Accelerated and Natural Weathering of GFRP Bars

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Abstract : Variations in strength and stiffness properties of Glass Fiber Reinforced Plastic (GFRP) bars are described under various conditioning schemes. The conditioning schemes include pH ranging from 12^0 to 120^0F, sustained stress ranging from 20% to 50% for a duration up to 3 years. Increase in temperature and stress resulted in some decrease in the strength of GFRP bars. Alkaline conditioning was more detrimental to the strength of GFRP bars than salt conditioning. Based on accelerated test results calibrated with respect to naturally aged test data, it is safe to conclude that the service life of the FRP bars with durable low viscosity urethane modified vinylester resin is about 60 years as a minimum with 20% sustained stress on the bar. Concrete cover protection on the GFRP bars enhanced the service life up to an additional 30 years.

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INTRODUCTION

Large scale use of glass FRP products is seriously hindered due to the absence of: (1) experimental or field data; (2) understanding of durability (aging) aspects under real-life weathering such as freeze-thaw cycles, alkaline and deicing chemical exposure (3) failure data under mechanical stress cycles (live loads). In this paper, accelerated aging results of GFRP bars exposed to varying humidity levels, temperatures, sustained stresses and pH levels are described. Aging results are calibrated using actual data obtained through previous efforts by other researchers (Litherland, 1981). A methodology is presented for correlating natural weathering data to our accelerated aging data with our accelerated aging data on GFRP bars.

OVERVIEW

Glass composition, glass homogeneity, temperature, stress, surrounding degradation media, resin type and composition influence the changes in mechanical, thermal and chemical properties of glass (1). Chemical Composition of E-Glass is given in Table 1.

Degradation mechanism of glass is mainly of two types: etching and leaching (1). Etching is produced by an alkali attack. As the silica network is attacked, other components of the glass are released. If there is no further accumulation of reaction products on the remaining glass surface and no change in the activity of the surrounding solution, reaction proceeds at a constant rate. However, any accumulation of reaction products in solution suppresses the reaction rate, such that, saturated silica will reduce the reaction rate to zero (1).

In the leaching process produced by an acid attack, hydrogen or hydronium ions exchange for alkali and other positive mobile ions in the glass. The remaining glass network, mainly silica, retains its integrity. It may become hydrated if the network is relatively unstable; or it may become more dense and stable than original glass. Unless the leached layer is removed or altered, reaction rate reduces even to zero. Acid reacts slowly with glass compared to alkali. There is not much difference in the effect of low acidic pH or that of pH 5 to 6 (1).

In this study, salt and alkaline attack on GFRP bars used for reinforcing concrete structures is studied. Concrete structures reinforced by GFRP bars are alkaline in nature and are exposed to rain, deicing salts or other chemicals depending on their function and location. Hence, the objective of this study was to establish mechanical properties of GFRP bars under salt and alkaline conditioning with temperature variations typical of the harsh field conditions and evaluate their long-term durability for design purposes.

CONDITIONING METHODS

For room temperature tests, bars were placed in a 3 ft. x 4 ft. polyurethane tank filled with salt or alkaline solution. Salt solution consisted of 97% water and 3% sodium chloride whereas alkaline solution consisted of 97.4% water, 0.2% calcium hydroxide, 1.4% potassium hydroxide, and 1% sodium hydroxide.

For freeze-thaw temperature conditioning, bars were placed in separate 3 ft. x 4ft. polyurethane tanks containing salt or alkaline solution. The tanks were covered with lids and positioned inside a Thermotron environmental chamber. Chamber temperature varied between 12.2^0F to 120.2^0F (-11^0C to 49^0C) with an average weighted temperature of 93.68^0F (34.27^0C), where, weighted chamber temperature is calculated by considering the duration of each temperature. Weighted single average chamber temperature was necessary while correlating the accelerated weathering to natural weathering.

For conducting sustained stress tests, bars were conditioned in specially designed single and multiple cell steel frames manufactured at CFC laboratory and treated with anti-corrosive coatings. The frames were drilled with holes conforming to the bar diameter. Bars were stressed using prestressing chucks and a Dywidag jack. Stressing frame provided two locations within the stressed region of the bar, one for conditioning and the other for strain monitoring.

At a time, six bars were stressed one after the other in a multiple cell frame (Fig. 1). It was intended to use two stress levels of 20% and 40%. Resulting sustained stresses were equal to 15 to 42% of the ultimate stress after losses. Relaxation and loss of stress were monitored on the bars. For freeze-thaw conditioning, stressed multiple cell frames filled with the required solution.

