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FREEZE-THAW CYCLING EFFECT ON THE BEHAVIOR OF CFFT MEMBERS

Hamdy M. Mohamed

Associate Professor, College of Engineering, Applied Science University (ASU), Bahrain, In Partnership with London South Bank University, London, United Kingdom (corresponding author: hamdy.mohamed@asu.edu.bh)

ABSTRACT

Previous studies have demonstrated the high performance of the concrete-filled fiber-reinforced polymer tubes technique (CFFTs) as confining material for concrete structures. However, the lack of several concerns related to the behavior of the CFFT as a protective jacket against harsh environmental effects has limited the full implement of this technique. The environmental effects such as freeze-thaw cycles may affect materials properties, which may affect the structural response of the CFFT members as well. This study presents the results of experimental and theoretical work to investigate the durability short and long-term behavior of CFFT members. Test variables include type and duration of the freeze-thaw exposure in (fresh water and). CFFT cylinders (150 x 300 mm) were exposed to 100 and 300 freeze-thaw cycles in saturation in fresh water. Then, uni-axial compression tests were conducted in order to evaluate the change of mechanical properties of the test cylinders due to the freeze-thaw exposure by comparing the stress-strain behavior and their ultimate load capacity. Test results indicated that the confinement using the CFFT technique significantly protect the concrete when subjected to freeze-thaw exposure. Environmental Reduction Factor was proposed to account for the environmental effects when predicting the confined compressive strength of CFFT cylinder.

1. INTRODUCTION

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Corrosion of steel reinforcement causes continual degradation to the civil infrastructures and it has prompted the need for challenges to minimize the corrosion activity to the reinforced concrete structures. Recently, the use of fibre-reinforced polymers (FRP) tubes as structurally integrated stay-in-place forms for concrete members, such as beams, columns, bridge piers, piles and fender piles has emerged as an innovative solution to the corrosion problem. In such integrated systems, FRP tubes may act as a permanent form, often as a protective jacket for concrete, and especially as external reinforcement in the primary and secondary directions such as for confinement. Furthermore, the use of concrete-filled FRP tubes (CFFT) technique is predicated on performance advantages linked to their high strength-to-weight ratios, expand the service life of structures, enhance corrosion resistance, and potentially high durability.

Although the (CFFT) technique has become an adapted structural system for different concrete structures, there is a lack of the experimental work regarding the durability effect, short and long term durability of the CFFT is the most important factor needed for CFFT widely implemented application for new constructions. Problems with deteriorated infrastructures in marine settings and cold regions are mainly due to exposure to salt water and subject structures to force of water freezing and expanding due to turns into ice. Both earlier and more recent studies have revealed that the freeze-thaw cycles can significantly reduce the effects of confinement due to materials degradation. Karbhari and Eckel 1994 reported a reduction of more than 30% in the ductility of glass FRP-confined concrete as an effect of freeze-thaw cycles combined with moisture. Callery et al. (2000) studied the change in response of FRP composite wrapped concrete cylinders by using an extensive program of environmental effects. Test results indicated that, the specimens exposed to low temperature showed higher failure load when compared to specimens kept at room temperature. Furthermore, in dry environment, the freeze-thaw effect was found to be very low; however only the hoop strain is affected resulting in more brittle failure mode (Karbhari et al. 2000). Teng et al. (2003) investigated the effect of the freeze-thaw cycles thawing process in water on performance of columns wrapped with glass FRP. Recent study by El-Hasha et al. (2010) investigated the effects of freeze-thaw cycles after exposure to heating and cooling cycles (23 to 45C) on the behavior of concrete cylinder confined with CFRP sheets. The test results indicated that the freezing and thawing reduced the compressive strength. This paper presents an experimental program conducted at Sherbrooke

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University to evaluate the long-term durability performance of the CFFT members under freeze-thaw condition. The test results were used to propose the Environmental Reduction Factors for design purposes of new structure considering the effect freeze/thaw cycles on the strength capacity of CFFT cylinders. Also, the regression analysis was used to predict the Service Life Environmental Reduction Factors to design CFFT member for up to 75 years.

