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PHYSICAL, MECHANICAL, AND DURABILITY PERFORMANCE OF GFRP SQUARE REINFORCING BARS EXPOSED TO ALKALINE SOLUTION

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ABSTRACT

This paper presents an experimental study that investigated the mechanical, physical, and durability characterization of square glass fibre-reinforced polymer (GFRP) bars exposed to alkaline solution. The GFRP square bars were exposed to alkaline solution at 22, 40, and 60°C to accelerate the effect of the concrete environment. The measured tensile strengths of the GFRP square bars before and after exposure were considered as a measure of the durability performance of the specimens and were used for long-term properties prediction based on the Arrhenius theory. The test results showed the very high long-term durability of square GFRP bars exposed to alkaline solutions. According to the predictions, even after a service life of 100 years at 32ºC , the tensile-strength retention of the tested GFRP bars would still be over 95% for GFRP square bars.

KEYWORDS: Durability; FRP; Glass, Aging; Predictions; Mechanical properties.

INTRODUCTION

In recent times, consideration has been given to the option of replacing steel as the reinforcing bars in concrete structures such as bridges, buildings, and other structures. In such structures, steel reinforcement deteriorates due to its exposure to environmental agents. As a replacement to steel reinforcement, fiber reinforced polymers (FRP) bars are being increasingly used in the concrete structures due to their high strength to weight ratio, light weight, noncorrosive, and nonconductive (El-Salakawy et al. 2003, El-Sayed et al. 2006; Razaqpur and Isgor 2006). Glass fiber reinforced polymer (GFRP) bars are the most popular to be used significantly in many infrastructure applications, including bridge decks, pavements, walls, and other systems, especially due to their low cost as compared to the other fibers. Unfortunately, in some special conditions, such as in a high alkalinity environment, the long-term performance of the GFRP is still an unresolved question. Strength of the glass fibers and resin matrix, the two constituents of the GFRP materials, can decrease when subjected to a wet alkaline environment (Robert et al. 2009, Bank et al. 2003). Therefore, the durability of GFRP bars is not straightforward topic, it tends to be more complex than corrosion of steel reinforcement because the durability of the FRPs is related not only to the strength of its constitutive materials (fibers and matrix) but also to the integrity of the interface between these two components while aging. A deterioration of this interface reduces the transfer of the loads between fibers and thus weakens the composite materials (Almusallam et al. 2013).

In the past decade, considerable research has been conducted to assess the suitability of FRP reinforcement in reinforced concrete structures (Riebel and Keller 2007; Micelli, F., and Nanni, A. 2004; Chen et al. 2006). The work of these researchers had highlighted on the short-term performance of FRP reinforced concrete structures or on the durability of FRP reinforcing bars subjected to aging in alkaline solution. Some researchers have reported on the durability of FRP bars embedded in moist concrete which simulate the real conditions of application and also on the adverse effects of the presence of cracks and microcracks in the FRP bars on their long-term durability (Robert et al. 2009).

This study aimed at assessing the environmental durability of square GFRP bars used as internal reinforcement of concrete subjected to an alkaline solution. The study simulated rather aggressive conditions by immersing GFRP bars in an alkaline solution at different elevated temperatures for 292 days.

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EXPERIMENTAL PROGRAM

Material

Square GFRP bars were used in this study. The bars were made of continuous E-glass impregnated in a vinylester resin using the pultrusion process. The fiber mass fraction was 72 % as determined by thermogravimetric analysis according to ASTM E1131. The relative density of the GFRP bars according to ASTM D792 was 2.09. The bars had a nominal dimension of 14.1x14.1 mm. The mechanical and physical properties of the GFRP reference bars are summarized in Table 1.

Table 1 Mechanical properties of reinforcing bars

Bar type	Bar size (mm)	Area (mm^2)	Elastic tensile modulus (GPa)	Tensile Strength (MPa)	Ultimate strain (%)
Square GFRP bars					
GFRP	Sq. 14.1	200	47.5	642	1.36

Environmental Aging

All square and circular GFRP bars were cut into 1840 mm lengths, as specified by ACI 440.3R-04 B2. The bars were divided into two series: 1) unconditioned reference samples; and 2) conditioned samples (45 GFRP bars) immerged in an alkaline solution. The alkaline solution was prepared using calcium hydroxide, potassium hydroxide, and sodium hydroxide (118.5 g of Ca(OH)2 + 0.9 g of NaOH + 4.2 g of KOH in 1 L of deionized water) according to CSA S806 and ACI 440.3R. The pH of the alkali solution was 12.8. It is worth noting that the alkaline environment in concrete has a pH above 12 (ACI 440.3R-04). The specimens were kept at three different exposure temperatures (22°C, 40°C, 60°C). The aging at ambient temperature (22°C) was performed by immersing the GFRP in a container filled with alkaline solution at room temperature. The containers were covered with polyethylene sheeting to prevent water evaporation during conditioning. Furthermore, the water level was kept constant throughout the study to avoid a pH increase resulting from a decreased water level and significant increase of alkaline ions in the solution. Two environmental chambers were used to accelerate the degradation of the GFRP specimens at 40°C and 60°C. The immersion temperatures were chosen to accelerate the degradation effect of aging, but they were not high enough to produce any thermal-degradation mechanisms. Table 2 provides a summary of the environmental conditioning and the number of samples used for the durability study.

