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LONG-TERM PERFORMANCE OF GFRP REBARS UNDER SEVERE ENVIRONMENTS

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INTRODUCTION:

Fiber reinforced plastics (FRP) are advanced man-made composite materials manufactured by a synthetic assembly of high strength fibers with a light matrix and some selected fillers. FRP have been widely used in aeronautical and chemical engineering for more than 20 years. However, their applications in civil engineering works are rather recent. Currently, there are many types of FRP commercially produced but the most common type used for structural applications, for economic reasons, is the glass fiber reinforced plastics (GFRP). GFRP are non corrosive, lighter, and stronger (in tension) than steel.

Unfortunately, in some special conditions, such as in high alkalinity environment, the long-term performance of the GFRP is still unresolved question. This is so because of the fact that glass fibers (GF), one of the main constituents of the GFRP materials, loose great portion of their strength when subjected to wet alkaline environment. Tests carried out on glass fiber reinforced concrete (GFRC) [Shah et al., 1988; Soroushian et al., 1993] indicated that even if alkali resistance glass fibers are used, composites fabricated with glass fibers show a high reduction in flexural strength, toughness and modulus of rupture when subjected to accelerated aging tests. Sen et al [1993] also investigated the durability of S-2 glass/epoxy pretentioned beams exposed to wet/dry cycles in a 15% salt solution and found that GFRP rebars lost their effectiveness within 3-9 months of exposure. Porter et. al. [1997] exposed three different types of number 3 E-glass FRP rebars (manufactured using an isophthalic polyester resin) to high alkaline solution and a maximum temperature of 60 °C for a period of 2 to 3 months. Their test results indicated that the accelerated aging severely reduced the ultimate tensile strength and the maximum strain capacity of the GFRP rebars. Tannous and Saadatmanesh [1998] investigated the influence of eight different environments on the tensile strength, elastic modulus and ultimate strain at failure for number 3 and number 5 E-glass FRP manufactured through pultrusion process using polyester or vinyl ester resin matrix for a period of 6 months. The environments considered in the study included water at 25 °C, saturated $Ca(OH)_2$ solution with pH of 12 at 25°C, saturated Ca $(OH)_2$ solution with pH of 12 at 60°C, HCl solution with pH of 3 at 25 °C, NaCl 3.5% by weight solution at 25 °C, NaCl + $CaCl_2$ (2:1) 7% by weight solution at 25 °C and NaCl + $MgCl_2$ (2:1) 7% by weight solution at 25 °C. The investigators reported that, under the environments considered in the study, the highest losses in strength after 6 months (in both vinyl ester and polyester fibers) were in de-icing salt and alkaline solution. However, the losses in the vinyl ester rebars were lower. They also reported that although significant losses in strength were observed, limited changes in the elastic modulus and ultimate strain at failure were recorded.

Such degradation in the durability of GFRP brought into view the urgent need to evaluate the long term performance of GFRP rebars and, in turn, the concrete structures reinforced by them before they can be prescribed for reinforcing concrete structures. It is of particular importance to point out here that GFRP materials are relatively new and there is only little experience with their long-term performance in natural environment.

One of the well-known techniques for predicting the service life at some specified conditions is via the application of accelerated test methods. The most common one is immersion in hot water or hot liquid, identical to that the structure will be subjected to for various period of time and determining the change in the engineering properties induced by such exposure [Litherland et al., 1981; Aindo et al., 1983]

