DURABILITY OF FIBER REINFORCED POLYMER IN BRIDGE CONCRETE DECK

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ABSTRACT

The use of embedded reinforcement in concrete provides economical and durable composite material for bridge deck. Steel is the most used reinforcement for bridge concrete deck. The alkalinity of capillary pores in concrete as the product of cement hydration produces the passive film shielding and protecting the steel from corrosion. However, bridge deck is the exposed structure that is vulnerable to the aggressive substances such as chloride and carbon dioxide. The presences of these two substances are well known will disturb the stability of the passive film and subsequently the steel will start to corrode. In order to mitigate the bridge concrete deck deterioration due to the corrosion of steel reinforcement, fiber reinforced polymer is currently introduced as promising alternative reinforcement. Fiber reinforced polymer is corrosion resistance material that its application as reinforcement will bear bridge concrete deck with longer service-live. Because of its new application, the long term durability of fiber reinforced polymer embedded in concrete and its impact to the structural integrity is still on concern. In this paper, the state of the art of current study on the durability of fiber reinforced polymer as reinforcement for bridge concrete deck and where it should go will be discussed.

Keywords: durability, fiber reinforced polymers, concrete, bridge deck

1. INTRODUCTION

The use of steel as reinforcement in bridge concrete deck satisfies the needs of economical and ductile materials. However, as the bridge is placed in aggressive environment, steel reinforcement will undergo corrosion that leads into unsatisfactorily period of service live. Reported in 2005 (Gremel & Steere, 2005), approximately 15% of 590,000 bridges in the United States are structurally experienced deficiencies and most of them were caused by the corrosion of steel sections and steel reinforcement. In fact, the concrete environment protects the steel from corrosion by creating the passive film surfacing the steel. Nevertheless, vulnerability of concrete (especially bridge concrete deck) to the aggressive substance such as chloride and carbon dioxide will disturb this passive film and yield the corrosion of steel reinforcement. In order to mitigate this corrosion issue, fiber reinforced polymer (FRP) is currently proposed and studied for being used as reinforcement for bridge concrete deck.

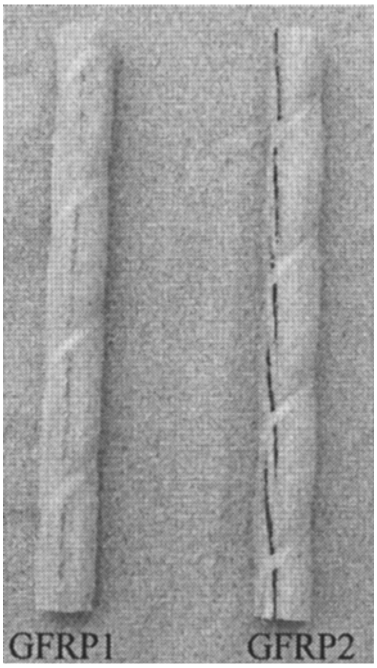


Figure 1. Typical GFRP bars (Chen et al., 2006)

FRP is the composite material that consists of fiber embedded in polymer matrix (Myers & Viswanath, 2006). The commonly used fibers are carbon, aramid and glass and the commonly used polymer matrix includes polyester vinylester and epoxy. The function of the polymer matrix is to hold the fibers together and to protect them from aggressive environment (Bakis et al., 2007). Generally, the polymer based reinforcement bars are named depend on the type of fibers embedded in the matrix. The reinforcements with carbon, aramid and glass are, respectively, called CFRP (carbon fiber reinforced polymer), AFRP (aramid fiber reinforced polymer) and GFRP (glass fiber reinforced polymer). GFRP (typical GFRP bars are shown in Figure 1) is gaining more popularity for being used in the construction area since this type of FRP is relatively cheaper compare to the others two. Because of its extensive popularity, there were more studies performed to learn about the durability of GFRP reinforcements in concrete environment. From the durability point of view, generally, GFRP is less durable compare to CFRP or AFRP, and CFRP is the most durable.

