Effect of Environmental Exposure on the External Strengthening of Concrete with Composites—Short Term Bond Durability

V. M. KARBHARI* AND M. ENGINEER**
Division of Structural Engineering (MC 0085)
University of California, San Diego
9500 Gilman Drive
La Jolla, CA 92093

ABSTRACT: The pressing need for rehabilitation and retrofit strategies that encompasses new and emerging materials and technologies, results from the need to simultaneously repair existing structures while attempting to increase both their performance levels and life spans. A large number of techniques currently exist for strengthening highway bridges ranging from the use of external post-tensioning to the addition of epoxy bonded steel plates to the tension surface. The use of composite plates for the purpose of external reinforcement has considerable potential. However, there is a critical need to investigate the degradation of the composite-concrete interface after exposure to environmental conditions that include moisture, sea water, freezing and freeze-thaw. In this investigation, the effect of five different environmental conditions on the performance of plated beams is considered from aspects related to materials and durability. It is shown that the selection of the appropriate resin system is critical to success, and the dangers of selecting systems with low glass transition temperatures and drastic drops in instantaneous modulus as a function of temperature are discussed. Two different resin systems are compared using the same fibrous reinforcement and an overall view of durability at the concrete-composite interface is elucidated.

KEY WORDS: infrastructure rehabilitation, composites, plates, external reinforcement, environmental durability, interface.

1. INTRODUCTION

THE DETERIORATION AND critical need for renewal of civil infrastructure has recently been the focus of considerable discussion in North America, Europe and Japan. The retention of existing facilities (buildings, bridges, transportation arteries, etc.) as well as the need to upgrade them to fill expanding needs has reached critical proportions. The replacement and rebuilding of most of the exist-

*Author to whom correspondence should be addressed.
**Graduate Research Assistant, now at the University of Michigan.

0731-6844/96/12 1194-23 $10.00/0

ing civil infrastructure is not a feasible option in most cases for reasons that range from economics (cost of resources) and logists (excessive disruption of neighboring facilities, lack of access and new land) to those related to the socio-economic impact of detours/delays/inconvenience over considerably long periods of time on inhabitants and industrial output. Factors such as this make the use of rapid and cost-efficient strengthening, rehabilitation and retrofit options very attractive. However, the complexity of these efforts is often misunderstood and the project is treated as though it were part of routine maintenance. Successful implementation of such a strategy requires knowledge not only in aspects related to design, but also in materials, degradation and durability of joints and connections, and in the analysis of retrofitted structures to predict effects of local response on the entire structural system.

The pressing need for rehabilitation and retrofit strategies that encompass new and emerging materials and technologies results from the need to simultaneously repair existing structures while attempting to increase both their performance levels and life spans. Of the roughly half million highway bridges in the United States more than 1100 are either structurally deficient or functionally obsolete due to reasons such as the general age of the structure, steady increase in weight of vehicles and traffic density, changes in the use of the structure, misdesign or poor/faulty original construction, deterioration due to environmental attack (including corrosion), and poor maintenance practices. In addition to bridge elements such as beams and girders, there is also an equal need to address deteriorating parking garage structures, masonry walls, load-bearing walls, concrete facades, curtain walls, and aesthetic/architectural outcrops. A key element that must be kept in mind during the selection of retrofit and renewal options is the effect of corrosion. In addition to degradation due to moisture ingress in general, a large number of structures are in close vicinity of a marine environment, and others are subjected to the effects of road-salt usage. Steel corrodes both when used externally or when embedded in concrete (through the ingress of moisture and salt).

A large number of techniques currently exist for strengthening highway bridges ranging from the use of external post-tensioning to the addition of epoxy bonded steel plates to the tension surface. In 1987, Klaiber et al. (1987) reported on the use of eight different techniques for the strengthening of existing bridge decks. Interestingly, at that time, the use of the technique of external steel plating was considered premature as it was felt that there was insufficient data regarding the durability of the epoxy joint between the steel plate and concrete. Considerable field implementation has however been reported of this option ranging from its use in apartments to arched and prestressed bridges (Bresson, 1972; Dussek, 1980; Jones et al., 1980; Macdonald and Calder, 1982). A comprehensive review of field applications and research in this area has been presented by McKenna and Erki (1994) and hence will not be repeated. The principle of this technique is fairly simple in that it consists of bonding (or otherwise connecting) a steel plate to the tension flange of a beam, thereby increasing both strength and stiffness. Jacks or other pressurizing equipment may be employed to keep the epoxy bond under pressure during cure [Figure 1(a)].

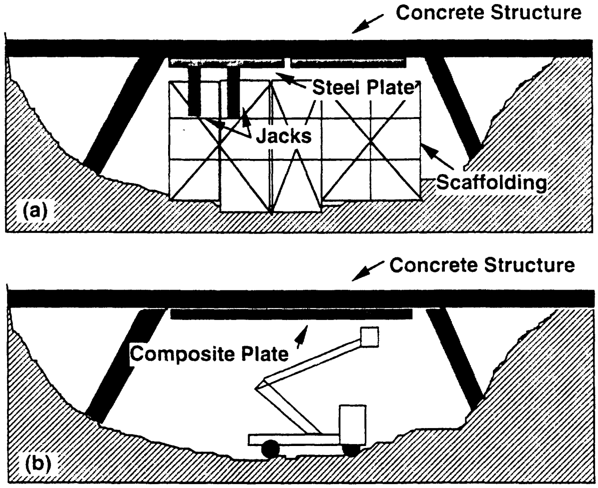


Figure 1. External strengthening through the use of externally bonded reinforcement plates: (a) steel plates; (b) composite plates.

Although extensively used in Europe, this method suffers from a number of disadvantages ranging from difficulty in placement to concerns related to overall durability. The plates are heavy and hence difficult to handle during erection. At the minimum, jacks, extensive scaffolding and winches or cranes are needed. The length of an individual plate is generally restricted to a maximum of 6–10 m so as to facilitate erection. In actuality, lengths may be significantly less due to weight and size handling problems in close quarters or through existing utilities. The length restriction often necessitates the use of joints which need special attention in design since welding is not possible in the field. This is due to the fact the connection between the steel plates and the concrete is effected through adhesives which would be destroyed during the welding process. In addition to the corrosion that may take place on the steel plate itself, a number of these plates have been noticed to undergo corrosion at the joint between the steel and the adhesive causing loosening of the plate and failure due to bond failure. There is also the possibility of the bonded steel plate falling off in a buckling mode if loaded in compression. Nevertheless the technique has been used widely and a number of studies have been conducted on its efficacy in the field. A major concern, and one that has surprisingly not received significant attention from the research community is the danger of corrosion at the steel-epoxy interface which can adversely affect bond durability and response, with premature failure/collapse being the result.

Composite plates, in comparison are lighter and hence easier to handle. They have high specific stiffness and specific strength ratios, outstanding fatigue behavior and are corrosion resistant. They can be easily bonded to the concrete surface on site without the use of extensive scaffolding and jacks, requiring a minimal of support equipment [Figure 1(b)]. In addition they can be formed on site and hence can be used in very close quarters and in areas where access is limited. The use of a lower total weight not only increases the ease of retrofit, but also results in better cost-efficiency. Further, the use of this technique does not necessitate closure of all traffic lanes or a major disturbance of existing traffic patterns since extensive scaffolding, barriers, and heavy equipment are not needed. Although the materials cost attributed to composites is higher than that of steel, it is the total systems cost, including equipment, time and detour costs, that need to be considered when making a comparison. Although this technique has been investigated by a number of researchers (Meier, 1987; Saadatmanesh and Ehsani, 1989; Ehsani and Saadatmanesh, 1990; Triantafillou and Deskovic, 1991; Ritchie et al., 1991; Meier et al., 1993), the critical effect of the environment on bond durability and changes in overall response have not been investigated till recently (Xie et al., 1995), although the importance of such tests prior to field application has been stresed (Saadatmanesh and Ehsani, 1990).