In previous work [Alhozaimy and Alsayed, 1999; Alsayed and Al-Hozaimy 1998, Al-Hozaimy, 1999] in which the durability of the GFRP rebars immersed in alkaline solution, it was concluded that the long term behavior of GFRP rebars are very much dependent on their chemical composition and manufacturing techniques. It was also recommended that, it is advisable not to use any type of GFRP rebars as a major reinforcing material for concrete structures that are anticipated to be used under hot moist environmental conditions unless the actual long term behavior of that particular type under such field conditions is well established. One of the leading manufacturers of the GFRP rebars in the United States of America had the chance to see the results of that study and also studies by other researchers in different places around the world. As a result, many manufacturers decided to improve their product to cope up with the concrete environment whether used in hot-dry, wet-cold or in hot-coastal areas. As a result, the second generation of GFRP rebars are now produced. The manufacturers are now claiming that their new products have high resistance to humidity, heat, alkalinity, and acids. Not only that, but they are approaching ministry of Transportation, General Corporation of water desalination Royal commission for Jobail and Yanbo', ARAMCO as well as many other governmental and private organization with their claims. It is now well established that the durability of the composite rods are very much dependent on the fiber type, sizing of the matrix, manufacturing process and the resin type [Alsayed and Alhozaimy, 1998; Benmokrane and Masmoudi, 1996; Rahman et al., 1998; Bakis et al., 1998; GangaRao and Vijay, 1997]. It is hoped that due to the close collaborations between the industries and the research institutes, there always be improvement on the quality and the durability of the composite materials.

Due to the rate of infrastructure deterioration due to the steel corrosion some of those governmental and private organization are now seriously considering the utilization of the GFRP rebars to replace steel in some of the new or the repaired structures. One of the leading manufacturers of GFRP rebars is now claiming that they have produced new generation of the rebars with greater resistance to most deleterious materials of the previous generation of the bars and yet with no change in the cost. The new generation of the rebars did show some better performance when subjected to some limited tests. They are now receiving some wide acceptance in the area. The manufacturers of one of the well known GFRP bars are now claiming that they have, produced a new generation of the GFRP bars that has greater resistance to alkaline and to other environmental conditions and yet with the same cost of the previous generation. However, there is no long term data available about the new rebars. Therefore, it is worthwhile to investigate the claimed improvement in the durability of the new generation of the rebars.

In this investigation an extensive experimental program to investigate the long term behavior of the new generation of GFRP rebars subjected to tap water, seawater, and alkaline solution is currently investigated. The tests are carried out considering four different temperature in the laboratory (23, 35, 50 and 65 °C) and three different conditions for GFRP bars. Namely: coated with low alkali cement paste; coated with high alkali cement paste and uncoated bars.

Environmental al Exposure

A thorough review of the literature was carried out to determine the environmental conditions that most likely to attack the GFRP bars. It was found that alkaline environment (PH 12.5 to 13) represent the most aggressive and damaging environment to both the fibers and the resins [Benmokrane and Rahman, 1996; Sheard et al., 1997, Litherland et al., 1981; Alsayed and alhozaimy, 1998]. Other reports also indicated that exposure to salt and sea water may cause severe deterioration to GFRP materials [Sen et al., 1993; GangaRoa and Vijay, 1997].

To predict the long-term behavior of GFRP rebars in concrete in short amount of time, accelerated aging technique can be confidently used to predict the long-term behavior under any climate conditions [Litherland et al., 1981; Aindow et al., 1983; Oakley et al., 1981]. The investigations showed that the accelerated there is positive correlation between accelerated aging data and data for specimens subjected to real fields exposure. Therefore, the accelerated aging technique is adapted in this study.

Local Cement

According to ASTM C150, cement is considered low alkali cement when alkalis (equivalent = Na_2O + o.66 K_2O) is below 0.6%. However, in a previous study [Alhozaimy and Alsayed, 1998] low alkali cement of Na_2O equivalent = o.2% was used which represents the alkali content of Alyamamah cement of Riyadh. It seems, however, that it is difficult to produce low alkali-cement economically. Not only are sources of low alkali cements becoming scarcer, but also modern process tends to concentrate the alkalis in the clinker during the manufacturing of cement. Nowadays there are eight cement factories operating in the Kingdome of Saudi Arabia which produces cement with different alkalis. A factor that was not considered in our previous study and may limit the result of the previous study to Alyamamah cement (the main cement factory in Riyadh, Saudi Arabia).

GFRP Rebars

The GFRP rebars used in this investigation were of E-glass type which contained 70% fibers. They were manufactured through hybrid pultrosion/compression modeling process which introduces the roving into a continuous motion series of pressure controlled die. The rebars were composed of three layers. Urethane-Modified Vinyl Ester were used for the two outermost layers whereas the unsaturated polyester resin was used in the interior layer. The rebars had a diameter of 9.5 mm (0.375 in) and a tensile strength of 756MPa.

