test Method: ASTM D 3039/D 3039M - 00 Nominal Specimen Size (Length × Width × Thickness): 254 mm × 12.7 mm × 1.3 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 8 weeks						
Strength						
Mean (MPa)	2625.16	2755.70	2793.97	2689.11	2562.18	2698.44
STD (MPa)	114.08	96.94	112.22	141.08	171.94	133.76
Max (MPa)	2732.97	2869.08	2947.18	2784.80	2759.58	2821.72
Min (MPa)	2463.94	2646.00	2686.33	2479.73	2347.77	2481.17
CV	0.04	0.04	0.04	0.05	0.07	0.05
No. specimens	4	4	5	4	4	5
Modulus						
Mean (GPa)	142.05	140.5	141.20	139.47	141.75	142.67
STD (GPa)	6.92	3.05	2.15	3.14	8.19	1.49
Max (GPa)	150.09	144.27	144.70	142.29	153.98	144.09
Min (GPa)	133.18	136.94	139.46	135.99	136.72	140.59
CV	0.05	0.02	0.02	0.02	0.06	0.01
No. specimens	4	4	5	4	4	5
Exposure period: 24 weeks						
Strength						
Mean (MPa)		2589.57				2694.91
STD (MPa)		249.81				231.05
Max (MPa)		2799.40				2871.29
Min (MPa)		2246.46				2309.92
CV		0.10				0.09
No. specimens		4				5
Modulus						
Mean (GPa)		135.29				140.29
STD (GPa)		5.11				10.40
Max (GPa)		139.93				151.16
Min (GPa)		129.80				129.10
CV		0.04				0.07
No. specimens		4				5

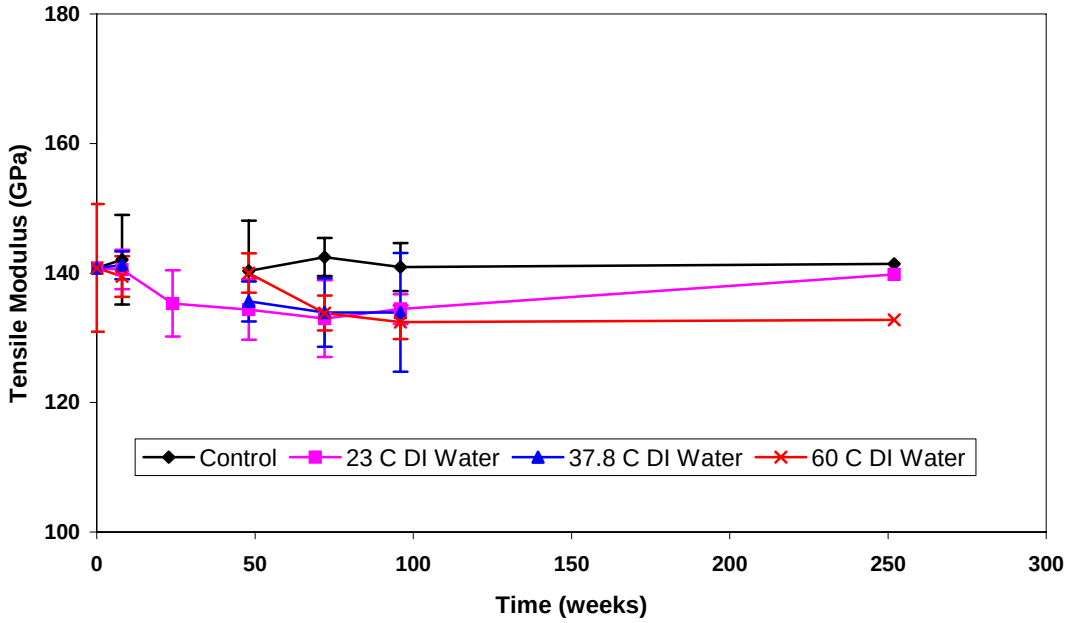
B). Tensile Test (contd.)

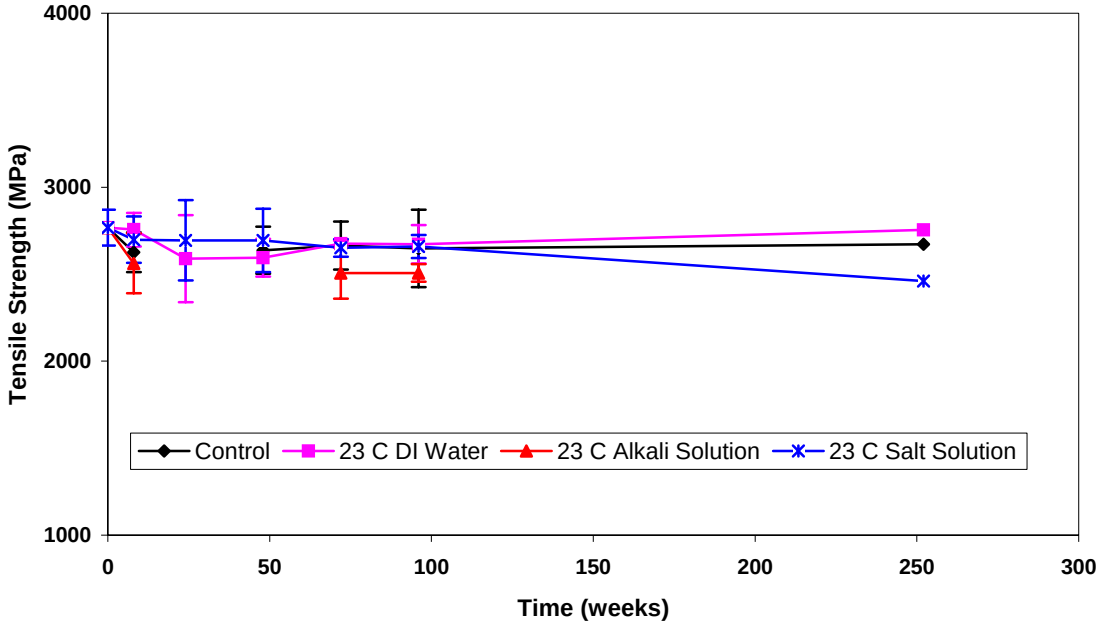
Material: Carbon fiber reinforced epoxy produced by pultrusion Manufacturer: SCCI Test Method: ASTM D 3039/D 3039M - 00 Nominal Specimen Size (Length × Width × Thickness): 254 mm × 12.7 mm × 1.3 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 48 weeks						
Strength						
Mean (MPa)	2637.68	2595.09	2597.68	2563.93		2694.05
STD (MPa)	134.72	108.73	199.80	80.39		182.68
Max (MPa)	2757.91	2686.31	2777.10	2686.00		2867.87
Min (MPa)	2492.08	2437.92	2293.55	2477.08		2463.66
CV	0.05	0.04	0.08	0.03		0.07
No. specimens	3	5	5	5		5
Modulus						
Mean (GPa)	140.32	134.37	135.60	139.99		134.56
STD (GPa)	7.78	4.68	3.08	3.04		2.48
Max (GPa)	145.14	141.93	139.91	142.94		136.79
Min (GPa)	131.34	129.93	131.63	135.33		131.61
CV	0.06	0.04	0.02	0.02		0.02
No. specimens	3	5	5	5		5
Exposure period: 72 weeks						
Strength						
Mean (MPa)	2664.09	2675.04	2575.50	2282.07	2506.78	2651.13
STD (MPa)	137.90	16.77	109.04	140.47	146.79	50.28
Max (MPa)	2748.34	2699.90	2687.44	2446.58	2693.08	2711.42
Min (MPa)	2504.95	2664.08	2469.62	2073.43	2297.63	2606.14
CV	0.05	0.01	0.04	0.06	0.06	0.02
No. specimens	3	4	3	5	5	4
Modulus						
Mean (GPa)	142.46	132.95	133.90	133.82	131.92	134.83
STD (GPa)	2.94	5.93	5.30	2.71	6.35	1.63
Max (GPa)	145.15	140.53	141.02	136.70	139.45	136.32
Min (GPa)	139.32	126.67	126.72	129.51	126.71	133.38
CV	0.02	0.05	0.04	0.02	0.05	0.01
No. specimens	3	4	3	5	5	4

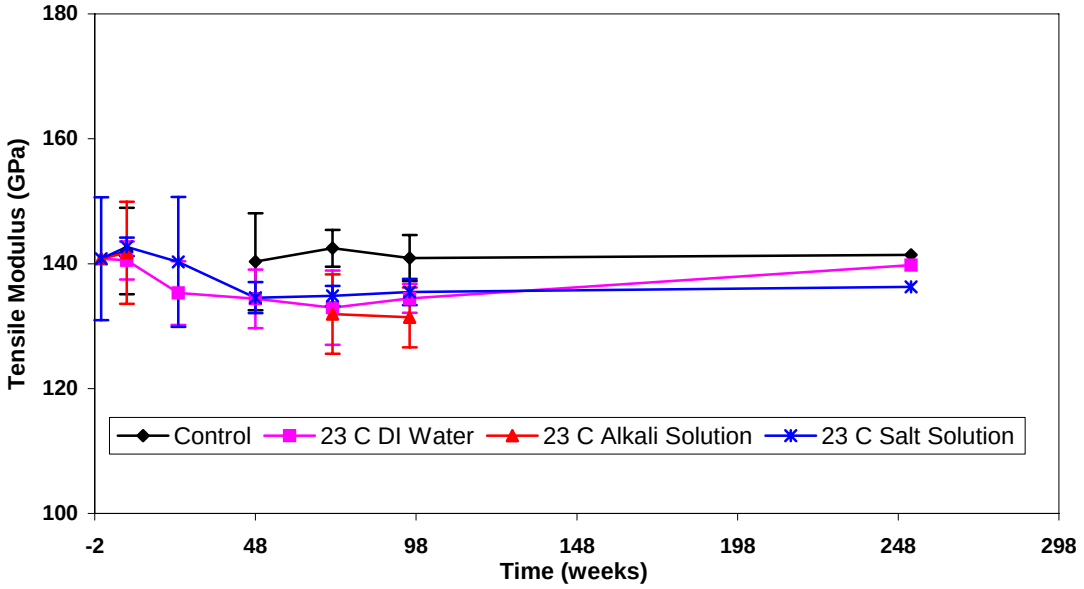
B). Tensile Test (contd.)

Material: Carbon fiber reinforced epoxy produced by pultrusion Manufacturer: SCCI Test Method: ASTM D 3039/D 3039M - 00 Nominal Specimen Size (Length × Width × Thickness): 254 mm × 12.7 mm × 1.3 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 96 weeks						
Strength						
Mean (MPa)	2648.15	2671.79	2445.64	2211.93	2507.22	2659.46
STD (MPa)	222.08	110.65	302.36	161.12	50.38	66.72
Max (MPa)	2775.69	2788.27	2686.55	2383.66	2572.39	2750.93
Min (MPa)	2252.95	2521.93	2031.27	2025.49	2436.71	2568.09
CV	0.08	0.04	0.12	0.07	0.02	0.03
No. specimens	5	4	4	5	5	5
Modulus						
Mean (GPa)	140.90	134.44	133.91	132.39	131.40	135.48
STD (GPa)	3.70	2.30	9.17	2.61	4.78	2.10
Max (GPa)	146.23	137.67	146.01	135.62	137.77	138.48
Min (GPa)	136.98	132.69	126.19	129.84	126.36	133.09
CV	0.03	0.02	0.07	0.02	0.04	0.02
No. specimens	5	4	4	5	5	5
Exposure period: 252 weeks						
Strength						
Mean (MPa)	2672.85	2755.12		2156.18		2460.25
STD (MPa)						
Max (MPa)	2726.71	2798.57				2797.80
Min (MPa)	2618.98	2711.66				2122.70
CV						
No. specimens	2	2		1		2
Modulus						
Mean (GPa)	141.43	139.76		132.78		136.30
STD (GPa)						
Max (GPa)	141.96	142.13				137.22
Min (GPa)	140.89	137.39				135.38
CV						
No. specimens	2	2		1		2


4000
3000
2000
1000
Tensile Strength (MPa)
0
50
100
150
200
250
300
Time (weeks)
Control
23 C DI Water
37.8 C DI Water
60 C DI Water


180
160
140
120
100
Tensile Modulus (GPa)
0
50
100
150
200
250
300
Time (weeks)
Control
23 C DI Water
37.8 C DI Water
60 C DI Water


4000
3000
2000
1000
Tensile Strength (MPa)
0
50
100
150
200
250
300
Time (weeks)
Control
23 C DI Water
23 C Alkali Solution
23 C Salt Solution


180
160
140
120
100
Tensile Modulus (GPa)
-2
48
98
148
198
248
298
Time (weeks)
Control
23 C DI Water
23 C Alkali Solution
23 C Salt Solution

C). Flexural Test

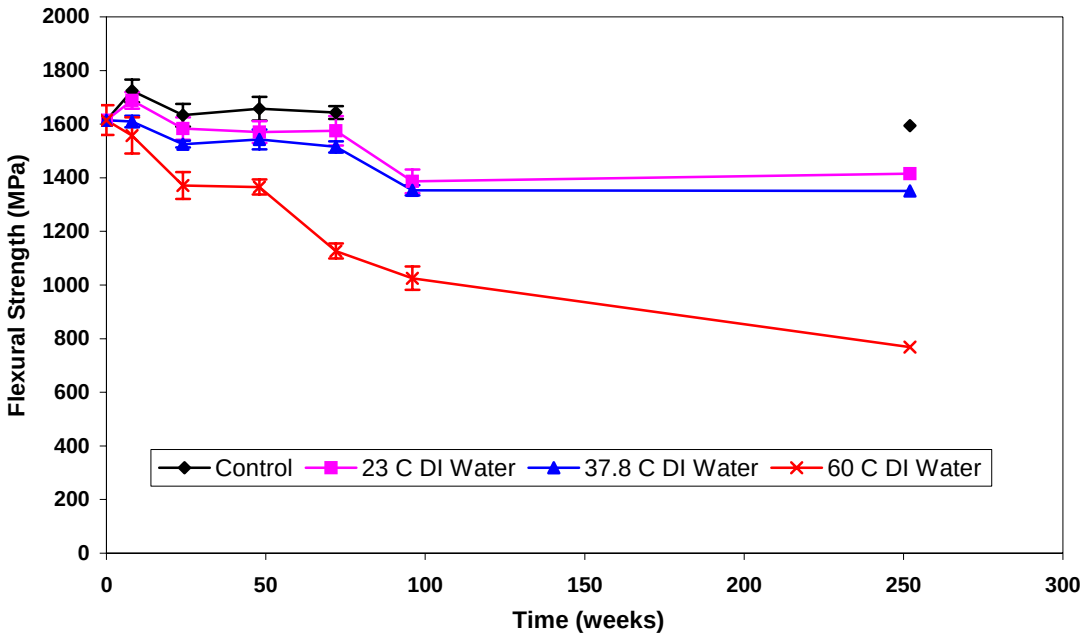
Material: Carbon fiber reinforced epoxy produced by pultrusion Manufacturer: SCCI Test Method: ASTM D 790 - 03 (3 point bending) Nominal Specimen Size (Length × Width × Thickness): 68.6 mm × 12.7 mm × 1.3 mm Span: 21 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing	
Condition	After preconditioning
Strength	
Mean (MPa)	1614.88
STD (MPa)	55.43
Max (MPa)	1702.41
Min (MPa)	1559.94
CV	0.03
No. specimens	5

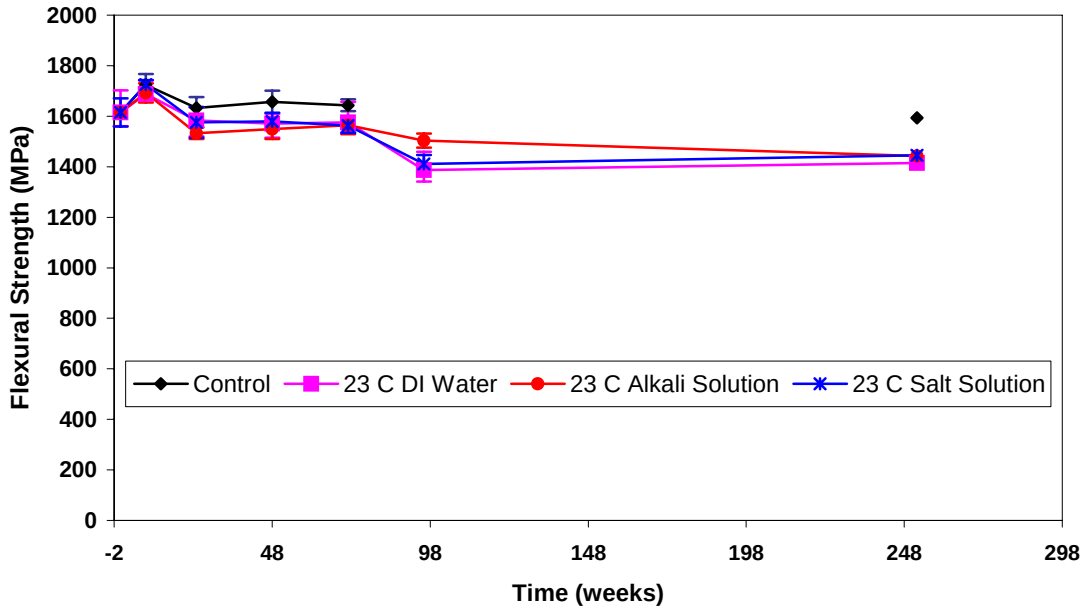
C). Flexural Test (contd.)

Material: Carbon fiber reinforced epoxy produced by pultrusion Manufacturer: SCCI Test Method: ASTM D 790 - 03 (3 point bending) Nominal Specimen Size (Length × Width × Thickness): 68.6 mm × 12.7 mm × 1.3 mm Span: 21 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 8 weeks						
Strength						
Mean (MPa)	1724.29	1688.04	1609.63	1557.85	1691.98	1725.73
STD (MPa)	42.36	30.95	21.11	67.15	37.98	16.69
Max (MPa)	1771.59	1741.46	1640.36	1632.42	1757.60	1747.26
Min (MPa)	1682.48	1666.59	1592.19	1450.30	1663.88	1707.53
CV	0.02	0.02	0.01	0.04	0.02	0.01
No. specimens	5	5	4	5	5	5
Exposure period: 24 weeks						
Strength						
Mean (MPa)	1633.06	1583.54	1525.65	1370.99	1532.38	1575.55
STD (MPa)	42.77	41.88	12.02	50.34	22.74	60.56
Max (MPa)	1675.92	1635.64	1539.62	1417.42	1562.84	1637.42
Min (MPa)	1582.88	1520.29	1510.39	1316.08	1503.74	1478.00
CV	0.03	0.03	0.01	0.04	0.01	0.04
No. specimens	4	5	4	5	5	5
Exposure period: 48 weeks						
Strength						
Mean (MPa)	1657.16	1570.16	1543.11	1365.52	1548.48	1579.27
STD (MPa)	44.34	40.64	36.73	28.37	38.08	34.86
Max (MPa)	1707.50	1609.35	1591.38	1400.17	1608.69	1612.68
Min (MPa)	1609.76	1515.08	1489.57	1334.65	1507.04	1524.97
CV	0.03	0.03	0.02	0.02	0.02	0.02
No. specimens	5	4	5	5	5	5

C). Flexural Test (contd.)

Material: Carbon fiber reinforced epoxy produced by pultrusion Manufacturer: SCCI Test Method: ASTM D 790 – 03 (3 point bending) Nominal Specimen Size (Length × Width × Thickness): 68.6 mm × 12.7 mm × 1.3 mm Span: 21 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 72 weeks						
Strength						
Mean (MPa)	1643.33	1575.74	1515.37	1126.99	1564.90	1562.63
STD (MPa)	23.40	54.88	20.86	28.34	35.47	28.19
Max (MPa)	1675.85	1656.37	1534.51	1165.59	1606.38	1595.98
Min (MPa)	1615.89	1536.13	1484.99	1099.95	1508.54	1530.69
CV	0.01	0.03	0.01	0.03	0.02	0.02
No. specimens	5	4	5	5	5	5
Exposure period: 96 weeks						
Strength						
Mean (MPa)		1386.54	1353.39	1025.24	1503.92	1411.13
STD (MPa)		44.59	18.88	43.42	27.83	35.70
Max (MPa)		1459.66	1378.73	1093.21	1542.24	1473.18
Min (MPa)		1340.76	1333.23	977.83	1466.19	1381.88
CV		0.03	0.01	0.04	0.02	0.03
No. specimens		5	4	5	5	5
Exposure period: 252 weeks						
Strength						
Mean (MPa)	1593.93	1415.34	1350.26	768.06	1442.17	1445.16
STD (MPa)						
Max (MPa)	1653.34	1451.92	1365.82	798.47	1443.15	1501.90
Min (MPa)	1534.51	1378.76	1334.70	737.65	1441.18	1388.42
CV						
No. specimens	2	2	2	2	2	2


2000
1800
1600
1400
1200
1000
800
600
400
200
0
Flexural Strength (MPa)
0
50
100
150
200
250
300
Time (weeks)
Control
23 C DI Water
37.8 C DI Water
60 C DI Water


2000
1800
1600
1400
1200
1000
800
600
400
200
0
Flexural Strength (MPa)
-2
48
98
148
198
248
298
Time (weeks)
Control
23 C DI Water
23 C Alkali Solution
23 C Salt Solution

D). Short Beam Shear Test

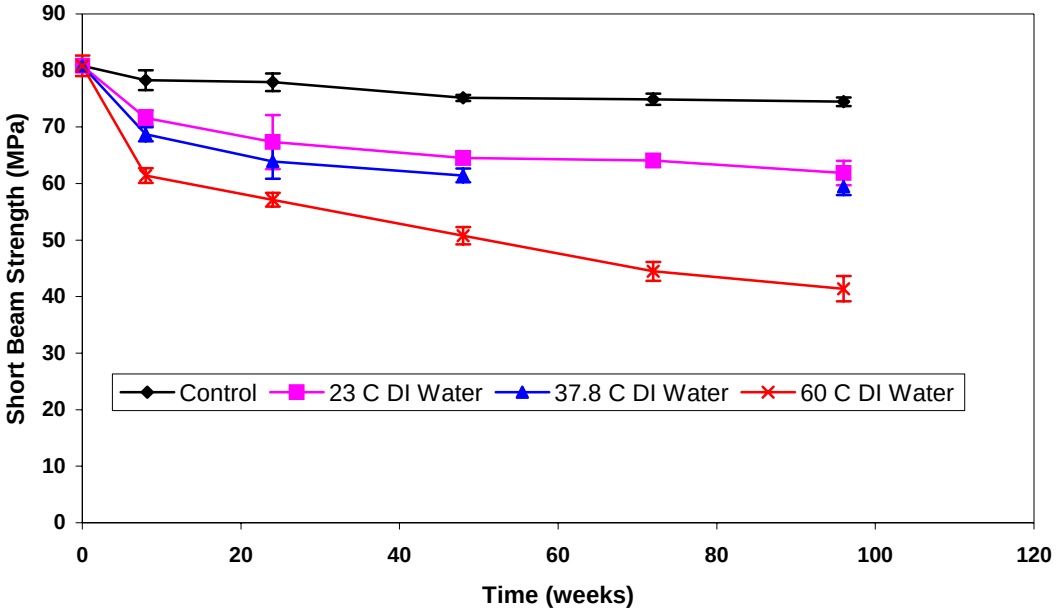
Material: Carbon fiber reinforced epoxy produced by pultrusion Manufacturer: SCCI Test Method: ASTM D 2344/D 2344M - 00 Nominal Specimen Size (Length × Width × Thickness): 12.7 mm × 4.0 mm × 1.3 mm Span: 7.0 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing	
Condition	After preconditioning
Strength	
Mean (MPa)	80.82
STD (MPa)	1.82
Max (MPa)	82.34
Min (MPa)	77.96
CV	0.02
No. specimens	5

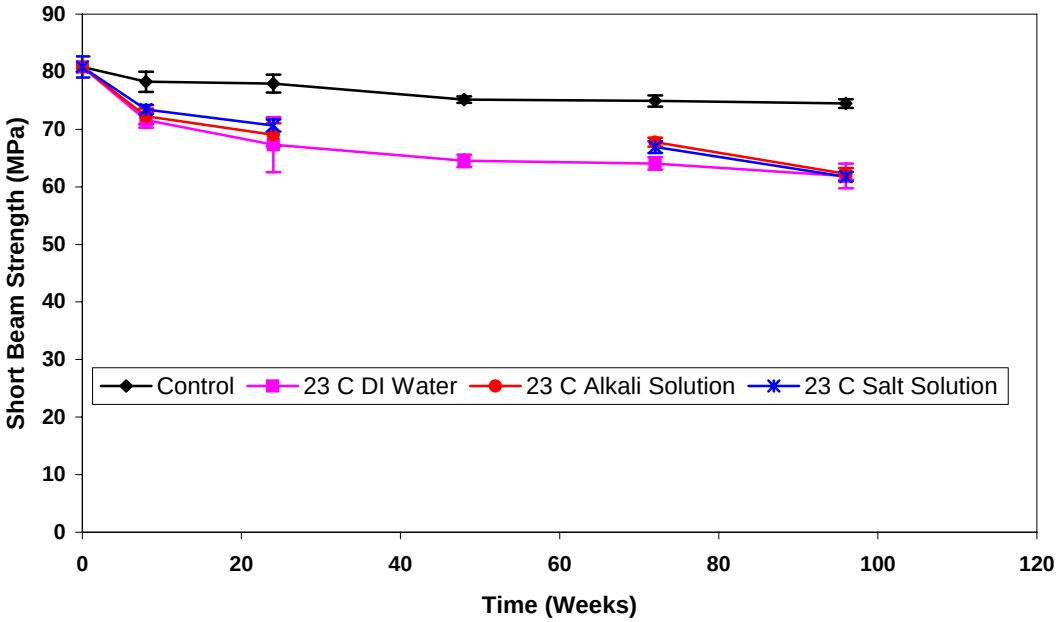
D). Short Beam Shear Test (contd.)