FRP is the “corrosion” resistant material. However, the other types of degradation manifest themselves into this type of reinforcement. One of the well known degradations of FRP in concrete environment is the alkali attack. This degradation will lead to the deficiency of mechanical properties of FRP and surrounding concrete and subsequently will affect the structural integrity. In this paper, the mechanism of FRP deterioration in concrete environment and the factors affecting the durability of FRP embedded in bridge concrete deck as well as the study on the development of accelerated aging test will be discussed. Furthermore, the recommendations of the future research needs are also included.

2. CEMENT HYDRATION

Cement particle is basically composed by Tricalcium silicate (C_3S), Dicalcium silicate (C_2S), Tricalcium aluminate (C_3A) and Tetracalcium aluminoferrite (C_4AF) (Mindess et al., 2003). When the cement particles are mixed with water, it will hydrate with the following reactions (where C is CaO, S is SiO_2, A is Al_2O_3, F is Fe_2O_3, S is SO_4 and H is H_2O).

$$2C_3S + 11H \rightarrow C_3S_2H_8 + 3CH \tag{1}$$

$$2C_2S + 9H \rightarrow C_3S_2H_8 + CH \tag{2}$$

$$C_3A + 3C\bar{S}H_2 + 26H \rightarrow C_6A\bar{S}_3H_{32} \tag{3}$$

$$C_4AF + 3C\bar{S}H_2 + 21H \rightarrow C_6(A,F)\bar{S}_3H_{32} + (F,A)H_3 \tag{4}$$

As can be seen from the first two reactions above (Equations 1 and 2), $Ca(OH)_2$ molecules are released to the capillary pore created during the hydration of cement that will result in high alkaline environment (pH = ~13) of concrete. This environmental condition is highly influencing the durability of FRP embedded in concrete environment as will be discussed later.

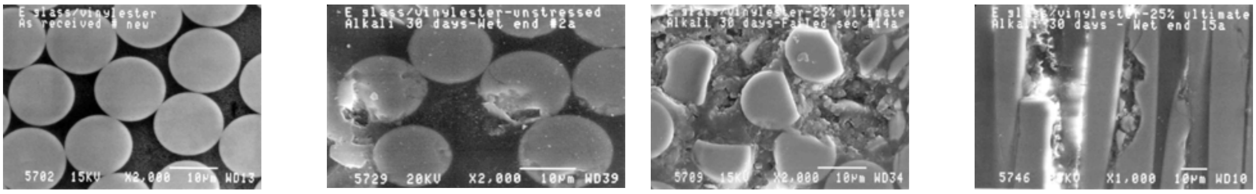
3. MECHANISMS OF FRP DETERIRATION IN ALKALINE ENVIRONEMENT

As has been mentioned earlier in introduction section, glass fiber is the most popular reinforcement used in FRP that made GFRP were mostly studied in the previous research projects. Hayashi et al. (Hayashi et al., 1985), as was cited by Soroushian et al. (Soroushian et al., 1993), said that GFRP bars are chemically and physically degraded in concrete environment. The chemical degradation is caused by the alkali attack in moist concrete environment making the glass fibers lose some of their tensile strengths and the physical degradation is due to the tendency of cement hydration products, especially calcium hydroxides ($Ca(OH)_2$), filling up spaces between and around the filaments of glass fibers. The chemical changes of the FRP due to its susceptibility to the alkali environment can be analyzed by energy-dispersive x-ray analysis (EDX) and its physical deterioration mechanism can be observed under scanning electron microscopy (SEM).

Glass fiber is constituted by silica constituents that provide the tensile strength to the GFRP. In the condition that the GFRP is made up by the use of the alkaline resistant resin, the mechanism of the deterioration is started by resin cracking under load and followed by diffusion of the hydroxyl ions (one of the cement hydration products), which will reacts chemically with silica. As the consequence, the silica constituents will dissolve its silicon-oxygen-silicon structure as shown in Equation 5 (Rajan et al., 2002). This dissolution leads to severe strength loss of GFRP.

$$-Si-O-Si+OH^{-} \rightarrow -Si-OH+SiO-(in\ solution) \tag{5}$$

Figure 1 shows the examples of the scanning electron micrographs of GFRP with vinylester resin prior (as received) and after to the exposures of alkaline environment and loading.