The focus of this paper is on the evaluation of short-term environmental exposure effects on the bond between composite plates used for the strengthening of concrete and the concrete substrate as determined through tests on small scale mortar specimens. The study thus emphasizes materials and durability aspects rather than structural aspects per se.

2. MATERIALS AND TEST METHODOLOGY

In order to assess the effect of environmental exposure on aspects related to durability of the composite plate scheme, including that of the concrete-composite bond, a simplistic scheme of using small cement mortar beams as the base was used. Since the focus of the investigation was on bond durability and performance effects due to environmental exposure, this scale configuration was deemed to be suitable. It should therefore be kept in mind that the emphasis is on the relative changes in performance and the effects on the plated structural elements as a result of environmental exposure, rather than on the actual strengthening efficiency of the scheme on actual reinforced concrete beams (which has already been demonstrated by others). A 1:3 (cement:sand) mortar with a water cement ratio of 0.45 was used to prepare beams of 330.3 mm (13 in) length, 50.8 mm (2 in) width and 25.4 mm (1 in) depth. The mix was allowed to set in molds for 24 hours at 20°C after which they were allowed to cure for 28 days in water. The 28 day average strength of the mortar was 25.91 MPa (3757 psi) with a modulus of 21.53 GPa (3.12×10^6 psi) as determined by cylinder tests. The experimentally measured modulus compares well with the value given by the ACI building code on the basis of compressive strength (The ACI formulae predict a value of 24.06 GPa (3.49×10^6 psi)).

The composite plates were formed on the beams using a wet-layup type procedure. The composite reinforcement was in the form of unidirectional tow sheet, properties of which are given in Table 1. In this process, the dry fibrous reinforcement, which is all unidirectional in this case, is impregnated with a resin system during placement itself. The composite is thus formed at the same time

Table 1. Basic properties of the fiber reinforcement.

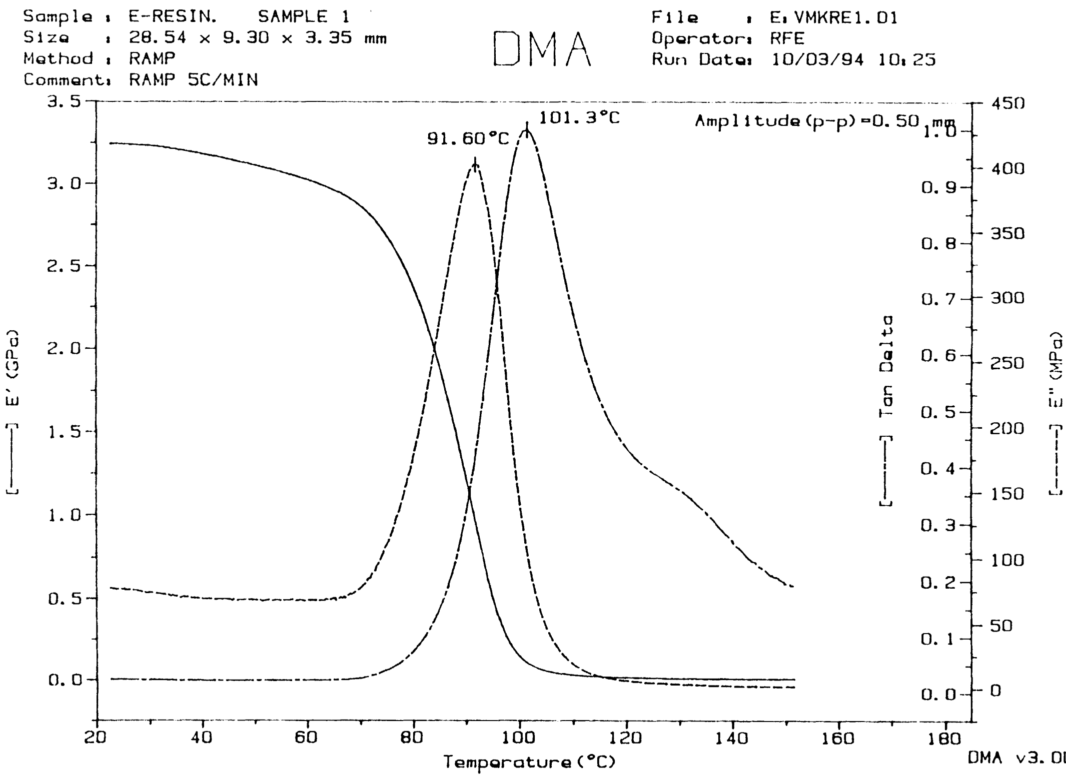
Fiber Name	Fiber Type	Weight (g/m^2)	Tensile Strength (MPa)	Tensile Modulus (GPa)
FTS-C1-30	Carbon	300	3479	227
FTS-GE-30	Glass	300	1515	76

as it bonds to concrete. In this case the resin system thus serves the dual purpose of impregnating and bonding the fibers, and bonding the composite to the concrete. It is through this factor that the method differs from the adhesive bonding of preimpregnated plates to the concrete surface. This form of construction (wet layup) has been extensively used in Japan and has been touted as being a more efficient means of placing the composite on the field, rather than the method of first making a composite plate to exact size and contours (which may not be possible) and then adhesively bonding it to the substrate surface. It was hence decided to use this technique as the basis for the current investigation.

Two different types of resins were used in order to form the matrix for the composite. Both represent resin systems already in use in civil infrastructure demonstration projects. The first was a proprietary system based on an epoxy backbone used by the Tonen Corporation extensively in its projects in Japan (hereafter referred to as resin system T), whereas the second was a commercial epoxy—Epon DPL 862 from Shell (hereafter referred to as resin system E). Catalysts were used for both systems to ensure a room temperature cure. The first system had a proprietary catalyst which was added in a 2:1 ratio (resin:catalyst), whereas the Epon 862 was catalyzed by Ancamine 1636 in the ratio of four parts resin to one part hardener.† Both systems were cured using room temperature cure formulations, similar to that usable in the field.

A comparison of glass transition temperatures (T_g) through the use of Dynamic Mechanical Analysis (DMA) on neat resin samples showed that the Epon 862 had a T_g that was significantly higher than that of the other system. The E system showed a glass transition temperature of over 90°C [Figure 2(a)], whereas the T system gave a much lower glass transition temperature after room temperature cure [Figure 2(b)]. From Figures 2(a) and 2(b) it is also seen that the T resin system shows a more drastic drop in elastic properties with the value of E' tending to 0 as early as 60°C as compared to the 100°C level for the E resin system. The combination of the two different resin systems and the two fiber tow sheet systems results in a total of four different composites that were used in the study as reported in Table 2. The abbreviations used in the last column represent the resin system and fiber type (e.g., TC represents a composite fabricated using

†The use of commercial names is provided for purposes of reference only, and is not intended to serve as a means of endorsement in any way.



