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DURABILITY PERFORMANCE OF GLASS FIBER REINFORCED PLASTIC REINFORCEMENT IN HARSH ENVIRONMENTS

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ABSTRACT

The use of glass fiber reinforced plastic (GFRP) reinforcement as a building construction material has increased in recent years. In particular, GFRP reinforcement for concrete has recently been developed and introduced into the international market. The assessment of the durability performance of GFRP reinforcement in harsh environments is of primer importance in order to promote the utilization of this material in concrete construction.

The paper presents the scope, objectives and preliminary results of on-going extensive research program at KFUPM on the durability performance of GFRP reinforcement bars. The preliminary results cover the durability performance of one type of GFRP bars after 3 and 6 months under harsh environments both as stand-alone and with concrete. The exposure solutions include alkaline, alkaline + chloride, acid, seawater and sabkha, in addition to out-door exposure.

Keywords: *Acid solution, Alkaline solution, Bond strength, Durability, GFRP bars, Moisture absorption, Seawater, Sabkha, Tensile strength, Weight loss.*

الملخص

زاد استخدام المواد البلاستيكية المعززة بالألياف الزجاجية كمواد بناء في السنوات القليلة الماضية. وبشكل خاص فان قضبان البلاستيك المعززة بالألياف الزجاجية لتعزيز وتقوية الخرسانة تم تطويرها حديثا وأدخلت إلى سوق الإنشاء. إن تقييم متانة هذه القضبان تحت الظروف البيئية المحلية القاسية يعتبر مطلب أساسي لتحديد مدى الاستفادة من استعمال هذه المواد في المنشئات الخرسانية.

هذه الدراسة تسرد الأهداف لبرنامج شامل تقوم به جامعة الملك فهد للبترول و المعادن لتقييم أداء ومتانة القضبان البلاستيكية المعززة بالألياف الزجاجية تحت الظروف البيئية المحلية القاسية. كما أنه سيتم عرض بعض النتائج الأولية لهذا البرنامج، علما بأن هذه النتائج تشمل نوع واحد من هذه القضبان و معرضه لظروف بيئية محليه قاسيه لمدة ثلاثة و ستة أشهر مع/ و بدون الخرسانة. تشمل الظروف البيئية محلول قلوي و محلول قلوي+ كلوريد الصوديوم و محلول حمضي و ماء البحر و محلول السبخة، إضافة إلى التعرض المباشر للجو الخارجي.

1. INTRODUCTION

The use of glass fiber reinforced plastic (GFRP) reinforcement as a building construction material has increased in recent years. In particular, GFRP reinforcement for concrete has recently been developed and introduced into the international market. As compared with steel, the GFRP reinforcement has several features including its lightweight, which is about 1/4 that of steel, corrosion resistance, electric and magnetic insulation, and easy handling. These reinforcements claim to have advantages over conventional steel bars in concrete structures exposed to corrosive environments, such as where deicing salts are present, marine or soil media, environments with corrosive gases, and exposure to chemicals. These reinforcements are also advantageous in concrete structures where electric or electromagnetic insulation is required, such as in aluminum and copper smelting plants, manholes for electric and telecommunication equipment, hospitals and airport control towers, military applications; or when high strength-to-weight ratio is required.

The constituent materials in GFRP reinforcing bars are glass fibers and matrices (i.e. the relatively ductile component which binds and protects the fibers). Several manufacturing methods have been used for the production of GFRP reinforcement bars. The majority of the products are made by pultrusion in combination with other operations, such as filament winding to create the deformations on the surface of the otherwise smooth rod. Depending on the source, these deformations are referred to as helical wrapping, coiling, etc. Pultruded rods have also been produced with depressions or indentations. In several instances, the surface of the final product is coated with sand particles to improve the bond characteristics with concrete.

There are rising concerns about changes in the mechanical properties for such materials under long-term exposure to adverse environmental conditions. Therefore, to fully utilize their potential, the response of these bars when exposed to harsh environments must be investigated. The tensile and bond strengths of GFRP bars are the most important characteristics for establishing the design procedures and recommendations for their applications.