(a) (b) (c) (d)

Figure 1. Scanning electron micrograps of GFRP with vinylester resin with the condition of (a) as received and expossed to alkaline environrnent as well as (b) unstressed after 30 days, (c) stressed to 25 % of ultimate tensile strength after 30 days and (d) its longitudinal failed section (Rajan et al., 2002)

Mukherjee and Arwikar (Mukherjee and Arwikar, 2005) did the tests of exposing the GFRP bars into the alkaline solution at temperature of 60 °C for the period of 3, 6 and 12 months. In their studies the physical and chemical degradations of the bars were, respectively, investigated with the aid of SEM and EDX along with ICP-MS tests. SEM tests showed that the alkali attacked the matrix within the range of 1 mm from the surface of the bars, which were indicated by the creation of the voids in this area. The size and the quantity of the voids were increasing as the time of exposure to the alkaline environment was prolonged. However, the rate of the voids produced was decreased from 6 to 12 months compare to 3 to 6 months exposure times. The observed maximum size of voids for the bar exposed to the alkali environment for 3, 6 and 12 months were, respectively, 70 μm, 125 μm and 140 μm. Figure 2 shows the results of SEM tests of the specimens after being exposed to the alkaline environment for 3, 6 and 12 months. It was stated that based on the results from EDX and ICP-MS tests, there was no indication of glass fiber damaged due to their adopted conditioning tests.