Material: Carbon fiber reinforced epoxy produced by pultrusion Manufacturer: SCCI Test Method: ASTM D 2344/D 2344M - 00 Nominal Specimen Size (Length × Width × Thickness): 12.7 mm × 4.0 mm × 1.3 mm Span: 7.0 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 8 weeks						
Strength						
Mean (MPa)	78.26	71.60	68.71	61.43	72.25	73.44
STD (MPa)	1.75	1.34	1.25	1.29	1.35	0.80
Max (MPa)	81.08	72.50	70.26	62.57	74.02	74.23
Min (MPa)	76.56	69.26	67.16	59.44	70.64	72.41
CV	0.02	0.02	0.02	0.02	0.02	0.01
No. specimens	5	5	5	5	5	5
Exposure period: 24 weeks						
Strength						
Mean (MPa)	77.92	67.33	63.89	57.12	69.05	70.64
STD (MPa)	1.56	4.77	3.04	1.21	2.00	1.06
Max (MPa)	79.96	70.83	67.40	59.23	71.03	71.84
Min (MPa)	76.18	59.21	59.85	56.14	66.29	69.58
CV	0.02	0.07	0.05	0.02	0.03	0.02
No. specimens	4	5	5	5	5	5
Exposure period: 48 weeks						
Strength						
Mean (MPa)	75.15	64.52	61.43	50.76		
STD (MPa)	0.55	1.10	1.20	1.54		
Max (MPa)	75.74	65.83	63.15	52.07		
Min (MPa)	74.55	63.28	60.26	48.15		
CV	0.01	0.02	0.02	0.03		
No. specimens	5	5	5	5		

D). Short Beam Shear Test (contd.)

Material: Carbon fiber reinforced epoxy produced by pultrusion Manufacturer: SCCI Test Method: ASTM D 2344/D 2344M - 00 Nominal Specimen Size (Length × Width × Thickness): 12.7 mm × 4.0 mm × 1.3 mm Span: 7.0 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 72 weeks						
Strength						
Mean (MPa)	74.91	64.06		44.47	67.77	66.91
STD (MPa)	0.98	1.10		1.67	0.76	1.03
Max (MPa)	76.58	65.20		46.46	68.52	68.57
Min (MPa)	74.26	62.55		41.98	67.00	66.02
CV	0.01	0.02		0.04	0.01	0.02
No. specimens	5	4		5	3	5
Exposure period: 96 weeks						
Strength						
Mean (MPa)	74.46	61.89	59.46	41.40	62.23	61.78
STD (MPa)	0.77	2.15	1.49	2.22	1.02	0.81
Max (MPa)	75.35	65.32	61.00	44.88	63.72	62.35
Min (MPa)	73.30	59.53	57.97	39.34	60.94	60.45
CV	0.01	0.03	0.03	0.05	0.02	0.01
No. specimens	5	5	5	5	5	5


Short Beam Strength (MPa)
Time (weeks)
Control
23 C DI Water
37.8 C DI Water
60 C DI Water


Short Beam Strength (MPa)
Time (Weeks)
Control
23 C DI Water
23 C Alkali Solution
23 C Salt Solution

E). Dynamic Mechanical Thermal Analysis

Material: Carbon fiber reinforced epoxy produced by pultrusion Manufacturer: SCCI Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 25 °C and 250 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 1.3 mm, span = 28 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing	
Condition	After preconditioning
T_g by tanδ (Mean)	145.64 °C $[\pm^{0.09}_{0.15}]$ *
tanδ height (Mean)	0.23 $[\pm^{0.01}_{0.01}]$
T_g by E''(Mean)	141.47 °C $[\pm^{0.36}_{0.38}]$
T_g by E'(Mean)	134.73 °C $[\pm^{0.48}_{0.49}]$
E' at T_g – 40 °C (Mean)	5.22×10^{10} Pa $[\pm^{2.25\times10^{9}\text{ Pa}}_{2.36\times10^{9}\text{ Pa}}]$
E' at T_g + 40 °C (Mean)	1.23×10^{10} Pa $[\pm^{1.87\times10^{9}\text{ Pa}}_{1.47\times10^{9}\text{ Pa}}]$
No. specimens	3

* Data is reported as Mean [± Bounds]

E). Dynamic Mechanical Thermal Analysis (contd.)

Material: Carbon fiber reinforced epoxy produced by pultrusion Manufacturer: SCCI Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 25 °C and 250 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 1.3 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 8 weeks						
T_g by tanδ (Mean)	149.33 °C [$\pm^{0.95}_{1.27}$]	142.09 °C [$\pm^{0.23}_{0.37}$]	140.41 °C [$\pm^{1.24}_{0.95}$]	138.80 °C [$\pm^{0.94}_{0.64}$]	143.22 °C [$\pm^{2.23}_{1.26}$]	143.06 °C [$\pm^{1.01}_{1.01}$]
tanδ height (Mean)	0.21 [$\pm^{0.00}_{0.01}$]	0.21 [$\pm^{0.00}_{0.00}$]	0.23 [$\pm^{0.01}_{0.01}$]	0.22 [$\pm^{0.00}_{0.01}$]	0.21 [$\pm^{0.01}_{0.01}$]	0.21 [$\pm^{0.01}_{0.01}$]
T_g by E''(Mean)	146.27 °C [$\pm^{1.03}_{1.27}$]	138.77 °C [$\pm^{1.14}_{0.78}$]	137.31 °C [$\pm^{0.62}_{0.70}$]	135.30 °C [$\pm^{2.39}_{2.33}$]	139.51 °C [$\pm^{0.14}_{0.27}$]	138.98 °C [$\pm^{1.22}_{1.22}$]
T_g by E'(Mean)	141.72 °C [$\pm^{1.03}_{1.43}$]	130.61 °C [$\pm^{2.13}_{2.96}$]	122.21 °C [$\pm^{0.81}_{0.57}$]	118.77 °C [$\pm^{3.30}_{4.42}$]	127.00 °C [$\pm^{10.19}_{6.30}$]	135.73 °C [$\pm^{3.31}_{3.31}$]
E' at T_g – 40 °C (Mean, Pa)	5.38×10^{10} [$\pm^{5.68\times10^9}_{4.42\times10^9}$]	5.70×10^{10} [$\pm^{7.48\times10^9}_{4.46\times10^9}$]	5.43×10^{10} [$\pm^{1.99\times10^9}_{2.76\times10^9}$]	5.72×10^{10} [$\pm^{2.88\times10^9}_{2.75\times10^9}$]	5.62×10^{10} [$\pm^{4.22\times10^9}_{7.56\times10^9}$]	6.88×10^{10} [$\pm^{3.85\times10^9}_{3.85\times10^9}$]
E' at T_g + 40 °C (Mean, Pa)	1.70×10^{10} [$\pm^{1.25\times10^9}_{1.60\times10^9}$]	1.64×10^{10} [$\pm^{2.26\times10^9}_{2.05\times10^9}$]	1.60×10^{10} [$\pm^{2.07\times10^9}_{1.60\times10^9}$]	1.67×10^{10} [$\pm^{2.28\times10^9}_{3.85\times10^9}$]	1.85×10^{10} [$\pm^{2.82\times10^9}_{2.52\times10^9}$]	2.35×10^{10} [$\pm^{7.57\times10^8}_{7.57\times10^8}$]
No. specimens	3	3	3	3	3	2

E). Dynamic Mechanical Thermal Analysis (contd.)

Material: Carbon fiber reinforced epoxy produced by pultrusion Manufacturer: SCCI Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 25 °C and 250 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 1.3 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 24 weeks						
T_g by tanδ (Mean)	140.50 °C [$\pm^{0.54}_{1.01}$]	131.38 °C [$\pm^{0.43}_{0.33}$]	130.18 °C [$\pm^{0.46}_{0.46}$]	129.30 °C [$\pm^{0.40}_{0.43}$]	133.54 °C [$\pm^{0.83}_{1.16}$]	133.40 °C [$\pm^{1.33}_{1.10}$]
tanδ height (Mean)	0.23 [$\pm^{0.00}_{0.00}$]	0.20 [$\pm^{0.01}_{0.01}$]	0.20 [$\pm^{0.00}_{0.00}$]	0.24 [$\pm^{0.01}_{0.00}$]	0.22 [$\pm^{0.01}_{0.01}$]	0.21 [$\pm^{0.01}_{0.01}$]
T_g by E''(Mean)	138.66 °C [$\pm^{0.83}_{0.77}$]	129.39 °C [$\pm^{0.41}_{0.34}$]	126.38 °C [$\pm^{0.50}_{0.50}$]	125.41 °C [$\pm^{0.38}_{0.39}$]	129.49 °C [$\pm^{0.39}_{0.29}$]	129.02 °C [$\pm^{0.71}_{1.22}$]
T_g by E'(Mean)	132.10 °C [$\pm^{5.69}_{3.26}$]	121.39 °C [$\pm^{4.19}_{2.59}$]	121.13 °C [$\pm^{0.63}_{0.63}$]	119.37 °C [$\pm^{0.10}_{0.14}$]	120.45 °C [$\pm^{3.05}_{5.60}$]	118.50 °C [$\pm^{1.32}_{1.76}$]
E' at T_g – 40 °C (Mean, Pa)	5.96×10^{10} [$\pm^{4.60\times10^9}_{7.41\times10^9}$]	7.03×10^{10} [$\pm^{2.10\times10^9}_{2.92\times10^9}$]	7.10×10^{10} [$\pm^{9.99\times10^9}_{9.99\times10^9}$]	6.52×10^{10} [$\pm^{5.40\times10^9}_{5.31\times10^9}$]	6.31×10^{10} [$\pm^{4.18\times10^9}_{6.62\times10^9}$]	5.96×10^{10} [$\pm^{8.97\times10^9}_{6.46\times10^9}$]
E' at T_g + 40 °C (Mean, Pa)	1.80×10^{10} [$\pm^{1.78\times10^9}_{2.20\times10^9}$]	2.38×10^{10} [$\pm^{1.36\times10^9}_{1.81\times10^9}$]	2.55×10^{10} [$\pm^{1.73\times10^8}_{1.73\times10^8}$]	2.11×10^{10} [$\pm^{1.23\times10^9}_{1.79\times10^9}$]	1.88×10^{10} [$\pm^{2.26\times10^9}_{1.13\times10^9}$]	1.79×10^{10} [$\pm^{9.96\times10^8}_{1.48\times10^9}$]
No. specimens	3	3	2	3	3	3

E). Dynamic Mechanical Thermal Analysis (contd.)

Material: Carbon fiber reinforced epoxy produced by pultrusion Manufacturer: SCCI Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 25 °C and 250 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 1.3 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 48 weeks						
T_g by tanδ (Mean)	142.01 °C [$\pm^{0.80}_{0.95}$]	131.93 °C [$\pm^{0.71}_{0.51}$]	131.24 °C [$\pm^{0.55}_{1.03}$]	129.03 °C [$\pm^{0.36}_{0.43}$]	133.12 °C [$\pm^{0.45}_{0.74}$]	132.44 °C [$\pm^{0.53}_{0.39}$]
tanδ height (Mean)	0.23 [$\pm^{0.02}_{0.01}$]	0.22 [$\pm^{0.01}_{0.00}$]	0.21 [$\pm^{0.01}_{0.01}$]	0.23 [$\pm^{0.01}_{0.01}$]	0.22 [$\pm^{0.01}_{0.01}$]	0.21 [$\pm^{0.00}_{0.00}$]
T_g by E''(Mean)	138.68 °C [$\pm^{0.97}_{1.37}$]	125.93 °C [$\pm^{1.29}_{0.94}$]	127.08 °C [$\pm^{2.23}_{1.77}$]	125.67 °C [$\pm^{0.48}_{0.37}$]	128.33 °C [$\pm^{1.30}_{0.78}$]	126.91 °C [$\pm^{1.97}_{1.11}$]
T_g by E'(Mean)	132.58 °C [$\pm^{2.22}_{2.08}$]	120.31 °C [$\pm^{2.76}_{1.77}$]	116.85 °C [$\pm^{5.58}_{6.84}$]	113.63 °C [$\pm^{1.61}_{1.23}$]	118.34 °C [$\pm^{5.21}_{4.21}$]	121.82 °C [$\pm^{5.00}_{2.89}$]
E' at T_g – 40 °C (Mean, Pa)	4.71×10^{10} [$\pm^{6.46\times10^{9}}_{8.20\times10^{9}}$]	4.62×10^{10} [$\pm^{4.12\times10^{9}}_{5.07\times10^{9}}$]	5.48×10^{10} [$\pm^{4.32\times10^{9}}_{6.19\times10^{9}}$]	5.41×10^{10} [$\pm^{2.86\times10^{9}}_{3.77\times10^{9}}$]	4.70×10^{10} [$\pm^{5.41\times10^{8}}_{7.57\times10^{8}}$]	5.51×10^{10} [$\pm^{7.12\times10^{9}}_{8.51\times10^{9}}$]
E' at T_g + 40 °C (Mean, Pa)	1.16×10^{10} [$\pm^{4.89\times10^{8}}_{5.90\times10^{8}}$]	1.03×10^{10} [$\pm^{1.34\times10^{9}}_{1.99\times10^{9}}$]	1.47×10^{10} [$\pm^{3.25\times10^{9}}_{2.20\times10^{9}}$]	1.28×10^{10} [$\pm^{5.40\times10^{8}}_{9.52\times10^{8}}$]	1.17×10^{10} [$\pm^{3.11\times10^{9}}_{2.57\times10^{9}}$]	1.39×10^{10} [$\pm^{1.84\times10^{9}}_{3.54\times10^{9}}$]
No. specimens	3	3	3	3	3	3

E). Dynamic Mechanical Thermal Analysis (contd.)

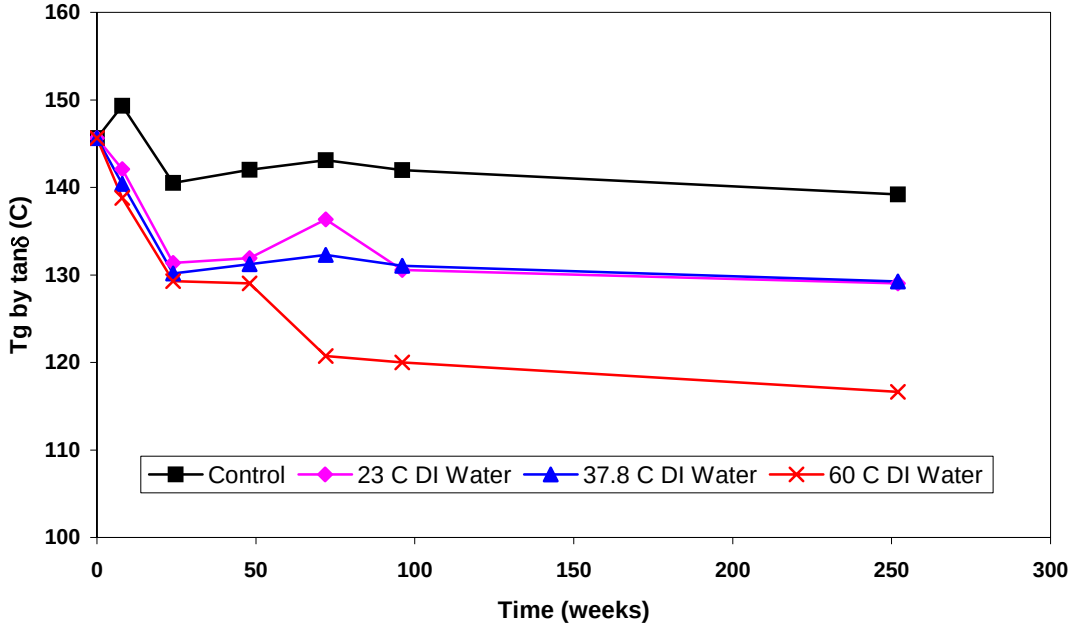
Material: Carbon fiber reinforced epoxy produced by pultrusion Manufacturer: SCCI Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 25 °C and 250 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 1.3 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 72 weeks						
T_g by tanδ (Mean)	143.09 °C [$\pm^{1.54}_{0.89}$]	136.34 °C [$\pm^{1.19}_{2.17}$]	132.27 °C [$\pm^{1.43}_{1.81}$]	120.73 °C [$\pm^{0.65}_{0.99}$]	130.56 °C [$\pm^{1.60}_{1.13}$]	132.65 °C [$\pm^{1.51}_{0.80}$]
tanδ height (Mean)	0.20 [$\pm^{0.01}_{0.01}$]	0.22 [$\pm^{0.01}_{0.01}$]	0.21 [$\pm^{0.00}_{0.01}$]	0.29 [$\pm^{0.01}_{0.01}$]	0.19 [$\pm^{0.00}_{0.01}$]	0.20 [$\pm^{0.00}_{0.00}$]
T_g by E''(Mean)	140.01 °C [$\pm^{0.86}_{0.54}$]	127.03 °C [$\pm^{0.95}_{0.73}$]	126.58 °C [$\pm^{0.38}_{0.68}$]	116.58 °C [$\pm^{0.74}_{1.02}$]	127.02 °C [$\pm^{0.85}_{0.72}$]	127.25 °C [$\pm^{0.42}_{0.47}$]
T_g by E'(Mean)	133.30 °C [$\pm^{1.06}_{1.60}$]	122.45 °C [$\pm^{1.11}_{1.79}$]	122.37 °C [$\pm^{2.42}_{1.51}$]	112.46 °C [$\pm^{1.25}_{1.93}$]	121.05 °C [$\pm^{0.62}_{1.11}$]	124.09 °C [$\pm^{2.51}_{2.73}$]
E' at T_g – 40 °C (Mean, Pa)	6.45×10^{10} [$\pm^{4.33\times10^{9}}_{8.11\times10^{9}}$]	5.39×10^{10} [$\pm^{6.05\times10^{9}}_{6.02\times10^{9}}$]	7.72×10^{10} [$\pm^{1.65\times10^{10}}_{1.19\times10^{10}}$]	5.78×10^{10} [$\pm^{6.68\times10^{9}}_{8.64\times10^{9}}$]	8.45×10^{10} [$\pm^{6.03\times10^{9}}_{4.12\times10^{9}}$]	8.20×10^{10} [$\pm^{2.07\times10^{10}}_{1.25\times10^{10}}$]
E' at T_g + 40 °C (Mean, Pa)	2.24×10^{10} [$\pm^{2.75\times10^{9}}_{2.46\times10^{9}}$]	6.22×10^{9} [$\pm^{1.17\times10^{9}}_{1.92\times10^{9}}$]	1.13×10^{10} [$\pm^{5.57\times10^{9}}_{3.42\times10^{9}}$]	1.29×10^{10} [$\pm^{3.23\times10^{9}}_{3.58\times10^{9}}$]	1.87×10^{10} [$\pm^{3.18\times10^{9}}_{5.84\times10^{9}}$]	1.34×10^{10} [$\pm^{4.00\times10^{9}}_{6.72\times10^{9}}$]
No. specimens	3	3	3	3	3	3

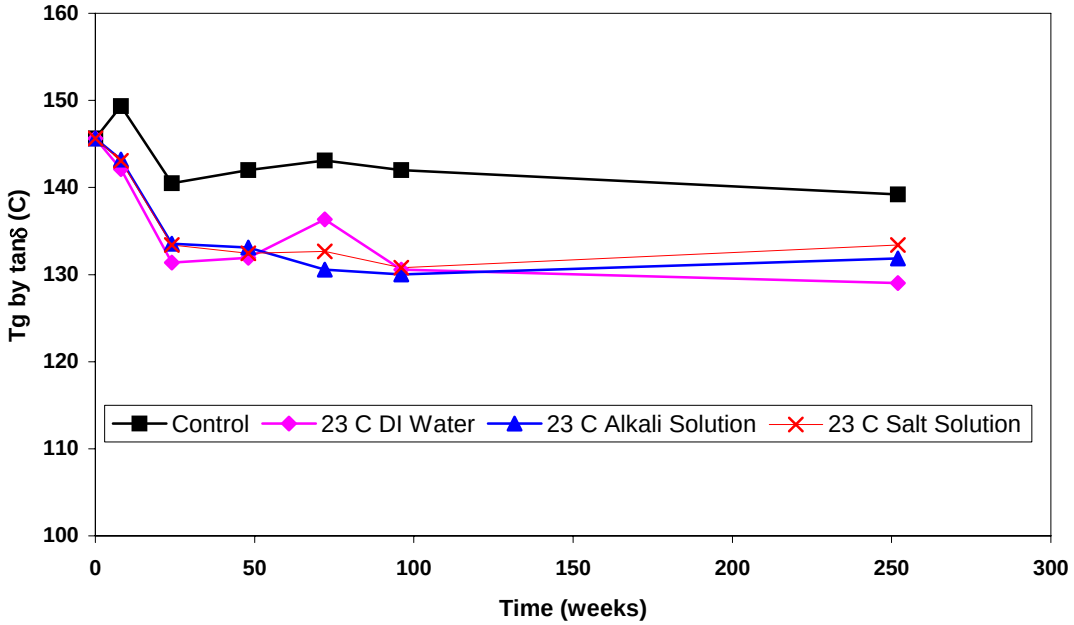
E). Dynamic Mechanical Thermal Analysis (contd.)

Material: Carbon fiber reinforced epoxy produced by pultrusion Manufacturer: SCCI Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 25 °C and 250 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 1.3 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 96 weeks						
T_g by tanδ (Mean)	141.98 °C [$\pm^{0.29}_{0.23}$]	130.56 °C [$\pm^{0.78}_{0.63}$]	131.05 °C [$\pm^{1.35}_{1.70}$]	119.99 °C [$\pm^{1.15}_{1.30}$]	130.01 °C [$\pm^{0.47}_{0.76}$]	130.78 °C [$\pm^{0.78}_{0.78}$]
tanδ height (Mean)	0.22 [$\pm^{0.01}_{0.01}$]	0.21 [$\pm^{0.00}_{0.00}$]	0.22 [$\pm^{0.00}_{0.01}$]	0.29 [$\pm^{0.02}_{0.02}$]	0.21 [$\pm^{0.03}_{0.03}$]	0.20 [$\pm^{0.01}_{0.01}$]
T_g by E''(Mean)	138.50 °C [$\pm^{0.38}_{0.45}$]	127.05 °C [$\pm^{0.60}_{0.73}$]	127.17 °C [$\pm^{2.55}_{1.62}$]	117.20 °C [$\pm^{0.61}_{1.13}$]	127.41 °C [$\pm^{0.87}_{1.35}$]	127.09 °C [$\pm^{0.81}_{0.65}$]
T_g by E'(Mean)	134.74 °C [$\pm^{1.10}_{1.23}$]	121.49 °C [$\pm^{1.52}_{1.34}$]	123.42 °C [$\pm^{3.19}_{3.08}$]	110.01 °C [$\pm^{1.43}_{2.35}$]	124.00 °C [$\pm^{1.77}_{1.77}$]	119.06 °C [$\pm^{0.76}_{1.42}$]
E' at T_g – 40 °C (Mean, Pa)	4.65×10^{10} [$\pm^{7.94\times10^{9}}_{6.17\times10^{9}}$]	5.92×10^{10} [$\pm^{1.17\times10^{10}}_{7.21\times10^{9}}$]	5.01×10^{10} [$\pm^{1.53\times10^{10}}_{9.90\times10^{9}}$]	5.62×10^{10} [$\pm^{6.24\times10^{9}}_{5.46\times10^{9}}$]	5.71×10^{10} [$\pm^{6.76\times10^{9}}_{5.54\times10^{9}}$]	6.78×10^{10} [$\pm^{5.07\times10^{9}}_{6.30\times10^{9}}$]
E' at T_g + 40 °C (Mean, Pa)	2.15×10^{10} [$\pm^{1.95\times10^{9}}_{3.26\times10^{9}}$]	2.16×10^{10} [$\pm^{4.18\times10^{8}}_{7.88\times10^{8}}$]	1.72×10^{10} [$\pm^{3.44\times10^{9}}_{4.05\times10^{9}}$]	1.75×10^{10} [$\pm^{9.82\times10^{8}}_{1.83\times10^{9}}$]	2.08×10^{10} [$\pm^{1.81\times10^{9}}_{3.29\times10^{9}}$]	1.91×10^{10} [$\pm^{1.75\times10^{9}}_{2.61\times10^{9}}$]
No. specimens	3	3	3	3	3	3

E). Dynamic Mechanical Thermal Analysis (contd.)