(a)

Figure 2. *Results of Dynamic Mechanical Analysis (DMA) tests on neat resin samples to determine glass transition temperatures and instantaneous moduli: (a) E-resin system and (b) T-resin system.*

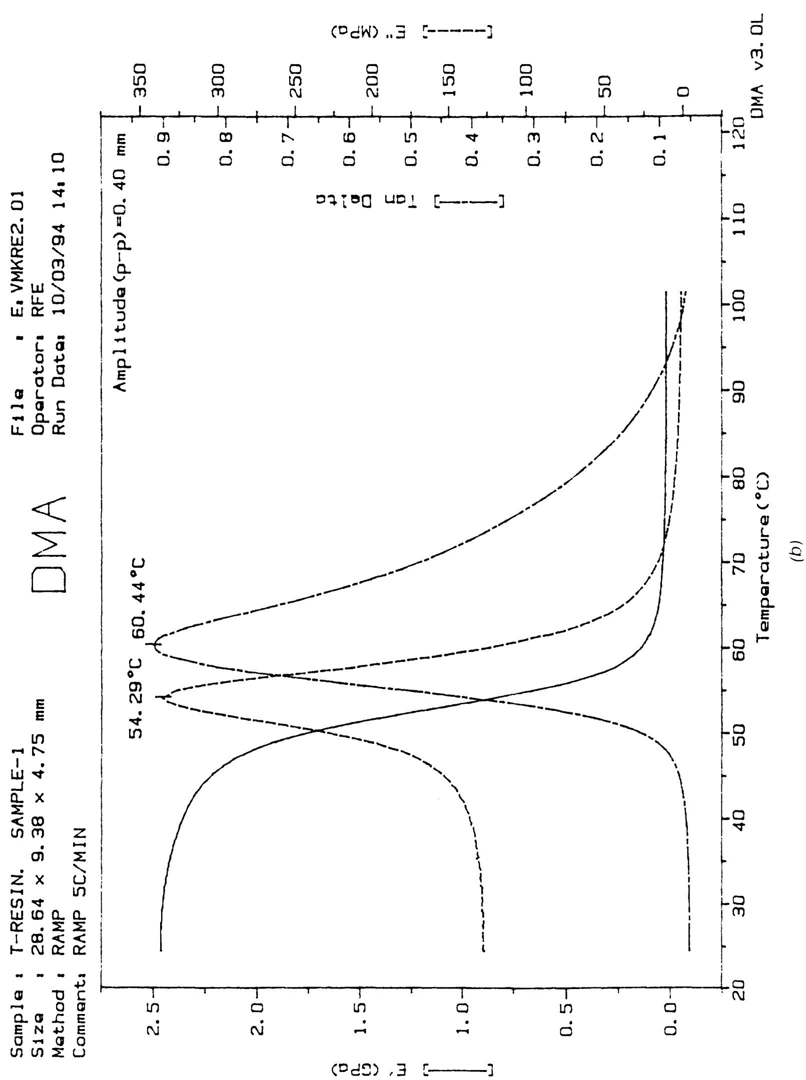


Figure 2 (continued). *Results of Dynamic Mechanical Analysis (DMA) tests on neat resin samples to determine glass transition temperatures and instantaneous moduli: (a) E-resin system and (b) T-resin system.*

Table 2. Notation for the composite systems used as external reinforcement.

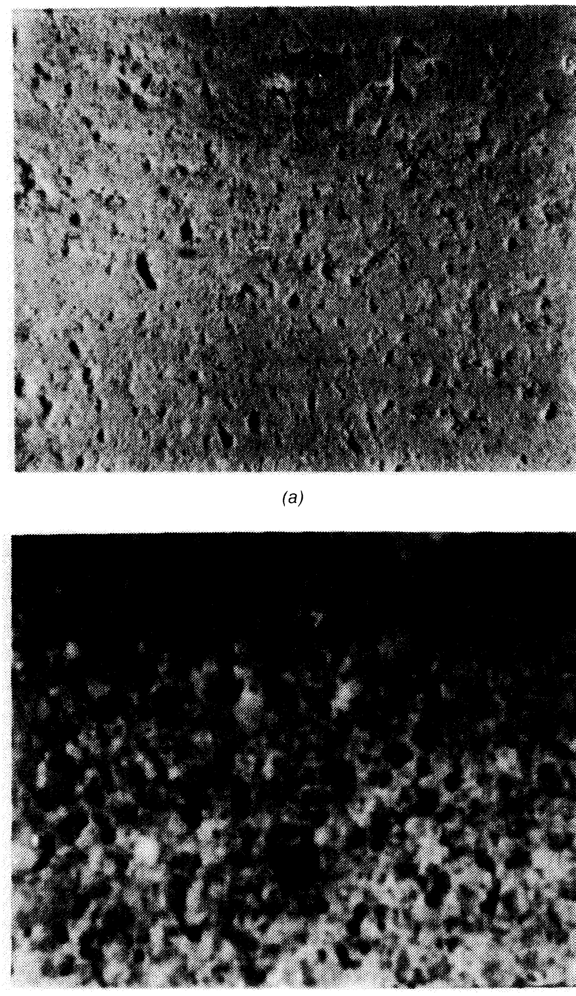
Tow Sheet Nomenclature	Fiber Type	Epoxy System	Abbreviation
FTS-C1-30	Carbon	Tonen	TC
FTS-GE-30	Glass	Tonen	TG
FTS-C1-30	Carbon	Epon 862 and Ancamine 1636	EC
FTS-GE-30	Glass	Epon 862 and Ancamine 1636	EG

the T resin system, and the carbon fiber tow sheet, C). These abbreviations will be used in further discussions.

In order to plate the beams, the surfaces were first abraded to remove laitance and to provide increased surface area for bonding. Figures 3(a) and 3(b) show stereomicrographs of the concrete surface before and after beading/abrasion respectively. The increase in nonplanarity after abrasion results in the promotion of mechanical interlocking between the epoxy and the concrete surface. A surface coat of primer was then applied to the beams. Individual layers of tow sheet were then placed and wet-out through application of the resin using a roller and pressure to ensure good wet-out. Three layers of fibrous reinforcement were used on each beam, extending over a length of 152.4 mm (6 in) centered over each specimen. The composite plated concrete specimens were allowed to cure for 1 week before any further handling. This method of fabrication differs from that used previously (Saadatmanesh and Ehsani, 1990; Meier et al., 1993) in that the composite plate is formed during the adhesion stage itself whereas in previous investigations the plate was prefabricated and then adhesively bonded to the concrete surface. The obvious difference is that in the latter there exists a layer of adhesive between the plate and the concrete, resulting in two separate interfaces—one between the concrete and the adhesive, and the second between the adhesive and the composite. In the method used herein the interface is actually between the composite and the concrete through the resin system itself and because of the method of application and the form of reinforcement used, fibers are actually in contact with the concrete surface itself allowing for better load transfer and direct redistribution of stresses.

Composite plates were also fabricated by themselves for testing in tension and the average results are listed in Table 3. It can be seen that there is an insignificant difference in tensile properties of similar fiber-based systems based on choice of epoxy under room temperature conditions.

Plated specimens were tested in four point loading (with composite plates on the tensile surface) with a span length of 203.2 mm (8 in) and loading at one-third points at a cross-head displacement rate of 0.127 cm/min. A minimum of four specimens were tested in each case and scatter bars are shown for all results reported in the figures. Deflection of the beams was recorded at midpoint using a spring loaded Linear Variable Differential Transformer (LVDT) system con-



(a)

(b)

Figure 3. *Stereomicrographs of the concrete surface (magnification of × 9): (a) before and (b) after the abrasion/glass beading procedure.*

Table 3. Tensile properties of composite plates.