TENSION TEST PROCEDURES

Uniaxial tension tests were performed on the unconditioned and conditioned GFRP bars using specially modified grips, developed at the CFC laboratory. Schedule 80 split steel pipes were used for gripping the bars using Pliogrip adhesive manufactured by Ashland Chemicals. Four feet long bars were used for testing purposes. Instrumentation consisted of strain gauges connected to data acquisition system, with the gages mounted on the bars at mid height.

RESULTS AND DISCUSSIONS

Unconditioned Test

For each bar type manufactured by International Grating Inc. (sand coated and designated as IG1 and IG2) or Marshall Industries (ribbed and designated as M1, M2 and M3) six specimens were tested and average values obtained are shown in Table 2. Low viscosity urethane modified vinylester resin was used for better durability in all bars. All the conditioned and unconditioned bars tested exhibited typical linear stress-strain relation. It was difficult to measure failure strain, because strain gages stopped functioning long before failure or readings were affected by bar wrap failure, matrix cracking or sand particle popping.

Conditioned Tests

Salt and Alkaline Conditioning:: Following the conditioning duration, minimum of two bars were taken out of the respective conditioning locations and tension tested by attaching grips and strain gages. Among salt and alkaline conditioning, alkaline conditioning proved to be more detrimental to the strength of GFRP bars. Freeze-thaw conditioning proved to degrade the GFRP bars earlier than the room temperature (Fig. 2A). It is to be noted that the room temperature in these experiments was 71.6^{0}F, whereas, average temperature of the freeze-thaw conditioning through environmental chamber was 93.68^{0}F.

For sand-coated bars, maximum strength reductions under salt and alkaline conditioning at room temperature were 18.5% and 32.2% respectively, over 15 months duration (Fig. 2A). Similarly maximum strength reductions in salt and alkaline conditioning under freeze-thaw conditions were 21.9% and 37.5% respectively, over 15 months duration (Fig. 2A).

For C-bars, maximum strength reductions in salt and alkaline conditioning at room temperature were 24.5% and 30% respectively, over 30 months duration (Fig. 2B). Similarly maximum strength reductions in salt and alkaline conditioning under freeze-thaw conditions were 51.5% and 55% respectively, over 30 months duration.

Salt and Alkaline Conditioning with Stress:: Strength reductions under salt and alkaline conditioning generally increased, with increasing sustained stress. The reductions were a maximum of 70.75% of the applied stress as compared to the bar at same age and salt-conditioning without any applied stress. Similarly, reductions were a maximum of 150% of the applied percent stress as compared to the unstressed bar at same age and alkaline-conditioning. These relationships are represented in eqns. (1) and (2).

$$\sigma_{salt(X,t)} = \sigma_{salt(t)} - \left(\frac{S.S.F}{100}\right)\left(\frac{X}{100}\right)\sigma_{salt(t)} \qquad (1)$$

$$\sigma_{alk(X,t)} = \sigma_{alk(t)} - \left(\frac{A.S.F}{100}\right)\left(\frac{X}{100}\right)\sigma_{alk(t)} \qquad (2)$$

Where,

$\sigma_{salt(X,t)}$ or $\sigma_{alk(X,t)}$ = Failure stress of salt or alkaline conditioned bars with applied sustained stress X% at age 't'

$\sigma_{salt(t)}$ or $\sigma_{alk(t)}$ = Failure stress of salt or alkaline conditioned bar without sustained stress at age 't'

S.S.F. = Salt Stress Factor (Conservatively 75% is chosen from the results)

A.S.F. = Alkaline Stress Factor (conservatively 150% is chosen from the results)

X = % Sustained Stress

For sand-coated bars under room temperature with sustained stress, maximum strength reductions in salt and alkaline conditioning were 22.9% (8 months of 27% applied stress) and 49.2% (6 months of 37% applied stress) respectively (Fig. 3). This is consistent with the expected trends of strength reduction due to salt and alkaline conditioning.

For sand-coated bars under freeze-thaw conditioning with sustained stress, maximum strength reductions in salt and alkaline conditioning were 25.6% (12 months of 35% applied stress) and 82.1% (12 months of 40% stress application) respectively. Static fatigue (also called stress corrosion) failures were also observed in some bars under this conditioning.

For C-bars with sustained stress, maximum strength reductions in salt and alkaline condition at room temperature were 25.2% (10 months of 32% applied stress) and 14.2% (8 months of 25% stress application) respectively.