Al-Zahrani et al. [1] conducted direct pull-out test using machined and wrapped glass/vinylester GRP rods with axisymmetric lugs. The results showed that the failure mode consisted of the shearing off of the lugs without concrete damage. Provided that enough confinement was used, it was found that the concrete strength had no noticeable effect on the bond strength and failure mode of the GFRP rods. The results also showed that the GFRP/concrete bond was controlled by the lug dimension and the shear strength of the resin.

Vijay et al. [2] conducted accelerated tests on glass fiber reinforced polymer reinforced concrete beams under salt and alkaline environments. The results showed tensile strength reduction in the extracted bars from the beams after 12 month exposure to the salt and alkaline

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environment compared to those unexposed. Acceleration of aging is higher in GFRP bars directly exposed to alkaline and freeze-thaw conditioning as opposed to the bars embedded in the pre-cracked concrete beams and exposed to the same conditioning by a factor of 2.

Fares and Hamid [3] examined the moisture absorption and predicted the associated changes in the mechanical properties of GFRP bars under accelerated environmental exposure. In terms of tensile strength reduction, higher losses were observed in alkaline and deicing salt solutions, whereas it was lowest in the case of water at room temperature. There was no significant reduction in the strength observed after one and two years of exposure to 7% $NaCl+CaCl_2$ solution.

Uomoto and Ohga [4] evaluated the chemical resistance of GFRP rods. The results showed that for inland exposure (UV radiations), GFRP rods showed no reduction in the tensile strength after 1 year of exposure and 19% reduction after 3 years, while under marine exposure no reduction after 1 year and only 1% reduction after 3 years of exposure. The tensile strength of GFRP rods was decreased with the increase in time when immersed in aqueous NaOH, and the failure pattern near the surface was different from that of the inner part of the rods. The failure near the surface occurred at a lower load and the failure of the inner part occurred at the maximum load.

Katz et al. [5] studied the bond properties of fiber reinforced polymer bars at temperatures ranging from room temperature to as high as 250°C. Test results showed reduction of 80 to 90% in the bond strength as the temperature increased from 20^oC to 250^oC. Ordinary deformed steel bars showed reduction of only 38% when compared with the FRP bars in the same temperature range. It was seen that the extent to which the bond mechanisms of a FRP bar depends on the polymer at the bar surface, which is the main parameter that influences the degradation in the bond strength of FRP bars to concrete at high temperatures. Bond in bar with polymeric lugs is seen to be affected more by the high temperature than the other bar's. Extensive damage to the surface of the rod was seen as the temperature at which the pullout of the bar rose, marked by yellowing of the bar and significant abrasion of the external layer.

Wang et al. [6] studied the basic bond behavior, bond strength, slip and bond stress-slip relationship of the FRP rods. The effects of the fiber material kind, configuration and elastic modulus of the rods on the bond of the rods were analyzed. An equation was proposed to predict the bond strength of FRP rods. Four types (shearing-off failure of rod windings, local mechanical frictional pullout, full frictional pullout and plain frictional pullout) of bond failure were observed and the type of failure of a FRP rod was principally determined by its configuration.

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Ehsani et al. [7] investigated experimentally the bond behavior of straight GFRP bars with 48 beams and 18 pullout specimens. The bar sizes included in the study were No. 3, 6, and 9. The results indicated that the splitting failure and bar pullout are controlled by concrete strength and depth of cover, but the bar fracture is controlled by the tensile capacity of the bars only.