Material	Modulus of Elasticity (GPa)	Ultimate Tensile Strength (MPa)	Percent Strain at Failure	Fiber Weight Fraction	Average Thickness (mm)
TG	22.68	532.15	2.49	57.36	0.76
TC	74.76	1241.67	1.74	54.82	1.14
EG	23.43	560.41	2.36	55.41	0.91
EC	70.67	1254.32	1.78	50.79	1.32

nected to a data acquisition system, such that load and deflection data was recorded simultaneously and continuously. The composite plates extended over a distance of 193 mm (7.6 in), thereby ensuring that the composite was completely on the tensile surface without extending beneath the supports. These tests were used to study the effect of the plates on overall behavior as a baseline for further environmental investigations. Specimens with the composite plates were subjected to the five environmental exposure conditions as listed in Table 4 for a period of 60 days and then tested in 4 point bend. This allowed for careful examination of the environmental effect at the transition points where the plates ended. Comparisons were made between specimens tested after exposure under ambient conditions with those exposed to the environmental conditions listed in Table 4. The as-built (i.e., ambient) conditions will be used as controls throughout. The exposure period was chosen so as to allow sufficient time for moisture saturation in the composite (which was experimentally determined prior to the start of the tests through tests conducted to assess moisture absorption in the composite and resin). It is also well recognized that most of the effects that cause losses in strength and stiffness due to moisture uptake occur during the first few months of immersion (Shenoi and Wellicome, 1993). After failure, the beams were cut perpendicular to the longitudinal axis to give uniform rectangular cross-sections which were studied under a WILD M5A Stereomicroscope to assess the interface between the composite and the concrete surface.

Table 4. Summary of environmental conditions.

Environmental Conditions	Details	Abbreviation
Ambient	20°C (65°F)	A
Water	Fresh water at ambient temperature	W
Synthetic Seawater	ASTM D1141 at ambient temperature	SW
Frozen	−15.5°C (4°F)	F
Freeze-thaw cycle	−15.5°C (4°F) for 24 hours followed by 20°C (65°F) for 24 hours	FT

3. RESULTS AND DISCUSSION

Before assessing the test data, it is important to consider the different factors that could affect the performance of the specimens. The flexural stiffness of the beams can be related to a number of factors including: (1) the flexural stiffness of the mortar; (2) the flexural stiffness of the composite plate; (3) the flexural stiffness of the epoxy as well as the existence (if any) of a resin rich interface between the composite reinforcing fibers and the concrete; (4) effect of the primer coat on filling minute cracks and voids in the concrete and thereby affecting overall stiffness; (5) adhesion between the mortar beam and the composite plate; and (6) the environmental exposure. In a similar manner, the factors affecting the load carrying capacity of the plated beams include: (1) the ultimate tensile strength of mortar; (2) the ultimate tensile strength of the composite; (3) the ultimate tensile strength of the epoxy; (4) degree of adhesion between the mortar beam and the composite plate; (5) level of stress concentration formed at the drop-off of the composite plate; and (6) the environmental exposure. It should be noted that although the effect of the stress concentration is not the focus of the current study, it is extremely important. R. N. Swamy, et al. (1987) in studies of strengthening through epoxy bonded steel plates, have shown that when the thickness of the beam changes from an unplated member to a plated member, high stress concentrations are present at the end of the plate when the beam is loaded in flexure causing changes in failure modes and significantly affecting behavior. In the case of steel plates used as an external means of strengthening, the stress concentrations have been shown to depend on the thickness of the plates and the modulus of elasticity of the plate itself, and this is not expected to change through the use of the composite plate.

The main function of the prime coat applied to the concrete surface is to prepare the surface for good adhesion by filling asperities, and sealing/filling cracks, thereby presenting a flat surface for the application of composite reinforcement. The prime coat itself is extremely thin but does serve to fill interstices and cracks and allowing for a good secondary bond to develop between the prime coat and the composite being wet-laid up on top. Since the prime coat is not allowed to cure before the application of the composite, the resulting bond between it and the composite layers is not truly a secondary chemical bond, but rather a primary bond with cure cycles slightly staggered.

After testing it was noticed that in some cases voids existed at the concrete-composite interface. This drawback is often cited as the main motivation for the use of prefabricated composite panels which can be adhesively bonded to the concrete surface. However, the use of a plate reduces the flexibility associated with the application of fabric over areas of uneven or changing geometry or in cases where access to the surface may be problematic due to the presence of utilities etc. The presence of voids at the interface is hypothesized to be due to one of a combination of the following reasons: (1) insufficient amount of epoxy applied during the bonding process; (2) high viscosity of the epoxy; (3) a high contact angle between the epoxy and the mortar beam, which would reduce the spreadability of the epoxy; (4) inability of the epoxy to displace air and water vapor adsorbed on the surface of the mortar beam; and/or (5) degradation due to environmental exposure. Further investigation of the peel and microstructural characteristics of the interface and bond region was conducted using a specially designed peel test results of which are reported elsewhere (Karbhari and Engineer, 1996). It is important to note that the differences between the base properties of the resin systems and their affinity for concrete will result in differences in behavior as shown in Figure 4 which shows representative load-deflection plots for specimens coated with a thin layer of the two resin systems as compared to the behavior of the uncoated base-line. It is of significance to note that the use of the T resin system resulted in a greater increase in flexural stiffness over that of the uncoated specimen, as compared to the E-resin system coated specimens. This can be related to the ability of the lower viscosity of resin system T enabling the filling of all the cracks and voids in the concrete, thereby giving the appearance of higher stiffness. Microscopic analysis also showed that the T system formed a thicker interface between the concrete and the composite, which further causes the increases seen.

Figures 5–7 show the failure loads, deflection at failure and flexural stiffnesses for the specimens plated with the four composite systems under ambient conditions. The performance levels and standard deviations (in parentheses) for the control (unplated) and the four types of plated specimens are also given in Table 5. It may be noted that the failure load levels of the specimens plated with the glass fiber–T resin combination were higher than those of the corresponding specimens plated with the glass fiber–E resin combination. The opposite was true with the specimens plated with the carbon tow sheet. The use of the stiffer and stronger (see Table 3 for details on properties of the composites) carbon fiber reinforced composites obviously resulted in the best overall performance as seen

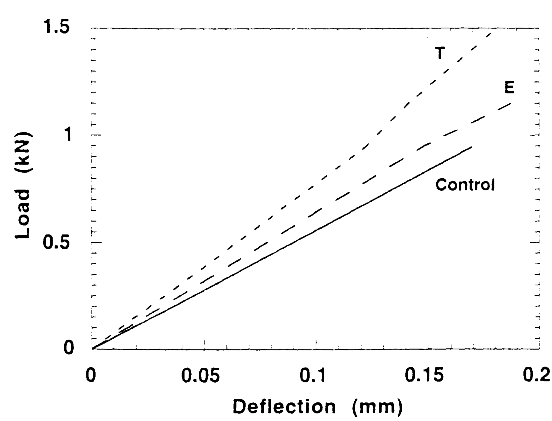


Figure 4. Apparent change in load-deflection behavior after application of resin systems on the tension surface of the concrete specimen due to the filling in of cracks and asperities as well as due to minor infusion of the resin into the concrete.