2. EXPERIMENTAL PROGRAM

2.1 Materials

In this study, GFRP tubes were used in the experimental program. The GFRP tubes are fabricated using filament winding technique; E-glass fibre and Epoxy resin are utilized for manufacturing these tubes. The internal diameter for all tubes is constant equal to 152 mm. Table 1 presents the details and mechanical properties of these tubes, where E_X and E_Y are the Young's modulus in the longitudinal and hoop direction. All specimens were constructed from the same batch of concrete using a ready-mix concrete, the concrete mixture was intended to provide 30 MPa. Ten plain concrete cylinders (152 x 305 mm) were tested at 28-days under axial load; the average concrete strength for ten cylinders was found 33.2 MPa.

Table 1. Dimension and mechanical properties of fiber reinforced polymer tubes

Tube type	D (mm)	t_{FRP} (mm)	No. of layers	Stacking sequence	E_{FRP} *(MPa)*	F_{FRPu} *(MPa)*	E_x (MPa)	F_x (MPa)
A	152	2.65	6	$[\pm 60]_3$	20690§	345§	8785*	57.90*

E_x and E_{FRP} are, respectively, the Young's modulus in the longitudinal and hoop directions; F_x and $F_{FRPu}$are, respectively, the ultimate tensile strength in the longitudinal and hoop directions; *Based on coupon test; § Based on split-disk test

2.2 Specimens details and preparation

Standard size (152 x 305 mm) plain concrete and CFFT cylinders were cast. The specimens were divided into different groups. First group was used to preserve virgin samples that were used as reference; therefore, they were kept at room temperature for a period equivalent to the 100 and/or 300 F/T cycle's hours to determine any increase in the concrete strength due to aging by the end of testing period. The other groups were exposed to 100 and/or 300 freeze/thaw cycles. The second group was submerged in fresh water. The main goal of these two sets was to evaluate the effect of combination the moisture and freeze-thaw cycling together. Table 2 provides the number of specimens according to how were utilized in the experiments.

Table 2. The typical number of test units for each type of the freeze thaw cycles.

Specimen code / **Type of condition**			**PC C**	**CFFT Tube-A**
Room temperature: Group (1)			6	6
Freeze-Thaw exposure	**F/T fresh water** Group (3)	100 cycles	3	3
		300 cycles	3	3

2.3 Freeze-Thaw Exposure and Test procedure

Conditioned specimens for saturated freeze-thaw were left in fresh baths and placed in the environmental chamber. The CFFT cylinders were spaced apart from each other and from the bottom of the box to allow the free circulation of the solution between and around the specimens. The solution level was kept constant throughout the study to avoid a pH increase which could be due to a solution level decrease and a significant increase of the concentration of the alkaline ions in the solution. The freezing cycles consisted of lowering the temperature in the middle of the saturated concrete specimens from 4.4°C to -17.8°C in a period of 16.5 h. The thawing cycles consisted of raising the temperature in the middle of the saturated concrete specimens from -17.8°C to 4.4°C in a period of 10.5 h for the saturated specimens. Those freeze-thaw hours were sufficient to vary the temperature of non-saturated specimens between (+28°C to -28°C). All specimens were brought to room temperature before being tested. Uniaxial compression tests were conducted until failure. The specimens were tested using a 6,000 kN capacity FORNEY machine, where the CFFT cylinders were setup vertically at the center of loading plates of the machine. The FORNEY machine, strain gauges and LVDTs were connected by a 20 channels Data Acquisition System and the data were recorded every second during the test.