Static Fatigue (stress Corrosion) at High Temperature:: High temperature, particularly 150^0F with stress and alkaline conditioning proved to be more detrimental than any other conditioning. Only sand-coated bars were conditioned at 150^0F with stress in the alkaline solution, whereas C-bars were conditioned without stress. Stress reduction was 84.7% within 4 months of 40% stress application (Fig. 3) including stress rupture.

Tensile Stiffness:: Many of the conditioned bars showed an increase in stiffness. An increase in stiffness associated with stress loss implies that the bar is more brittle than the unconditioned reference bar. A reduction in the stiffness associated with stress loss implies that the bar would elongate more at a given stress than the unconditioned bar. Some of the individual bars also exhibited small loss of stiffness for both bar types. Sand coated International Grating bars on a whole showed 5.9% increase in the stiffness considering different conditioning schemes. Considering all the test data, average stiffness increase was found to be 4.1% for M1 type and stiffness loss of 4.8% for M2 type Marshall Bars.

Failure Modes in Bars under Tension:: In most of the tension tests on sand coated bars helical wrappings started to fail between 50 to 60% of the ultimate stress in the middle-third of the gripped zone. Helical wrappings are provided on sand coated bars for improving bond between concrete and the bar. Salt conditioned bars had typical wrap failure followed by vertical splitting and fiber blooming in the middle third zone. Alkaline conditioned bars typically had "necking" failures, where, the outer portion affected by alkalinity would stretch and fail earlier than the inner core. C-bars under salt conditioning usually failed with vertical splitting, whereas the alkaline conditioned typically exhibited ‘necking’ failures.

CORRELATION OF ACCELERATED AND NATURAL WEATHERING

Accelerated aging methodologies can be used for predicting the long-term mechanical properties of FRP bars embedded in concrete. An accelerated aging methodology based on

Arrhenius temperature relationship has been suggested by Litherland et al. (2) for predicting the degradation in the mechanical properties of FRP over a given duration and its correlation with the natural aging.

Litherland et al. (2) have correlated their data with natural weathering samples of about 10 years. In their experiments, the media surrounding glass was cement representative, so as to achieve meaningful correlation of natural weathering to accelerated weathering. Some of the factors to be considered before using Litherland's method are:

- Mean annual temperature is the sole factor governing accelerating factors.
- Specimens used were without any sustained stress application.
- Present day manufacturing methods and durable resins necessitate a shift of the time scale factor while interpreting Litherland's data.

Our data at 34.27^0C designated as the WVU data in Fig. 4A were compared with data at 35^0C given by Litherland et al. (2) on strength reductions. Similar data trend and correlation were observed between our data at 22^0C and Litherland's data at 19^0C.

Accelerated aging under alkaline conditioning for freeze-thaw temperature fluctuations produced maximum strength reduction in the bars (i.e., among the ones without sustained stress). Hence, those data for the bars under alkaline condition and freeze-thaw fluctuation were chosen for correlation with natural weathering. In addition, data of bars extracted (Fig 4A) from tension side of concrete beams immersed in alkaline solution and subjected to freeze-thaw condition for 450 days are also represented. Good correlation was observed in terms of data lines being nearly parallel to each other and conforming to the temperature trend. It is worth noting that the bars embedded in pre-cracked concrete beams and exposed to alkaline solution (pH=13) experienced lower strength reductions as compared to the same bars exposed directly to same alkaline solution at the same temperature fluctuation, i.e., freeze-thaw. In essence, concrete cover helps in protecting GFRP bars.

It is interesting to note that the current state-of-the-art GFRP products with better resins and manufacturing techniques have taken three times longer duration than Litherland's specimens to attain the same reduction in strength after aging (Fig. 4.A). This implies that any calibration of our results with the natural weathering data given by Litherland (2) on strength reduction is more conservative due to better protection offered by the screened resin used in this investigation. Accelerated chamber weathering carried out in these experiments is calibrated with respect to Morgantown, West Virginia weather. Effect of stress on the bars is obtained using Eqn. 2.

From Fig. 4.B it follows that one day of chamber conditioning in these experiments is equivalent to 17 days of natural weathering at Morgantown, WV or 18 days of U.K. weathering as given by the calibrated Eqn. 3. Since, our results have a time scale factor of about 3 times those of Litherland’s results (Fig. 4.A), conservatively a time scale factor of two is used. With a conservative time scale factor, it follows that, one day of chamber conditioning in this study is equivalent to 34 days of natural weathering at Morgantown, WV, or 36 days of U.K. weathering.