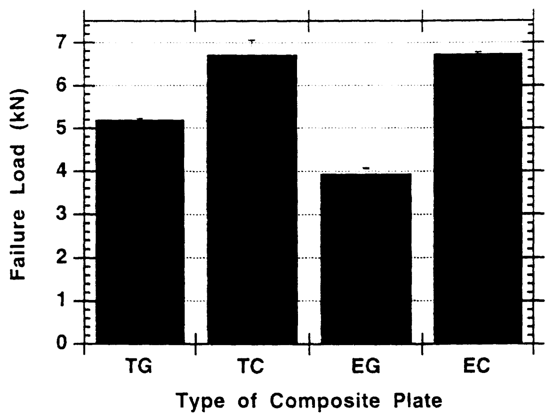


Figure 5. *Failure load levels for the plated specimens under ambient conditions (nomenclature is as given in Table 2).*

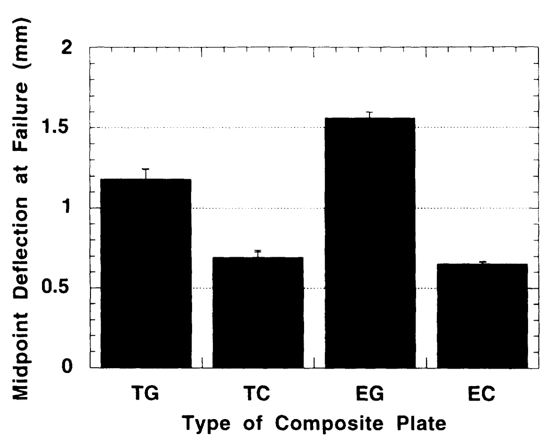


Figure 6. *Mid-point deflection levels for the plated specimens under ambient conditions (nomenclature is as given in Table 2).*

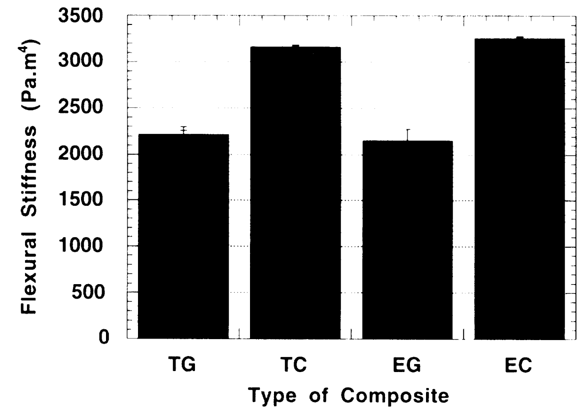


Figure 7. *Flexural stiffness (EI) levels for the plated specimens under ambient conditions (nomenclature is as given in Table 2).*

through higher failure loads, lower deflection and higher flexural stiffness. Although one might be tempted to conclude that the T resin system – primer combination is the most efficient, it should be remembered that the efficacy of a composite system for use in infrastructure renewal will depend not only on performance under ambient conditions, but more importantly on the changes effected on performance by different environmental exposures. The optimum system is thus one that not only has a sufficiently high level of performance, but also one that retains most of its performance attributes over the working range of environmental exposures.

Another factor that needs to be considered at the same time is that of failure modes and damage mechanisms. Failure was initiated in the specimens plated with the TG, TC and EC composites through cracking at the end of the plate followed by the formation of a diagonal shear crack through the concrete, whereas that in the EG specimens occurred through debonding of the laminate followed by the development of shear cracks in the concrete. This phenomenon is caused by a vertical relative displacement as shown in Figure 8 and needs to be carefully

Table 5. Overall comparison of response under ambient conditions.

Beam Type	Failure Load (kN)	Midpoint Deflection at Failure (mm)	Flexural Stiffness (Pa·m^4)
Control	0.91 (0.045)	0.176 (0.032)	1731 (75.73)
Plated (TG)	5.20 (0.025)	1.18 (0.064)	2219 (67.56)
Plated (TC)	6.71 (0.34)	0.69 (0.039)	3163.5 (15.25)
Plated (EG)	3.94 (0.131)	1.56 (0.038)	2158.7 (120.26)
Plated (EC)	6.73 (0.05)	0.65 (0.015)	3256 (19.58)

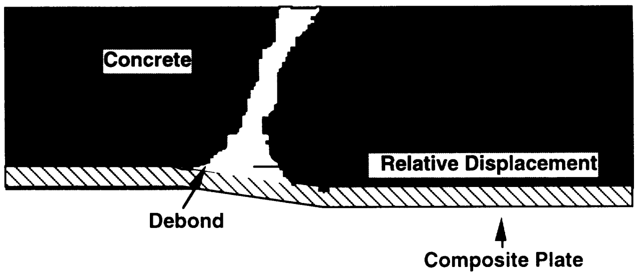


Figure 8. *Schematic of failure mechanism due to relative movement and debonding at the concrete-composite interface.*

considered during design. In all cases, however, peel and failure were gradual. The carbon fiber reinforced plates show almost linear behavior to failure as seen in Figure 9 whereas the glass reinforced plates show a change in stiffness at a point wherein some flexural cracks can be seen to form on the specimen tensile face in the concrete. This causes an overall reduction in stiffness with very small debonds initiating from the most severe of these but not propagating beyond the local vicinity of the crack. Both the glass fiber systems show considerable ability to carry load even after flexural crack initiation. The difference in behavior of the glass and carbon reinforced plated systems can be traced to the higher stiffnesses and strengths of the carbon fiber reinforced plates which are able to carry a significant portion of the load before showing any signs of distress.

3.1. Effects due to Environmental Exposures

As described in the section on test methodology, specimens were exposed to environments listed in Table 4 for a period of 1440 hours (60 days) before testing.

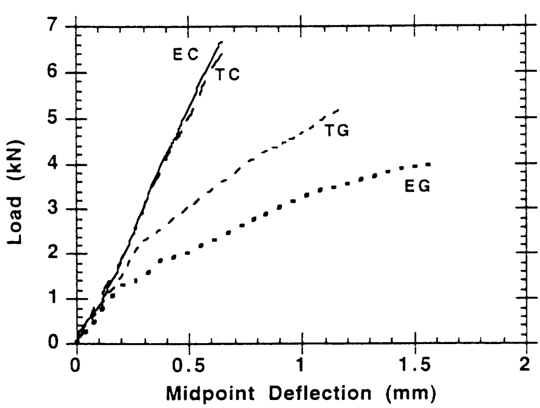


Figure 9. *Representative load-deflection profiles of plated specimens (ambient conditions).*

Overall, the most significant deterioration was seen after immersion in fresh water and sea water, with the minimum overall change resulting from the exposure to $-15.5°C$ (Figures 10–13).