Material: Carbon fiber reinforced epoxy produced by pultrusion Manufacturer: SCCI Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 25 °C and 250 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 1.3 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 252 weeks						
T_g by tanδ (Mean)	139.19 °C [$\pm^{0.37}_{0.37}$]	129.02 °C [$\pm^{1.01}_{1.01}$]	129.24 °C [$\pm^{0.50}_{0.50}$]	116.63 °C [$\pm^{2.82}_{2.82}$]	131.86 °C [$\pm^{1.02}_{1.02}$]	133.39 °C [$\pm^{0.67}_{0.67}$]
tanδ height (Mean)	0.22 [$\pm^{0.02}_{0.02}$]	0.20 [$\pm^{0.00}_{0.00}$]	0.21 [$\pm^{0.00}_{0.00}$]	0.31 [$\pm^{0.02}_{0.02}$]	0.22 [$\pm^{0.00}_{0.00}$]	0.22 [$\pm^{0.01}_{0.01}$]
T_g by E''(Mean)	134.60 °C [$\pm^{0.03}_{0.03}$]	124.67 °C [$\pm^{1.01}_{1.01}$]	124.58 °C [$\pm^{0.20}_{0.20}$]	111.88 °C [$\pm^{2.67}_{2.67}$]	123.40 °C [$\pm^{1.24}_{1.24}$]	125.70 °C [$\pm^{0.28}_{0.28}$]
T_g by E'(Mean)	130.55 °C [$\pm^{0.38}_{0.38}$]	121.74 °C [$\pm^{1.47}_{1.47}$]	119.52 °C [$\pm^{0.20}_{0.20}$]	107.32 °C [$\pm^{0.69}_{0.69}$]	116.01 °C [$\pm^{3.87}_{3.87}$]	122.16 °C [$\pm^{0.45}_{0.45}$]
E' at T_g – 40 °C (Mean, Pa)	5.60×10^{10} [$\pm^{2.31\times10^{9}}_{2.31\times10^{9}}$]	5.65×10^{10} [$\pm^{5.85\times10^{9}}_{5.85\times10^{9}}$]	6.32×10^{10} [$\pm^{3.23\times10^{9}}_{3.23\times10^{9}}$]	5.44×10^{10} [$\pm^{1.03\times10^{10}}_{1.03\times10^{10}}$]	5.23×10^{10} [$\pm^{1.32\times10^{9}}_{1.32\times10^{9}}$]	5.75×10^{10} [$\pm^{6.86\times10^{9}}_{6.86\times10^{9}}$]
E' at T_g + 40 °C (Mean, Pa)	8.60×10^{9} [$\pm^{1.68\times10^{9}}_{1.68\times10^{9}}$]	6.61×10^{9} [$\pm^{8.25\times10^{8}}_{8.25\times10^{8}}$]	1.41×10^{10} [$\pm^{2.60\times10^{9}}_{2.60\times10^{9}}$]	9.55×10^{9} [$\pm^{1.57\times10^{9}}_{1.57\times10^{9}}$]	6.15×10^{9} [$\pm^{1.41\times10^{8}}_{1.41\times10^{8}}$]	9.01×10^{9} [$\pm^{3.48\times10^{8}}_{3.48\times10^{8}}$]
No. specimens	2	2	2	2	2	2


160
150
140
130
120
110
100
Tg by tanδ (C)
0
50
100
150
200
250
300
Time (weeks)
Control
23 C DI Water
37.8 C DI Water
60 C DI Water


160
150
140
130
120
110
100
Tg by tanδ (C)
0
50
100
150
200
250
300
Time (weeks)
Control
23 C DI Water
23 C Alkali Solution
23 C Salt Solution

FYFE PREFABRICATED SYSTEM

GENERAL INFORMATION

Material: Adhesive
Manufacturer: FYFE
Resin Type: Solids filled epoxy
Fiber Type: N/A
Fabric Type: N/A
Fabric Weight: N/A
Type of Cure: Ambient Temperature
Method of Manufacture: Cast
Density: 0.88 g/cm^3
Fiber Volume Fraction: N/A
Resin Volume Fraction: N/A
Void Volume Fraction: N/A
Configuration: N/A

PROPERTIES

A). Moisture Uptake (Data for a period of 249 weeks)

Material: Adhesive Manufacturer: FYFE Test Method: Gravimetric, ASTM D 5229/D 5229M - 92 Nominal Specimen Size (Length × Width × Thickness): 25.4 mm × 25.4 mm × 6.1 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Curve shape		2-stage[1]	2-stage[1]	Sigmoidal[2]	2-stage[1]	2-stage[1]
M_{max} (%)	0.40	2.91	5.34	26.40	3.04	2.24
Time for M_{max}	At 164 week	At end	At end	At end	At end	At end
M_∞						
M_∞ (%) in stage 1 [3]		1.51	1.51	1.51	2.25	1.90
D (mm^2/s) in stage 1		4.80×10^{-7}	1.48×10^{-6}	1.19×10^{-5}	2.31×10^{-7}	2.32×10^{-7}
k (1/s$^{0.5}$) in stage 2		7.85×10^{-5}	1.75×10^{-4}	3.50×10^{-4}	2.63×10^{-5}	1.18×10^{-5}
2-stage formula (details see Ref.1)	$M_t = M_\infty\left(1+k\sqrt{t}\right)\left\{1-\exp\left[-7.3\left(\frac{Dt}{h^2}\right)^{0.75}\right]\right\}$					

1. Following Bao, L.R., Yee, A.F. and Lee, C.Y.C., "Moisture Absorption and Hygrothermal Aging in a Bismaleimide Resin" *Polymer*, 42, 2001, pp. 7327-7333.
2. Use 2-stage model to curve fit the data.
3. M_∞ determined following the graphical method in Tsotsis, T. K. and Weitsman, Y., "A Simple Graphical-Method For Determining Diffusion Parameters For 2-Stage Sorption In Composites." *Journal Of Materials Science Letters*, 13[22], 1994, pp. 1635-1636.

B). Tensile Test

Material: Adhesive Manufacturer: FYFE Test Method: ASTM D 638 - 99 Nominal Specimen Size: According to ASTM standard, Overall Length = 165 mm, Gage Length = 50 mm, Width of Narrow Section = 13 mm, Thickness = 6 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing	
Condition	After preconditioning
Strength	
Mean (MPa)	17.23
STD (MPa)	1.36
Max (MPa)	18.80
Min (MPa)	16.06
CV	0.08
No. specimens	5
Modulus	
Mean (GPa)	1.12
STD (GPa)	0.15
Max (GPa)	1.32
Min (GPa)	0.92
CV	0.14
No. specimens	5

B). Tensile Test (contd.)

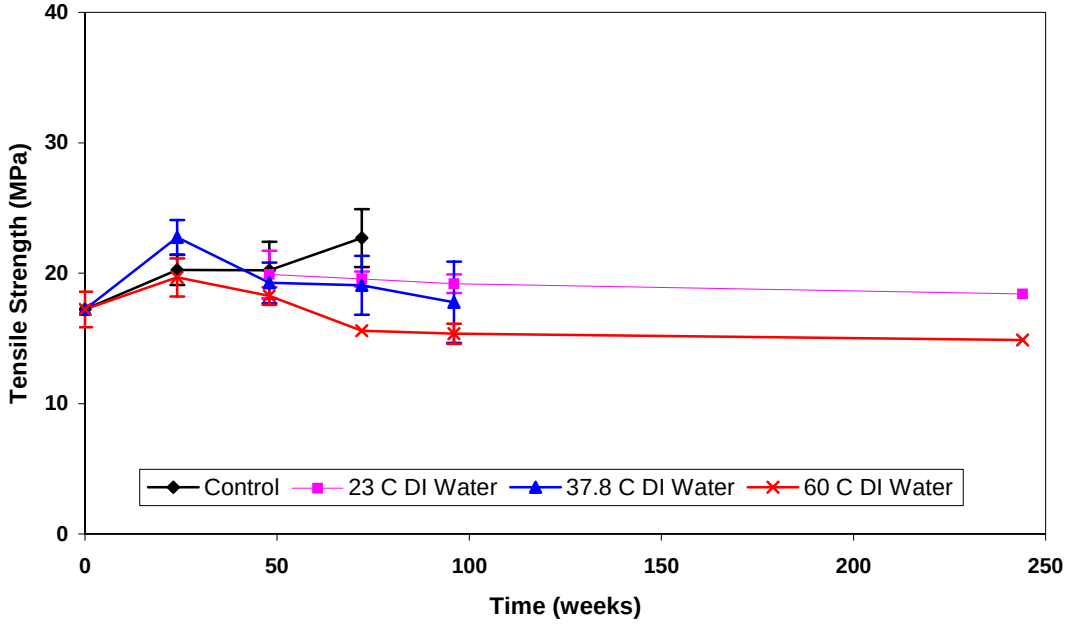
Material: Adhesive Manufacturer: FYFE Test Method: ASTM D 638 - 99 Nominal Specimen Size: According to ASTM standard Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 24 weeks						
Strength						
Mean (MPa)	20.25		22.74	19.67	18.89	21.23
STD (MPa)	1.15		1.32	1.46	0.81	0.87
Max (MPa)	21.53		23.92	21.21	20.22	21.92
Min (MPa)	18.85		21.31	17.28	18.16	19.97
CV	0.06		0.06	0.07	0.04	0.04
No. specimens	5		3	5	5	4
Modulus						
Mean (GPa)	1.25		1.16	1.07	1.11	1.19
STD (GPa)	0.08		0.07	0.24	0.04	0.18
Max (GPa)	1.36		1.20	1.42	1.14	1.42
Min (GPa)	1.14		1.11	0.80	1.04	0.97
CV	0.07		0.06	0.22	0.04	0.15
No. specimens	5		3	5	5	4
Exposure period: 48 weeks						
Strength						
Mean (MPa)	20.22	19.90	19.25	18.25	18.26	18.76
STD (MPa)	2.17	1.81	1.56	0.68	1.40	1.42
Max (MPa)	23.06	22.54	21.22	18.66	20.31	21.23
Min (MPa)	18.14	18.61	17.12	17.47	16.83	17.69
CV	0.11	0.09	0.08	0.04	0.08	0.08
No. specimens	5	4	5	3	5	5
Modulus						
Mean (GPa)	1.33	1.16	1.10	1.08	1.09	1.18
STD (GPa)	0.23	0.12	0.19	0.28	0.10	0.09
Max (GPa)	1.71	1.34	1.29	1.34	1.19	1.28
Min (GPa)	1.12	1.06	0.90	0.78	1.00	1.04
CV	0.17	0.11	0.18	0.26	0.09	0.08
No. specimens	5	4	5	3	5	5

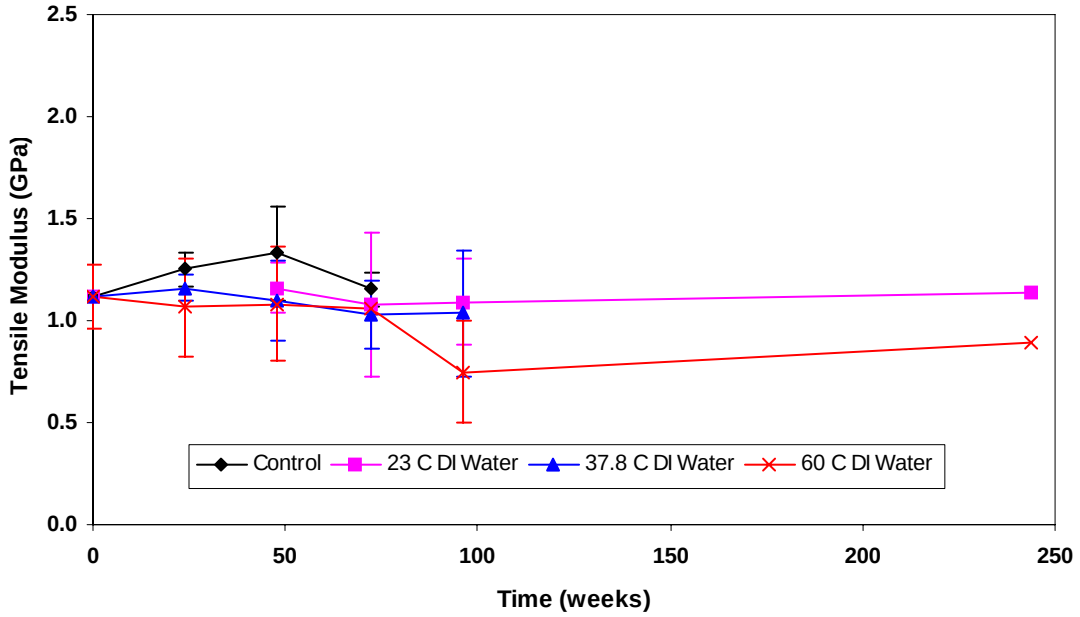
B). Tensile Test (contd.)

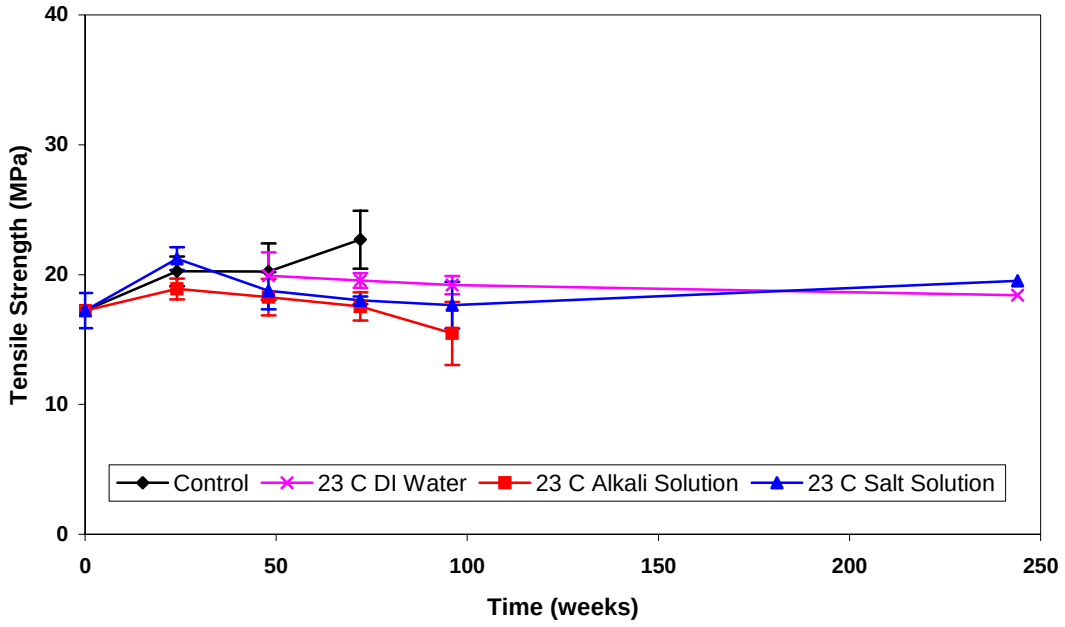
Material: Adhesive Manufacturer: FYFE Test Method: ASTM D 638 - 99 Nominal Specimen Size: According to ASTM standard Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 72 weeks						
Strength						
Mean (MPa)	22.69	19.55	19.07	15.58	17.55	18.02
STD (MPa)	2.23	0.57	2.25		1.09	0.30
Max (MPa)	24.21	20.17	21.80	16.13	18.95	18.33
Min (MPa)	19.48	18.73	17.22	15.03	16.32	17.74
CV	0.10	0.03	0.12		0.06	0.02
No. specimens	4	5	4	2	4	3
Modulus						
Mean (GPa)	1.15	1.08	1.03	1.05	1.08	1.18
STD (GPa)	0.08	0.35	0.17		0.08	0.25
Max (GPa)	1.22	1.63	1.20	1.13	1.14	1.42
Min (GPa)	1.04	0.73	0.84	0.98	1.00	0.92
CV	0.07	0.33	0.16		0.07	0.21
No. specimens	4	5	4	2	4	3
Exposure period: 96 weeks						
Strength						
Mean (MPa)		19.19	17.76	15.35	15.47	17.65
STD (MPa)		0.70	3.12	0.76	2.43	1.80
Max (MPa)		19.75	21.39	16.00	18.09	19.35
Min (MPa)		18.17	15.20	14.36	11.73	15.27
CV		0.04	0.18	0.05	0.16	0.10
No. specimens		4	5	4	5	5
Modulus						
Mean (GPa)		1.09	1.04	0.75	1.09	1.17
STD (GPa)		0.21	0.31	0.25	0.20	0.29
Max (GPa)		1.26	1.51	0.96	1.37	1.55
Min (GPa)		0.81	0.76	0.47	0.82	0.89
CV		0.19	0.30	0.33	0.19	0.25
No. specimens		4	5	4	5	5

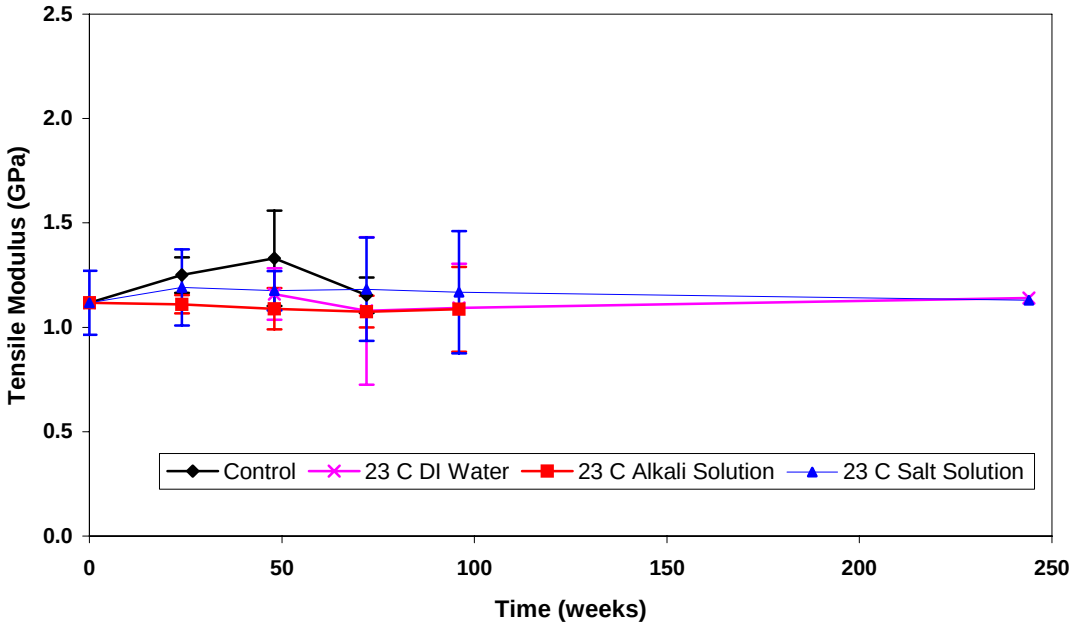
B). Tensile Test (contd.)

Material: Adhesive Manufacturer: FYFE Test Method: ASTM D 638 - 99 Nominal Specimen Size: According to ASTM standard Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 244 weeks						
Strength						
Mean (MPa)		18.40		14.88		19.53
STD (MPa)						
Max (MPa)		19.07		15.70		20.70
Min (MPa)		17.72		14.05		18.36
CV						
No. specimens		2		2		2
Modulus						
Mean (GPa)		1.14		0.89		1.13
STD (GPa)						
Max (GPa)		1.16		1.01		1.20
Min (GPa)		1.11		0.77		1.06
CV						
No. specimens		2		2		2


Tensile Strength (MPa)
40
30
20
10
0
0
50
100
150
200
250
Time (weeks)
Control
23 C DI Water
37.8 C DI Water
60 C DI Water


Tensile Modulus (GPa)
2.5
2.0
1.5
1.0
0.5
0.0
0
50
100
150
200
250
Time (weeks)
Control
23 C DI Water
37.8 C DI Water
60 C DI Water


Tensile Strength (MPa)
40
30
20
10
0
0
50
100
150
200
250
Time (weeks)
Control
23 C DI Water
23 C Alkali Solution
23 C Salt Solution


Tensile Modulus (GPa)
2.5
2.0
1.5
1.0
0.5
0.0
0
50
100
150
200
250
Time (weeks)
Control
23 C DI Water
23 C Alkali Solution
23 C Salt Solution

C). Dynamic Mechanical Thermal Analysis

Material: Adhesive Manufacturer: FYFE Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 25 °C and 140 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 6.1 mm, span = 28 mm Precondition: All specimens were preconditioned for 7 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing	
Condition	After preconditioning
T_g by tanδ (Mean)	71.47 °C $[\pm^{1.84}_{1.06}]$ *
tanδ height (Mean)	0.99 $[\pm^{0.03}_{0.05}]$
T_g by E''(Mean)	64.86 °C $[\pm^{0.96}_{0.94}]$
T_g by E'(Mean)	62.16 °C $[\pm^{0.33}_{0.49}]$
E' at T_g – 40 °C (Mean)	3.25×10^8 Pa $[\pm^{7.94\times10^7\ \mathrm{Pa}}_{4.15\times10^7\ \mathrm{Pa}}]$
E' at T_g + 40 °C (Mean)	2.31×10^6 Pa $[\pm^{4.75\times10^5\ \mathrm{Pa}}_{4.40\times10^5\ \mathrm{Pa}}]$
No. specimens	3

* Data is reported as Mean [± Bounds]

C). Dynamic Mechanical Thermal Analysis (contd.)

Material: Adhesive Manufacturer: FYFE Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 25 °C and 140 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 6.1 mm Precondition: All specimens were preconditioned for 7 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 24 weeks						
T_g by tanδ (Mean)	76.99 °C [$\pm^{1.57}_{1.70}$]	75.50 °C [$\pm^{1.63}_{0.83}$]	87.85 °C [$\pm^{2.09}_{2.79}$]	90.34 °C [$\pm^{2.14}_{2.52}$]	74.44 °C [$\pm^{1.32}_{0.92}$]	74.86 °C [$\pm^{4.00}_{2.92}$]
tanδ height (Mean)	0.83 [$\pm^{0.05}_{0.03}$]	0.69 [$\pm^{0.09}_{0.14}$]	0.49 [$\pm^{0.07}_{0.07}$]	0.52 [$\pm^{0.06}_{0.08}$]	0.73 [$\pm^{0.02}_{0.04}$]	0.62 [$\pm^{0.08}_{0.11}$]
T_g by E''(Mean)	68.86 °C [$\pm^{0.31}_{0.59}$]	66.75 °C [$\pm^{1.71}_{1.73}$]	80.10 °C [$\pm^{1.03}_{2.04}$]	78.22 °C [$\pm^{1.97}_{1.97}$]	65.84 °C [$\pm^{0.44}_{0.48}$]	65.61 °C [$\pm^{0.74}_{0.42}$]
T_g by E'(Mean)	65.66 °C [$\pm^{0.80}_{0.49}$]	61.93 °C [$\pm^{0.47}_{0.38}$]	76.51 °C [$\pm^{2.20}_{2.48}$]	70.42 °C [$\pm^{2.18}_{1.72}$]	62.55 °C [$\pm^{2.81}_{2.77}$]	62.40 °C [$\pm^{1.28}_{1.50}$]
E' at T_g – 40 °C (Mean, Pa)	2.51×10^8 [$\pm^{1.00\times10^8}_{7.92\times10^7}$]	1.10×10^8 [$\pm^{7.48\times10^7}_{7.15\times10^7}$]	1.78×10^8 [$\pm^{1.16\times10^8}_{9.38\times10^7}$]	1.43×10^8 [$\pm^{4.56\times10^7}_{4.94\times10^7}$]	1.98×10^8 [$\pm^{6.40\times10^7}_{8.56\times10^7}$]	1.72×10^8 [$\pm^{7.57\times10^7}_{1.35\times10^8}$]
E' at T_g + 40 °C (Mean, Pa)	2.53×10^6 [$\pm^{9.09\times10^4}_{1.50\times10^5}$]	2.62×10^6 [$\pm^{1.38\times10^6}_{1.03\times10^6}$]	5.39×10^6 [$\pm^{2.15\times10^6}_{2.99\times10^6}$]	5.77×10^6 [$\pm^{1.29\times10^6}_{1.64\times10^6}$]	3.44×10^6 [$\pm^{1.02\times10^6}_{9.81\times10^5}$]	2.36×10^6 [$\pm^{8.84\times10^5}_{8.52\times10^5}$]
No. specimens	3	3	3	3	3	3

C). Dynamic Mechanical Thermal Analysis (contd.)

Material: Adhesive Manufacturer: FYFE Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 25 °C and 140 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 6.1 mm Precondition: All specimens were preconditioned for 7 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 48 weeks						
T_g by tanδ (Mean)	76.59 °C [$\pm^{2.16}_{1.54}$]	75.75 °C [$\pm^{0.22}_{0.22}$]	92.45 °C	83.62 °C [$\pm^{2.88}_{1.45}$]	78.99 °C	81.29 °C
tanδ height (Mean)	0.84 [$\pm^{0.05}_{0.03}$]	0.71 [$\pm^{0.00}_{0.00}$]	0.50	0.63 [$\pm^{0.08}_{0.07}$]	0.60	0.55
T_g by E''(Mean)	70.18 °C [$\pm^{1.13}_{1.14}$]	69.55 °C [$\pm^{0.09}_{0.09}$]	79.75 °C	73.58 °C [$\pm^{1.50}_{1.65}$]	69.08 °C	69.10 °C
T_g by E'(Mean)	68.42 °C [$\pm^{0.09}_{0.14}$]	67.85 °C [$\pm^{0.04}_{0.04}$]	77.50 °C	70.75 °C [$\pm^{0.95}_{0.69}$]	66.00 °C	63.91 °C
E' at T_g – 40 °C (Mean, Pa)	2.00×10^8 [$\pm^{4.96\times10^7}_{5.03\times10^7}$]	2.94×10^8 [$\pm^{9.62\times10^7}_{9.62\times10^7}$]	2.12×10^8	2.30×10^8 [$\pm^{1.77\times10^8}_{1.25\times10^8}$]	1.26×10^8	1.90×10^8
E' at T_g + 40 °C (Mean, Pa)	2.62×10^6 [$\pm^{1.21\times10^6}_{9.14\times10^5}$]	4.65×10^6 [$\pm^{8.85\times10^5}_{8.85\times10^5}$]	5.88×10^6	3.54×10^6 [$\pm^{1.91\times10^6}_{1.56\times10^6}$]	3.70×10^6	2.11×10^6
No. specimens	3	2	1	3	1	1

C). Dynamic Mechanical Thermal Analysis (contd.)