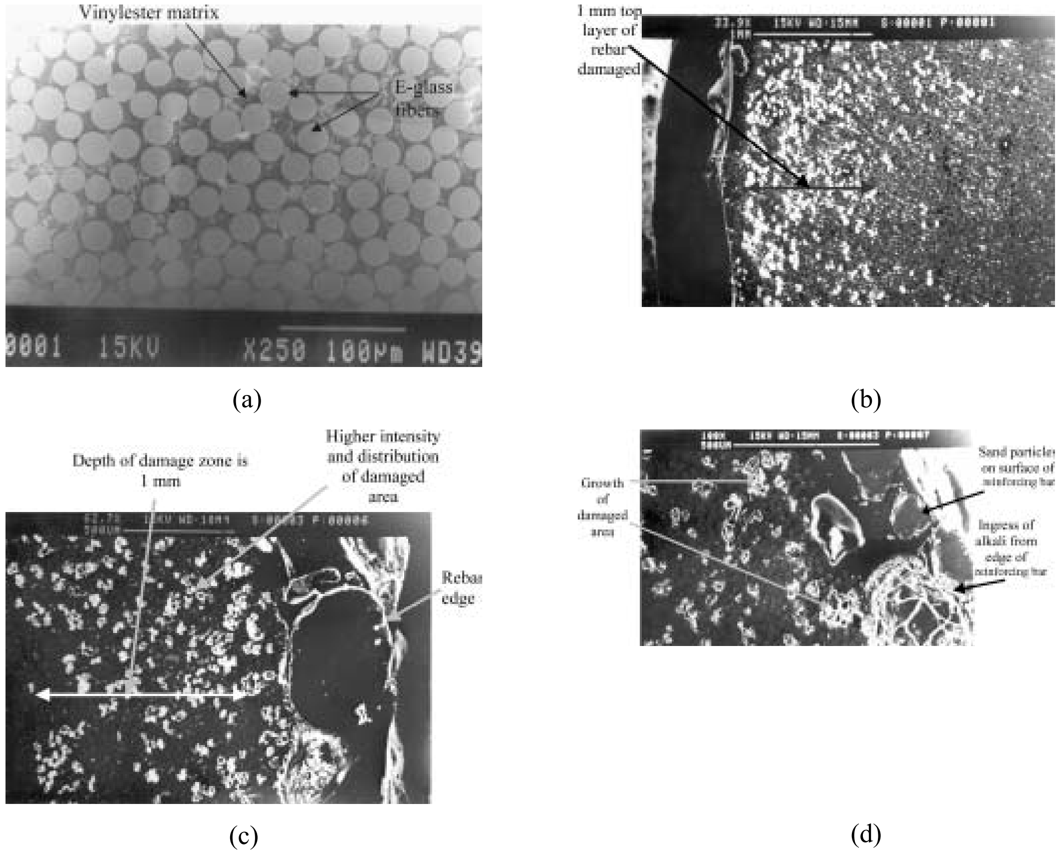


Figure 2. Scanning electron micrographs of (a) original GFRP bars and of damage near bar surface conditioned in 60°C alkali solution for (b) 3 months, (c) 6 months and (d) 12 months (Mukherjee and Arwikar, 2005)

4. DURABILITY OF FRP AS INTERNAL REINFORCEMENT OF BRIDGE CONCRETE DECK

The durability of FRP as reinforcements of bridge concrete deck is most likely influenced by the alkaline environment as well as by the attacks of FRP deteriorating substances. The former influence is naturally occur as the impact of embedding FRP in concrete and the latter are due to the diffusions of FRP attacking substances through the capillary pores of surrounding concrete. Furthermore, bridge concrete deck is also experiencing the cycles of wetting and drying during its service life. Based on the study performed by Pantuso et al. (1998) as was cited by Waldron et al. (2007), the tensile strength of FRP lowered by 21% for GFRP embedded in concrete under wetting and drying cycles for 60 days compared to that immersed in water for the same period of time. The most external common substances that manifest themselves in capillary pores of concrete are acid, carbon dioxide and chloride. Vijay and GangaRao (1999) stated that acids reacts slowly with glass fiber and the effects from low acidic pH and that of pH 5 to 6 are not much different. Carbonation is generally not affecting the durability of FRP but rather provides the benefit as it reduces the alkalinity of concrete environment (Ceroni et al., 2006). Soroushian et al. (Soroushian et al., 1993) found the lost of FRP tensile strength of 0.74% after being conditioned 14 days at 50% relative humidity (22 °C) and loaded (sustained) to 60% of ultimate tensile for 40 days in 3% NaCl solution.

Alkaline conditioning was found to be more detrimental to the FRP compare to the salt conditioning (Vijay and GangaRao, 1999).

Numbers of studies have been performed to understand the durability of FRP embedded in concrete. These studies involved the direct embedment of FRP in concrete as well as the use of simulated concrete pore solutions (Waldron et al., 2001). However, the differences in the manufactures and types of fibers and polymer matrixes and test procedures used in these studies lead to the difficulty of making the comparison and robust conclusion.

Sen et al. (Sen et al., 2002) exposed 36 GFRP rods to the solution with the pH ranging between 13.35 and 13.50. These 36 rods were divided in 4 groups with 9 specimens each. The 1st, 2nd, 3rd and 4th groups have the periods of exposure of 1, 3, 6 and 9 months, respectively. Of the nine specimens in each group, 3 were unstressed, 3 were stressed to 10% ultimate tensile strength and the other three were stressed to 15% (for the 3rd and 4th groups) and 25% (for the 1st and 2nd groups) ultimate tensile strength. The results of this study showed the lack durability of GFRP with vinylester matrix. All specimens stressed to 25% ultimate tensile strength failed within the exposure time of 25 days. Only one specimen stressed to 15% ultimate tensile strength survived for 6 months exposure time. All the specimens unstressed and stressed to 10% ultimate tensile strength did not fail within all periods of exposure times. Table 1 summarizes the averages of the tensile strength reductions for the specimens in each group.

Table 1. Coefficient of thermal expansion of FRP and steel (Sen et al., 2002)

Ultimate load of bars: 41.1 kN					
Effective area of bars: 50.3 mm					
Exposure time	Applied load, %	Average of strength reduction, %	Exposure time	Applied load, %	Average of strength reduction, %
1 month	0	50	6 month	0	64
	10	60		10	69
	25	100		15	92
3 month	0	63	9 month	0	63
	10	72		10	70
	25	100		15	100

The synthesis studies on the durabilities of FRP in alkaline environment can be found in the paper written by Waldron et al. (2001). Table 2 presents the summary of several published findings as were cited from Waldron et al. (2001).