Experimental Program:

To achieve the objective of the study, an extensive experimental program has been devised which takes into consideration the following variables:

- GFRP bar conditions:
  - coated with low alkali cement paste (Na_2 O equivalent = 0.2%)(Yamama Type I) (LACP)
  - coated with high alkali cement paste (Na_2 O equivalent = 1.0%) (HACP)
  - uncoated bars
- Water conditions

- ordinary tap water
- sea water procured from the Arabian sea – Eastern Province of Saudi Arabia
- alkaline solution (1.185 of $Ca(OH)_2$ + 9 g of Na OH + 42 g of K OH in 10 liters of water).

- Moist curing temperature
  - 23± 1 °C (laboratory environment)
  - 35 ± 1 °C
  - 50 ± 1 °C
  - 65 ± 1 °C

The test ages were selected as ending of 6, 12, 18, 24 and 30 months. The experimental program is detailed schematically in Figures 1 to 3.

Specimen Preparation:

GFRP bars of ϕ 10 mm and approximately 6 m long were procured. Each bar was cut into twelve pieces of length 500 mm each. The ends of all pieces were sealed with epoxy so that uniform resin coating can be achieved at the cross sections also. A total number of 194 pieces were prepared in this manner (190 pieces as shown in Figs. 1 to 3). Out of these 194 pieces, 50 pieces were left uncoated. 70 pieces were coated with low alkali cement (Yamama-Type I) paste of water/cement ratio of 0.6, 28 pieces were coated with high alkali cement paste of the same water/cement ratio and the remaining 4 pieces were left under laboratory conditions and considered as control specimens. To coat the GFRP bars with cement paste they were placed in plastic molds to give specimen size of 40 mm × 40 mm × 530 mm. Spacers prepared with cement paste were placed inside the molds at each end of the GFRP bar piece for centering it. The low alkali cement paste of 0.6 water/cement ratio was prepared in a paste/mortar mixer. After placing all the mixing water in the bowl, the cement was added and allowed to absorb water for 30 to 50 seconds. The paste was mixed for approximately four minutes at slow speed. It was then poured in the plastic molds while continuously stirring by long spoon. A plastic tamper was used to lightly tamp the paste around the GFRP bar piece. The high alkali cement paste was prepared in a similar manner with the exception that 3.62 kg of NaOH / 350 kg of low alkali cement (Yamama Type I) was used to increase the alkalinity of the cement (increased from Na_2O equivalent of 0.2% to 1.0%). The specified weight of NaOH pellets were dissolved in the mixing water and then cement added to it. Rest of the procedure was identical to the preparation of low alkali cement paste specimens.

The specimens were demolded after approximately twenty to twenty four hours and covered with wet burlap and polyethylene sheet for moist curing. After one week of moist curing, the specimens were taken out and placed on wooden racks for air curing for another week before immersing them in the tanks.

Apart from these 194 specimens, additional 33 GFRP bar pieces of ϕ 10 mm and 150 mm long with both ends sealed by epoxy were prepared to monitor the weight changes under specified environmental conditions. For this purpose, three bar pieces, cleaned by acetone, were immersed in each tank for periodic monitoring of weight changes.

Immersion Tanks

Twelve steel tanks, with dimensions of 400 mm × 900 mm in plan and 600 mm deep, were fabricated. They were provided with cover at the top, an opening, with valve at the bottom and painted with an enamel paint. Four of the tanks were covered from outside with an insulation material and fitted with electrical heaters, thermostat controlled, so as to maintain the temperature of water/solution to 35 ± 1, 50 ± 1 and 65 ± 1 °C. The tanks were designated as T1 through T4 (without heaters) and T5 through T12 (with heaters). Perforated racks, made up of Galvanized steel, were fabricated to facilitate placing of bar pieces inside the tanks.

The placement of prepared specimens in immersion tanks are summarized in Table 1.

The uncoated and coated specimens in ordinary tap water were placed in separate tanks, this has been done to minimize the leaching effect of coated specimen in ordinary water.

Test procedure

Once the specimens were taken out of the tanks and prior to testing they were thoroughly dried by clean cotton towels and weighted. The specimens were then placed in an oven operating at 60 ºC for 5 days, weighted again, left to cool down in room temperature and then subjected to tension test.