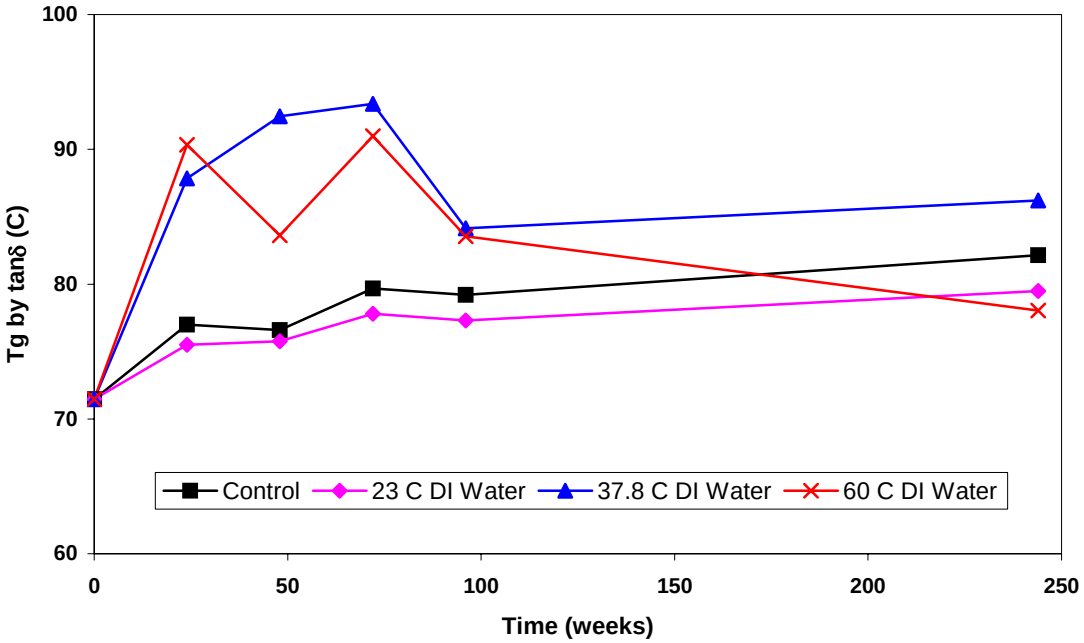
Material: Adhesive Manufacturer: FYFE Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 25 °C and 140 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 6.1 mm Precondition: All specimens were preconditioned for 7 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 72 weeks						
T_g by tanδ (Mean)	79.68 °C [$\pm^{2.48}_{2.48}$]	77.81 °C [$\pm^{3.87}_{3.87}$]	93.39 °C	90.97 °C [$\pm^{0.33}_{0.33}$]	80.58 °C [$\pm^{1.88}_{1.88}$]	77.44 °C [$\pm^{0.27}_{0.27}$]
tanδ height (Mean)	0.82 [$\pm^{0.05}_{0.05}$]	0.66 [$\pm^{0.06}_{0.06}$]	0.44	0.60 [$\pm^{0.03}_{0.03}$]	0.66 [$\pm^{0.02}_{0.02}$]	0.70 [$\pm^{0.01}_{0.01}$]
T_g by E''(Mean)	70.86 °C [$\pm^{0.92}_{0.92}$]	69.26 °C [$\pm^{1.11}_{1.11}$]	79.62 °C	76.10 °C [$\pm^{0.45}_{0.45}$]	68.24 °C [$\pm^{0.78}_{0.78}$]	69.82 °C [$\pm^{1.70}_{1.70}$]
T_g by E'(Mean)	68.89 °C [$\pm^{0.59}_{0.59}$]	67.70 °C [$\pm^{0.49}_{0.49}$]	73.84 °C	73.84 °C [$\pm^{0.93}_{0.93}$]	67.02 °C [$\pm^{0.33}_{0.33}$]	67.77 °C [$\pm^{0.53}_{0.53}$]
E' at T_g – 40 °C (Mean, Pa)	2.54×10^8 [$\pm^{1.54\times10^7}_{1.54\times10^7}$]	1.07×10^8 [$\pm^{1.41\times10^7}_{1.41\times10^7}$]	3.73×10^8	1.47×10^8 [$\pm^{9.83\times10^6}_{9.83\times10^6}$]	2.86×10^8 [$\pm^{4.88\times10^6}_{4.88\times10^6}$]	2.43×10^8 [$\pm^{2.60\times10^7}_{2.60\times10^7}$]
E' at T_g + 40 °C (Mean, Pa)	3.27×10^6 [$\pm^{6.25\times10^5}_{6.25\times10^5}$]	2.52×10^6 [$\pm^{7.83\times10^4}_{7.83\times10^4}$]	5.05×10^6	2.42×10^6 [$\pm^{1.98\times10^5}_{1.98\times10^5}$]	3.91×10^6 [$\pm^{1.54\times10^5}_{1.54\times10^5}$]	5.83×10^6 [$\pm^{1.52\times10^4}_{1.52\times10^4}$]
No. specimens	2	2	1	2	2	2

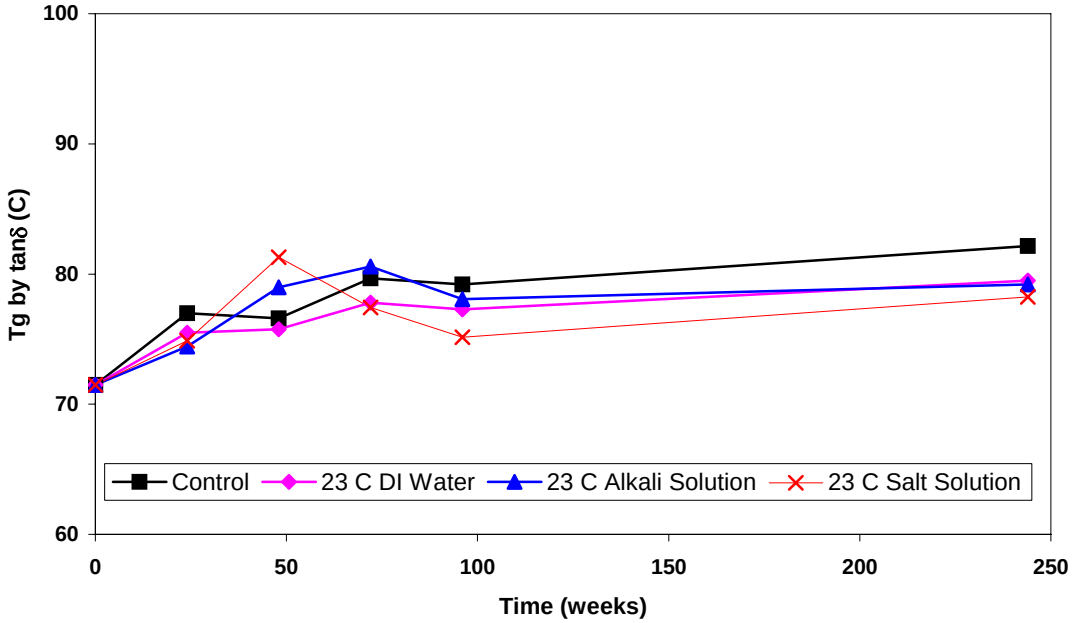
C). Dynamic Mechanical Thermal Analysis (contd.)

Material: Adhesive Manufacturer: FYFE Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 25 °C and 140 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 6.1 mm Precondition: All specimens were preconditioned for 7 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 96 weeks						
T_g by tanδ (Mean)	79.21 °C	77.29 °C [$\pm^{0.87}_{0.87}$]	84.14 °C [$\pm^{1.31}_{1.31}$]	83.55 °C [$\pm^{1.42}_{1.42}$]	78.08 °C [$\pm^{0.79}_{0.79}$]	75.15 °C
tanδ height (Mean)	0.74	0.74 [$\pm^{0.04}_{0.04}$]	0.51 [$\pm^{0.00}_{0.00}$]	0.73 [$\pm^{0.03}_{0.03}$]	0.62 [$\pm^{0.05}_{0.05}$]	0.77
T_g by E''(Mean)	71.87 °C	66.13 °C [$\pm^{0.27}_{0.27}$]	78.55 °C [$\pm^{0.20}_{0.20}$]	72.39 °C [$\pm^{0.45}_{0.45}$]	70.30 °C [$\pm^{2.26}_{2.26}$]	68.89 °C
T_g by E'(Mean)	70.61 °C	64.28 °C [$\pm^{0.22}_{0.22}$]	77.67 °C [$\pm^{0.08}_{0.08}$]	72.13 °C [$\pm^{0.55}_{0.55}$]	69.82 °C [$\pm^{2.17}_{2.17}$]	65.72 °C
E' at T_g – 40 °C (Mean, Pa)	1.59×10^{8}	2.56×10^{8} [$\pm^{7.32\times10^{7}}_{7.32\times10^{7}}$]	2.81×10^{8} [$\pm^{1.00\times10^{7}}_{1.00\times10^{7}}$]	3.32×10^{8} [$\pm^{4.56\times10^{7}}_{4.56\times10^{7}}$]	1.08×10^{8} [$\pm^{3.88\times10^{7}}_{3.88\times10^{7}}$]	3.42×10^{8}
E' at T_g + 40 °C (Mean, Pa)	1.66×10^{6}	4.60×10^{6} [$\pm^{1.63\times10^{6}}_{1.63\times10^{6}}$]	5.33×10^{6} [$\pm^{4.75\times10^{5}}_{4.75\times10^{5}}$]	5.25×10^{6} [$\pm^{1.59\times10^{6}}_{1.59\times10^{6}}$]	2.61×10^{6} [$\pm^{1.50\times10^{5}}_{1.50\times10^{5}}$]	5.93×10^{6}
No. specimens	1	2	2	2	2	1

C). Dynamic Mechanical Thermal Analysis (contd.)

Material: Adhesive Manufacturer: FYFE Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 25 °C and 140 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 6.1 mm Precondition: All specimens were preconditioned for 7 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 244 weeks						
T_g by tanδ (Mean)	82.15 °C [$\pm^{0.92}_{0.92}$]	79.50 °C [$\pm^{0.30}_{0.30}$]	86.20 °C [$\pm^{2.14}_{2.14}$]	78.04 °C	79.21 °C	78.24 °C [$\pm^{3.80}_{3.80}$]
tanδ height (Mean)	0.81 [$\pm^{0.02}_{0.02}$]	0.56 [$\pm^{0.01}_{0.01}$]	0.39 [$\pm^{0.04}_{0.04}$]	0.65	0.56	0.59 [$\pm^{0.06}_{0.06}$]
T_g by E''(Mean)	76.63 °C [$\pm^{0.08}_{0.08}$]	70.03 °C [$\pm^{1.02}_{1.02}$]	79.00 °C [$\pm^{3.05}_{3.05}$]	68.56 °C	70.04 °C	71.11 °C [$\pm^{2.94}_{2.94}$]
T_g by E'(Mean)	73.40 °C [$\pm^{0.05}_{0.05}$]	67.48 °C [$\pm^{0.50}_{0.50}$]	74.86 °C [$\pm^{0.10}_{0.10}$]	62.00 °C	66.52 °C	66.57 °C [$\pm^{1.03}_{1.03}$]
E' at T_g – 40 °C (Mean, Pa)	3.68×10^8 [$\pm^{1.25\times10^8}_{1.25\times10^8}$]	2.56×10^8 [$\pm^{2.61\times10^7}_{2.61\times10^7}$]	1.33×10^8 [$\pm^{1.35\times10^7}_{1.35\times10^7}$]	3.77×10^8	1.95×10^8	2.77×10^8 [$\pm^{1.03\times10^8}_{1.03\times10^8}$]
E' at T_g + 40 °C (Mean, Pa)	5.21×10^6 [$\pm^{1.07\times10^6}_{1.07\times10^6}$]	4.80×10^6 [$\pm^{4.72\times10^4}_{4.72\times10^4}$]	4.47×10^6 [$\pm^{1.58\times10^6}_{1.58\times10^6}$]	9.03×10^6	4.63×10^6	4.95×10^6 [$\pm^{1.51\times10^6}_{1.51\times10^6}$]
No. specimens	2	2	2	1	1	2


100
90
80
70
60
Tg by tanδ (C)
0
50
100
150
200
250
Time (weeks)
Control
23 C DI Water
37.8 C DI Water
60 C DI Water


100
90
80
70
60
Tg by tanδ (C)
0
50
100
150
200
250
Time (weeks)
Control
23 C DI Water
23 C Alkali Solution
23 C Salt Solution

GENERAL INFORMATION

Material: Carbon fiber reinforced epoxy, prefabricated strip
Manufacturer: FYFE
Resin Type: Epoxy
Fiber Type: Carbon
Fabric Type: N/A, Unidirectional tow
Fabric Weight: N/A
Type of Cure: Elevated Temperature
Method of Manufacture: Pullforming
Density: 1.53 g/cm^3
Fiber Volume Fraction: 0.62 (determined by acid digestion test)
Resin Volume Fraction: 0.37
Void Volume Fraction: 0.01
Configuration: Strip 101.8 mm wide × 1.9 mm thick

PROPERTIES

A). Moisture Uptake (Data for a period of 258 weeks)

Material: Carbon fiber reinforced epoxy, prefabricated strip Manufacturer: FYFE Test Method: Gravimetric, ASTM D 5229/D 5229M - 92 Nominal Specimen Size (Length × Width × Thickness): 25.4 mm × 25.4 mm × 1.9 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Curve shape	Flat	2-stage[1]	2-stage[1]	2-stage[1]	Sigmoidal[2]	2-stage[1]
M_{max} (%)	0.07	0.43	0.56	1.24	1.57	0.39
Time for M_{max}	At 173 weeks	At end	At end	At end	At 78 weeks	At end
M_∞	0.00					
M_∞ (%) in stage 1 [3]		0.32	0.32	0.32	1.40	0.27
D (mm^2/s) in stage 1		5.34×10^{-8}	2.56×10^{-7}	9.76×10^{-7}	2.84×10^{-8}	6.70×10^{-8}
k ($1/s^{0.5}$) in stage 2		2.19×10^{-5}	5.50×10^{-5}	1.97×10^{-4}	1.07×10^{-5}	3.08×10^{-5}
2-stage formula (details see Ref.1)	$M_t = M_\infty\left(1+k\sqrt{t}\right)\left\{1-\exp\left[-7.3\left(\frac{Dt}{h^2}\right)^{0.75}\right]\right\}$					

1. Following Bao, L.R., Yee, A.F. and Lee, C.Y.C., "Moisture Absorption and Hygrothermal Aging in a Bismaleimide Resin" *Polymer*, 42, 2001, pp. 7327-7333.
2. Use 2-stage model to curve fit the data.
3. M_∞ determined following the graphical method in Tsotsis, T. K. and Weitsman, Y., "A Simple Graphical-Method For Determining Diffusion Parameters For 2-Stage Sorption In Composites." *Journal Of Materials Science Letters*, 13[22], 1994, pp. 1635-1636.

B). Tensile Test

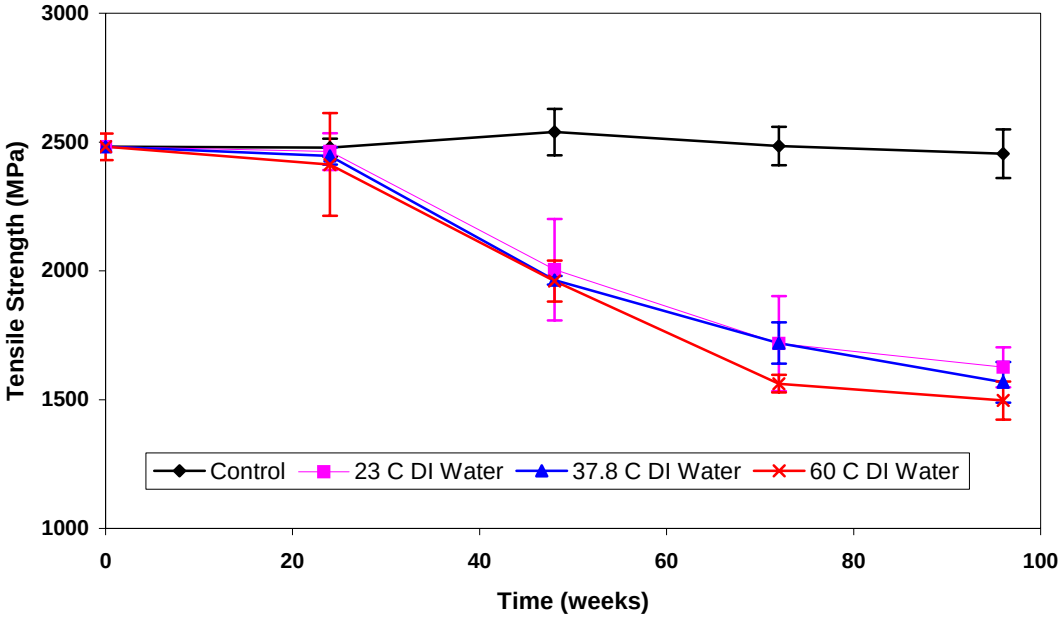
Material: Carbon fiber reinforced epoxy, prefabricated strip Manufacturer: FYFE Test Method: ASTM D 3039/D 3039M - 00 Nominal Specimen Size (Length × Width × Thickness): 254 mm × 12.7 mm × 1.9 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing	
Condition	After preconditioning
Strength	
Mean (MPa)	2481.65
STD (MPa)	51.38
Max (MPa)	2539.54
Min (MPa)	2406.27
CV	0.02
No. specimens	5
Modulus	
Mean (GPa)	126.77
STD (GPa)	3.37
Max (GPa)	129.87
Min (GPa)	121.21
CV	0.03
No. specimens	5

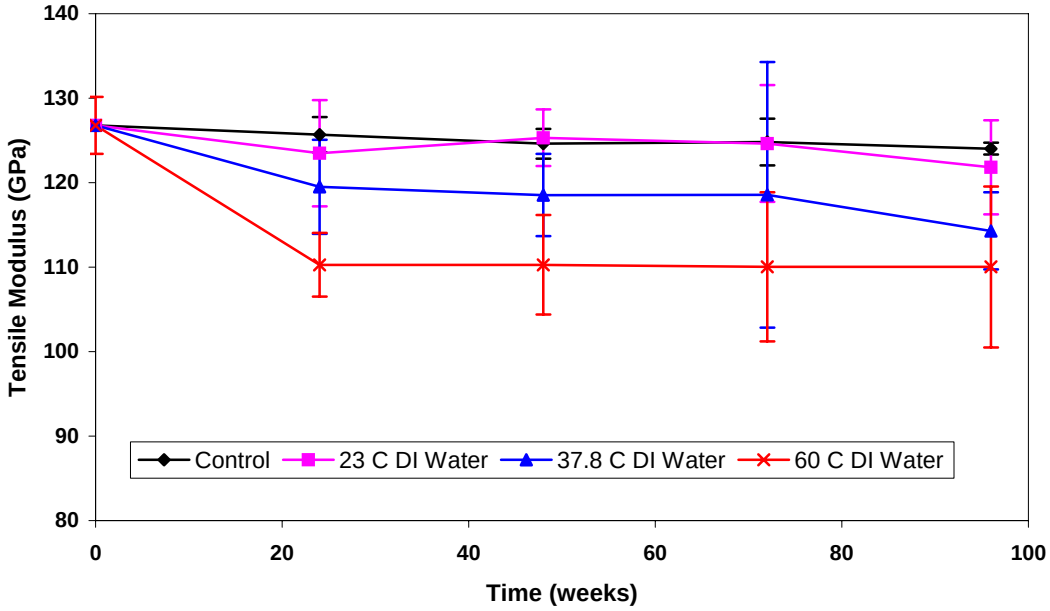
B). Tensile Test (contd.)

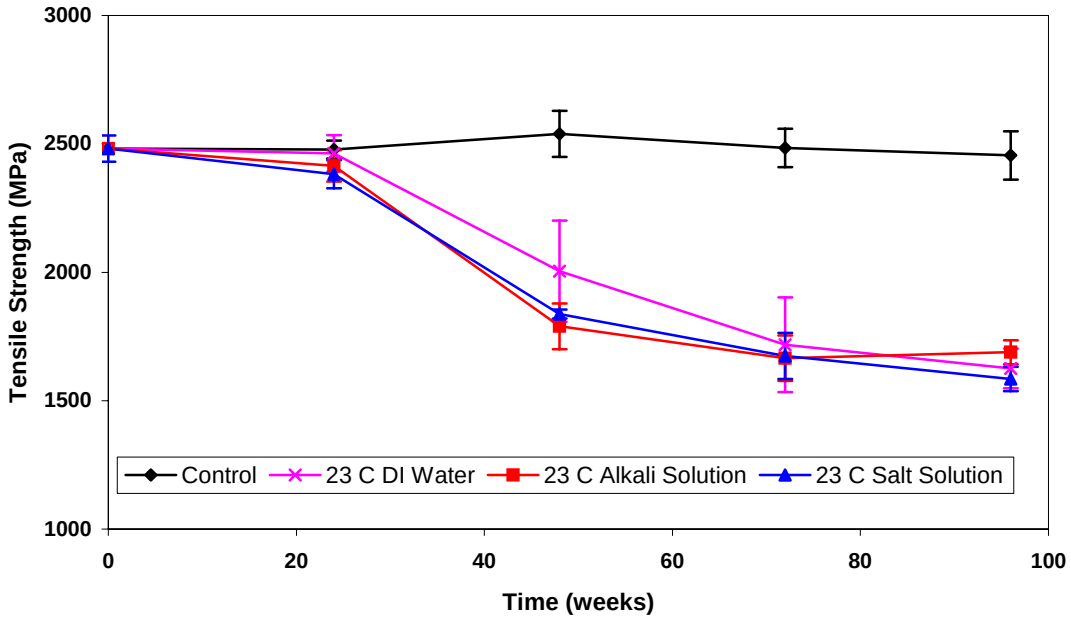
Material: Carbon fiber reinforced epoxy, prefabricated strip Manufacturer: FYFE Test Method: ASTM D 3039/D 3039M - 00 Nominal Specimen Size (Length × Width × Thickness): 254 mm × 12.7 mm × 1.9 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 24 weeks						
Strength						
Mean (MPa)	2478.14	2462.86	2446.34	2412.71	2414.40	2382.15
STD (MPa)	34.99	71.41	33.48	199.39	60.84	54.68
Max (MPa)	2511.29	2568.51	2487.15	2577.32	2505.01	2443.51
Min (MPa)	2426.27	2393.53	2407.15	2080.54	2342.97	2293.96
CV	0.01	0.03	0.01	0.08	0.03	0.02
No. specimens	5	5	4	5	5	5
Modulus						
Mean (GPa)	125.68	123.49	119.50	110.28	116.85	120.40
STD (GPa)	2.10	6.29	5.58	3.78	2.06	6.44
Max (GPa)	129.11	128.86	125.69	114.50	119.58	127.38
Min (GPa)	123.55	116.19	114.83	104.28	113.89	112.52
CV	0.02	0.05	0.05	0.03	0.02	0.05
No. specimens	5	5	4	5	5	5
Exposure period: 48 weeks						
Strength						
Mean (MPa)	2538.88	2004.54	1963.49	1960.09	1789.73	1837.69
STD (MPa)	89.85	196.54	17.21	79.16	88.81	17.24
Max (MPa)	2670.98	2208.69	1984.01	2070.37	1874.78	1851.54
Min (MPa)	2436.35	1749.46	1942.56	1883.27	1703.08	1807.98
CV	0.04	0.10	0.01	0.04	0.05	0.01
No. specimens	5	5	5	4	4	5
Modulus						
Mean (GPa)	124.61	125.31	118.54	110.28	116.06	119.15
STD (GPa)	1.76	3.35	4.88	5.88	7.14	2.84
Max (GPa)	126.40	128.71	124.60	114.27	124.56	123.24
Min (GPa)	122.64	121.49	112.30	101.59	107.59	115.39
CV	0.01	0.03	0.04	0.05	0.06	0.02
No. specimens	5	5	5	4	4	5

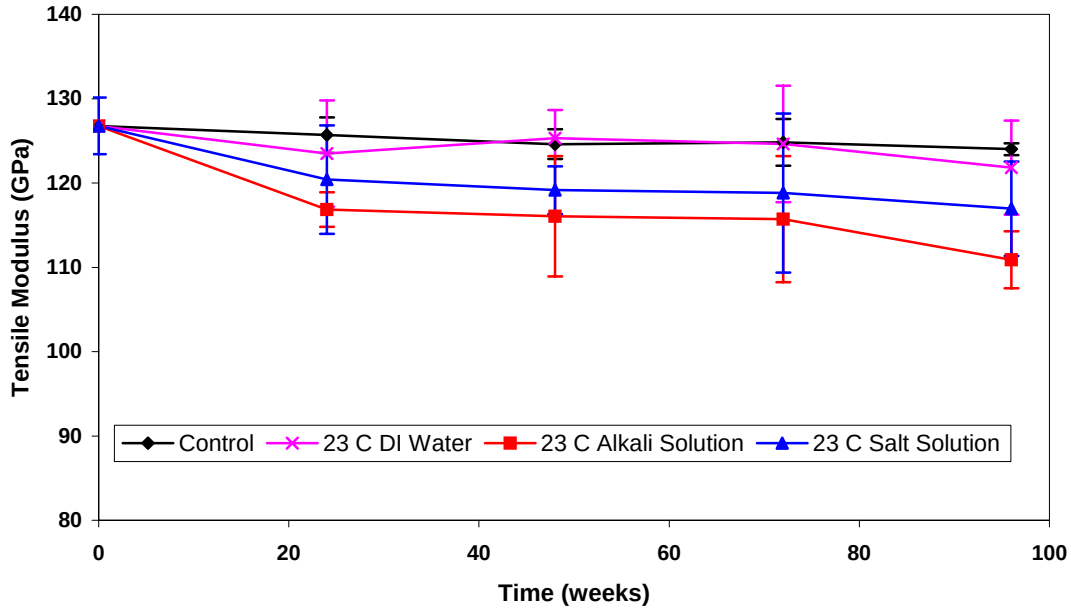
B). Tensile Test (contd.)

Material: Carbon fiber reinforced epoxy, prefabricated strip Manufacturer: FYFE Test Method: ASTM D 3039/D 3039M - 00 Nominal Specimen Size (Length × Width × Thickness): 254 mm × 12.7 mm × 1.9 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 72 weeks						
Strength						
Mean (MPa)	2484.12	1717.83	1719.70	1561.88	1665.71	1673.73
STD (MPa)	74.31	184.41	79.95	34.32	88.68	89.63
Max (MPa)	2570.27	1865.18	1809.94	1597.42	1735.93	1801.18
Min (MPa)	2412.40	1449.00	1647.23	1515.54	1535.84	1566.54
CV	0.03	0.11	0.05	0.02	0.05	0.05
No. specimens	5	4	5	4	4	5
Modulus						
Mean (GPa)	124.82	124.62	118.56	110.05	115.70	118.81
STD (GPa)	2.78	6.91	15.71	8.83	7.48	9.43
Max (GPa)	127.63	133.52	136.32	119.99	122.24	128.14
Min (GPa)	121.50	117.05	100.43	99.28	108.92	106.54
CV	0.02	0.06	0.13	0.08	0.06	0.08
No. specimens	5	4	5	4	4	5
Exposure period: 96 weeks						
Strength						
Mean (MPa)	2455.12	1625.82	1567.58	1496.47	1688.66	1584.49
STD (MPa)	94.31	77.40	78.98	73.83	46.74	47.70
Max (MPa)	2579.46	1726.75	1637.83	1563.30	1728.97	1643.90
Min (MPa)	2351.31	1562.08	1458.78	1372.03	1621.83	1517.71
CV	0.04	0.05	0.05	0.05	0.03	0.03
No. specimens	4	5	5	5	4	5
Modulus						
Mean (GPa)	124.02	121.81	114.29	110.03	110.90	116.95
STD (GPa)	0.70	5.58	4.56	9.53	3.37	5.59
Max (GPa)	124.82	127.11	119.27	115.53	113.62	120.81
Min (GPa)	123.10	113.73	106.86	93.34	106.11	107.12
CV	0.01	0.05	0.04	0.09	0.03	0.05
No. specimens	4	5	5	5	4	5


3000
2500
2000
1500
1000
Tensile Strength (MPa)
0
20
40
60
80
100
Time (weeks)
Control
23 C DI Water
37.8 C DI Water
60 C DI Water


140
130
120
110
100
90
80
Tensile Modulus (GPa)
0
20
40
60
80
100
Time (weeks)
Control
23 C DI Water
37.8 C DI Water
60 C DI Water


3000
2500
2000
1500
1000
Tensile Strength (MPa)
0
20
40
60
80
100
Time (weeks)
Control
23 C DI Water
23 C Alkali Solution
23 C Salt Solution


140
130
120
110
100
90
80
Tensile Modulus (GPa)
0
20
40
60
80
100
Time (weeks)
Control
23 C DI Water
23 C Alkali Solution
23 C Salt Solution

C). Dynamic Mechanical Thermal Analysis

Material: Carbon fiber reinforced epoxy, prefabricated strip Manufacturer: FYFE Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 25 °C and 220 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 1.9 mm, span = 28 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing	
Condition	After preconditioning
T_g by tanδ	140.05 °C $[\pm^{0.68}_{0.47}]$ *
tanδ height	0.54 $[\pm^{0.01}_{0.01}]$
T_g by E''	134.99 °C $[\pm^{0.15}_{0.11}]$
T_g by E'	131.06 °C $[\pm^{0.59}_{0.49}]$
E' at T_g – 40 °C	3.82×10^{10} Pa $[\pm^{5.33\times10^{9}\text{ Pa}}_{4.36\times10^{9}\text{ Pa}}]$
E' at T_g + 40 °C	1.70×10^{9} Pa $[\pm^{4.49\times10^{8}\text{ Pa}}_{6.19\times10^{8}\text{ Pa}}]$
No. specimens	3

* Data is reported as Mean [± Bounds]

E). Dynamic Mechanical Thermal Analysis (contd.)