Table 2. Tensile properties of the reference and conditioned square-GFRP test specimens

Immersion time (hr)	Temperature (ºC)	No. of specimens	Tensile strength (MPa)	Modulus of elasticity (GPa)
			Average	Average
0	22	5	642	47.5
1,000	22	5	636	46.8
	40	5	631	46.8
	60	5	614	46.2
3,000	22	5	626	47.1
	40	5	614	46.7
	60	5	598	46.9
7,000	22	5	617	46.5
	40	5	599	46.6
	60	5	583	46.8

Characterization of Physical Properties

Physical analyses were conducted on GFRP specimens Including: (1) GFRP fiber content, (2) moisture absorption, (3) cure ratio, and (4) glass transition temperature. These properties were determined according to CSA S807-10.

Fiber Content

Very small pieces of material was cut from the square GFRP bars, and were tested according to ASTM E1131 to determine the fiber content with different number of yarns (80, 100, 130, and 144 yarns). In order to achieve the minimum requirement of CSA S-807-10 (70% fiber content by weight or 55% as fiber content by volume). The samples were accurately weighed and heated at 550ºC for 5 hours.The weight loss (W_L) was recorded at a temperature equal to 550°C. The fiber content by weight was then calculated according to the following equation:

$$(F\%) = 100 \cdot (W_T - W_L) / W_T \quad (1)$$

where,
F% = fiber content
W_L = weight loss at 550°C
W_T = total weight of FRP sample

Water-Immersion Test

The moisture uptake at saturation of the GFRP bars was determined according to ASTM D570, with an only exception that the immersions were performed in tap water instead of distilled water. Three 50 mm long specimens were cut, dried, and weighed prior to immersion in water at 50°C for a period of three weeks. The samples were periodically removed from the water, surface dried, and weighed. The water

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content as a percentage of weight was calculated with Equation 2.

$$W_s = 100 \cdot (P_s - P_d)/P_d \qquad (2)$$

where P_s and P_d are the sample weights in saturated and dry states, respectively.

Cure Ratio

The cure ratio was determined according to ASTM D5028. The enthalpy of polymerization of the sample was measured by differential scanning calorimetry (DSC) and compared to the enthalpy of polymerization of pure resin, taking into account the weight percentage of resin in the matrix. Thirty to fifty milligrams of sample were accurately weighed and placed in an aluminum crucible. The samples were, then, heated from room temperature to 200°C at a heating rate of 20°C/min, and the area of the peak of polymerization was calculated.

Glass Transition Temperature

Glass transition temperature, Tg, was determined for GFRP specimens by DSC according to the ASTM E 1131 test method. Thirty to forty milligrams of composite sample were weighed and placed in an aluminum pan. The sample was then heated up to 200°C under nitrogen at a heating rate of 20°C/min. The value of Tg was taken at the mid-height of the heat-capacity (Cp) jump. Three specimens were tested and investigated.

Tensile Tests

All of the control GFRP specimens were tested under tension according to ASTM D7205. The GFRP specimen length as well as the length and diameter of the anchor to be used for the tensile test were calculated according to ASTM D7205. Before the test was conducted, steel tubes were attached to the GFRP test specimens according to ASTM D7205. **Error! Reference source not found.** shows the dimensions of the typical test specimens. The anchors were cast in a vertical position. The steel tubes and the GFRP specimens were axially aligned before the grout was applied. The specimen went through the concentric hole in the PVC caps and was thus held axially aligned inside the tube (ASTM D7205-A1.5 Anchor Casting Procedure). CRAS expansive cement was used in this study. The tests were carried out with a Baldwin testing. The test specimens were instrumented with one LVDT (200 mm in length) to capture specimen elongation during testing. For each tensile test, the specimen was mounted in the tensile machine with the steel-pipe anchors gripped by the wedges of the machine's upper and lower jaws. The average loading rate was 47.5 KN/min. The applied load and bar elongation were recorded with a computer data-acquisition system. Due to the brittle nature of FRP, no yielding occurred and the stress–strain behavior was linear.