Age in Natural Days/Day of Chamber Conditioning (y) = 0.098 e $^{0.0558T}$ (3)

Where, T=Temperature in ^{0}F.

Hence, chamber weathering of 30 months in alkaline conditioning corresponds to natural weathering of 1020 months, i.e., about 85 years (calculated with an average of 30.41 days/month or 365 days/year) at Morgantown, WV. This conversion is calibrated for specimens without stress. However, applying a reduction factor similar to eqn. (2) for a structure with 20% sustained load, equation (3) gives: age in natural days/day of chamber conditioning as 34-(150/100)x(20/100)x34 = 23.8 days. Hence, chamber weathering of 30 months under alkaline conditioning and selected freeze-thaw temperature corresponds to natural weathering of 704 months or 58.68 years of natural weathering with 20% sustained stress (calculated with an average of 30.41 days/month or 365 days/year).

CONCLUSIONS

- For sand-coated bars, maximum strength reductions in salt and alkaline conditioning at freeze-thaw temperature were 21.9% and 37.5% respectively, over 15 months.
- For C-bars, maximum strength reductions in salt and alkaline conditioning at freeze-thaw temperature were 51.5% and 55% respectively, over 30 months duration.
- Stress reduction in bars at 150^{0}F and immersed in alkaline solution was 84.7% within 4 months under an applied 40% sustained stress. One of the bars in this conditioning scheme failed under static fatigue.

- On an average, sand coated International Grating bars showed 5.9% increase in the tensile stiffness under different aging. On an average, tensile stiffness increase was found to be 4.1% for M1 type and stiffness loss of 4.8% for M2 type C-bars under different aging.
- Chamber weathering of 30 months under alkaline conditioning under the selected freeze-thaw temperature conservatively corresponds to natural weathering of 704 months or about 60 years with 20% sustained stress. However, concrete cover on the bars extends the service life up to 120 years.

REFERENCES

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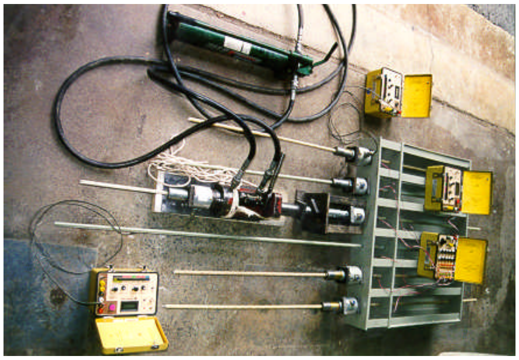
Keywords : GFRP, FRP, rebar, accelerated aging, weathering, conditioning, durability, calibration, strength, stiffness.

Table 1 Chemical Composition of E-Glass Fibers

SiO_2	Al_2O_3	CaO	MgO	B_2O_3	Na_2O_3	Others
54.5	14.5	17	4.5	8.5	0.5	0.5%

Table 2 Unconditioned Tensile Strength and Stiffness of Bars

Bar	Surface Texture	Strength Average MPa(ksi)	Stiffness Average GPa(x10^6 psi)
IG1	Sand coated	605.1 (87.82)	(42.8) 6.21
IG2	Sand coated	555.5 (80.63)	(35.5) 5.15
M1	Ribbed	608.2 (88.28)	(30.5) 4.42
M2	Ribbed	679.9 (98.68)	(39.69) 5.76
M3	Ribbed	747.8 (108.53)	(38.65) 5.61



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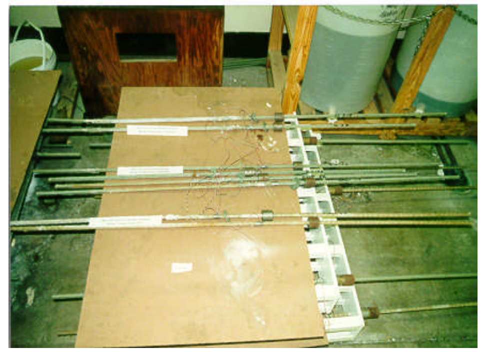

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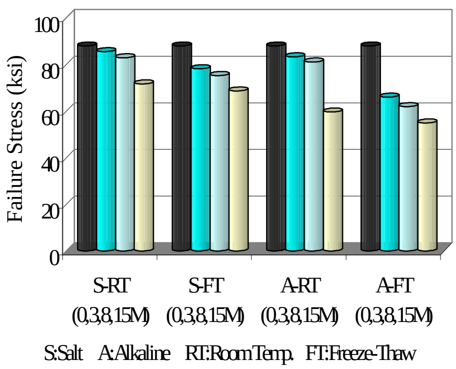