Al-Dulaijan et al. [8] studied the effect of accelerated environmental conditioning on the pullout behavior of glass/vinylester FRP reinforced concrete systems. They related these effects to the observed physico-mechnical properties of the reinforcement rods. Three rods with different surface configurations were used in the study. The specimens were environmentally conditioned in a saturated calcium hydroxide solution at a temperature of 60^{o}C for 28 days. Tests such as FRP/concrete direct pullout, FRP sonic resonance, and FRP short beam shear strength were carried out. Both, rods embedded in concrete and stand-alone, were used in the study. Degradation in the bond behavior was observed for pullout specimens conditioned in saturated calcium hydroxide solution at 60^{o}C for 28 days in comparison with the unconditioned specimens. Since the resin coating that covered the FRP rod controlled the bond mechanism, no numerical correlation of pullout load with the shear strength or elastic modulus was possible.

2. EXTENSIVE ON-GOING RESEARCH PROGRAM AT KFUPM

An extensive research program has started at KFUPM to examine the durability performance of different types of GFRP reinforcement bars. The main objectives of the research program is to investigate the durability performance of different types of GFRP reinforcing bars under laboratory and field conditions and identify the most promising areas of application of GFRP reinforcement bars.

In this program the GFRP bars have been investigated as stand-alone and with concrete; in different exposure conditions resemble the actual service environment in the Arabian Gulf. The exposure conditions include alkaline solution, alkaline+seawater solution, alkaline + sabkha solution, acidic solution, thermal variations, out-door exposure and fire. The durability performance has been evaluated through monitoring the changes in tensile strength, compressive strength and weight loss for the stand-alone GFRP bars, and bond strength for the GFRP bars with concrete. Moreover, the chemical and microstructure changes will be monitored using scanning electron microscopy (SEM).

Moreover, different types of commercially available GFRP reinforcing bars; both as stand-alone and with concrete were exposed in a field research station along the Arabian Gulf in the eastern province of Saudi Arabia, which represent the actual aggressive exposure conditions in the region which includes the tidal zone, below ground zone and above ground zone. The number of specimens was designed to cover 20-year period of monitoring.

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The program includes stand-alone GFRP bars; exposed to actual aggressive environments. One group of the specimens will be tested for tensile strength, compressive strength and weight loss, in addition to examining the chemical and microstructural changes using scanning electron microscopy (SEM). Another group will be cast in concrete to form pull-out specimens to be tested for bond strength. Moreover, the exposed specimens will be monitored visually for any sign of deterioration throughout the duration of the exposure.

Concrete specimens reinforced with GFRP bars in the form of beams under sustained loading, columns and pull-out specimens will be exposed (partially prepared and exposed). The testing at specific periods include bond strength and tensile strength of extracted GFRP bars from exposed concrete specimens. For the GFRP reinforced concrete beams under sustained loading, one group of the beams will be monitored for deflection, and other group will be tested for flexural behavior. The microstructural changes will be examined using scanning electron microscopy (SEM). Moreover, the exposed specimens will be monitored visually for any sign of deterioration throughout the duration of the study.

3. SIGNIFICANCE OF THE STUDY

Condition surveys of concrete structures in eastern Saudi Arabia indicated that corrosion of reinforcing steel is the principal causal factor for concrete deterioration in the region. Corrosion of steel reinforcement is by far the most effectively operative casual factor in concrete deterioration in the whole world, and it out-weighs other forms of deterioration [9]. Therefore, the solution to best protect reinforced concrete structures will be to make the reinforcement corrosion-resistant. Accordingly, the use of the GFRP reinforcement in concrete as a corrosion-resisting measure is really an important issue to be looked at and investigated, particularly in the exposure conditions of eastern Saudi Arabia. This investigation concentrates on the durability of these GFRP bars when exposed to harsh environments. The tensile and bond strengths of GFRP bars are the most important characteristics for establishing appropriate design procedures and recommendations for their applications.

4. TEST PROGRAM

This paper presents the preliminary results of the on-going laboratory investigation. The preliminary results cover the durability performance of one GFRP type under harsh environment after 3 and 6 months of exposure.

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4.1. Materials

The GFRP bar type used is commercially available and manufactured using continuous E-glass fibers (60 % by volume) and urethane modified vinyl ester resin with molded surface deformation. The size of the GFRP bar used was 10 mm in diameter. The GFRP bars were cut to 85 cm long for tension and bond tests and 10 cm for weight loss determination.