Material: Carbon fiber reinforced epoxy, prefabricated strip Manufacturer: FYFE Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 25 °C and 220 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 1.9 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 24 weeks						
T_g by tanδ	140.18 °C [$\pm^{0.96}_{1.06}$]	127.06 °C [$\pm^{1.49}_{0.87}$]	125.36 °C [$\pm^{3.10}_{4.71}$]	123.46 °C [$\pm^{2.28}_{1.94}$]	127.61 °C [$\pm^{1.70}_{2.79}$]	127.93 °C [$\pm^{0.54}_{0.46}$]
tanδ height	0.55 [$\pm^{0.02}_{0.02}$]	0.49 [$\pm^{0.01}_{0.01}$]	0.49 [$\pm^{0.01}_{0.01}$]	0.44 [$\pm^{0.03}_{0.02}$]	0.50 [$\pm^{0.02}_{0.01}$]	0.51 [$\pm^{0.02}_{0.01}$]
T_g by E''	134.69 °C [$\pm^{0.87}_{1.40}$]	121.57 °C [$\pm^{1.17}_{0.70}$]	120.12 °C [$\pm^{2.60}_{4.08}$]	119.03 °C [$\pm^{2.04}_{1.54}$]	121.35 °C [$\pm^{2.12}_{1.73}$]	122.64 °C [$\pm^{1.16}_{0.66}$]
T_g by E'	131.74 °C [$\pm^{0.88}_{1.12}$]	116.68 °C [$\pm^{2.78}_{1.46}$]	116.25 °C [$\pm^{3.30}_{4.62}$]	111.19 °C [$\pm^{1.42}_{0.75}$]	119.76 °C [$\pm^{1.88}_{2.35}$]	121.49 °C [$\pm^{0.72}_{1.01}$]
E' at T_g – 40 °C (Pa)	4.04×10^{10} [$\pm^{2.82\times10^{9}}_{2.32\times10^{9}}$]	3.39×10^{10} [$\pm^{4.33\times10^{9}}_{5.78\times10^{9}}$]	2.70×10^{10} [$\pm^{4.56\times10^{9}}_{6.30\times10^{9}}$]	3.19×10^{10} [$\pm^{9.76\times10^{8}}_{1.28\times10^{9}}$]	3.15×10^{10} [$\pm^{3.13\times10^{9}}_{4.87\times10^{9}}$]	3.18×10^{10} [$\pm^{6.14\times10^{9}}_{7.59\times10^{9}}$]
E' at T_g + 40 °C (Pa)	1.71×10^{9} [$\pm^{6.27\times10^{8}}_{8.33\times10^{8}}$]	1.57×10^{9} [$\pm^{5.39\times10^{7}}_{1.04\times10^{8}}$]	1.11×10^{9} [$\pm^{3.14\times10^{8}}_{4.47\times10^{8}}$]	1.36×10^{9} [$\pm^{2.54\times10^{8}}_{2.22\times10^{8}}$]	1.41×10^{9} [$\pm^{2.67\times10^{8}}_{2.45\times10^{8}}$]	1.44×10^{9} [$\pm^{4.24\times10^{8}}_{3.89\times10^{8}}$]
No. specimens	3	3	3	3	3	3

E). Dynamic Mechanical Thermal Analysis (contd.)

Material: Carbon fiber reinforced epoxy, prefabricated strip Manufacturer: FYFE Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 25 °C and 220 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 1.9 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 48 weeks						
T_g by tanδ	137.30 °C [$\pm^{0.08}_{0.08}$]	127.62 °C [$\pm^{0.94}_{0.83}$]	126.21 °C [$\pm^{2.24}_{1.42}$]	122.44 °C [$\pm^{1.21}_{2.13}$]	127.95 °C [$\pm^{1.22}_{0.66}$]	126.49 °C [$\pm^{0.66}_{1.05}$]
tanδ height	0.54 [$\pm^{0.01}_{0.01}$]	0.47 [$\pm^{0.04}_{0.05}$]	0.49 [$\pm^{0.05}_{0.03}$]	0.44 [$\pm^{0.04}_{0.03}$]	0.47 [$\pm^{0.03}_{0.02}$]	0.48 [$\pm^{0.00}_{0.00}$]
T_g by E''	133.23 °C [$\pm^{0.52}_{0.52}$]	121.74 °C [$\pm^{1.00}_{1.37}$]	121.16 °C [$\pm^{0.28}_{0.45}$]	117.80 °C [$\pm^{1.18}_{2.18}$]	121.89 °C [$\pm^{1.45}_{1.02}$]	120.65 °C [$\pm^{1.89}_{1.69}$]
T_g by E'	129.76 °C [$\pm^{0.60}_{0.60}$]	119.56 °C [$\pm^{0.79}_{0.74}$]	117.80 °C [$\pm^{0.67}_{0.64}$]	115.19 °C [$\pm^{1.79}_{2.67}$]	119.51 °C [$\pm^{1.50}_{0.99}$]	118.56 °C [$\pm^{1.93}_{1.76}$]
E' at T_g – 40 °C (Pa)	4.35×10^{10} [$\pm^{2.44\times10^{9}}_{2.44\times10^{9}}$]	2.87×10^{10} [$\pm^{1.23\times10^{10}}_{9.75\times10^{9}}$]	3.38×10^{10} [$\pm^{6.18\times10^{9}}_{3.35\times10^{9}}$]	3.24×10^{10} [$\pm^{3.11\times10^{9}}_{2.10\times10^{9}}$]	3.53×10^{10} [$\pm^{3.02\times10^{9}}_{3.39\times10^{9}}$]	2.83×10^{10} [$\pm^{7.10\times10^{9}}_{5.22\times10^{9}}$]
E' at T_g + 40 °C (Pa)	3.34×10^{9} [$\pm^{5.02\times10^{8}}_{5.02\times10^{8}}$]	1.08×10^{9} [$\pm^{7.79\times10^{8}}_{4.87\times10^{8}}$]	1.68×10^{9} [$\pm^{6.12\times10^{8}}_{6.76\times10^{8}}$]	2.04×10^{9} [$\pm^{7.55\times10^{7}}_{7.50\times10^{7}}$]	1.35×10^{9} [$\pm^{3.71\times10^{8}}_{2.16\times10^{8}}$]	1.11×10^{9} [$\pm^{6.29\times10^{8}}_{4.32\times10^{8}}$]
No. specimens	2	3	3	3	3	3

E). Dynamic Mechanical Thermal Analysis (contd.)

Material: Carbon fiber reinforced epoxy, prefabricated strip Manufacturer: FYFE Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 25 °C and 220 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 1.9 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 72 weeks						
T_g by tanδ	137.48 °C [$\pm^{0.03}_{0.03}$]	125.58 °C [$\pm^{0.63}_{0.63}$]	124.26 °C [$\pm^{0.40}_{0.40}$]	121.40 °C	126.17 °C [$\pm^{0.14}_{0.14}$]	126.17 °C [$\pm^{0.70}_{0.70}$]
tanδ height	0.55 [$\pm^{0.01}_{0.01}$]	0.48 [$\pm^{0.01}_{0.01}$]	0.47 [$\pm^{0.00}_{0.00}$]	0.45	0.48 [$\pm^{0.02}_{0.02}$]	0.48 [$\pm^{0.01}_{0.01}$]
T_g by E''	131.71 °C [$\pm^{0.80}_{0.80}$]	118.50 °C [$\pm^{0.71}_{0.71}$]	119.06 °C [$\pm^{0.22}_{0.22}$]	117.23 °C	120.40 °C [$\pm^{0.16}_{0.16}$]	120.36 °C [$\pm^{0.08}_{0.08}$]
T_g by E'	129.50 °C [$\pm^{1.34}_{1.34}$]	115.45 °C [$\pm^{0.74}_{0.74}$]	117.49 °C [$\pm^{0.93}_{0.93}$]	111.43 °C	118.16 °C [$\pm^{0.00}_{0.00}$]	117.70 °C [$\pm^{1.00}_{1.00}$]
E' at T_g – 40 °C (Pa)	3.39×10^{10} [$\pm^{6.29\times10^9}_{6.29\times10^9}$]	3.10×10^{10} [$\pm^{2.52\times10^9}_{2.52\times10^9}$]	3.13×10^{10} [$\pm^{4.03\times10^9}_{4.03\times10^9}$]	3.35×10^{10}	2.93×10^{10} [$\pm^{5.65\times10^9}_{5.65\times10^9}$]	2.74×10^{10} [$\pm^{8.36\times10^9}_{8.36\times10^9}$]
E' at T_g + 40 °C (Pa)	1.45×10^9 [$\pm^{4.00\times10^8}_{4.00\times10^8}$]	1.15×10^9 [$\pm^{7.92\times10^7}_{7.92\times10^7}$]	1.18×10^9 [$\pm^{2.30\times10^8}_{2.30\times10^8}$]	1.47×10^9	1.16×10^9 [$\pm^{2.49\times10^8}_{2.49\times10^8}$]	1.08×10^9 [$\pm^{1.20\times10^6}_{1.20\times10^6}$]
No. specimens	2	2	2	1	2	2

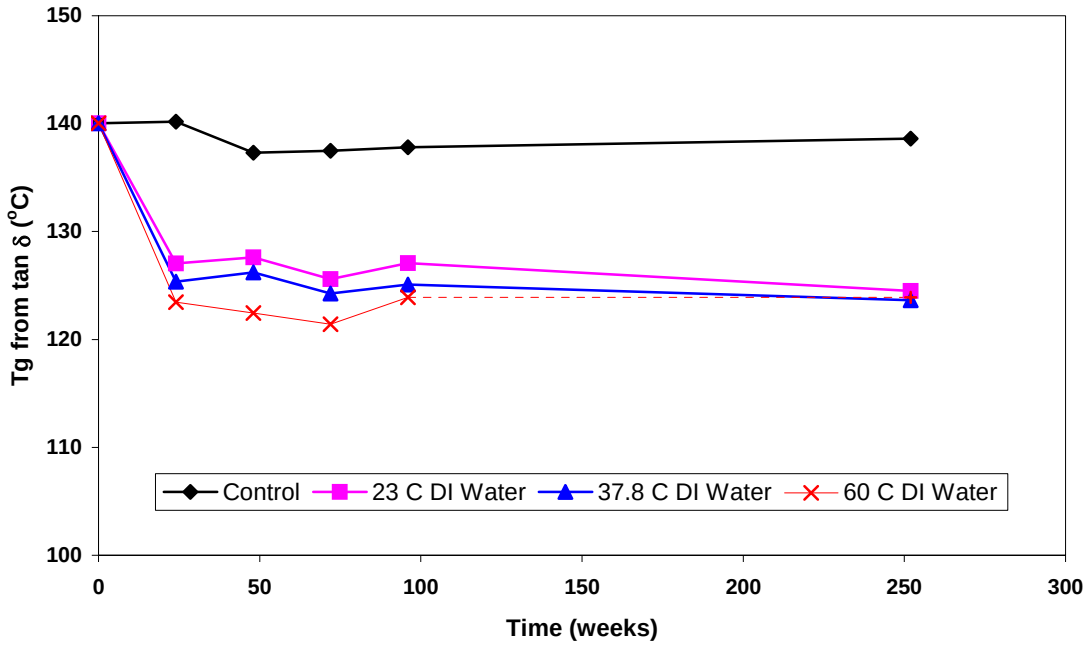
E). Dynamic Mechanical Thermal Analysis (contd.)

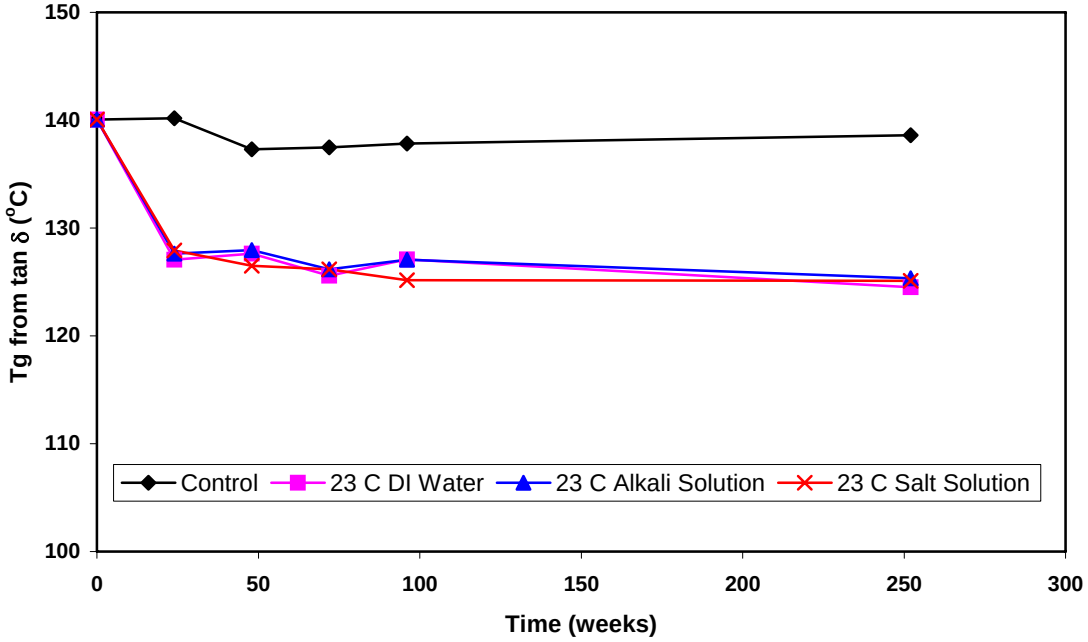
Material: Carbon fiber reinforced epoxy, prefabricated strip Manufacturer: FYFE Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 25 °C and 220 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 1.9 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 96 weeks						
T_g by tanδ	137.82 °C	127.09 °C $[\pm^{1.03}_{1.03}]$	125.08 °C $[\pm^{1.05}_{1.05}]$	123.90 °C $[\pm^{1.15}_{1.15}]$	127.07 °C $[\pm^{0.23}_{0.23}]$	125.16 °C $[\pm^{2.87}_{2.87}]$
tanδ height	0.54	0.53 $[\pm^{0.00}_{0.00}]$	0.53 $[\pm^{0.05}_{0.05}]$	0.49 $[\pm^{0.02}_{0.02}]$	0.49 $[\pm^{0.01}_{0.01}]$	0.51 $[\pm^{0.05}_{0.05}]$
T_g by E''	131.91 °C	120.72 °C $[\pm^{0.42}_{0.42}]$	118.94 °C $[\pm^{1.29}_{1.29}]$	118.42 °C $[\pm^{0.37}_{0.37}]$	121.64 °C $[\pm^{0.25}_{0.25}]$	120.13 °C $[\pm^{3.21}_{3.21}]$
T_g by E'	129.28 °C	118.16 °C $[\pm^{0.28}_{0.28}]$	117.71 °C $[\pm^{0.73}_{0.73}]$	115.88 °C $[\pm^{0.29}_{0.29}]$	119.32 °C $[\pm^{0.12}_{0.12}]$	116.47 °C $[\pm^{2.70}_{2.70}]$
E' at T_g – 40 °C (Pa)	5.41×10^{10}	5.25×10^{10} $[\pm^{1.12\times10^{10}}_{1.12\times10^{10}}]$	4.47×10^{10} $[\pm^{1.74\times10^{9}}_{1.74\times10^{9}}]$	5.48×10^{10} $[\pm^{2.72\times10^{9}}_{2.72\times10^{9}}]$	4.41×10^{10} $[\pm^{3.46\times10^{9}}_{3.46\times10^{9}}]$	5.47×10^{10} $[\pm^{1.45\times10^{10}}_{1.45\times10^{10}}]$
E' at T_g + 40 °C (Pa)	1.74×10^{9}	2.32×10^{9} $[\pm^{5.71\times10^{8}}_{5.71\times10^{8}}]$	2.14×10^{9} $[\pm^{3.69\times10^{8}}_{3.69\times10^{8}}]$	3.29×10^{9} $[\pm^{5.76\times10^{8}}_{5.76\times10^{8}}]$	1.66×10^{9} $[\pm^{8.94\times10^{8}}_{8.94\times10^{8}}]$	2.59×10^{9} $[\pm^{1.04\times10^{9}}_{1.04\times10^{9}}]$
No. specimens	1	2	2	2	2	2

E). Dynamic Mechanical Thermal Analysis (contd.)

Material: Carbon fiber reinforced epoxy, prefabricated strip Manufacturer: FYFE Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 25 °C and 220 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 1.9 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 252 weeks						
T_g by tanδ	138.62 °C [$\pm^{0.46}_{0.46}$]	124.51 °C [$\pm^{0.04}_{0.04}$]	123.64 °C	123.90 °C	125.34 °C [$\pm^{1.18}_{1.18}$]	125.11 °C [$\pm^{0.47}_{0.47}$]
tanδ height	0.55 [$\pm^{0.02}_{0.02}$]	0.50 [$\pm^{0.00}_{0.00}$]	0.51		0.44 [$\pm^{0.01}_{0.01}$]	0.51 [$\pm^{0.01}_{0.01}$]
T_g by E''	132.79 °C [$\pm^{0.73}_{0.73}$]	120.15 °C [$\pm^{0.34}_{0.34}$]	118.97 °C		121.08 °C [$\pm^{1.23}_{1.23}$]	120.02 °C [$\pm^{0.36}_{0.36}$]
T_g by E'	131.49 °C [$\pm^{0.38}_{0.38}$]	118.40 °C [$\pm^{1.05}_{1.05}$]	116.89 °C		120.28 °C [$\pm^{1.73}_{1.73}$]	118.02 °C [$\pm^{0.52}_{0.52}$]
E' at T_g – 40 °C (Pa)	3.52×10^{10} [$\pm^{7.78\times10^{9}}_{7.78\times10^{9}}$]	3.55×10^{10} [$\pm^{2.69\times10^{8}}_{2.69\times10^{8}}$]	3.31×10^{10}		2.89×10^{10} [$\pm^{4.42\times10^{9}}_{4.42\times10^{9}}$]	3.98×10^{10} [$\pm^{3.55\times10^{9}}_{3.55\times10^{9}}$]
E' at T_g + 40 °C (Pa)	2.13×10^{9} [$\pm^{5.25\times10^{8}}_{5.25\times10^{8}}$]	2.26×10^{9} [$\pm^{3.15\times10^{8}}_{3.15\times10^{8}}$]	2.54×10^{9}		1.38×10^{9} [$\pm^{2.84\times10^{8}}_{2.84\times10^{8}}$]	2.26×10^{9} [$\pm^{3.34\times10^{8}}_{3.34\times10^{8}}$]
No. specimens	2	2	1	+	2	2

+: Not statistically sufficient


150
140
130
120
110
100
Tg from tan δ (°C)
0
50
100
150
200
250
300
Time (weeks)
Control
23 C DI Water
37.8 C DI Water
60 C DI Water


150
140
130
120
110
100
Tg from tan δ (°C)
0
50
100
150
200
250
300
Time (weeks)
Control
23 C DI Water
23 C Alkali Solution
23 C Salt Solution

FYFE WET LAYUP SYSTEM

GENERAL INFORMATION

Material: Epoxy
Manufacturer: FYFE
Resin Type: 2 component epoxy
Fiber Type: N/A
Fabric Type: N/A
Fabric Weight: N/A
Type of Cure: Ambient Temperature
Method of Manufacture: Cast
Density: 1.08 g/cm^3
Fiber Volume Fraction: N/A
Resin Volume Fraction: N/A
Void Volume Fraction: N/A
Configuration: N/A

PROPERTIES

A). Moisture Uptake (Data for a period of 260 weeks)

Material: Epoxy Manufacturer: FYFE Test Method: Gravimetric, ASTM D 5229/D 5229M - 92 Nominal Specimen Size (Length × Width × Thickness): 25.4 mm × 25.4 mm × 6.1 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Curve shape		2-stage[1]	2-stage[1]	Sigmoidal[2]	2-stage[1]	2-stage[1]
M_{max} (%)	0.49	3.04	2.90	2.36	3.42	2.79
Time for M_{max}	At 198 weeks	At end	At end	At 72 weeks	At end	At end
M_∞						
M_∞ (%) in stage 1 [3]		2.44	2.52	2.19	2.80	2.20
D (mm^2/s) in stage 1		6.69×10^{-8}	1.84×10^{-7}	9.92×10^{-7}	7.33×10^{-8}	5.63×10^{-8}
k (1/s$^{0.5}$) in stage 2		1.90×10^{-5}	1.10×10^{-5}	6.30×10^{-6}	1.68×10^{-5}	2.19×10^{-5}
2-stage formula (details see Ref.1)	$M_t = M_\infty\left(1+k\sqrt{t}\right)\left\{1-\exp\left[-7.3\left(\frac{Dt}{h^2}\right)^{0.75}\right]\right\}$					

1. Following Bao, L.R., Yee, A.F. and Lee, C.Y.C., "Moisture Absorption and Hygrothermal Aging in a Bismaleimide Resin" *Polymer*, 42, 2001, pp. 7327-7333.
2. Use 2-stage model to curve fit the data.
3. M_∞ determined following the graphical method in Tsotsis, T. K. and Weitsman, Y., "A Simple Graphical-Method For Determining Diffusion Parameters For 2-Stage Sorption In Composites." *Journal Of Materials Science Letters*, 13[22], 1994, pp. 1635-1636.

B). Tensile Test

Material: Epoxy Manufacturer: FYFE Test Method: ASTM D 638 - 99 Nominal Specimen Size: According to ASTM standard, Overall Length = 165 mm, Gage Length = 50 mm, Width of Narrow Section = 13 mm, Thickness = 6 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing	
Condition	After preconditioning
Strength	
Mean (MPa)	64.91
STD (MPa)	5.81
Max (MPa)	69.96
Min (MPa)	55.82
CV	0.09
No. specimens	5
Modulus	
Mean (GPa)	3.40
STD (GPa)	0.11
Max (GPa)	3.59
Min (GPa)	3.29
CV	0.03
No. specimens	5

B). Tensile Test (contd.)

Material: Epoxy Manufacturer: FYFE Test Method: ASTM D 638 - 99 Nominal Specimen Size: According to ASTM standard Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 24 weeks						
Strength						
Mean (MPa)	63.10	61.74	61.20	60.90	64.05	62.66
STD (MPa)	5.88	2.40	4.19	8.39	3.09	7.23
Max (MPa)	69.51	64.40	64.33	66.63	66.46	69.46
Min (MPa)	57.96	58.69	55.04	48.55	59.63	52.07
CV	0.09	0.04	0.07	0.14	0.05	0.12
No. specimens	5	5	4	4	5	5
Modulus						
Mean (GPa)	3.51	3.22	2.86	2.83	3.07	3.01
STD (GPa)	0.09	0.04	0.06	1.04	0.21	0.16
Max (GPa)	3.61	3.28	2.93	3.97	3.31	3.27
Min (GPa)	3.42	3.18	2.80	1.72	2.86	2.87
CV	0.02	0.01	0.02	0.37	0.07	0.05
No. specimens	5	5	4	4	5	5
Exposure period: 48 weeks						
Strength						
Mean (MPa)	64.79	61.68	61.01	59.35	55.95	59.69
STD (MPa)	3.49	3.55	4.93	1.98	3.18	0.75
Max (MPa)	69.61	67.58	66.48	62.40	59.27	60.96
Min (MPa)	60.40	58.79	54.64	56.96	52.41	58.96
CV	0.05	0.06	0.08	0.03	0.06	0.01
No. specimens	5	5	4	5	5	5
Modulus						
Mean (GPa)	3.43	2.89	2.72	2.62	2.92	2.89
STD (GPa)	0.30	0.25	0.29	0.35	0.40	0.17
Max (GPa)	3.77	3.17	3.13	2.97	3.59	3.14
Min (GPa)	3.04	2.64	2.51	2.13	2.61	2.72
CV	0.09	0.09	0.11	0.13	0.14	0.06
No. specimens	5	5	4	5	5	5

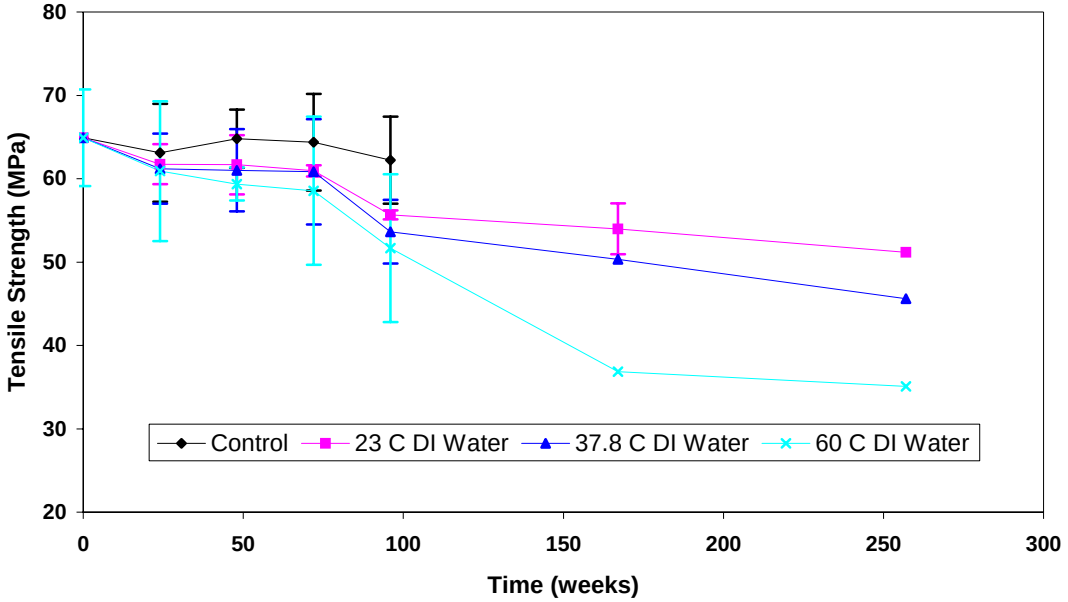
B). Tensile Test (contd.)