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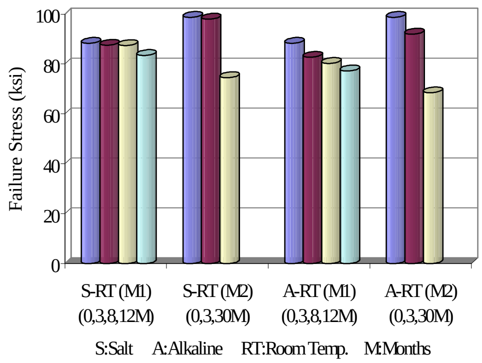
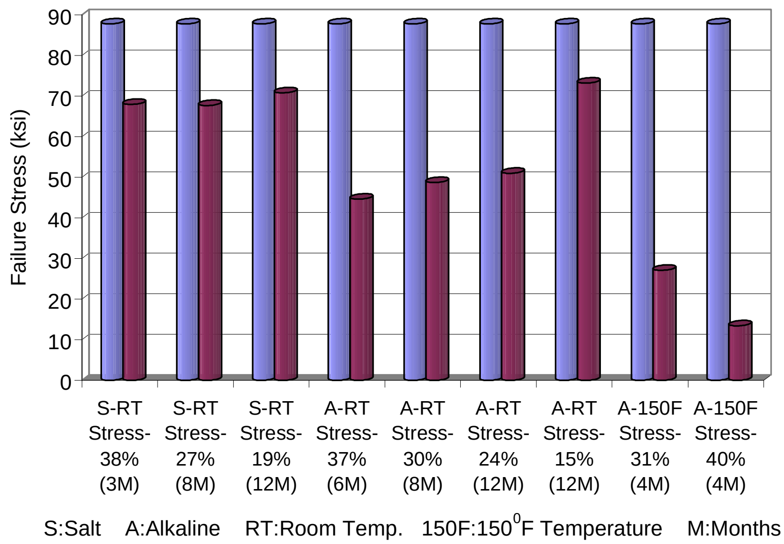
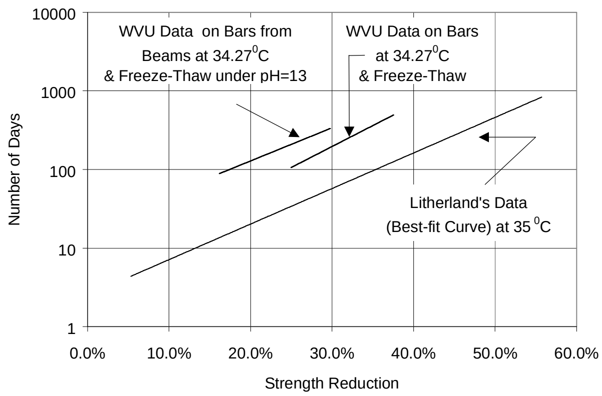


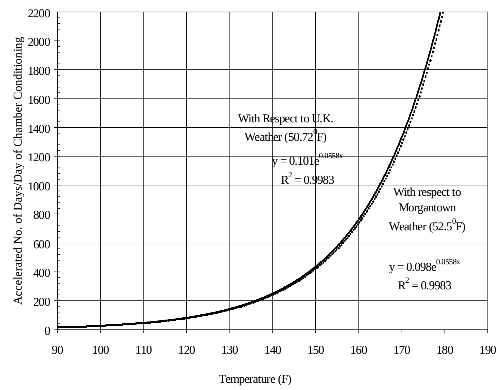
(B)

Note: 1ksi=6.89MPa



Note: 1ksi=6.89MPa ; $[T]^0C=[(1.8)T+32)]^0F$; $[T]^0F=[(T-32)/1.8]^0C$





Note: 1ksi=6.89MPa ; [T]^{0}C=[(1.8)T+32)]^{0}F; [T]^{0}F=[(T-32)/1.8]^{0}C

Fig. 1. Sand Coated and C- Bars in Multiple Cell Frames A) Stressed; B) Destressed

Fig. 2 Tensile Failure Stress Variation under Different Conditioning Schemes A) Sand-Coated Bars; B) C-Bars

Fig. 3 Tensile Stress Variation in Conditioned Sand-coated Bars

Fig. 4 A) Calibration of Accelerated Weathering Data by WVU and Litherland et al.; B) Converting Accelerated Weathering to Natural Weathering