Normal concrete mixture made of Portland cement (370 kg/m^3), water/cement ratio of 0.4, coarse/fine aggregate ratio of 1.6 and superplasticizer.

4.2. Stand-alone GFRP bars

The stand-alone GFRP bars were exposed to the conditions representative of the actual aggressive service environments in the Arabian Gulf during which specimens were retrieved and tested after three and six months. The various solutions were maintained at 22 ± 2°C and 60 ± 2°C. The high temperature was used to accelerate the impact on the performance properties of GFRP bars. For conditioning, Plexiglass containers with dimensions of 73 cm (L) X 33 cm (W) X 23 cm (D) were fabricated and equipped with two heaters to maintain the temperature of the solutions at 60 ± 2°C. Each container accommodate 12 bars fitted and sealed through 11 mm diameter holes in two opposite sides for the purpose to limit the exposure to the middle 30 cm portion of the bar without damaging the grip areas at both ends of each bar (see Figure 1.). For all the conditions below, GFRP specimens were retrieved and tested after three and six months. The accelerated laboratory exposure conditions are listed below:

- **Alkaline solution (pH = 13.5):** The GFRP bars were placed in an alkaline solution [0.6 N KOH + 0.2 N NaOH + Saturated $Ca(OH)_2$] with a constant pH of 13.5. This exposure represents the concrete environment.

- **Alkaline + Chloride solution (pH = 13.4):** This exposure represents the aggressive environmental condition where all the offshore and marine structures encounter. The alkaline solution with a concentration of 3% NaCl simulating the marine environment was used.

- **Acidic solution (pH = 3.1):** Glass fiber reinforced plastic (GFRP) bars were exposed to an acidic solution [0.6% Acetic Acid] with a constant pH of 3.1.

- **Out-Door Exposure:** The GFRP bars wee exposed continuously to outside natural environment.

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The effect of the above exposure conditions on GFRP bars were evaluated by conducting the following tests:

- **Tension:** The tensile test was conducted to determine the tensile strength and elastic modulus of the GFRP bars. The tensile test was conducted before and after the conditioning in the various exposure conditions reported above. The GFRP bars were cut to 85 cm length, both ends of each bar were bonded to steel tube anchors 20 cm long using high strength two components epoxy adhesive system. The tension tests were performed using 250 kN capacity INSTRON universal testing machine and utilizing 5 cm gage length extensometer to measure elongation.

- **Moisture absorption and weight loss:** The initial mass of the GFRP bars before immersion in the various solutions were recorded. For moisture absorption, bars were removed every month from these solutions and surface dried before the mass was recorded. For the weight loss, bars were removed and oven dried at 60 ± 2°C for 24 hours after which the change in mass was determined.