Water absorption causes two effects at the macroscopic level that lead to deterioration of the resin (and resin-concrete bond), namely a general reduction of mechanical properties and weight gain due to uptake of water. Penetration of water into the composite occurs by diffusion through the resin (which it should be remembered also serves as the adhesive in this investigation) and capillary flow through microcracks and voids along imperfect interfaces. The first interface is that between the fibers and the resin, and the second is that between the resin and the concrete itself. Although the former occurs at a small scale, the latter could be significant from the outset of exposure if cracks and voids are not filled in by the primer coat. Mechanical properties degrade as seen in Figures 10–13 due to plasticization of the resin, which makes it more compliant. This is in line with earlier results reported by Jones et al. (1984) and Ellis and Karasz (1984) on the effect of water on compliance changes in epoxy resins. It can be noted on

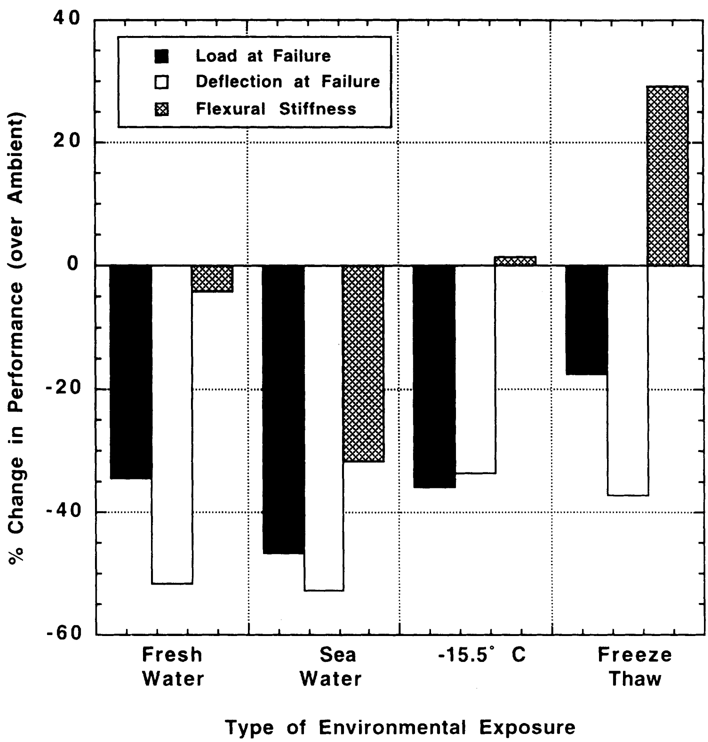


Figure 10. *Percentage change in performance levels in TG plated systems as a function of environmental exposure.*

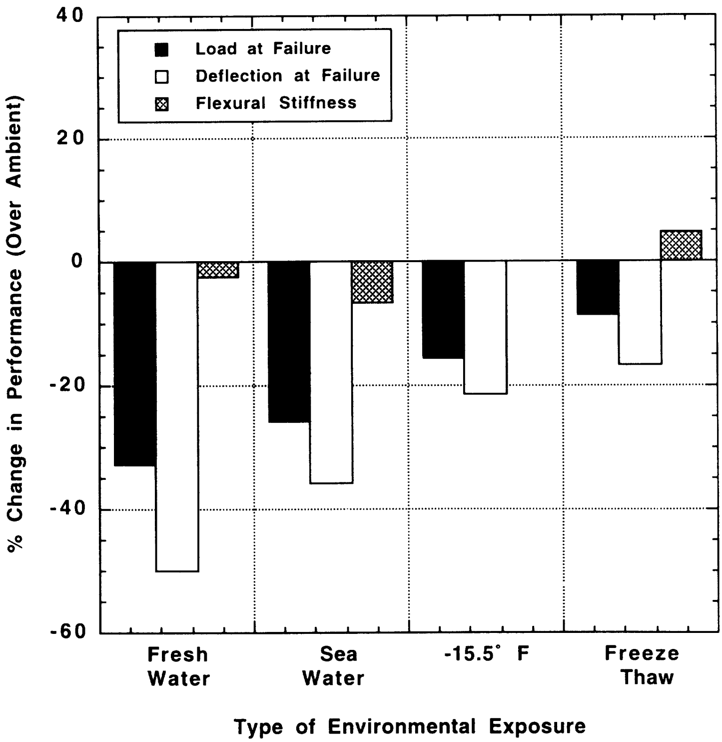


Figure 11. *Percentage change in performance levels in TC plated systems as a function of environmental exposure (% change in flexural stiffness after exposure to −15.5°C is negligible).*

comparison of Figures 10–13 that the maximum changes in load levels were due to the effect of water in the T-resin based plated specimens, with plated beams showing drops of 34.58% and 32.86% from ambient for the glass and carbon reinforced plated specimens respectively as compared to 14.59% and 23.73% for the same systems (glass and carbon respectively) when the E resin system was used. Debonding stresses across the fiber-resin interface have been reported to result from resin swelling and osmotic pressure as well as chemical attack on the fiber surface (Walter and Ashbee, 1982; Boll et al., 1985; Weitsman, 1987).

Although an intensive study was not conducted at the interface level as part of the current study, microscopic examination of the composite did show some degradation at that level after exposure to sea water. Tests conducted on neat resin samples show that the T resin systems showed a weight gain almost 40% in excess of that shown by the E system after immersion in water. It is to be noted that the structure of the resin system has the potential to influence the uptake of water based on the degree of hydrophilic nature of the polymer network due to the presence of differing contents of amine and hydroxyl functionalities. This is often demonstrated by a fall in glass transition temperature (T_g) as a consequence of moisture uptake (Illinger and Sprouse, 1978). Although the stoichiometry and chemical content of the two systems was not completely known to the investigators, a difference in the lowering of glass-transition temperatures between the two resin systems was noted through Dynamic Mechanical Analysis (DMA) tests (Table 6). DMA tests on the neat resin after immersion in water for 60 days show a drop of 20% and 12% in T_g for the T and E resin systems respectively. It was also noted that the T_g's of the composites fell about 10.75% for both the glass- and carbon-fiber reinforced T systems, whereas the drop was about 9.5% for the corresponding E systems after the same 60 day immersion in water. These trends would seem to provide further evidence of the role of matrix degradation in the drastic changes in load carrying capacities and structural stiffnesses (as in Figures 10–13) seen in the plated specimens after immersion in fresh water. It should however, be noted that the T_g of epoxies have been seen to reverse after

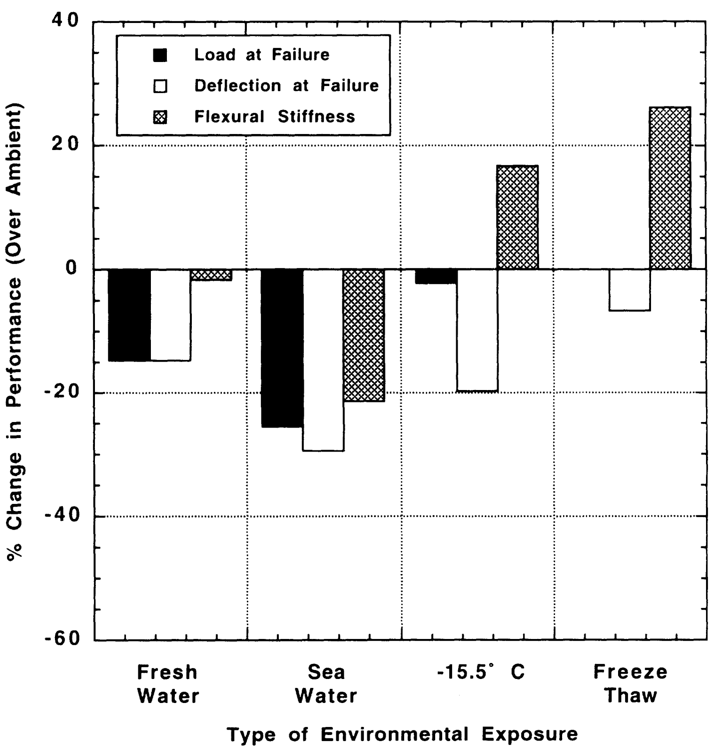


Figure 12. *Percentage change in performance levels in EG plated systems as a function of environmental exposure (% change in failure load after exposure to freeze-thaw cycling is negligible).*