Test results and discussion

At this stage of testing, only limited data were collected. These are for specimens immersed for up to 6 months in different temperature and liquid solutions as presented in Table 1. Therefore, the test results presented in this paper are limited to the first six months of the experimental program. Other results will be published upon availability.

The weight gain in the GFRP rebars as a percentage of the original weight is presented in Fig. 2. The results show that under all environmental conditions considered in this study, the gain in weight is minimal. However, moist absorption, even a small percentage, may have some deleterious effect on the engineering characteristics of the rebars. They may cause a plasticization of the matrix and a reduction in the glass transition temperature.

The reduction in the tensile strength of the rebars after six months of immersion into different environmental conditions are presented in Table 3. As can be seen in the results that under normal temperature (23 ºC), regardless of the environmental conditions, there is no reduction in the tensile strength. However, as the solution temperature increased (accelerating the degradation process), the tensile strength reduction increased. This is true for all environmental conditions. The highest reduction occurs in the specimens immersed in the 65 ºC. tank. This may represent a 100 years in real life. Further, the results indicated that the coated specimens (higher alkalinity) suffer more reduction in the tensile strength that the counterpart uncoated specimens. The degradation also increased when the coat contains higher concentration of alkalinity. It is interesting to observe that the tensile strength degradation in the specimens immersed in the sea water sea water was only 2.65% for the uncoated specimens. The ratio increased to 3.11 and 12.7% when the specimens coated LACP and HACP, respectively. This may lead to the fact that the alkalinity in the cement is the driving force of the degradation of the GFRP rebars.

It is worthwhile to mention here that similar study was carried out earlier on two types of GFRP rebars [Alhozaimy, 1999]. The reduction in the tensile strength of the two types of GFRP rebars (types B and C where type B is the previous version of the rebars used in this study) after being exposed to different solutions at room and 40 ºC deg. For eight months are reproduced in Table 3. Although the exposure period and solution temperature reported in Table 3 differ from those in Table 2, it can be easily recognized the improvement on the durability of the new generation of the rebars as compared to the previous one.

Conclusions

It is too early to state a conclusive conclusions at this stage of test results. However, the results are encouraging and the improvement in the durability of the new generation of the rebars considered in this study under the different severe environments are quite obvious.

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Table 1: Detail of Immersion Tanks *

Tank Designation	Temperature ^{o}C	Contents of the Tank
T1	23 ± 1	Uncoated specimens in ordinary tap water
T2	23 ± 1	Coated LACP + HACP specimens in ordinary tap water

T3	23 ± 1	Coated LACP & HACP specimens in sea water
T4	23 ± 1	Uncoated specimens in Alkaline solution
T5	35 ± 1	Uncoated specimens in ordinary tap water
T6	35 ± 1	Coated LACP + HACP specimens in ordinary tap water
T7	35 ± 1	Coated LACP + HACP specimens in sea water
T8	50 ± 1	Uncoated specimens in ordinary tap water
T9	50 ± 1	Coated LACP + HACP specimens in ordinary tap water
T10	50 ± 1	Coated LACP & HACP specimens in sea water
T11	50 ± 1	Uncoated specimens in Alkaline solution
T12	65 ± 1	Coated LACP & HACP specimens in ordinary tap water

* Each tank contains 3 specimens for weight loss monitoring in addition to the above specimens.

Table 2: Percentage of weight gain in GFRP rebars after 6 months of exposure to different environmental conditions

Water Temperature (^{o}C)	Water Conditions			
	Tap water		Sea Water	Alkali Solution
	Uncoated	Coated	Uncoated	Uncoated
23	0.0	0.22	0.27	0.14
35	0.27	0.0	0.18	---
50	0.0	0.0	0.41	0.31
65	---	0.27		

Table 3 : Percentage of tensile strength reduction of GFRP rebars after beings subjected to different environmental conditions for six months