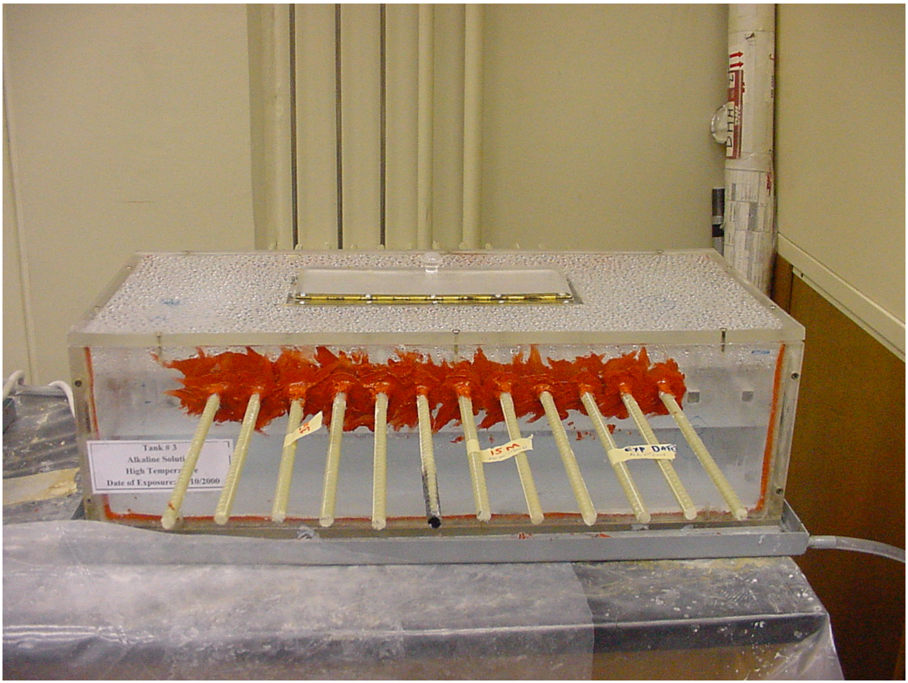

Figure 1. Typical setup for the conditioning of GFRP bars.

4.3. GFRP bars with concrete

The bond strength of GFRP bars with concrete was determined using cubic concrete specimens with 15 cm in dimension and single GFRP bar embedded vertically along the central axis of each specimen with 5 cm embedment length. The specimens were cured in water for 28 days. The developed compressive strength of concrete was 35.8 MPa. During the exposure, specimens were retrieved and tested after three and six months. The GFRP reinforced concrete specimens were subjected to the following exposure conditions that resemble the local aggressive conditions:

- **Seawater Exposure:** This exposure represents the aggressive condition where all the offshore and marine structures encounter. The prepared specimens were subjected to continuous immersion in seawater at a temperature of 22 ± 2°C.

- **Sulfate+Chloride (Sabkha) Solution:** This exposure represents the aggressive environmental condition where underground structures encounter near the Arabian Gulf coastal areas. A sulfate-chloride solution with a concentration of (15.7% Cl^- + 0.55% SO_4^{--}) that resemble the sabkha environment will be used [10]. The prepared specimens were subjected to continuous immersion in the sabkha solution at a temperature of 22 ± 2°C.

The effect of the above exposure conditions on the GFRP bars and concrete was determined using the direct pull-out test. Through which the loaded end of the bar was bonded to steel tube anchor 20 cm long using high strength two components epoxy adhesive system and tested using 250 kN capacity INSTRON universal testing machine. The bar slips at the loaded and free ends were recorded using LVDT's.

5. TEST RESULTS AND DISCUSSION

5.1. Stand-alone GFRP bars

The effect of different exposure conditions on the tensile strength and modulus of elasticity of the GFRP bar after 3 and 6 months is summarized in Tables 1and 2, respectively.

Among the different exposure conditions considered in this study, alkaline solution has the most aggressive effect on the tensile strength at both 22 ± 2 and 60 ± 2 °C. After six months of continuous immersion in alkaline solution at a temperature of 60 ± 2 °C, the GFRP bars experienced a reduction of 35.9 % compared to 27.3 % and 25.7 % in alkaline + chloride and acid solutions, respectively.

The outdoor exposure did not show any noticeable effect on the tensile strength. The only effect inflected was the change to more yellowish color. However, the direct exposure of

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stand-alone GFRP bars to outdoor weather may adversely affect the bond with concrete due to degradation of the polymer constituents of the surface configuration. Results will be reported when become available.

During tension test the failure in both conditioned and unconditioned GFRP bars initiated in the middle portion of the bar and then extend to the entire length between the grip in the form of vertical splitting as depicted in Figure 2.

Table 1. Tensile strength of GFRP bars under different exposure conditions.