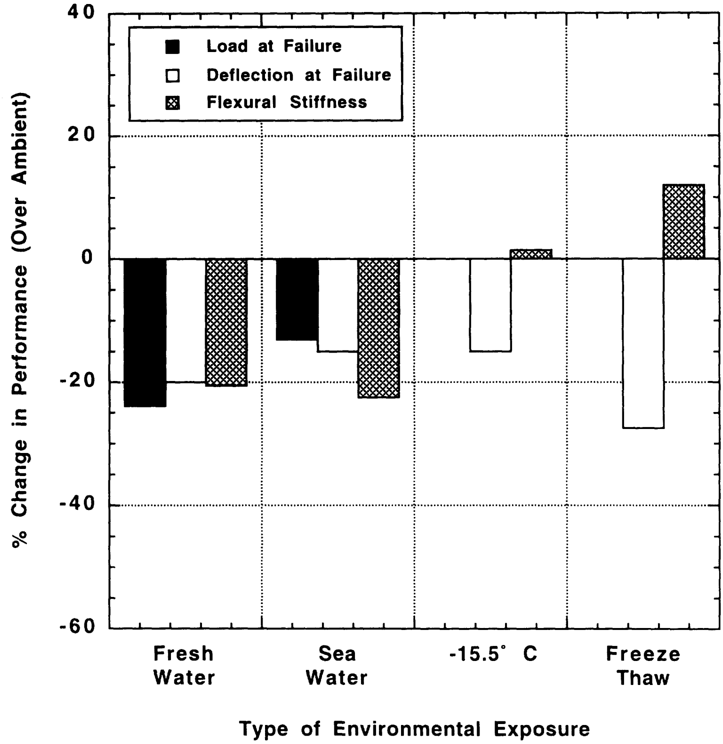


Figure 13. *Percentage change in performance levels in EC plated systems as a function of environmental exposure (% change in load at failure after exposure to $-15.5°C$ and freeze-thaw cycling s negligible).*

drying (Netravali et al., 1985; Illinger and Sprouse, 1978). It must however be kept in mind, that in the field, structures made of concrete will be exposed to constant humidity and moisture in some cases, and these structures are likely to contain some moisture which would migrate towards the epoxy-concrete interface. In some instances, such as in the use of plates on the soffit of hollow box girders the plates may in fact trap in moisture. Therefore it is essential that we consider the case of moisture uptake in selecting the appropriate resin system and in setting suitable safety factors. Shenoi and Wellicome (1993) in fact suggest the application of a partial safety factor of 1.1–1.2 to account for long-term water induced degradation for maritime applications. It is also important to keep in mind that deterioration and degradation is seen at the composite-concrete interface as well. Figure 14 shows a stereomicrograph on the concrete-composite interface after immersion in water for 60 days. The interface shows some local degradation and voids, as well as effects of plasticization.

It is clear that environmental durability depends not only on the resin charac-

Table 6. Percentage change in T_g (from ambient) after exposure to the two aqueous environments.

Composite System	Environmental Condition	
	Water	Sea Water
TG	−10.19%	−8.99
EG	−9.98%	−11.08
TC	10.75%	−11.61
EC	−9.54%	−9.36

teristics but also on the type of fiber used. A quick comparison of Figures 10 and 11 show that the degradation in performance levels is greater for the glass fiber reinforced systems than for the carbon fiber reinforced systems. The E-glass fibers are primarily calcium aluminoborosilicates with a maximum alkali content of 2%. E-glass fibers are susceptible to stress-corrosion and pitting in the presence of water, which is exacerbated by salt water. Carbon fibers are not susceptible to the same mechanisms and therefore degrade to a lesser degree. While comparing the results of Figures 12 and 13, it should be noted that full compatibility of sizing was not achieved between the two tow sheet systems and the E resin system, causing some deviations in behavior at the interfacial level especially with carbon fibers. It can also be seen from Figures 10–13 that immersion in sea water causes a greater degradation in stiffness than seen after immersion in fresh water in all cases. In all cases except the EG case (glass fibers in resin system E) the drop in T_g was seen to be slightly more after immersion in water as compared

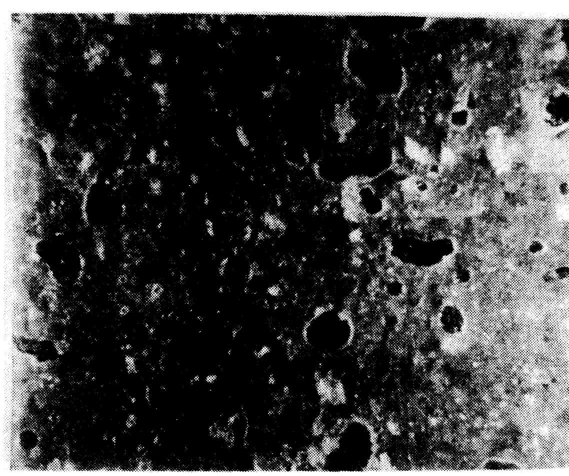


Figure 14. *Stereomicrograph of concrete-composite interface showing effect of immersion in water on the resin layer.*

to that after immersion in sea water. The values, however are fairly close in some cases. It should be noted that the drop in T_g is not only due to changes in the resin, but also that in the composite itself through changes at the interfacial level.

Exposure to $-15.5\,^{\circ}$C was seen to result in a decrease in the level of failure load in all plated specimens, with the systems wherein the T resin was used as the matrix and bonding agent showing the most significant changes. The drop in strength after exposure to the $-15.5\,^{\circ}$C temperature is in line with the earlier results of Dutta (1988; 1992) and Karbhari and Pope (1994). Again it is noteworthy that the drop in load and deflection levels is greater for specimens plated with the T resin system, than those plated with the E-system (Figures 10–13). This once again emphasizes the importance of selection of the composite components from the aspect of durability—since it would appear that the E system shows minimal changes after exposure. Exposure to a cold regions type environment is known to increase the flexural stiffness of vinyl ester and epoxy systems and this is reflected in the results obtained for the plated systems as well. It is again noted that the systems reinforced with glass fibers show greater effects after exposure than do the carbon reinforced plated systems, reinforcing the susceptibility of glass fibers to environmental exposure related changes. It is of considerable interest to note that in all cases interfacial fracture energies, G_{IC} and G_{IIC} increased for all cases after exposure to the $-15.5\,^{\circ}$C environment, which can primarily be traced to the higher bending stress levels achievable under these conditions. The freeze-thaw condition represents a case wherein both plasticization and matrix stiffening take place and an exact determination of effects and causes is difficult especially as related to the present case wherein changes in the concrete, composite and the composite-concrete interface must be considered. The interested reader is referred to the excellent work of Lord and Dutta (1988) in compiling and reviewing effects of low-temperature environmental cycling on the properties and degradation mechanisms in composites.