Table 2. Several published findings from the studies on the performance of FRP in concrete environment as were cited from Waldron et al. (2001)

Author	Type of FRP	Type of polymer matrix	Environment	Temperature	Period of test	Observation
Banks et al. (1998)	GFRP	Vinylester	NH_4OH (30%)	23 °C	224 days	12% tensile strength loss.
Steckel et al. (1998)	CFRP and GFRP	Vinylester	$CaCO_3$ (pH = 9.5)	23 °C	125 days	No effect was observed except one specimen experienced 10% loss in Young's modulus.
Tannous and Saadatmanesh (1998)	AFRP and CFRP	Vinylester	$Ca(OH)_2$ (pH = 12)	25 °C and 60 °C	1 year	AFRP specimens immersed at 25 °C and 60 °C were, respectively, showed reductions of 4.3% and 6.4% in tensile strength but CFRP specimens were unaffected.
Porter et al. (1997)	GFRP and CFRP	Vinylester	Solution with pH of 12.5 - 13	60 °C	3 months	Three GFRP systems lost 55-73% tensile strength but CFRP systems were unaffected.
Uomoto and Nishimura (1997)	GFRP, AFRP and AGFRP	Vinylester	$Na(OH)_2$	40 °C	120 days	GFRP lost 70% tensile strength but AFRP and AGFRP were unaffected.
Chin et al. (1998)	Not declared	Vinylester and iso-polyester	Alkali	Elevated temperatures	Not declared	80% and 40% tensile strengths remaining were observed for vinylester and iso-polyester, respectively.
Bakis et al. (1998)	GFRP	Vinylester and vinylester/polyester	$Ca(OH)_2$	80 °C	28 days	Rods with vinylester matrix were less affected than rods with vinylester/polyester matrix.
Rahman et al. (1998)	GFRP and CFRP	Vinylester	Na(OH) (58g/l)	70 °C	370 days	Under tensile loadings of 0.3 ultimate tensile strength, GFRP failed at 45 days.
Gangarao and Vijay (1997)	GFRP	Not declared	Solution with pH of 13	Not declared	201 days	1% – 76% were observed for stressed (level was not declared) specimens. .
Clarke and Sheard (1998)	CFRP and GFRP	Not declared	Solution with pH of 12.5	38 °C	6 months	CFRP specimens performed less well than GFRP after 6 months exposure.
Arockiasamy et al. (1998)	CFRP cables	Not declared	Alkali with pH of 13 - 14	Not declared	9 months	0% strength reduction.
Shears et al. (1997)	GFRP and CFRP	Not declared	Various alkaline solution	20 – 38 °C	12 months	No mechanical and physical deterioration observed.

5. ACCELERATED AGING TEST TO PREDICT LONG TERM DURABILTY OF FRP

In order to evaluate the long term durability of FRP in concrete environment, some accelerating tests were developed through the courses of the previous studies. These accelerated aging tests were expected can yield the presentation of the real environment that is influencing the long term durability of FRP. ACI Committee 440 proposed an accelerated aging test, which involves the exposure of FRP into the alkaline environment at 60 ^oC with and without stress but there were still the questions on the procedures, magnitude of sustained loads, type of simulated alkali environment and duration of exposure (Chen et al., 2006). One of the most promising procedures was developed by Chen et al. (2006). By the use of modified Arrhenius relationship (Equation 5), Chen et al. (2006) proposed one method of accelerated aging test that can be used to predict the lost of FRP (GFRP were used in their study) tensile strength exposed to the specific simulated solution. In their study, Chen et al. (2006) were using two different solutions (Table 3) and two different GFRP bars (the only difference between these two bars was on their types of glass fibers) with vinylester polymer matrix.