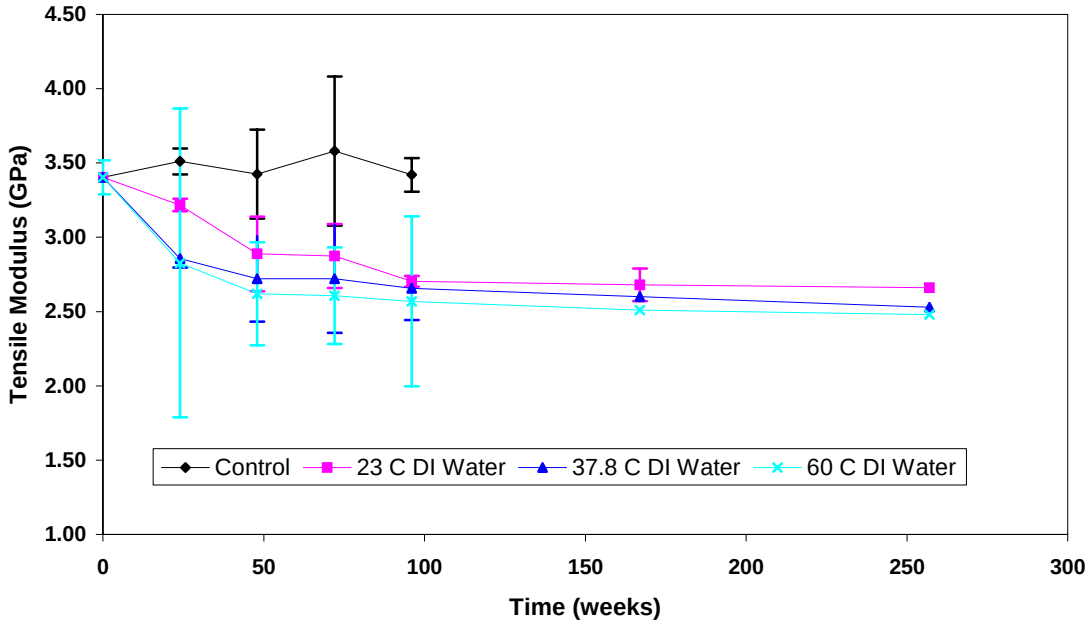
Material: Epoxy Manufacturer: FYFE Test Method: ASTM D 638 - 99 Nominal Specimen Size: According to ASTM standard Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 72 weeks						
Strength						
Mean (MPa)	64.36	60.94	60.83	58.56	54.35	59.38
STD (MPa)	5.80	0.69	6.31	8.89	2.49	5.31
Max (MPa)	71.27	61.61	69.29	66.93	58.28	67.21
Min (MPa)	55.45	60.18	53.15	44.88	51.47	52.59
CV	0.09	0.01	0.10	0.15	0.05	0.09
No. specimens	5	4	5	5	5	5
Modulus						
Mean (GPa)	3.58	2.87	2.72	2.61	2.89	2.74
STD (GPa)	0.50	0.22	0.36	0.33	0.40	0.43
Max (GPa)	4.37	3.09	3.14	2.78	3.26	3.09
Min (GPa)	3.04	2.58	2.30	2.03	2.32	2.14
CV	0.14	0.07	0.13	0.12	0.14	0.16
No. specimens	5	4	5	5	5	5
Exposure period: 96 weeks						
Strength						
Mean (MPa)	62.24	55.67	53.64	51.68	53.39	54.60
STD (MPa)	5.22	0.54	3.82	8.87	3.95	2.97
Max (MPa)	69.88	56.22	56.69	62.22	56.50	57.69
Min (MPa)	56.73	54.99	47.04	39.47	46.84	51.94
CV	0.08	0.01	0.07	0.17	0.07	0.05
No. specimens	5	4	5	5	5	4
Modulus						
Mean (GPa)	3.42	2.70	2.66	2.57	2.60	2.66
STD (GPa)	0.11	0.04	0.21	0.57	0.47	0.28
Max (GPa)	3.54	2.75	2.82	3.38	3.10	3.03
Min (GPa)	3.26	2.66	2.29	1.96	1.87	2.39
CV	0.03	0.01	0.08	0.22	0.18	0.11
No. specimens	5	4	5	5	5	4

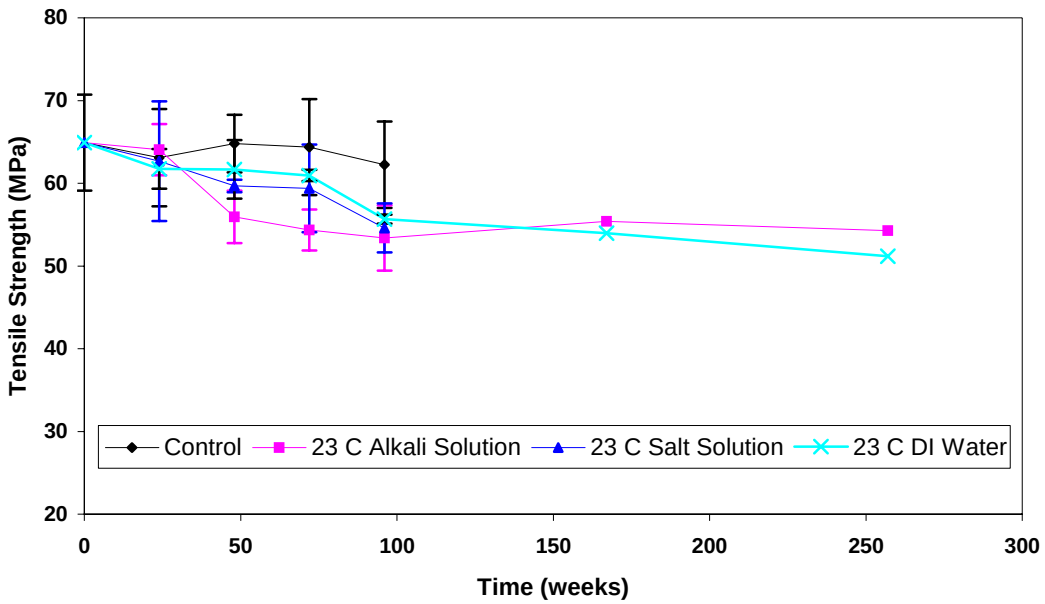
B). Tensile Test (contd.)

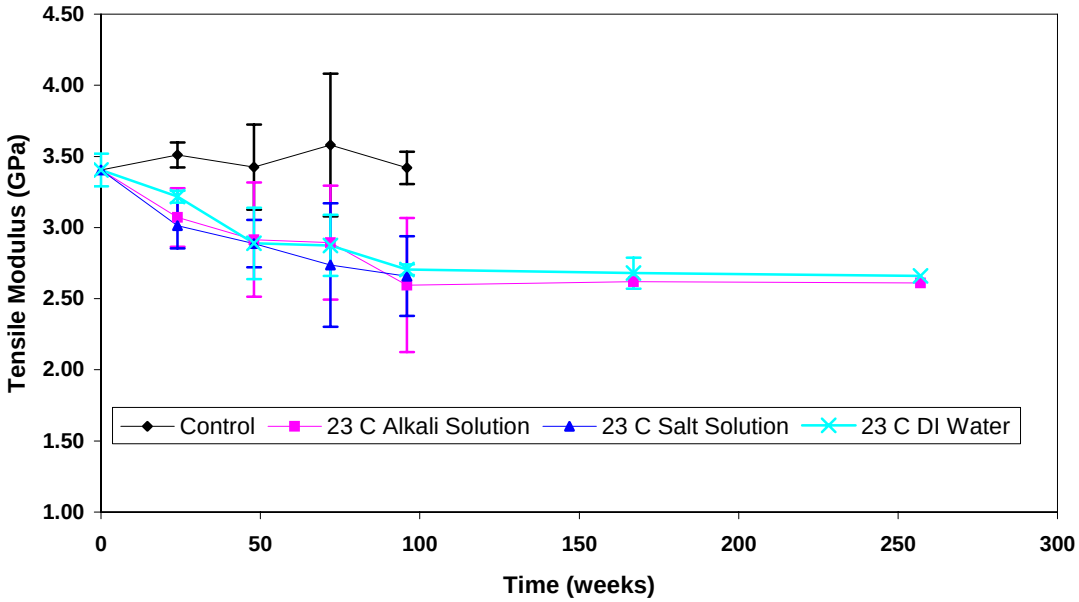
Material: Epoxy Manufacturer: FYFE Test Method: ASTM D 638 - 99 Nominal Specimen Size: According to ASTM standard Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 167 weeks						
Strength						
Mean (MPa)		53.98	50.32	36.86	55.40	
STD (MPa)						
Max (MPa)						
Min (MPa)						
CV						
No. specimens		+	+	1	+	
Modulus						
Mean (GPa)		2.68	2.60	2.51	2.62	
STD (GPa)						
Max (GPa)						
Min (GPa)						
CV						
No. specimens		+	+	1	+	
Exposure period: 257 weeks						
Strength						
Mean (MPa)		51.17	45.61	35.08	54.26	
STD (MPa)						
Max (MPa)						
Min (MPa)						
CV						
No. specimens		+	+	+	+	
Modulus						
Mean (GPa)		2.66	2.53	2.48	2.61	
STD (GPa)						
Max (GPa)						
Min (GPa)						
CV						
No. specimens		+	+	+	+	

+ : Not statistically sufficient


Tensile Strength (MPa)
80
70
60
50
40
30
20
0
50
100
150
200
250
300
Time (weeks)
Control
23 C DI Water
37.8 C DI Water
60 C DI Water


Tensile Modulus (GPa)
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0
50
100
150
200
250
300
Time (weeks)
Control
23 C DI Water
37.8 C DI Water
60 C DI Water


Tensile Strength (MPa)
80
70
60
50
40
30
20
0
50
100
150
200
250
300
Time (weeks)
Control
23 C Alkali Solution
23 C Salt Solution
23 C DI Water


Tensile Modulus (GPa)
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0
50
100
150
200
250
300
Time (weeks)
Control
23 C Alkali Solution
23 C Salt Solution
23 C DI Water

C). Dynamic Mechanical Thermal Analysis

Material: Epoxy Manufacturer: FYFE Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 30 °C and 160 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 6.1 mm, span = 28 mm Precondition: All specimens were preconditioned for 7 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing	
Condition	After preconditioning
T_g by tanδ	77.70 °C [$\pm^{0.45}_{0.29}$] *
tanδ height	1.49 [$\pm^{0.01}_{0.01}$]
T_g by E''	71.61 °C [$\pm^{0.91}_{0.61}$]
T_g by E'	68.78 °C [$\pm^{0.57}_{0.55}$]
E' at T_g – 40 °C	9.31×10^8 Pa [$\pm^{5.19\times10^8\ \mathrm{Pa}}_{3.06\times10^8\ \mathrm{Pa}}$]
E' at T_g + 40 °C	4.67×10^6 Pa [$\pm^{4.43\times10^5\ \mathrm{Pa}}_{3.77\times10^5\ \mathrm{Pa}}$]
No. specimens	3

* Data is reported as Mean [± Bounds]

C). Dynamic Mechanical Thermal Analysis (contd.)

Material: Epoxy Manufacturer: FYFE Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 30 °C and 160 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 6.1 mm Precondition: All specimens were preconditioned for 7 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 24 weeks						
T_g by tanδ	81.25 °C [$\pm^{0.64}_{0.50}$]	79.10 °C [$\pm^{0.63}_{1.00}$]	100.97 °C [$\pm^{2.85}_{3.26}$]	108.02 °C [$\pm^{5.47}_{2.81}$]	79.51 °C [$\pm^{0.86}_{0.74}$]	
tanδ height	1.28 [$\pm^{0.06}_{0.04}$]	0.98 [$\pm^{0.06}_{0.06}$]	0.64 [$\pm^{0.03}_{0.04}$]	0.45 [$\pm^{0.03}_{0.04}$]	0.93 [$\pm^{0.05}_{0.03}$]	
T_g by E''	74.32 °C [$\pm^{0.31}_{0.55}$]	74.08 °C [$\pm^{1.12}_{0.74}$]	91.61 °C [$\pm^{1.68}_{1.35}$]	99.00 °C [$\pm^{2.98}_{3.61}$]	73.26 °C [$\pm^{1.53}_{2.45}$]	
T_g by E'	71.16 °C [$\pm^{2.21}_{2.04}$]	68.65 °C [$\pm^{1.95}_{2.29}$]	89.59 °C [$\pm^{1.23}_{1.12}$]	95.63 °C [$\pm^{3.33}_{2.82}$]	69.26 °C [$\pm^{1.36}_{1.35}$]	
E' at T_g – 40 °C (Pa)	8.47×10^8 [$\pm^{1.49\times10^8}_{2.38\times10^8}$]	6.35×10^8 [$\pm^{1.81\times10^8}_{2.14\times10^8}$]	4.53×10^8 [$\pm^{1.34\times10^8}_{9.50\times10^7}$]	1.01×10^9 [$\pm^{2.09\times10^8}_{4.11\times10^8}$]	5.57×10^8 [$\pm^{3.03\times10^8}_{2.56\times10^8}$]	
E' at T_g + 40 °C (Pa)	4.93×10^6 [$\pm^{3.07\times10^5}_{5.43\times10^5}$]	5.39×10^6 [$\pm^{2.13\times10^6}_{1.31\times10^6}$]	6.86×10^6 [$\pm^{9.53\times10^5}_{1.29\times10^6}$]	1.52×10^7 [$\pm^{4.59\times10^6}_{4.01\times10^6}$]	5.54×10^6 [$\pm^{1.02\times10^6}_{9.81\times10^5}$]	
No. specimens	3	3	3	3	3	

C). Dynamic Mechanical Thermal Analysis (contd.)

Material: Epoxy Manufacturer: FYFE Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 30 °C and 160 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 6.1 mm Precondition: All specimens were preconditioned for 7 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 48 weeks						
T_g by tanδ	83.16 °C [$\pm^{0.54}_{0.76}$]	82.33 °C [$\pm^{1.39}_{1.45}$]	98.12 °C [$\pm^{0.26}_{0.24}$]	104.43 °C [$\pm^{0.71}_{1.01}$]	81.75 °C	84.95 °C
tanδ height	1.19 [$\pm^{0.03}_{0.06}$]	0.82 [$\pm^{0.09}_{0.07}$]	0.63 [$\pm^{0.03}_{0.03}$]	0.48 [$\pm^{0.03}_{0.05}$]	0.88	0.76
T_g by E''	76.92 °C [$\pm^{0.87}_{1.09}$]	76.45 °C [$\pm^{2.70}_{1.89}$]	91.00 °C [$\pm^{1.38}_{0.85}$]	99.73 °C [$\pm^{0.24}_{0.26}$]	76.05 °C	76.88 °C
T_g by E'	74.39 °C [$\pm^{1.74}_{2.57}$]	72.15 °C [$\pm^{2.60}_{1.66}$]	86.90 °C [$\pm^{1.17}_{1.44}$]	95.28 °C [$\pm^{0.52}_{0.62}$]	68.57 °C	73.13 °C
E' at T_g – 40 °C (Pa)	6.89×10^8 [$\pm^{1.79\times10^8}_{3.29\times10^8}$]	4.07×10^8 [$\pm^{2.33\times10^8}_{2.81\times10^8}$]	6.21×10^8 [$\pm^{3.37\times10^8}_{1.86\times10^8}$]	5.46×10^8 [$\pm^{1.05\times10^8}_{1.75\times10^8}$]	4.00×10^8	5.50×10^8
E' at T_g + 40 °C (Pa)	5.62×10^6 [$\pm^{2.43\times10^5}_{2.57\times10^5}$]	6.00×10^6 [$\pm^{2.31\times10^6}_{1.46\times10^6}$]	8.62×10^6 [$\pm^{3.48\times10^6}_{1.83\times10^6}$]	1.09×10^7 [$\pm^{2.47\times10^6}_{3.24\times10^6}$]	5.54×10^6	3.82×10^6
No. specimens	3	3	3	3	1	1

C). Dynamic Mechanical Thermal Analysis (contd.)

Material: Epoxy Manufacturer: FYFE Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 30 °C and 160 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 6.1 mm Precondition: All specimens were preconditioned for 7 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 72 weeks						
T_g by tanδ (Mean)	86.28 °C [$\pm^{1.50}_{1.41}$]	84.33 °C [$\pm^{0.93}_{0.71}$]	100.72 °C [$\pm^{3.16}_{2.79}$]	104.38 °C [$\pm^{0.67}_{1.09}$]	83.76 °C [$\pm^{0.10}_{0.07}$]	83.56 °C [$\pm^{0.31}_{0.45}$]
tanδ height (Mean)	1.08 [$\pm^{0.02}_{0.01}$]	0.84 [$\pm^{0.06}_{0.03}$]	0.64 [$\pm^{0.05}_{0.04}$]	0.50 [$\pm^{0.01}_{0.01}$]	0.86 [$\pm^{0.05}_{0.05}$]	0.77 [$\pm^{0.04}_{0.03}$]
T_g by E''(Mean)	79.08 °C [$\pm^{0.21}_{0.31}$]	77.01 °C [$\pm^{0.19}_{0.28}$]	93.09 °C [$\pm^{2.63}_{2.41}$]	97.29 °C [$\pm^{1.41}_{1.01}$]	78.25 °C [$\pm^{0.87}_{1.48}$]	76.56 °C [$\pm^{0.97}_{0.63}$]
T_g by E'(Mean)	76.17 °C [$\pm^{0.44}_{0.56}$]	73.73 °C [$\pm^{1.39}_{1.29}$]	89.75 °C [$\pm^{3.79}_{3.88}$]	93.04 °C [$\pm^{1.12}_{1.07}$]	73.76 °C [$\pm^{1.60}_{1.30}$]	71.67 °C [$\pm^{1.96}_{2.12}$]
E' at T_g – 40 °C (Mean, Pa)	4.33×10^8 [$\pm^{1.38\times10^8}_{1.19\times10^8}$]	8.20×10^8 [$\pm^{5.22\times10^7}_{3.01\times10^7}$]	2.73×10^8 [$\pm^{1.28\times10^8}_{2.15\times10^8}$]	4.55×10^8 [$\pm^{1.67\times10^8}_{9.30\times10^7}$]	3.80×10^8 [$\pm^{1.01\times10^8}_{1.09\times10^8}$]	5.59×10^8 [$\pm^{1.29\times10^8}_{9.97\times10^7}$]
E' at T_g + 40 °C (Mean, Pa)	4.22×10^6 [$\pm^{1.67\times10^5}_{2.03\times10^5}$]	6.54×10^6 [$\pm^{1.13\times10^6}_{1.41\times10^6}$]	9.33×10^6 [$\pm^{1.97\times10^6}_{3.73\times10^6}$]	9.90×10^6 [$\pm^{1.90\times10^6}_{2.01\times10^6}$]	7.09×10^6 [$\pm^{2.60\times10^6}_{1.80\times10^6}$]	5.39×10^6 [$\pm^{1.59\times10^6}_{1.56\times10^6}$]
No. specimens	3	3	3	3	3	3

C). Dynamic Mechanical Thermal Analysis (contd.)

Material: Epoxy Manufacturer: FYFE Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 30 °C and 160 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 6.1 mm Precondition: All specimens were preconditioned for 7 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 96 weeks						
T_g by tanδ (Mean)	88.15 °C [$\pm^{0.31}_{0.45}$]	85.49 °C [$\pm^{0.96}_{1.28}$]	100.22 °C [$\pm^{1.77}_{3.26}$]	104.05 °C [$\pm^{0.66}_{0.91}$]	85.37 °C [$\pm^{1.17}_{0.84}$]	85.70 °C [$\pm^{0.92}_{1.00}$]
tanδ height (Mean)	1.12 [$\pm^{0.03}_{0.03}$]	0.87 [$\pm^{0.04}_{0.04}$]	0.58 [$\pm^{0.01}_{0.01}$]	0.49 [$\pm^{0.01}_{0.01}$]	0.80 [$\pm^{0.02}_{0.02}$]	0.72 [$\pm^{0.01}_{0.01}$]
T_g by E''(Mean)	82.73 °C [$\pm^{0.07}_{0.05}$]	78.95 °C [$\pm^{0.79}_{0.63}$]	93.74 °C [$\pm^{1.21}_{0.67}$]	98.79 °C [$\pm^{0.35}_{0.43}$]	80.35 °C [$\pm^{1.62}_{1.15}$]	81.92 °C [$\pm^{2.46}_{1.88}$]
T_g by E'(Mean)	80.57 °C [$\pm^{0.49}_{0.78}$]	76.26 °C [$\pm^{2.78}_{2.31}$]	90.38 °C [$\pm^{2.84}_{1.85}$]	95.45 °C [$\pm^{0.26}_{0.37}$]	77.92 °C [$\pm^{0.27}_{0.46}$]	75.08 °C [$\pm^{4.14}_{2.97}$]
E' at T_g – 40 °C (Mean, Pa)	4.97×10^8 [$\pm^{6.17\times10^7}_{7.83\times10^7}$]	9.12×10^8 [$\pm^{4.35\times10^8}_{6.09\times10^8}$]	3.81×10^8 [$\pm^{5.74\times10^7}_{7.37\times10^7}$]	7.42×10^8 [$\pm^{3.11\times10^8}_{3.03\times10^8}$]	4.62×10^8 [$\pm^{8.79\times10^7}_{4.71\times10^7}$]	4.59×10^8 [$\pm^{1.01\times10^8}_{1.99\times10^8}$]
E' at T_g + 40 °C (Mean, Pa)	6.50×10^6 [$\pm^{1.61\times10^5}_{2.34\times10^5}$]	8.98×10^6 [$\pm^{8.63\times10^5}_{1.43\times10^6}$]	7.84×10^6 [$\pm^{1.15\times10^6}_{2.21\times10^6}$]	1.16×10^7 [$\pm^{1.33\times10^6}_{1.14\times10^6}$]	7.55×10^6 [$\pm^{1.16\times10^6}_{5.96\times10^5}$]	5.59×10^6 [$\pm^{5.36\times10^5}_{4.13\times10^5}$]
No. specimens	3	3	3	3	3	3

C). Dynamic Mechanical Thermal Analysis (contd.)

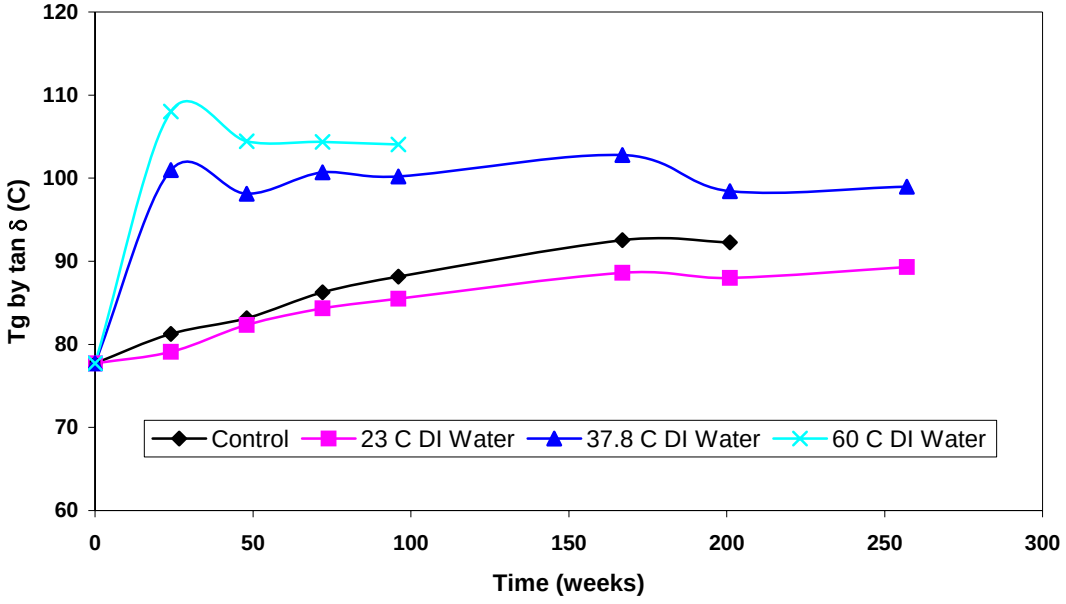
Material: Epoxy Manufacturer: FYFE Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 30 °C and 160 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 6.1 mm Precondition: All specimens were preconditioned for 7 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 167 weeks						
T_g by tanδ (Mean)	92.53 °C [$\pm^{0.64}_{0.64}$]	88.63 °C [$\pm^{0.83}_{0.83}$]	102.77 °C [$\pm^{1.01}_{1.01}$]		87.53 °C [$\pm^{0.48}_{0.48}$]	89.27 °C [$\pm^{0.22}_{0.22}$]
tanδ height (Mean)	1.03 [$\pm^{0.02}_{0.02}$]	0.84 [$\pm^{0.00}_{0.00}$]	0.67 [$\pm^{0.01}_{0.01}$]		0.86 [$\pm^{0.02}_{0.02}$]	0.84 [$\pm^{0.01}_{0.01}$]
T_g by E''(Mean)	85.60 °C [$\pm^{0.54}_{0.54}$]	81.70 °C [$\pm^{0.25}_{0.25}$]	94.89 °C [$\pm^{0.74}_{0.74}$]		80.62 °C [$\pm^{0.77}_{0.77}$]	80.62 °C [$\pm^{0.36}_{0.36}$]
T_g by E'(Mean)	84.31 °C [$\pm^{1.44}_{1.44}$]	79.62 °C [$\pm^{0.42}_{0.42}$]	92.44 °C [$\pm^{0.11}_{0.11}$]		78.65 °C [$\pm^{0.26}_{0.26}$]	77.76 °C [$\pm^{0.72}_{0.72}$]
E' at T_g – 40 °C (Mean, Pa)	5.15×10^8 [$\pm^{8.40\times10^7}_{8.40\times10^7}$]	8.00×10^8 [$\pm^{2.15\times10^7}_{2.15\times10^7}$]	1.34×10^9 [$\pm^{8.99\times10^7}_{8.99\times10^7}$]		8.64×10^8 [$\pm^{3.23\times10^8}_{3.23\times10^8}$]	1.33×10^9 [$\pm^{2.14\times10^8}_{2.14\times10^8}$]
E' at T_g + 40 °C (Mean, Pa)	5.81×10^6 [$\pm^{3.53\times10^5}_{3.53\times10^5}$]	8.70×10^6 [$\pm^{9.36\times10^5}_{9.36\times10^5}$]	1.33×10^7 [$\pm^{8.77\times10^5}_{8.77\times10^5}$]		8.40×10^6 [$\pm^{8.60\times10^5}_{8.60\times10^5}$]	1.27×10^7 [$\pm^{8.76\times10^5}_{8.76\times10^5}$]
No. specimens	2	2	2		2	2

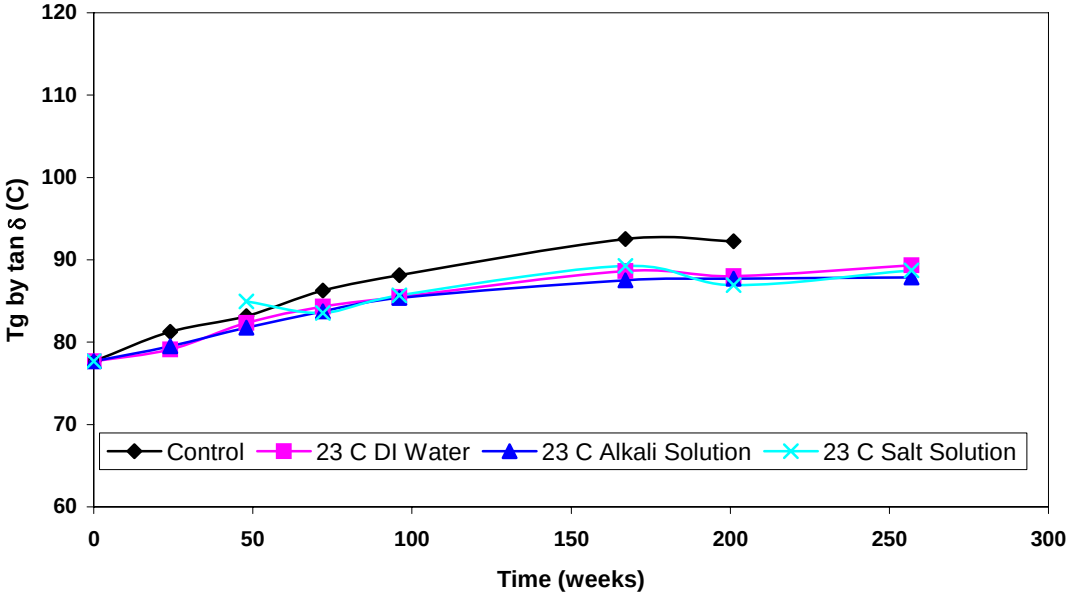
C). Dynamic Mechanical Thermal Analysis (contd.)