4. SUMMARY AND CONCLUSIONS

This paper deals with the aspect of environmental effects on the short term durability of retrofitted concrete components. The plating technique has been shown to be a viable method of retrofitting and strengthening structural elements such as bridge deck soffits and girders. Composites show considerable potential for use in such applications. However, a great deal of attention needs to be paid to the appropriate selection of fiber and resin systems to avoid significant deterioration of performance levels due to environmental exposure. The results of the present investigation show that immersion in water (such as might be expected through entrapment of water in hollow box girders, and due to high water levels) presents a challenge, especially if the resin system (or adhesive) is chosen incorrectly. The use of low T_g resin systems is seen to result in significant deterioration and loss of efficiency of the strengthening scheme. It is stressed that the selection of appropriate resin systems is critical and that a failure to do so will result in structural collapse due to aging and environmental degradation. It is also stressed that structural engineers need to be aware of the fact that ambient conditions and weather conditions differ from region to region, as well as from country to country, and that a system that shows satisfactory behavior under one set of environmental conditions need not necessarily show even acceptable performance in another. In the present investigation, it is clear that the use of carbon fibers and the higher T_g (and more stable) E-resin system will lead to more durable retrofit measures. Carbon fiber reinforced composites combine the high strength- and stiffness-to-weight ratios with outstanding fatigue properties and may be the leading contenders for use in infrastructure renewal. However, it is stressed that the higher cost of carbon fibers needs to be offset using a cost-performance benefit analysis after comparison to lower cost, but more durable fibers such as S-glass (Karbhari and Shulley, 1994). Further investigations on long-term durability especially as related to the use of higher T_g epoxy systems, hybrids and composite plating schemes that include the use of gel-coats (or sacrificial layers) as in maritime structures, is needed before strategies for the use of composites for infrastructure rehabilitation are widely adopted in the field. The future appears bright for the introduction of new techniques and materials, but the adoption must proceed after a thorough and appropriate assessment of materials and their durability have been completed.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge discussions on durability and degradation mechanisms with Drs. R. L. McCullough and S. McKnight, both of the Center for Composite Materials, University of Delaware. They would also like to acknowledge helpful discussions with Dr. Chao H. Hu, Assistant Highway Director-Design, Department of Transportation, Delaware on the topics of durability and engineering design data.

REFERENCES

Boll, D. J., W. D. Bascom and B. Motiee. 1985. "Moisture Absorption by Structural Epoxy-Matrix Carbon-Fiber Composites," *Composites Science and Technology,* 24(4):253–273.

Bresson, J. 1972. "Strengthening by Bonded Reinforcing of the Underpass on CD 126 on the Southern Autoroute," *Annales Publics,* France, 297:2–24.

Dussek, I. J. 1980. "Strengthening of Bridge Beams and Similar Structures by Means of Epoxy-Resin Bonded External Reinforcement," *Transportation Research Record 785,* pp. 21–24.

Dutta, P. K. 1988. "Structural Fiber Composite Materials for Cold Regions," *ASCE Journal of Cold Regions Engineering,* 2(3):124–134.

Dutta, P. K. 1992. "Low Temperature Compressive Strength of Glass-Fiber Reinforced Polymer Composites," *Proceedings of the 11th Conference on Offshore Mechanics and Arctic Engineering,* Calgary, Canada.

Ehsani, M. R. and H. Saadatmanesh. 1990. "Fiber Composite Plates for Strengthening Bridge Beams," *Composite Structures,* 15:343–355.

Ellis, T. S. and F. E. Karasz. 1984. *Polymers,* 25:664–669.

Illiger, J. and J. F. Sprouse. 1978. *Am. Chem. Soc. Org. Coat. Plast. Chem.*, 175th ACS Meeting, 38:497–502.

Jones, R., R. N. Swamy, J. Bloxham and A. Bouderbalah. 1980. "Composite Behavior of Concrete Beams with Epoxy Bonded External Reinforcement," *International Journal of Cement Composites and Lightweight Concrete,* 292:91–107.

Jones, C. J., R. F. Dickson, T. Adam, H. Reiter and B. Harris. 1984. *Proceedings of the Royal Society of London*, A396:315–338.

Karbhari, V. M. and M. Engineer. 1996. "Investigation of Bond between Concrete and Composites: Use of a Peel Test," *Journal of Reinforced Plastics and Composites*, In Press.

Karbhari, V. M. and G. Pope. 1994. "Impact and Flexure Properties of Glass/Vinyl Ester Composites in Cold Regions," *ASCE Journal of Cold Regions Engineering*, 8(1):1-20.

Karbhari, V. M. and S. B. Shulley. 1995. "Use of Composites for the Rehabilitation of Steel Structures—Determination of Bond Durability," *ASCE Journal of Materials in Civil Engineering*, 7(4):239-251.

Klaiber, F. W., K. F. Dunker, T. G. Wipf and W. W. Sanders. 1987. "Methods of Strengthening Existing Highway Bridges," NCHRP Report No. 293, Transportation Research Board, Crowthorne, England.

Lord, H. W. and P. K. Dutta. 1988. "On the Design of Polymeric Composite Structures for Cold Regions Applications," *Journal of Reinforced Plastics and Composites*, 7:435–458.

Macdonald, M. D. and A. J. J. Calder. 1982. "Bonded Steel Plating for Strengthening Concrete Structures," *International Journal of Adhesion and Adhesives*, 2(2):119–127.

McKenna, J. K. and M. A. Erki. 1994. "Strengthening of Reinforced Concrete Flexural Members Using Externally Applied Steel Plates and Fiber Composite Sheets—A Survey," *Canadian Journal of Civil Engineering*, 21(1):16–24.

Meier, U. 1987. "Bridge Repair with High Performance Composite Materials," *Material und Technik*, 4:125–128.

Meier, U., M. Deuring, H. Meier and G. Schwegler. 1993. "Strengthening of Structures with Advanced Composites," in *Alternative Materials for the Reinforcement and Prestressing of Concrete*, J. L. Clarke, ed., Glasgow: Blackie Academic & Professional, pp. 153–171.

Netravali, A. N., R. E. Fornes, R. D. Gilbert and J. D. Memory. 1985. *Journal of Applied Polymer Science*, 30:1573–1578.

Ritchie, P. A., D. A. Thomas, L-W. Lu and G. M. Connelly. 1991. "External Reinforcement of Concrete Beams Using Fiber Reinforced Plastics," *ACI Structural Journal*, 88(4):490–499.

Saadatmanesh, H. and M. R. Ehsani. 1990. "Fiber Composite Plates Can Strengthen Beams," *Concrete International*, (March):65–71.

Shenoi, R. A. and J. F. Wellicome. 1993. *Composite Materials in Maritime Structures, Vol. 1: Fundamental Aspects*, Cambridge: Cambridge University Press, p. 45.

Swamy, R. N., R. Jones and J. W. Bloxham. 1987. "Structural Behavior of Reinforced Concrete Beams Strengthened by Epoxy-Bonded Steel Plates," *The Structural Engineer*, 2:59–68.

Triantafillou, T. C. and N. Deskovic. 1991. "Innovative Prestressing with FRP Sheets: Mechanics of Short-Term Behavior," *ASCE Journal of Engineering Mechanics*, 117(7):1652–1672.

Walter, E. and K. H. G. Ashbee. 1982. "Osmosis in Composite Materials," *Composites*, pp. 365–368.

Weitsman, Y. 1987. "Coupled Damage and Moisture Transport in Fiber-Reinforced Polymeric Composites," *International Journal of Solids and Structures*, 23:1003–1025.

Xie, M., S. V. Hoa and X. R. Xiao. 1995. "Bonding Steel Reinforced Concrete with Composites," *Journal of Reinforced Plastics and Composites*, 14(9):949–964.