Table 3. Compositions of simulated concrete pore solutions (Chen et al., 2006)

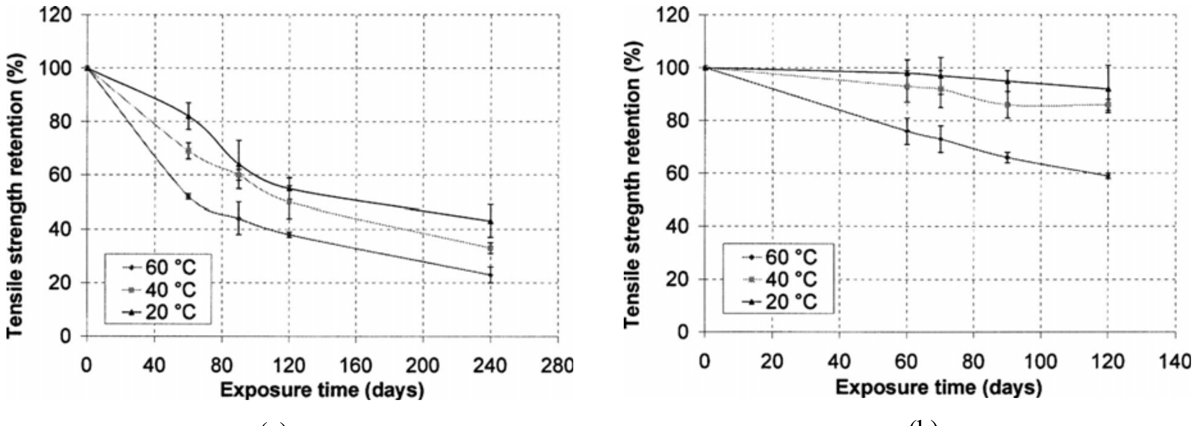
Solution type	Quantities (g/L)		
	NaOH	KOH	$Ca(OH)_2$
1	2.4	19.6	2
2	0.6	1.4	0.037

In the first step, this method involved the exposure of FRP into a certain solution at several different periods and temperatures (Table 4).

Table 4. Environmental exposure of GFRP bars (Chen et al., 2006)

Bar type	Solution type	Temperature	Exposure time			
			(days)	(days)	(days)	(days)
GFRP1	1	60	60	90	120	240
		40	60	90	120	240
		20	60	90	120	240
GFRP2	2	60	60	70	90	120
		40	60	70	90	120
		20	60	70	90	120

Next (the second step), the tensile strength of each specimen exposed to a certain condition as is presented in Table 4 were determined. Additionally, the tensile strengths for the unconditioned specimens were also determined and used as controls. Then, the tensile strengths of conditioned specimens were expressed as the percentages of the tensile strengths of the unconditioned specimens as shown in Figure 3.

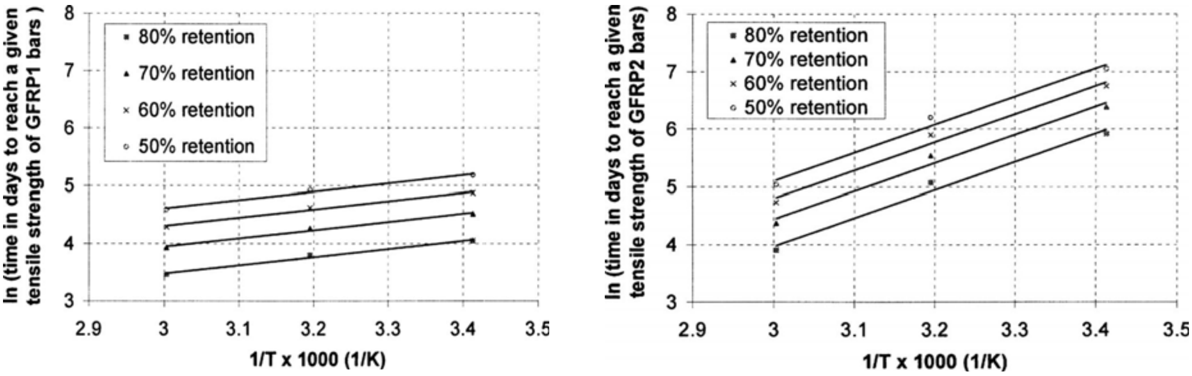


(a) (b)