LONG-TERM PREDICTIONS

Equation (3) expresses the Arrhenius relation, in terms of the degradation rate [**Nelson, 1990**]

$$k = A\exp\left(\frac{-E_a}{RT}\right) \qquad (3)$$

where k = degradation rate (1/time); A = constant relative to the material and degradation process; E_a = activation energy of the reaction; R = universal gas constant; and T = temperature in Kelvin. The primary assumption of this model is that only one dominant degradation mechanism of the material operates during the reaction and that this mechanism will not change with time and temperature during the exposure [**Chen et al., 2006**]. Only the rate of degradation will be accelerated with the temperature increase. Equation (3) can be transformed into:

$$\frac{1}{k} = \frac{1}{A}\exp\left(\frac{E_a}{RT}\right) \qquad (4)$$

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

From equation (4), the degradation rate k can be expressed as the inverse of time needed for a material property to reach a given value [Chen et al., 2006]. From equation (5) one can further observe that the logarithm of time needed for a material property to reach a given value is a linear function of $1/T$ with the slope of E_a/R [Chen et al., 2006]. E_a and A can be easily calculated by using the slope of the regression and the point of intersection between the regression and the Y axis respectivelv.

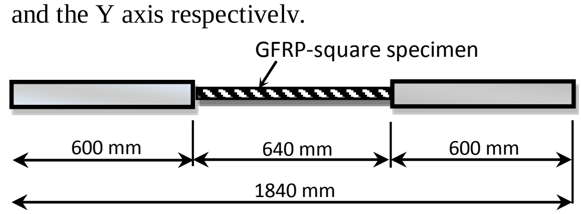

Figure 1. Tensile test dimension of test square GFRP-bar

TESTS RESULTS AND DISCUSSION

Physical Properties of GFRP Bars

The test results indicated that the glass-fiber content by weight for square-GFRP bars was 72 %, which is accepted according to CSA S-807-10. The test result also showed that the mass percentages of water uptake after 24 h and at saturation were found to be 1.1% and 1.31% on average. The water-absorption

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values obtained exceeded the limits specified in CSA S-807-10 (2%). The material's cure ratio was high (close to 100%). The glass transition temperature was not clearly visible from the thermo-grams obtained by differential scanning calorimetry (DSC), two very small shifts were observed at 105° and 130°C. It was not, however, possible to confirm that these shifts were caused by the glass transition of one, two, or a blend of resins. The average transvrse coefficient of thermal expansion of the tested bars was around 23.5±0.8 x $10^{-6o}C^{-1}$.

Effect of Conditioning on Tensile Strength

Figure 2 shows the retention of the tensile strength of the conditioned GFRP square specimens according to immersion duration. The tensile test of unconditioned specimens showed an approximately linear behavior up to failure. Specimens failed through the rupture of fibers. No chemicals deposit was observed on the surface of the GFRP bars before testing.

Table 2 presents the results of experimental that were obtained during the tensile tests concerning the ultimate tensile strength of GFRP tested specimens after immersion at 22°C, 40°C, and 60°C. As shown in Table 2, the tensile strength for unconditioned GFRP specimens was equal to 642 MPa. The ultimate tensile strength of GFRP bars was reduced to 614, 598, 583 MPa after 1000, 3000, and 7000 hours, respectively, exposure to alkaline solution at 60°C for square GFRP bars

Figure 2 shows that the ultimate tensile strength of GFRP bars decreased by 10 % with an increase of immersion duration (7000 hr) or temperature (60ºC) . Also, It can be seen that for duration of immersion of 3000 hours at 60ºC, the loss of resistance is equal to 5 % for GFRP bars. The variation of tensile strength is probably related to the slight increase of the moisture absorption with time leading to plasticizing effects on the polymer matrix.

Effect of Conditioning on Young's Modulus

Figure 3 shows the slight change in the elastic modulus of aged bars with time of immersion at various temperatures. Indeed, it can be observed from the measured results that after 7000 hours, the loss of elastic modulus is negligible and all aged GFRP bars are not affected by the higher temperature or the exposure to alkaline solution. This result shows that elastic modulus of bars is not affected by aging in mining environment simulated in the present study. This result can be explained by the fact that the Young's modulus of unidirectional GFRP materials is more related to the fiber properties which are not affected by alkaline solution.