		Average tensile strength (MPa)	
Unexposed		699.2 ± 6.1	
Condition	**Temperature(°C)**	**3 months**	**6 months**
Alkaline	22 ± 2	686.7 ± 12.2	682.2
	60 ± 2	546.9 ± 16.0	447.9 ± 7.6
Alkaline+chloride	22 ± 2	677.8 ± 15.9	678.6 ± 6.5
	60 ± 2	554.9 ± 49.9	508.2 ± 12.5
Acid	22 ± 2	725.1 ± 20.8	693.3 ± 19.9
	60 ± 2	583.4 ± 25.4	519.5 ± 12.4
Outdoor	-	702.4 ± 19.6	704.8 ± 18.9

Figure 2. Typical failure mode of GFRP bar in tension.

With regard to the modulus of elasticity, alkaline and alkaline+chloride solutions showed more effect on the modulus of elasticity than the acid solution at both 22 and 60 °C. After six months of continuous immersion in alkaline+chloride solution at a temperature of 60 °C, the GFRP bars experienced a reduction of 25.2 % compared to 22.3 % in alkaline solution. While the GFRP bars in acid solution showed 12.9 % reduction after 6 months of continuous immersion.

After 6 months of outdoor exposure the GFRP bars experienced 8.4% reduction in modulus of elasticity, although as reported above no effect was detected on the tensile strength.

Table 2. Modulus of elasticity of GFRP bars under different exposure conditions.

		Average modulus of elasticity (GPa)	
Unexposed		39.5 ± 2.0	
Condition	**Temperature(°C)**	**3 months**	**6 months**
Alkaline	22 ± 2	38.0 ± 2.0	34.0 ± 1.0
	60 ± 2	30.3 ± 1.0	30.7 ± 2.1
Alkaline+chloride	22 ± 2	36.2 ± 0.5	36.3 ± 2.4
	60 ± 2	34.0 ± 3.1	29.6 ± 0.8
Acid	22 ± 2	37.5 ± 1.8	34.4 ± 4.0
	60 ± 2	39.2 ± 1.2	35.4 ± 3.8
Outdoor	-	36.9 ± 0.4	36.2 ± 0.7

The moisture absorption and weight loss results after 6 months of continuous immersions are presented in Table 3. The moisture absorption values in the three solutions were less than 1%. As expected the 60 °C temperature gave higher moisture absorption than the room temperature, and hence higher degree of deterioration. Which agree with the tension test results. At high temperature the GFRP bars in alkaline and alkaline+chloride solutions showed higher moisture absorption than acid solution.

The weight loss results showed similar trend as the moisture absorption results. The weight loss in all solutions were less than 0.1 %. Compared to moisture absorption, weight loss measurement needs very careful control during conditioning, handling and weighing, due to insignificant weight loss expected.

The results show that moisture absorption can be used as qualitative indicator of the durability performance of GFRP bars in different solutions.

Table 3. Moisture absorption and weight loss of GFRP bars after 6 months immersion different conditions.

Solution	Temperature(°C)	Moisture absorption (%)	Weight loss (%)
Alkaline	22 ± 2	0.336 ± 0.117	-0.057 ± 0.020
	60 ± 2	0.570 ± 0.114	-0.067 ± 0.001
Alkaline+chloride	22 ± 2	0.341 ± 0.069	-0.067 ± 0.001
	60 ± 2	0.564 ± 0.036	-0.091 ± 0.040
Acid	22 ± 2	0.316 ± 0.039	-0.067 ± 0.116
	60 ± 2	0.498 ± 0.040	-0.045 ± 0.039

5.2. Bond strength of GFRP bars with concrete

The bond strength results of the continuously immersed specimens in seawater and sabkha solutions up to six months are listed in Table 4.

The bond force at the interface between GFRP bar and concrete can be transferred by adhesion resistance, friction resistance and mechanical interlock due to surface irregularity. With adequate cover and confinement, the concrete compressive strength does not affect the bond strength. The bond strength of deformed GFRP bars primarily depends on the interlock mechanism between the bar surface deformation and concrete. Therefore, the bond strength degradation may not be expected without disintegrating the polymer system of the bar surface deformation or loss of confinement due to concrete deterioration.