Figure 3. Tensile strength retentions of (a) GFRP1 and (b) GFRP2 bars exposed respectively to solution 1 and 2 at 20, 40 and 60 ^oC (Chen et al., 2006)

In the third step, by the use of the plots (Figure 3) of tensile strength retention (%) against the exposure time (days), the time required to achieve 80%, 70%, 60% and 50% retentions at each temperature were predicted. Next, these predicted times were expressed in logarithm natural (ln) and were plotted against (1/T x 1000) as shown in Figure 4, where T is the temperature in Kelvin unit. By analyzing these two plots, the value of E_a/R in Arrhenius relationship as expressed in Equation 5 can be found and the results are shown in Table 5. In Equation 5, k is degradation rate (1/time), A is constant of material and degradation process, E_a is activation energy, R is universal gas constant and T is temperature (Kelvin).

$$\ln\left(\frac{1}{k}\right) = \frac{E_a}{R \cdot T} - \ln(A) \tag{5}$$



(a) (b)

Figure 4. Arrhenius plots of tensile strength degradation for (a) GFRP1 and (b) GFRP2 (Chen et al., 2006)

Table 5. Coefficients of regression equations for Arrhenius plots (Chen et al., 2006)

Tensile strength retention, %	GFRP1 bars in solution 1		GFRP2 bars in solution 2	
	E_a/R	r	E_a/R	r
50	1.420	0.99	4.891	0.99
60	1.423	0.99	4.892	0.99
70	1.420	0.99	4.891	0.99
80	1.420	0.99	4.892	0.99

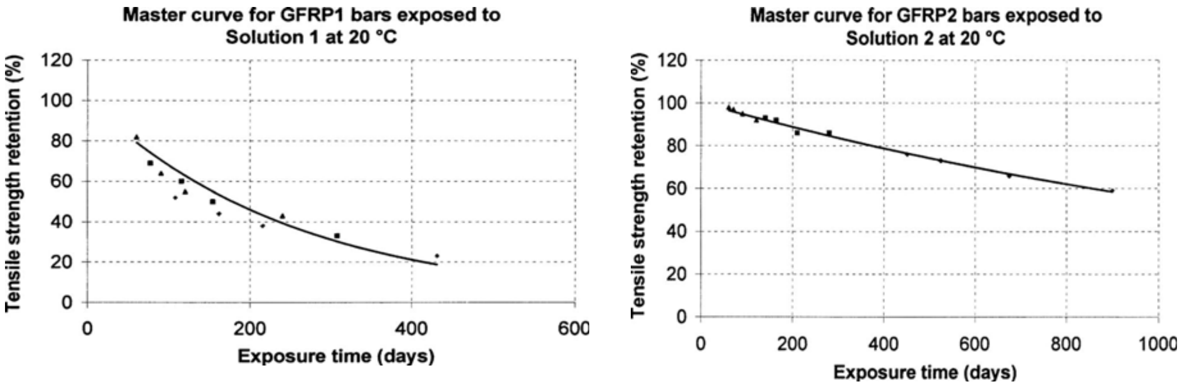
For the fourth step, the data of tensile strength retentions (%) obtained at 40 °C and 60 °C as shown in Figure 3 can be used to obtain accelerated aging test results for the condition at 20 °C by multiplying them with the acceleration factor as can be calculated using Equation 6. The value of E_a/R for GFRP1 and GFRP2 are obtained from Table 5. Where AF is acceleration factor and t_1 and t_0 are, respectively, times required for some property to reach a given value at temperatures of T_1 and T_0. The definitions of E_a and R are the same as those for Equation 5.

$$AF = \frac{t_0}{t_1} = \exp\left[\frac{E_a}{R} \cdot \left(\frac{1}{T_0} - \frac{1}{T_1}\right)\right] \tag{6}$$

Table 6 presents the values of acceleration factors for experiments on GFRP1 and GFRP2. Figure 5 shows the plots as was previously presented in Figure 1 after all of the data were multiplied by the acceleration factor (AF) as shown in Table 6.