Material: Epoxy Manufacturer: FYFE Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 30 °C and 160 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 6.1 mm Precondition: All specimens were preconditioned for 7 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 201 weeks						
T_g by tanδ (Mean)	91.63 °C	85.92 °C	98.44 °C		87.72 °C	86.93 °C
tanδ height (Mean)	1.12	0.77	0.57		0.86	0.83
T_g by E''(Mean)	85.87 °C	77.72 °C	92.12 °C		79.55 °C	78.33 °C
T_g by E'(Mean)	83.28 °C	76.06 °C	87.91 °C		77.07 °C	75.78 °C
E' at T_g – 40 °C (Mean, Pa)	1.10×10^9	1.27×10^9	7.28×10^8		1.44×10^9	1.42×10^9
E' at T_g + 40 °C (Mean, Pa)	6.84×10^6	8.69×10^6	9.57×10^6		1.34×10^7	8.39×10^6
No. specimens	1	1	1		1	1

C). Dynamic Mechanical Thermal Analysis (contd.)

Material: Epoxy Manufacturer: FYFE Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 30 °C and 160 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 6.1 mm Precondition: All specimens were preconditioned for 7 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 257 weeks						
T_g by tanδ (Mean)		89.32 °C	98.97 °C		87.87 °C	88.70 °C
tanδ height (Mean)		0.83	0.67		0.77	0.82
T_g by E''(Mean)		80.97 °C	92.23 °C		81.00 °C	80.47 °C
T_g by E'(Mean)		80.41 °C	90.66 °C		79.57 °C	78.09 °C
E' at T_g – 40 °C (Mean, Pa)		9.53×10^8	7.14×10^8		7.40×10^8	1.03×10^9
E' at T_g + 40 °C (Mean, Pa)		8.17×10^6	9.65×10^6		9.07×10^6	1.36×10^7
No. specimens		1	1		1	1


120
110
100
90
80
70
60
Tg by tan δ (C)
0
50
100
150
200
250
300
Time (weeks)
Control
23 C DI Water
37.8 C DI Water
60 C DI Water


120
110
100
90
80
70
60
Tg by tan δ (C)
0
50
100
150
200
250
300
Time (weeks)
Control
23 C DI Water
23 C Alkali Solution
23 C Salt Solution

Material: Carbon fiber reinforced epoxy
Manufacturer: FYFE
Resin Type: Epoxy
Fiber Type: Carbon
Fabric Type: N/A
Fabric Weight: N/A
Type of Cure: Ambient Temperature
Method of Manufacture: Wet lay-up
Density: 1.46 g/cm^3
Fiber Volume Fraction: 0.29
Resin Volume Fraction: 0.68
Void Volume Fraction: 0.03
Configuration: N/A

PROPERTIES

A). Moisture Uptake (Data for a period of 260 weeks)

Material: Carbon fiber reinforced epoxy Manufacturer: FYFE Test Method: Gravimetric, ASTM D 5229/D 5229M - 92 Nominal Specimen Size (Length × Width × Thickness): 25.4 mm × 25.4 mm × 2.6 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Curve shape		2-stage[1]	2-stage[1]	Sigmoidal[2]	2-stage[1]	2-stage[1]
M_{max} (%)	0.24	2.04	2.53	4.25	2.26	1.67
Time for M_{max}	At 162 week	At end	At end	At end	At 159 week	At end
M_∞						
M_∞ (%) in stage 1 [3]		1.58	1.45	1.30	2.25	1.43
D (mm^2/s) in stage 1		7.51×10^{-8}	3.20×10^{-7}	1.11×10^{-6}	4.93×10^{-8}	6.27×10^{-8}
k (1/s$^{0.5}$) in stage 2		1.85×10^{-5}	4.99×10^{-5}	1.95×10^{-4}	1.00×10^{-18}	1.06×10^{-5}
2-stage formula (details see Ref.1)	$M_t = M_\infty\left(1+k\sqrt{t}\right)\left\{1-\exp\left[-7.3\left(\frac{Dt}{h^2}\right)^{0.75}\right]\right\}$					

1. Following Bao, L.R., Yee, A.F. and Lee, C.Y.C., "Moisture Absorption and Hygrothermal Aging in a Bismaleimide Resin" *Polymer*, 42, 2001, pp. 7327-7333.
2. Use 2-stage model to curve fit the data.
3. M_∞ determined following the graphical method in Tsotsis, T. K. and Weitsman, Y., "A Simple Graphical-Method For Determining Diffusion Parameters For 2-Stage Sorption In Composites." *Journal Of Materials Science Letters*, 13[22], 1994, pp. 1635-1636.

B). Tensile Test

Material: Carbon fiber reinforced epoxy Manufacturer: FYFE Test Method: ASTM D 3039/D 3039M - 00 Nominal Specimen Size (Length × Width × Thickness): 254 mm × 12.7 mm × 2.6 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing	
Condition	After preconditioning
Strength	
Mean (MPa)	787.69
STD (MPa)	81.93
Max (MPa)	887.29
Min (MPa)	695.80
CV	0.10
No. specimens	5
Modulus	
Mean (GPa)	59.26
STD (GPa)	5.45
Max (GPa)	66.45
Min (GPa)	52.81
CV	0.09
No. specimens	5

B). Tensile Test (contd.)

Material: Carbon fiber reinforced epoxy Manufacturer: FYFE Test Method: ASTM D 3039/D 3039M - 00 Nominal Specimen Size (Length × Width × Thickness): 254 mm × 12.7 mm × 2.6 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 24 weeks						
Strength						
Mean (MPa)	763.41	759.16	724.35	667.37	730.60	731.88
STD (MPa)	74.19	63.85	62.32	47.46	36.27	39.72
Max (MPa)	878.52	862.76	786.40	717.65	773.31	784.65
Min (MPa)	705.71	694.82	620.82	598.11	688.16	692.49
CV	0.10	0.08	0.09	0.07	0.05	0.05
No. specimens	5	5	5	5	4	5
Modulus						
Mean (GPa)	54.44	57.87	57.80	57.74	57.50	58.49
STD (GPa)	2.19	1.15	4.92	9.25	0.89	1.67
Max (GPa)	56.61	59.13	62.41	68.89	58.70	61.38
Min (GPa)	51.34	56.12	52.12	47.13	56.57	57.16
CV	0.04	0.02	0.09	0.16	0.02	0.03
No. specimens	5	5	5	5	4	5
Exposure period: 48 weeks						
Strength						
Mean (MPa)	777.98	717.26	716.79	654.60	686.94	728.75
STD (MPa)	44.31	18.56	46.18	23.50	50.85	26.64
Max (MPa)	842.53	749.53	769.94	683.76	770.40	763.40
Min (MPa)	741.92	703.47	672.08	629.64	638.29	704.11
CV	0.06	0.03	0.06	0.04	0.07	0.04
No. specimens	4	5	5	4	5	4
Modulus						
Mean (GPa)	55.94	57.51	57.63	57.07	54.43	57.27
STD (GPa)	3.05	1.81	2.77	10.15	6.91	4.08
Max (GPa)	58.70	59.74	60.23	70.40	65.55	61.23
Min (GPa)	52.70	55.90	54.39	48.18	46.81	51.57
CV	0.05	0.03	0.05	0.18	0.13	0.07
No. specimens	4	5	5	4	5	4

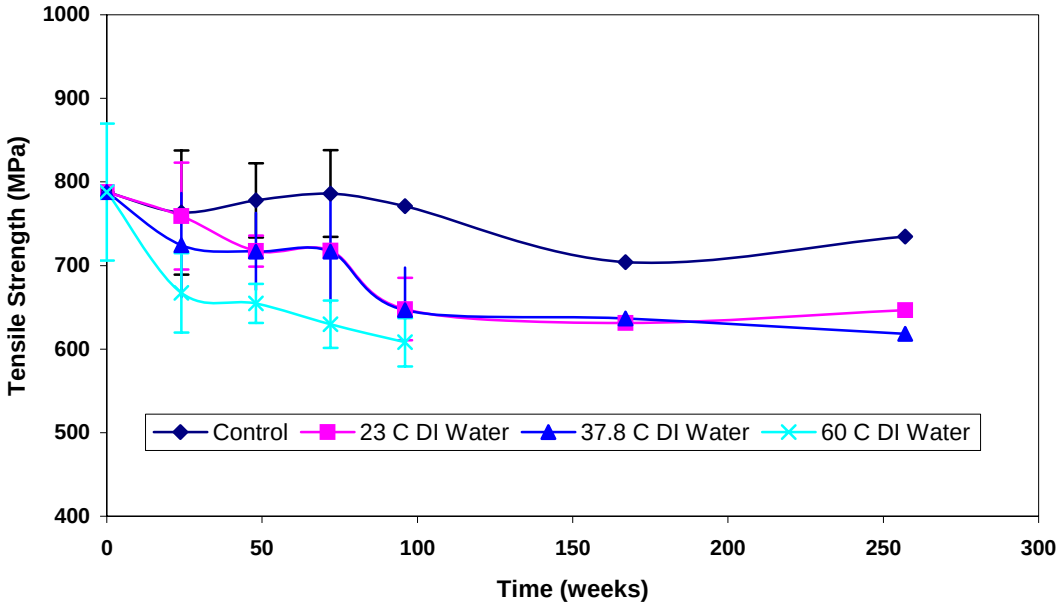
B). Tensile Test (contd.)

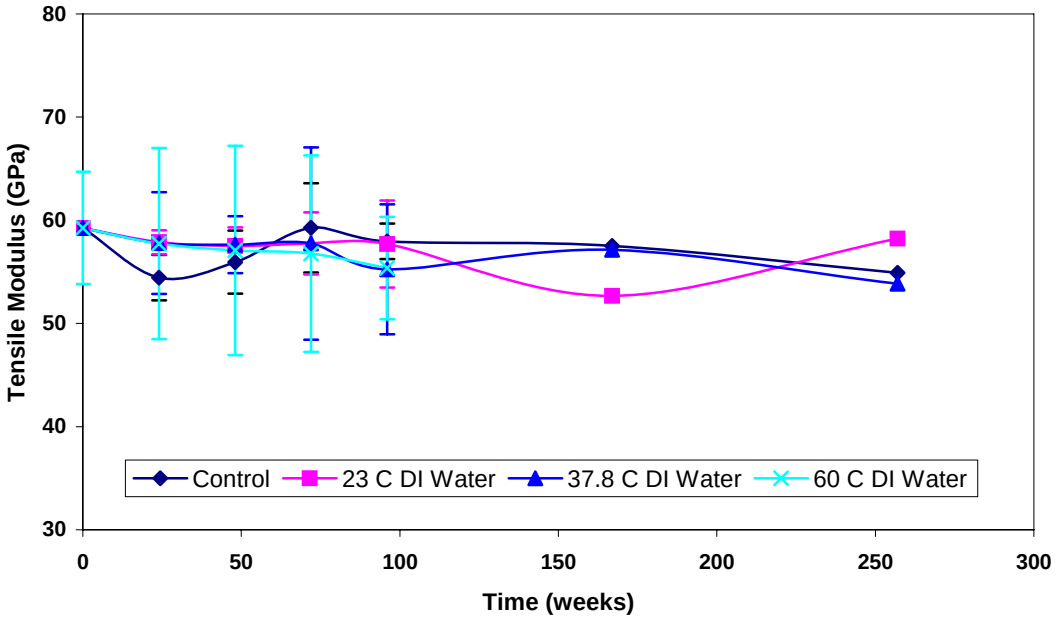
Material: Carbon fiber reinforced epoxy Manufacturer: FYFE Test Method: ASTM D 3039/D 3039M - 00 Nominal Specimen Size (Length × Width × Thickness): 254 mm × 12.7 mm × 2.6 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 72 weeks						
Strength						
Mean (MPa)	786.14	717.73	716.65	629.75	684.16	721.83
STD (MPa)	51.86	6.41	61.05	28.51	46.29	27.06
Max (MPa)	836.05	726.54	804.21	675.71	749.25	745.02
Min (MPa)	716.00	710.23	666.75	603.68	633.33	692.00
CV	0.07	0.01	0.09	0.05	0.07	0.04
No. specimens	4	5	5	5	5	4
Modulus						
Mean (GPa)	59.27	57.75	57.75	56.77	52.79	56.98
STD (GPa)	4.34	3.01	9.32	9.53	9.89	7.08
Max (GPa)	65.19	62.16	66.78	67.24	64.86	65.72
Min (GPa)	55.65	55.12	45.65	47.79	42.09	51.10
CV	0.07	0.05	0.16	0.17	0.19	0.12
No. specimens	4	5	5	5	5	4
Exposure period: 96 weeks						
Strength						
Mean (MPa)	771.13	647.83	646.43	608.19	669.06	655.04
STD (MPa)	5.43	37.29	51.06	28.85	8.61	111.36
Max (MPa)	776.52	711.70	719.32	652.17	674.95	753.86
Min (MPa)	764.37	619.57	600.04	575.17	653.95	516.29
CV	0.01	0.06	0.08	0.05	0.01	0.17
No. specimens	5	5	4	5	5	5
Modulus						
Mean (GPa)	57.96	57.70	55.26	55.38	52.69	56.86
STD (GPa)	1.72	4.21	6.30	4.97	9.31	1.69
Max (GPa)	59.74	63.27	64.21	62.22	63.25	58.44
Min (GPa)	55.65	52.19	49.42	50.70	38.51	54.08
CV	0.03	0.07	0.11	0.09	0.18	0.03
No. specimens	5	5	4	5	5	5

B). Tensile Test (contd.)

Material: Carbon fiber reinforced epoxy Manufacturer: FYFE Test Method: ASTM D 3039/D 3039M - 00 Nominal Specimen Size (Length × Width × Thickness): 254 mm × 12.7 mm × 2.6 mm Precondition: All specimens were preconditioned for 30 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 167 weeks						
Strength						
Mean (MPa)	703.93	631.32	636.64		601.08	640.33
STD (MPa)		37.48	51.53		33.99	66.43
Max (MPa)	716.43	680.10	670.96		622.85	723.04
Min (MPa)	691.42	588.97	577.38		551.05	585.05
CV		0.06	0.08		0.06	0.10
No. specimens	2	4	3		4	4
Modulus						
Mean (GPa)	57.52	52.68	57.14		54.24	57.36
STD (GPa)		1.55	0.61		12.50	5.92
Max (GPa)	64.63	54.74	57.73		72.87	64.94
Min (GPa)	50.41	51.01	56.52		46.72	51.64
CV		0.03	0.01		0.23	0.10
No. specimens	2	4	3		4	4
Exposure period: 257 weeks						
Strength						
Mean (MPa)	734.84	646.58	618.09		584.69	622.32
STD (MPa)						
Max (MPa)	765.01	685.06				702.63
Min (MPa)	704.67	608.09				542.00
CV						
No. specimens	2	2	+		+	2
Modulus						
Mean (GPa)	54.92	58.23	53.84		51.88	56.21
STD (GPa)						
Max (GPa)	57.89	58.67				61.33
Min (GPa)	51.95	57.79				51.08
CV						
No. specimens	2	2	+		+	2

+ : Not statistically sufficient


1000
900
800
700
600
500
400
Tensile Strength (MPa)
0
50
100
150
200
250
300
Time (weeks)
Control
23 C DI Water
37.8 C DI Water
60 C DI Water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60
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40
30
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100
150
200
250
300
Time (weeks)
Control
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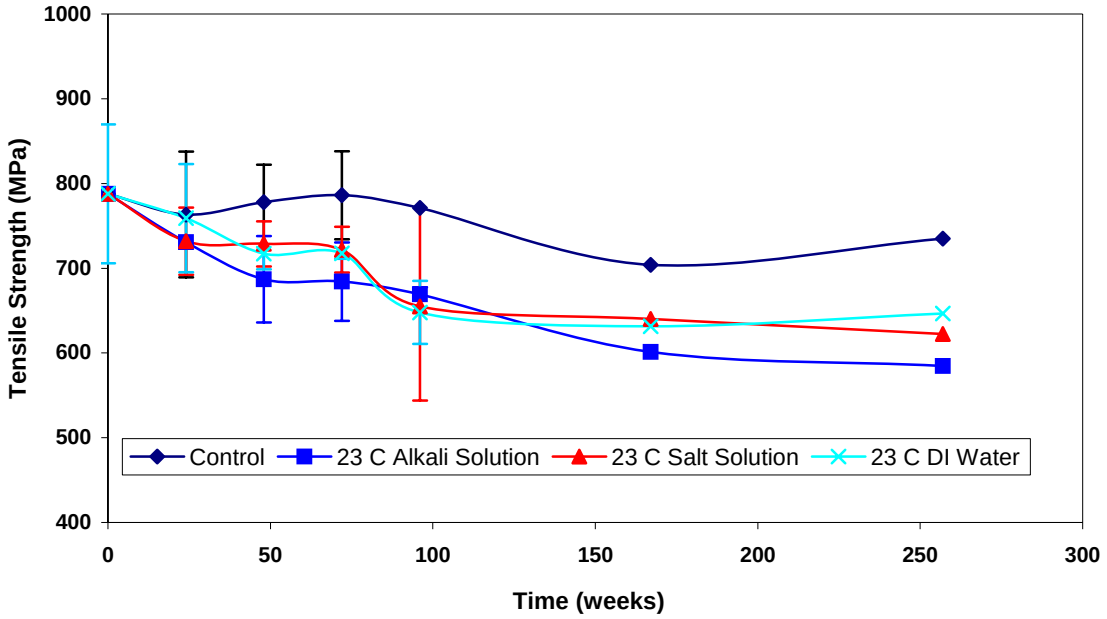
37.8 C DI Water
60 C DI Water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900
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500
400
Tensile Strength (MPa)
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50
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200
250
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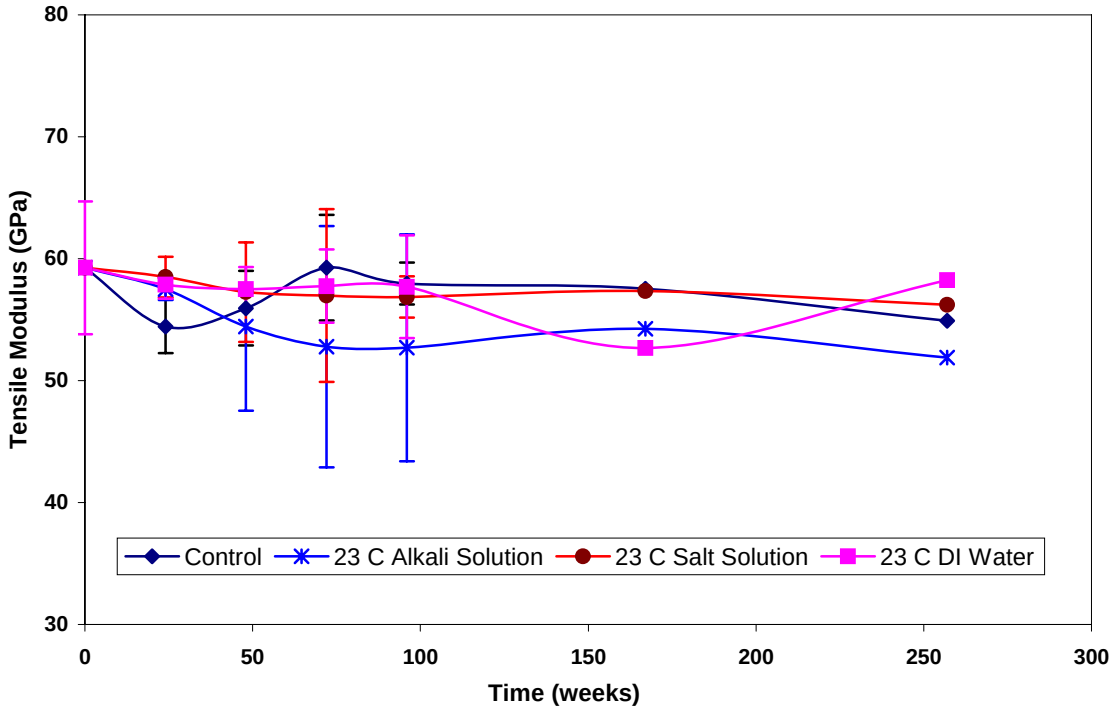
Time (weeks)
Control
23 C Alkali Solution
23 C Salt Solution
23 C DI Water


80
70
60
50
40
30
Tensile Modulus (GPa)
0
50
100
150
200
250
300
Time (weeks)
Control
23 C Alkali Solution
23 C Salt Solution
23 C DI Water

C). Dynamic Mechanical Thermal Analysis

Material: Carbon fiber reinforced epoxy Manufacturer: FYFE Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 30 °C and 160 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 2.6 mm, span = 28 mm Precondition: All specimens were preconditioned for 7 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing	
Condition	After preconditioning
T_g by tanδ (Mean)	69.78 °C $[\pm^{0.13}_{0.18}]$ *
tanδ height (Mean)	0.71 $[\pm^{0.10}_{0.06}]$
T_g by E''(Mean)	64.66 °C $[\pm^{0.67}_{0.44}]$
T_g by E'(Mean)	62.14 °C $[\pm^{0.49}_{0.71}]$
E' at T_g – 40 °C (Mean)	1.34×10^{10} Pa $[\pm^{4.89\times10^{9}\text{ Pa}}_{3.48\times10^{9}\text{ Pa}}]$
E' at T_g + 40 °C (Mean)	2.90×10^{8} Pa $[\pm^{2.20\times10^{7}\text{ Pa}}_{2.60\times10^{7}\text{ Pa}}]$
No. specimens	3

* Data is reported as Mean [± Bounds].

C). Dynamic Mechanical Thermal Analysis (contd.)

Material: Carbon fiber reinforced epoxy Manufacturer: FYFE Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 30 °C and 160 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 2.6 mm Precondition: All specimens were preconditioned for 7 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 24 weeks						
T_g by tanδ (Mean)	73.63 °C [$\pm^{0.98}_{1.00}$]	75.05 °C [$\pm^{1.72}_{3.02}$]	85.08 °C [$\pm^{0.31}_{0.18}$]	102.71 °C [$\pm^{0.86}_{0.56}$]	72.68 °C [$\pm^{1.10}_{1.56}$]	
tanδ height (Mean)	0.64 [$\pm^{0.08}_{0.08}$]	0.46 [$\pm^{0.08}_{0.09}$]	0.49 [$\pm^{0.03}_{0.02}$]	0.35 [$\pm^{0.01}_{0.02}$]	0.51 [$\pm^{0.02}_{0.03}$]	
T_g by E''(Mean)	68.39 °C [$\pm^{0.83}_{0.58}$]	66.95 °C [$\pm^{2.17}_{3.21}$]	81.13 °C [$\pm^{0.76}_{0.86}$]	95.85 °C [$\pm^{1.00}_{0.55}$]	66.95 °C [$\pm^{0.81}_{1.17}$]	
T_g by E'(Mean)	65.17 °C [$\pm^{0.61}_{0.41}$]	60.16 °C [$\pm^{1.86}_{1.42}$]	75.93 °C [$\pm^{0.59}_{0.87}$]	91.92 °C [$\pm^{0.54}_{0.31}$]	60.93 °C [$\pm^{2.23}_{2.17}$]	
E' at T_g – 40 °C (Mean, Pa)	7.17×10^{9} [$\pm^{2.72\times10^{9}}_{3.93\times10^{9}}$]	6.83×10^{9} [$\pm^{9.17\times10^{9}}_{5.08\times10^{9}}$]	4.76×10^{9} [$\pm^{1.90\times10^{9}}_{2.50\times10^{9}}$]	7.87×10^{9} [$\pm^{3.49\times10^{9}}_{4.50\times10^{9}}$]	1.10×10^{10} [$\pm^{2.20\times10^{9}}_{3.60\times10^{9}}$]	
E' at T_g + 40 °C (Mean, Pa)	1.63×10^{8} [$\pm^{5.83\times10^{7}}_{4.77\times10^{7}}$]	2.13×10^{8} [$\pm^{2.05\times10^{8}}_{1.45\times10^{8}}$]	2.79×10^{8} [$\pm^{6.53\times10^{7}}_{4.67\times10^{7}}$]	2.20×10^{8} [$\pm^{6.24\times10^{7}}_{8.26\times10^{7}}$]	2.69×10^{8} [$\pm^{1.08\times10^{8}}_{6.60\times10^{7}}$]	
No. specimens	3	3	3	3	3	

C). Dynamic Mechanical Thermal Analysis (contd.)