PREDICTION OF LONG-TERM BEHAVIOR AND SERVICE LIFE

Prediction of service life of the square GFRP bars at mean annual temperature (MATs) of 32ºC were calculated. The Arrhenius plot can be used to extrapolate the service life necessary to reach the established tensile-strength retention levels (PR) for any temperature. Consequently, predictions were made for tensile-strength retention as a function of time for immersions at 32°C. Figure 4 shows the general relationship between the PR and the predicted

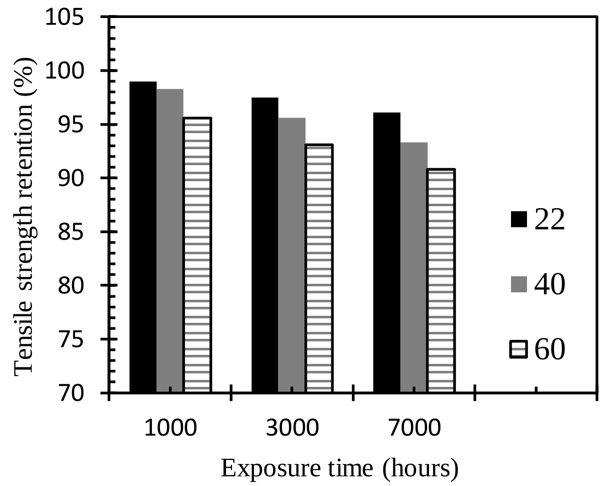

Figure 2.Tensile strength retention of conditioned GFRP square bars aged in alkaline solution at 22°C, 40°C, and 60°C

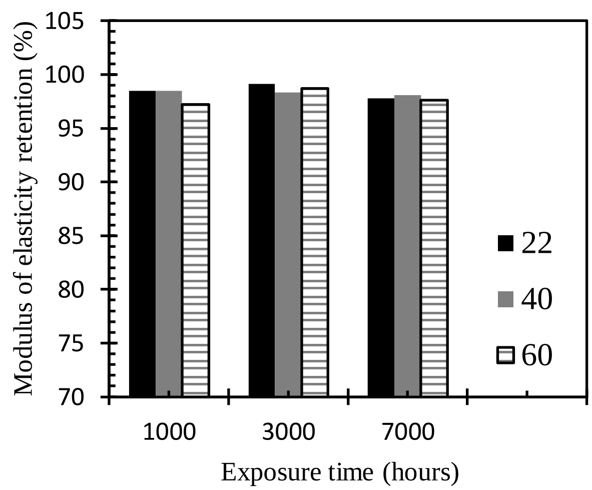

Figure 3. Elastic Modulus of reference and conditioned GFRP square bars aged in alkaline solution at 22°C, 40°C, and 60°C

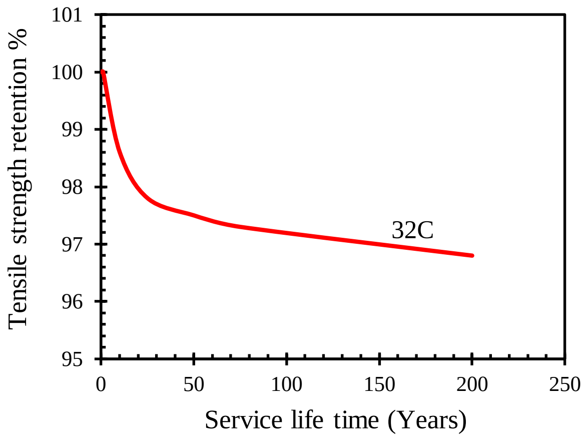

Figure 4. General relation between the PR and the predicted service life at a mean annual temperature of 32ºC (Singapore)

service life at the two MATs. It can be seen that the predicted strength-property retention level (PR) for the specimens immersed at an isotherm temperature of 32°C would be affected over 200 years by aproximetraly 4% decresing of the ultimate tensile strength. As expected, these results show that the long-term tensile strength of the GFRP was affected by the alkaline environment in a warm climate.

CONCLUSIONS

In this paper, square GFRP bars were exposed to alkaline solution to simulating the alkaine effect of concrete at 22°C, 40°C, and 60°C to accelerate the effect of the environment effects. In addition, differential scanning calorimetry (DSC) and scanning electron microscopy (SEM) were used to characterize the physical properties of the GFRP specimens. Based on the results of this study, the following conclusions may be drawn on the tested products:

1- The test observation indicates that the glass-fiber content was 72.2% by weight and the water uptake at saturation was equal to 1.1%. The cure ratio of the material was very high (close to 100%).

2- The change in tensile strength of the condituioned GFRP bars was minor even at high temperatures (60ºC) making for a more aggressive environment.

3- The results indicate that specimen strength was affected by increased immersion time at higher temperatures. The test results after 7,000 h of immersion in the alkaline solution at 60ºC reveal a 10 % reduction in tensile strength. The tensile-strength reduction was attributed to the development of microcracks in the epoxy resin, resulting essentially from the existing defects in the material.

4- Long-term-behavior predictions of the conditioned specimens were made with a method based on the Arrhenius theory. Accordingly, the long-term prediction of the tensile-strength retention was still over 96 % for mean annual temperatures of 32°C. This prediction show that the GFRP are durable with respect to the concrete environment, as simulated by specimen immersion in an alkaline solution with a pH of 12.8. It was shown that the service life of 200 years would be needed to attain a tensile-strength retention of less than 96%.

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