Temperature of the solution (°C)	Solution Conditions					
	Tap Water			Sea Water		Alkali Solution
	Coated with LACP	Coated with HACP	Uncoated	Coated with LACP	Coated with HACP	Uncoated
23	0.0	0.0	0.0	0.0	0.0	0.0
35	2.65	0.0	2.38	1.26	0.0	-
50	8.99	11.04	2.65	3.11	12.70	13.65
65	33.99	39.02				

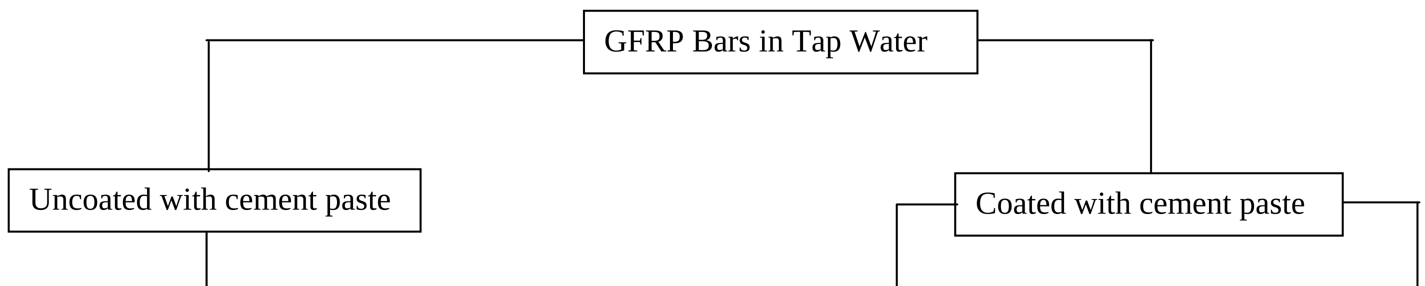
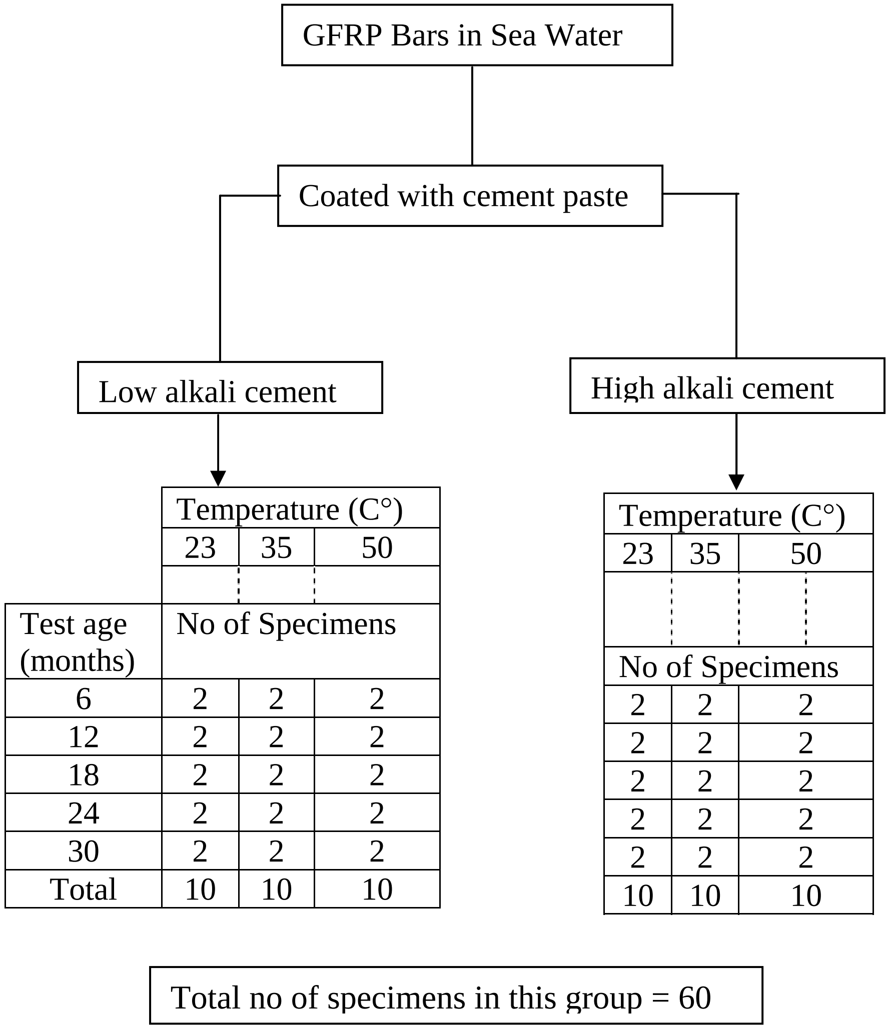