The results presented in Table 4, do not show any indication of bond degradation due to the continuous immersion in both seawater and sabkha solutions for six months. To the contrary the bond strength values of the conditioned specimens were comparable or slightly higher than the bond of the unexposed specimens. This clearly indicates that the rate of bond degradation is very slow due to concrete confinement. Bond results of longer exposure periods under high temperature as well as wet/dry cycles will be reported when available.

Based on visual examination of GFRP bars and split concrete blocks after each test, it was concluded that all the specimens experienced the same failure mode of shearing off of the bar deformations with no damage to concrete as shown in Figure 3.

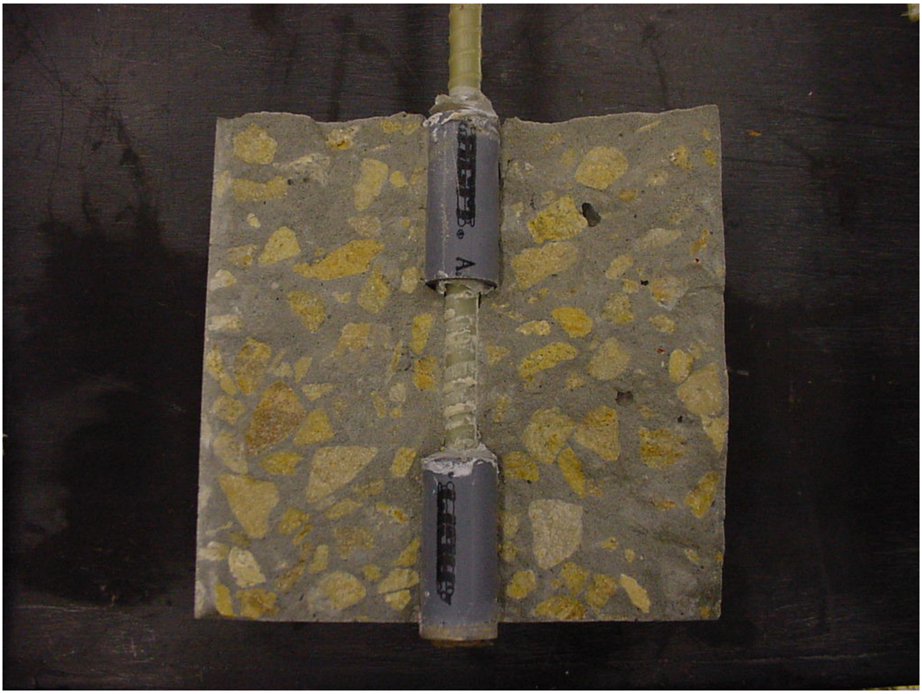

Figure 3. Interface between GFRP bar and concrete of bond failed specimen

Table 4. Bond strength of GFRP bars with concrete under different exposure conditions.

	Average bond strength* (MPa)	
Unexposed	13.5 ± 1.1	
Condition	3 months	6 months
Seawater	11.4 ± 1.9	13.3 ± 2.1
Sabkha	13.9 ± 2.6	15.9 ± 1.2

* All specimens failed in bond

6. CONCLUSIONS

Based on the results of six months environmental conditioning, the following conclusions can be drawn:

- The increase in temperature is the most effective method of accelerating the deterioration process.

- Both the alkaline and alkaline+chloride solutions have more detrimental effect on GFRP bars than acid solution.

- Apart from the change in color, no reduction in tensile strength and up to 8.4 % reduction in modulus of elasticity were observed in the GFRP bars after 6 months of outdoor exposure.

- Moisture absorption measurement at high temperature can be a good tool to assess the quality of different types of GFRP bars.

- After 6 months of exposure to seawater and sabkha solutions, no sign of bond deterioration was noticed. Longer periods with high temperature as well as wet/dry cycles have been considered in the on-going program.

- In order to adequately promote the utilization and application of GFRP bars in concrete construction, it is extremely important to put more stress on the durability issue of GFRP bars in both accelerated laboratory conditions and actual field environments.

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