Material: Carbon fiber reinforced epoxy Manufacturer: FYFE Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 30 °C and 160 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 2.6 mm Precondition: All specimens were preconditioned for 7 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 48 weeks						
T_g by tanδ (Mean)	77.16 °C [$\pm^{1.10}_{1.10}$]	76.03 °C [$\pm^{2.04}_{1.17}$]	86.37 °C [$\pm^{0.59}_{0.33}$]	98.77 °C [$\pm^{0.29}_{0.15}$]	74.88 °C [$\pm^{0.82}_{1.06}$]	77.22 °C [$\pm^{2.00}_{2.00}$]
tanδ height (Mean)	0.62 [$\pm^{0.03}_{0.03}$]	0.42 [$\pm^{0.07}_{0.08}$]	0.49 [$\pm^{0.05}_{0.06}$]	0.39 [$\pm^{0.04}_{0.06}$]	0.51 [$\pm^{0.05}_{0.05}$]	0.43 [$\pm^{0.05}_{0.05}$]
T_g by E''(Mean)	71.67 °C [$\pm^{0.37}_{0.37}$]	69.87 °C [$\pm^{2.05}_{1.72}$]	81.76 °C [$\pm^{0.46}_{0.31}$]	94.58 °C [$\pm^{0.87}_{0.60}$]	69.02 °C [$\pm^{0.69}_{0.96}$]	71.01 °C [$\pm^{0.42}_{0.42}$]
T_g by E'(Mean)	68.07 °C [$\pm^{0.24}_{0.24}$]	65.34 °C [$\pm^{2.23}_{2.65}$]	77.63 °C [$\pm^{2.06}_{1.05}$]	89.36 °C [$\pm^{0.55}_{0.80}$]	62.29 °C [$\pm^{0.08}_{0.07}$]	66.41 °C [$\pm^{2.13}_{2.13}$]
E' at T_g – 40 °C (Mean, Pa)	6.65×10^{9} [$\pm^{1.50\times10^{9}}_{1.50\times10^{9}}$]	4.38×10^{9} [$\pm^{2.25\times10^{9}}_{1.82\times10^{9}}$]	6.86×10^{9} [$\pm^{2.32\times10^{9}}_{3.17\times10^{9}}$]	6.07×10^{9} [$\pm^{4.03\times10^{9}}_{3.51\times10^{9}}$]	1.20×10^{10} [$\pm^{5.18\times10^{9}}_{5.26\times10^{9}}$]	5.40×10^{9} [$\pm^{4.40\times10^{9}}_{4.40\times10^{9}}$]
E' at T_g + 40 °C (Mean, Pa)	2.55×10^{8} [$\pm^{2.50\times10^{6}}_{2.50\times10^{6}}$]	1.94×10^{8} [$\pm^{9.56\times10^{7}}_{9.82\times10^{7}}$]	2.52×10^{8} [$\pm^{1.53\times10^{7}}_{1.77\times10^{7}}$]	2.51×10^{8} [$\pm^{1.53\times10^{7}}_{2.77\times10^{7}}$]	3.13×10^{8} [$\pm^{2.47\times10^{8}}_{1.59\times10^{8}}$]	2.11×10^{8} [$\pm^{1.24\times10^{8}}_{1.24\times10^{8}}$]
No. specimens	2	3	3	3	3	2

C). Dynamic Mechanical Thermal Analysis (contd.)

Material: Carbon fiber reinforced epoxy Manufacturer: FYFE Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 30 °C and 160 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 2.6 mm Precondition: All specimens were preconditioned for 7 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 72 weeks						
T_g by tanδ (Mean)	76.48 °C [$\pm^{0.80}_{0.73}$]	79.57 °C [$\pm^{3.72}_{2.29}$]	89.73 °C [$\pm^{0.60}_{0.93}$]	97.66 °C [$\pm^{0.72}_{0.46}$]	76.87 °C [$\pm^{2.27}_{1.32}$]	77.03 °C [$\pm^{2.22}_{1.22}$]
tanδ height (Mean)	0.69 [$\pm^{0.04}_{0.03}$]	0.50 [$\pm^{0.11}_{0.07}$]	0.50 [$\pm^{0.02}_{0.03}$]	0.42 [$\pm^{0.11}_{0.07}$]	0.45 [$\pm^{0.07}_{0.09}$]	0.49 [$\pm^{0.02}_{0.01}$]
T_g by E''(Mean)	71.59 °C [$\pm^{0.53}_{0.39}$]	72.61 °C [$\pm^{1.10}_{0.99}$]	86.22 °C [$\pm^{1.86}_{1.01}$]	93.42 °C [$\pm^{1.46}_{0.82}$]	71.76 °C [$\pm^{1.94}_{1.45}$]	71.97 °C [$\pm^{1.78}_{1.68}$]
T_g by E'(Mean)	67.63 °C [$\pm^{0.58}_{0.57}$]	68.19 °C [$\pm^{4.30}_{3.20}$]	80.13 °C [$\pm^{0.78}_{0.93}$]	88.59 °C [$\pm^{2.33}_{2.49}$]	66.86 °C [$\pm^{3.12}_{3.63}$]	65.16 °C [$\pm^{3.38}_{2.49}$]
E' at T_g – 40 °C (Mean, Pa)	1.13×10^{10} [$\pm^{2.26\times10^{9}}_{1.51\times10^{9}}$]	6.74×10^{9} [$\pm^{4.06\times10^{9}}_{2.51\times10^{9}}$]	5.81×10^{9} [$\pm^{8.20\times10^{8}}_{1.42\times10^{9}}$]	5.78×10^{9} [$\pm^{1.80\times10^{9}}_{1.53\times10^{9}}$]	6.54×10^{9} [$\pm^{5.76\times10^{9}}_{5.09\times10^{9}}$]	6.43×10^{9} [$\pm^{8.03\times10^{8}}_{8.57\times10^{8}}$]
E' at T_g + 40 °C (Mean, Pa)	2.71×10^{8} [$\pm^{7.80\times10^{7}}_{1.43\times10^{8}}$]	3.56×10^{8} [$\pm^{8.97\times10^{7}}_{9.03\times10^{7}}$]	1.89×10^{8} [$\pm^{3.43\times10^{7}}_{3.57\times10^{7}}$]	1.68×10^{8} [$\pm^{2.70\times10^{7}}_{2.00\times10^{7}}$]	2.72×10^{8} [$\pm^{1.47\times10^{8}}_{1.25\times10^{8}}$]	1.99×10^{8} [$\pm^{1.93\times10^{7}}_{3.07\times10^{7}}$]
No. specimens	3	3	3	3	3	3

C). Dynamic Mechanical Thermal Analysis (contd.)

Material: Carbon fiber reinforced epoxy Manufacturer: FYFE Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 30 °C and 160 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 2.6 mm Precondition: All specimens were preconditioned for 7 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 96 weeks						
T_g by tanδ (Mean)	81.77 °C [$\pm^{0.69}_{1.38}$]	78.67 °C [$\pm^{0.45}_{0.74}$]	90.15 °C [$\pm^{0.46}_{0.37}$]	98.37 °C [$\pm^{1.57}_{1.00}$]	80.78 °C [$\pm^{5.93}_{3.19}$]	79.56 °C [$\pm^{0.81}_{1.43}$]
tanδ height (Mean)	0.76 [$\pm^{0.01}_{0.01}$]	0.52 [$\pm^{0.01}_{0.01}$]	0.46 [$\pm^{0.01}_{0.03}$]	0.48 [$\pm^{0.05}_{0.06}$]	0.45 [$\pm^{0.07}_{0.12}$]	0.48 [$\pm^{0.06}_{0.04}$]
T_g by E''(Mean)	76.62 °C [$\pm^{0.77}_{0.93}$]	72.55 °C [$\pm^{1.22}_{1.11}$]	85.81 °C [$\pm^{0.48}_{0.54}$]	90.05 °C [$\pm^{1.49}_{1.06}$]	76.36 °C [$\pm^{3.24}_{1.82}$]	72.35 °C [$\pm^{2.00}_{1.99}$]
T_g by E'(Mean)	72.68 °C [$\pm^{0.37}_{0.73}$]	66.83 °C [$\pm^{3.70}_{2.63}$]	80.70 °C [$\pm^{0.34}_{0.25}$]	85.67 °C [$\pm^{0.90}_{1.09}$]	72.90 °C [$\pm^{3.38}_{1.75}$]	67.41 °C [$\pm^{5.85}_{3.73}$]
E' at T_g – 40 °C (Mean, Pa)	9.59×10^{9} [$\pm^{5.86\times10^{9}}_{3.36\times10^{9}}$]	1.08×10^{10} [$\pm^{2.10\times10^{9}}_{3.95\times10^{9}}$]	1.08×10^{10} [$\pm^{3.18\times10^{9}}_{2.84\times10^{9}}$]	7.20×10^{9} [$\pm^{1.55\times10^{9}}_{2.74\times10^{9}}$]	6.53×10^{9} [$\pm^{4.26\times10^{9}}_{5.94\times10^{9}}$]	7.67×10^{9} [$\pm^{1.56\times10^{9}}_{1.92\times10^{9}}$]
E' at T_g + 40 °C (Mean, Pa)	1.48×10^{8} [$\pm^{6.08\times10^{7}}_{8.17\times10^{7}}$]	3.43×10^{8} [$\pm^{2.03\times10^{8}}_{1.36\times10^{8}}$]	2.81×10^{8} [$\pm^{6.68\times10^{7}}_{7.65\times10^{7}}$]	2.08×10^{8} [$\pm^{4.31\times10^{7}}_{4.85\times10^{7}}$]	1.87×10^{8} [$\pm^{7.46\times10^{7}}_{9.00\times10^{7}}$]	2.56×10^{8} [$\pm^{1.63\times10^{7}}_{1.99\times10^{7}}$]
No. specimens	3	3	3	3	3	3

C). Dynamic Mechanical Thermal Analysis (contd.)

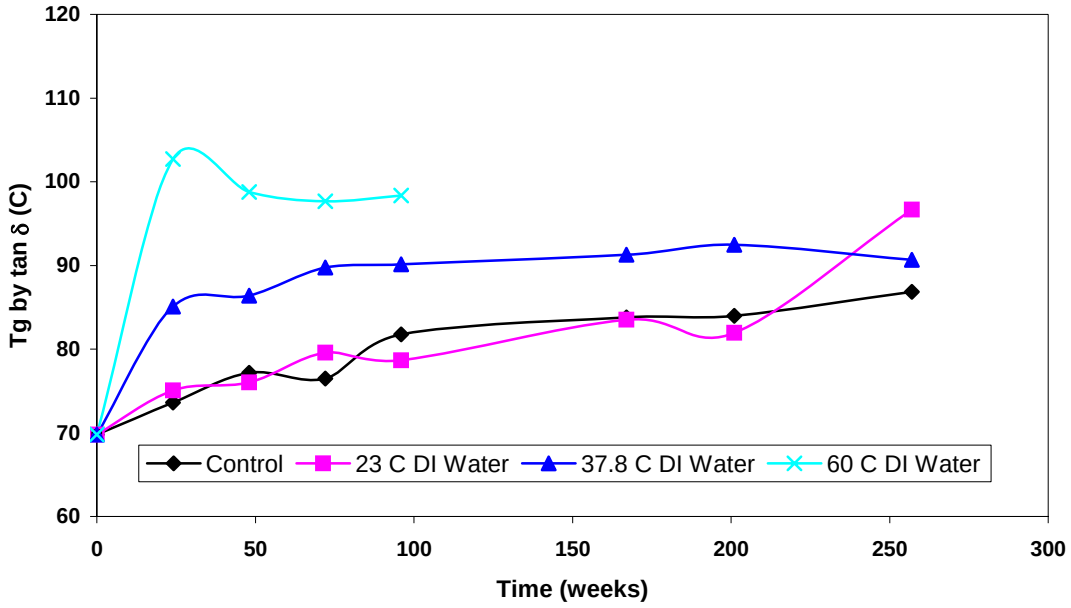
Material: Carbon fiber reinforced epoxy Manufacturer: FYFE Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 30 °C and 160 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 6.1 mm Precondition: All specimens were preconditioned for 7 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 167 weeks						
T_g by tanδ (Mean)	83.79 °C [$\pm^{0.49}_{0.49}$]	83.52 °C [$\pm^{0.34}_{0.34}$]	91.27 °C [$\pm^{0.20}_{0.20}$]		80.14 °C [$\pm^{0.35}_{0.35}$]	81.24 °C [$\pm^{0.69}_{0.69}$]
tanδ height (Mean)	0.71 [$\pm^{0.01}_{0.01}$]	0.45 [$\pm^{0.08}_{0.08}$]	0.49 [$\pm^{0.05}_{0.05}$]		0.51 [$\pm^{0.02}_{0.02}$]	0.52 [$\pm^{0.04}_{0.04}$]
T_g by E''(Mean)	79.13 °C [$\pm^{0.50}_{0.50}$]	76.98 °C [$\pm^{0.73}_{0.73}$]	85.38 °C [$\pm^{0.16}_{0.16}$]		74.53 °C [$\pm^{1.24}_{1.24}$]	75.93 °C [$\pm^{0.50}_{0.50}$]
T_g by E'(Mean)	75.87 °C [$\pm^{0.64}_{0.64}$]	75.09 °C [$\pm^{0.45}_{0.45}$]	82.40 °C [$\pm^{0.38}_{0.38}$]		71.54 °C [$\pm^{1.72}_{1.72}$]	71.51 °C [$\pm^{4.28}_{4.28}$]
E' at T_g – 40 °C (Mean, Pa)	1.04×10^{10} [$\pm^{2.84\times10^{8}}_{2.84\times10^{8}}$]	5.55×10^{9} [$\pm^{1.73\times10^{9}}_{1.73\times10^{9}}$]	8.17×10^{9} [$\pm^{9.01\times10^{8}}_{9.01\times10^{8}}$]		1.37×10^{10} [$\pm^{4.94\times10^{9}}_{4.94\times10^{9}}$]	9.39×10^{9} [$\pm^{5.01\times10^{9}}_{5.01\times10^{9}}$]
E' at T_g + 40 °C (Mean, Pa)	2.27×10^{8} [$\pm^{9.02\times10^{7}}_{9.02\times10^{7}}$]	2.13×10^{8} [$\pm^{1.78\times10^{7}}_{1.78\times10^{7}}$]	2.47×10^{8} [$\pm^{8.38\times10^{7}}_{8.38\times10^{7}}$]		3.49×10^{8} [$\pm^{4.69\times10^{7}}_{4.69\times10^{7}}$]	2.40×10^{8} [$\pm^{8.54\times10^{6}}_{8.54\times10^{6}}$]
No. specimens	2	2	2		2	2

C). Dynamic Mechanical Thermal Analysis (contd.)

Material: Carbon fiber reinforced epoxy Manufacturer: FYFE Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 30 °C and 160 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 6.1 mm Precondition: All specimens were preconditioned for 7 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 201 weeks						
T_g by tanδ (Mean)	83.28 °C	79.35 °C	92.48 °C		78.95 °C	81.18 °C
tanδ height (Mean)	0.66	0.52	0.50		0.49	0.37
T_g by E''(Mean)	79.81 °C	75.12 °C	88.79 °C		71.77 °C	72.78 °C
T_g by E'(Mean)	74.92 °C	73.04 °C	82.33 °C		68.38 °C	70.40 °C
E' at T_g – 40 °C (Mean, Pa)	6.42×10^9	8.14×10^9	6.99×10^9		8.38×10^9	4.27×10^9
E' at T_g + 40 °C (Mean, Pa)	2.09×10^8	2.90×10^8	4.92×10^8		2.04×10^8	2.45×10^8
No. specimens	1	1	1		1	1

C). Dynamic Mechanical Thermal Analysis (contd.)

Material: Carbon fiber reinforced epoxy Manufacturer: FYFE Test Method: ASTM E 1640 - 99 Preload Strain: 0.025% Frequency: 1 Hz Mode: three point bending Heating Rate: 5 °C/min between 30 °C and 160 °C Nominal Specimen Size (Length × Width × Thickness): 46 mm × 9 mm × 6.1 mm Precondition: All specimens were preconditioned for 7 days at 23 °C and 30% relative humidity (RH) to ensure a uniform baseline, prior to exposure and testing						
Temperature (°C)	23	23	37.8	60	23	23
Condition	In a Humidity Chamber at 30% RH.	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Deionized Water	Immersed in Alkali Solution (Concrete Leachate)	Immersed in 5% NaCl Solution
Exposure period: 257 weeks						
T_g by tanδ (Mean)	86.86 °C	96.66 °C	90.68 °C		79.48 °C	80.91 °C
tanδ height (Mean)	0.58	0.47	0.52		0.45	0.55
T_g by E''(Mean)	83.38 °C	90.72 °C	85.86 °C		72.38 °C	74.97 °C
T_g by E'(Mean)	73.63 °C	89.33 °C	82.46 °C		67.00 °C	72.58 °C
E' at T_g – 40 °C (Mean, Pa)	7.14×10^{9}	7.23×10^{9}	8.74×10^{9}		6.85×10^{9}	1.09×10^{10}
E' at T_g + 40 °C (Mean, Pa)	1.21×10^{8}	2.77×10^{8}	2.54×10^{8}		2.37×10^{8}	2.54×10^{8}
No. specimens	1	1	1		1	1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Tg by tan δ (C)
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250
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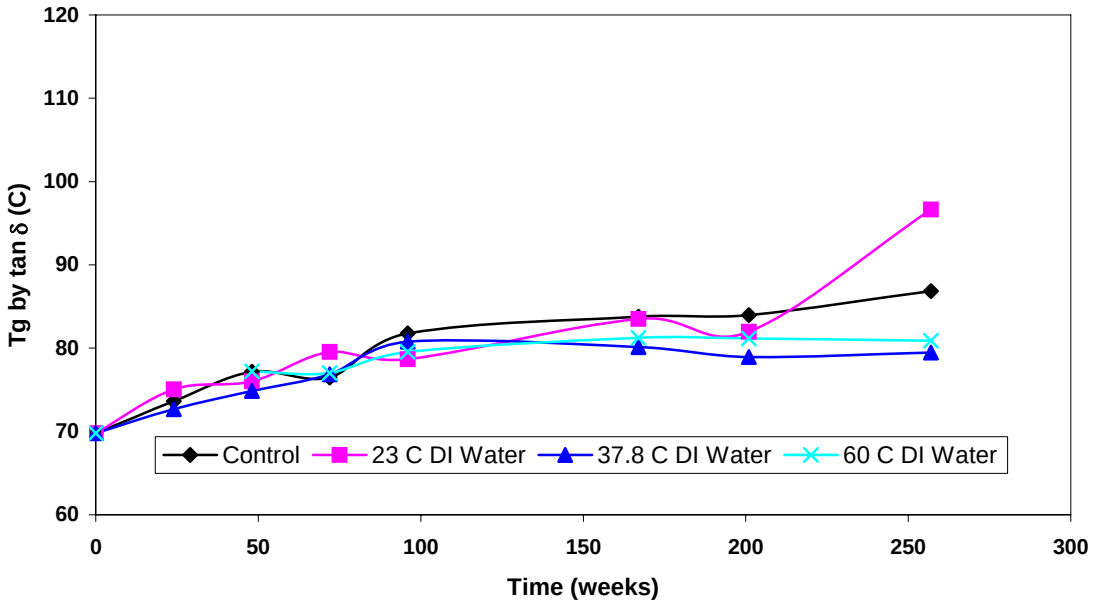
Time (weeks)
Control
23 C DI Water
37.8 C DI Water
60 C DI Water


120
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Tg by tan δ (C)
0
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100
150
200
250
300
Time (weeks)
Control
23 C DI Water
37.8 C DI Water
60 C DI Water

5. REFERENCES

Abanilla, M.A., Karbhari, V.M. and Li, Y. (2005) "Development of long-term durability and design parameters for carbon/epoxy materials used in external rehabilitation of concrete," Proceedings of the Third International Conference on Construction Materials, Vancouver, Canada, August 2005, 12 pp

ACI-440.2R-02 (2002): Design and construction of externally bonded FRP systems for strengthening concrete structures, American Concrete Institute, Farmington Hills, MI.

ASME-RTP-1d-1998 (1998), Addenda to ASME-RTP-1-1995 edition, Reinforced Thermoset Plastic Corrosion Resistant Equipment, ASME, New York, NY.

ASME Boiler and Pressure Vessel Code X (2001), FRP Plastic Pressure Vessels, ASME, New York.

ASTM D3171 (2004). Standard test methods for constituent content of composite materials. American Society for Testing and Materials, Pittsburgh, PA.

Austin, S., Robin, P. and Pan V (1995) "Tensile bond testing of concrete repairs," RILEM Materials & Structures, 28, pp. 249-259.

BS 4994 (1987), British Standard Specification for Design and Construction of Vessels and Tanks in Reinforced Plastics," British Standards Institute.

Cable, C.W. (1991), "The Effect of Defects in Glass-Reinforced Plastics," Marine Technology, Vol. 28[2], 91.

Chalmers, D.W. (1988), "The Properties and Uses of Marine Structural Materials," Marine Structures, Vol. 1, pp. 47-70.

Dutta, P. K. (1988). "Structural fiber composite materials for cold regions." ASCE Journal of Cold Regions Engineering, 2(3), pp. 124–134.

Evans, T.W., Swann, R.F. and Troffer, M.A. (1991), "The Submarine Perspective," Proceedings of the National Conference on the Use of Composite Materials in Load-Bearing Marine Structures, National Academy Press, Washington, DC, pp. 11-17.

Gadke, M. (1985). "Response of statically tested unnotched specimens: Mechanical properties and damage mechanisms of carbon fiber-reinforced composites" DFVLR Rep. No. DFVLR-FB85-45, Institut fur Strukturmechanik, Braunschweig, West Germany.

Gibbs and Cox, Inc. Marine Design Manual for Fiberglass Reinforced Plastics (McGraw Hill, New York), 1960.

Horiguchi, T. and Saeki, N. (1997). "Effect of test methods and quality of concrete on bond strength of CFRP sheet," Proceedings of the 3rd International Symposium on Non-Metallic (FRP) Reinforcement for Concrete Structures, pp. 265-270.

Jones, C.J. and Dickson, R.F. (1984), "The Environmental Fatigue Behavior of Reinforced Plastics," Proceedings of the Royal Society of London, A396, pp. 315-338.

Karbhari, V.M. and Abanilla, M.A. (2007), "Design factors, reliability, and durability prediction of Wet Layup Carbon/Epoxy Used in External Strengthening," Composites B, 38[1], pp. 10-23.

Karbhari, V.M., Chin, J.W. and Reynaud, R. (2001), “Gap Analysis for Durability of Fiber Reinforced Polymer Composites in Civil Infrastructure,” CERF Report, 127 pp.

Karbhari, V. M., and Li, Y (2001), “Safety Factors and Materials Design Allowables for FRP Composites – Application to Civil Infrastructure,” Proceedings of the 33rd International SAMPE Technical Conference, Seattle, 14 pp.

Karbhari, V.M. and Engineer, M. (1996a), "Investigation of bond between concrete and composites: Use of a peel test," Journal of Reinforced Plastics and Composites, 15[2], pp. 208-227.

Karbhari, V.M. and Engineer, M. (1996b), “Effect of environmental exposure on the external strengthening of concrete with composites-Short term bond durability,” Journal Of Reinforced Plastics And Composites, 15[12], pp. 1194-1216.

Lord, H. W., and Dutta, P. K. (1988). “On the design of polymer composite structures for cold regions applications,” Journal of Reinforced Plastics and Composites, 7, pp. 435–458.

Mouritz, A.P., Gellert, E., Burchill, P. and Challis, K. (2001), “Review of Advanced Composite Structures for Naval Ships and Vessels,” Composite Structures, Vol. 53, pp. 21-41.

NASA Design and Manufacturing Guidelines for Aerospace Composites (2000), Guideline No. GD-ED-2205, 11pp. in NASA TM4322 – NASA Preferred Reliability Practices for Design and Test, Part 2: Guidelines.

Puccini, G. Environmental Aspects in Composite Materials in Maritime Structures, Vol. 1, Eds. R.A. Shenoi and J.F. Wellicome, 1993, pp. 44-85 (Cambridge University Press, Cambridge, UK).

Rege, S.K. and Lakkad, S.C. (1983) “Effect of salt water on fibre reinforced plastics,” Fibre Science and Technology, 19, pp. 317-324.

Reynaud, D., Karbhari, V.M. and Seible, F. (1999), “The HITEC Evaluation Program for Composite Column Wrap Systems for Seismic Retrofit,” Proceedings of the International Composites Exposition, Cincinnati, OH, pp. 4A/1-6.

Sagi-mani, D., Narkis, M., Siegmann, A., Joseph, R. and Dodivk, H. (1998), “The Effect of Marine Environment on a Vinylester Resin and Its Highly Filled Particulate Quartz Composite,” Journal of Applied Polymer Science, Vol. 69, pp. 2229-2234.

Seim, W., Hormann, M., Karbhari, V.M. and Seible, F. (2001) "External FRP poststrengthening of scaled concrete slabs," ASCE Journal of Composites in Construction, 5[2], pp. 67-75

Soulier, J.P. (1988), “Interaction of Fiber Epoxy Composites With Different Saltwater Solutions Including Isotonic Liquid,” Polymer Communications, 29, pp. 243-246.

Wu, L., Murphy, K., Karbhari, V.M. and Zhang, J.S. (2002), “Short-term Effects of Sea Water on E-Glass/Vinylester Composites,” Journal of Applied Polymer Science, Vol. 84[14], pp. 2760-2767.

Zhang, J.S., Karbhari, V.M., Wu, L. and Reynaud, D. (2002), “Field Exposure Based Durability Assessment of FRP Column Wrap Systems,” *Composites: Part B*, Vol. 32. 2001, pp. 589-598.