Figure 1: Experimental program for GFRP bars immersed in tap water



Low alkali cement:

Test age (months)	Temperature (C°) 23	35	50
	No of Specimens		
6	2	2	2
12	2	2	2
18	2	2	2
24	2	2	2
30	2	2	2
Total	10	10	10

High alkali cement:

Temperature (C°) 23	35	50
No of Specimens		
2	2	2
2	2	2
2	2	2
2	2	2
2	2	2
10	10	10

Figure 2: Experimental program for GFP bars immersed in sea water

GFRP Bars in Alkali Solution
(Uncoated bars)

Test age (months)	No. of Specimens — Temperature C° 23	50
6	2	2
12	2	2
18	2	2
24	2	2
30	2	2
Total	10	10

Total no. of specimens in this group = 20

Figure 3: Experimental program for GFP bars immersed in alkali solution

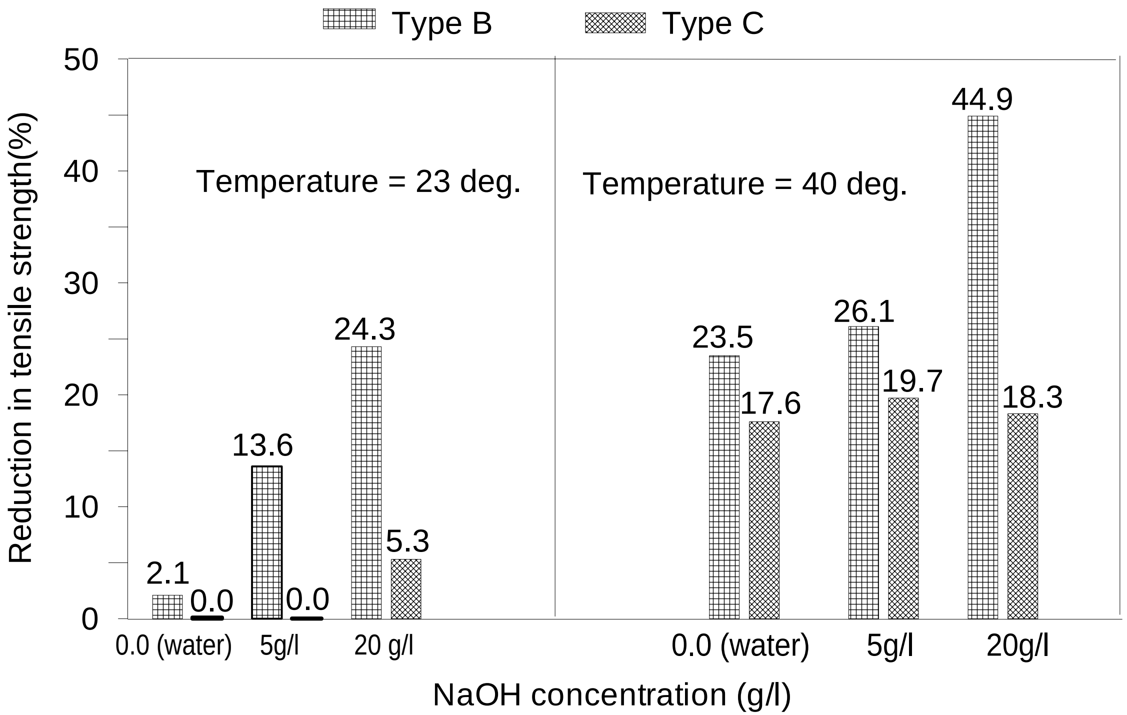


Figure 4 Effect of curing temperature on tensile strength reduction of Type B and C GFRP rebars (Uncoated specimens at 8 months)