Table 6. Values for accelerated factors (Chen et al., 2006)

Temperature, °C	GFRP1 bars in solution 1	GFRP2 bars in solution 2
60	1.80	7.50
40	1.28	2.33
20	1.00	1.00



(a) (b)

Figure 5. Tensile strength retention versus exposure time for (a) GFRP1 and (b) GFRP2 bars (Chen et al., 2006)

As the final step, in order to find the expressions that allow the prediction of tensile strength retention (%) of GFRP1 and GFRP2 at a certain period of exposure in solution 1 and 2 at 20 ^{o}C, Equation 7 was used. In this equation, Y is tensile strength retention (%), t is exposure time (days) and τ is constant that can be obtained through regression analysis. Table 7 shows the values of τ and coefficient correlations (r) for GFRP1 and GFRP2 as were obtained using regression analysis.

$$Y = 100 \cdot \exp\left(-\frac{t}{\tau}\right) \quad (7)$$

Table 7. Coefficients of regression equations for master curves (Chen et al., 2006)

Bar type	Solution type	τ	r
GFRP1	1	256	0.92
GFRP2	2	1667	0.99

6. CONCLUSION AND FUTURE RESEARCH NEED

Based on the literature reviews on the previous studies on the durability of FRP reinforcement embedded in concrete including for the bridge deck, conclusions can be withdrawn as follows:

1. At this time, there is no available standard that can be followed to perform the test of the durability performance of FRP. This situation leads to the difficulty of comparing the results of one research to the others.
2. Because of the FRP is experiencing the degradation, the reduction factor during design should be taken in order to provide safe structure. The existing design codes and guidelines (in Japan, Canada, USA and Norway) have been developed to take account of specific environmental and time effects in a similar way. The philosophy identifies the main time depending situations and introduces a series of strength reduction factors to account for potential deterioration of FRP in these condition. Table 8 shows the reduction factors that are adopted in various codes.

Table 8. Reduction factors (Ceroni et al., 2006)

Factor	ACI 440	NS 3473	CHBDC	JSCE	BISE	CNR
Reduction for environmental deterioration	C_E	η_{env}	Φ_{FRP}	$1/\gamma_{fm}$	$1/\gamma_m$	η_a
	GFRP: 0.7-0.8	GFRP: 0.5	GFRP: 0.75	GFRP: 0.77	GFRP: 0.3	GFRP: 0.7-0.8
	AFRP: 0.8-0.9	AFRP: 0.9	AFRP: 0.85	AFRP: 0.87	AFRP: 0.5	AFRP: 0.8-0.9
	CFRP: 0.9-1.0	CFRP: 1.0	CFRP: 0.85	CFRP: 0.87	CFRP: 0.6	CFRP: 0.9-1.0

In order to get the full benefit of the use of FRP reinforcement for bridge concrete deck, the following studies in the future are required to be performed.

1. The standard tests that allow the prediction of the long term performance of FRP durability need to be developed and standardized.

2. The study to optimize the quality of FRP – This study should come up with the specification that standardizes the production of FRP with the minimum performance that meets the need of economical service live of bridge concrete deck.
3. The studies on the chloride attack to the degradation of mechanical properties of FRP were insufficient to make robust conclusion (Waldron et al, 2001).
4. Additionally, refer to the study conducted by Karbhari et al. (2003) on the review of the gap of the research to understand the durability of FRP, the following future acts were recommended to be performed:
   a. Collection, assessment and appropriate documentation of available data in a form useable by the civil engineer/designer.
   b. Testing over extended (more than 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.
   c. Testing under combined conditions (stress, moisture, solution, temperature, and/or other regimes) at both the materials and structural levels is critical.
   d. Assessment and characterization of the effects of incomplete cure and under cure, especially for ambient temperature cure systems, are essential.
   e. Development of standardized solutions and conditions for laboratory studies that closely simulate actual field conditions.
   f. 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 and intended and accidental damage.

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