3. EXPERIMENTAL PROGRAM

3.1 Effects of freeze-thaw cycles on compressive strength

It is well known that the freeze-thaw cycling affect each of the concrete; the FRP composite; and the CFFT act as integrated system. Therefore, herein not only effects of freeze-thaw on the ultimate strength level will presented, but also the important effects on the damage, failure mechanism and the basis changes on overall behavior will be reviewed. The control plain concrete (unconfined) tested after the total period gave strength of 33.2 MPa. The experimental results of the freeze-thaw effect on the average compressive strength (f'_c) were reported in Table 3.

In comparison with the unconfined cylinders exposed to 100 and 300 F/T cycles in air as it can be found in El-zefzafy 2013, fresh reductions in (f'_c) of the unconfined exposed cylinders by 10.3, was observed after 100 F\T cycles. Also, reductions by 26.7 the plain concrete conditioned to 300 F/T cycles in air, was reported. This reduction is attributed to the freeze thaw action on the concrete itself. It should be noted at this point that this reduction occurred although air entrainment concrete was used in this study to minimal the freeze-thaw effect as much as possible. On the other hand, a slight increase by 9.8% in the average compressive strength due to the freeze-thaw in fresh water was reported, which falls within overall scatter bounds. One possible explanation for that is the post curing of the plain concrete cylinder while submerged in water. Test results for conditioned specimens, in terms of axial compressive strength and ultimate axial and hoop strains are reported in Table 3, for CFFT specimens, in comparison with the virgin specimens kept at room temperature. Results from axial compression test, after the different type of 100 freeze-thaw exposure seems to have no effect, indicating slight reduction in strength, at the average ultimate strength over the confined specimens kept at room temperature. With regard to types of the freeze-thaw exposure used in this study, the short-term freeze thaw in salt water had the most effect on the average strength resulting in (2.9%) reduction.

Table 3. Overall response characteristics for confined concrete (CFFT) cylinders

Specimen code	***Average failure level***							
	100 F/T Cycles				***300 F/T Cycles***			
	Load kN	***f'_{cc} strength (MPa)***	***Axial strain***	***Radial strain***	***Load kN***	***f'_{cc} strength (MPa)***	***Axial strain***	***Radial strain***
Group (1): Room temperature								
A -R1	1297.15	71.5	0.028 0.036	0.026 0.028	1306.6	72.0	0.030 0.041	0.022 0.036
A -R2	1290.1	72.1	0.023 0.045	0.030 0.037	1288	71.1	0.031 0.037	0.025 0.035
A -R3	1311.3	72.3	0.035 0.036	0.027 0.028	1216	67	0.033 0.034	0.027 0.029
Average	1299.52	71.6	0.034	0.029	1270.2	70	0.034	0.029
SD	10.8	0.61	0.023	0.017	47.9	2.7	0.003	0.001
f/t in Group (2): fresh water								
A -F1	1293.14	72.31	0.050 0.040	0.049 0.032	891.2*	49.1	0.009 0.009	0.011 0.011
A -F2	1194.35	65.85	0.026 0.035	0.034 0.029	1017.9	56.1	0.016 0.009	0.016 0.006
A -F3	1284.24	70.82	0.030 0.037	0.029 0.026	1109.8	61.2	0.023 0.010	0.024 0.029
Average	1256.58	69.67	0.036	0.033	109.8	58.7	0.0193	0.0229
SD	55.8	3.37	0.008	0.008	109.8	6.1	0.006	0.009

First letter refers to the type of the tube thickness. Second letter refers to the type of condition (R: room temperature, F: freeze-thaw exposure in fresh water, S: freeze-thaw exposure in salt water). Third is a number refers to the number of specimen.

On the other hand, the reduction reached up to 16.2% for CFFT, after 300 F/T cycles in fresh water. This could be attributed in large part to two possible reasons; first is the tendency of the glass fiber, in submerged specimens, to be damaged because the moisture extract ions from the fiber which in turn leads to degradation of the fiber, such as cracks in the fiber surface (Kumar and Gupta1998). Second reason could be probably the plasticization of matrix, induced due to submerged in water, which could make the polymer softer and cause micro-crakes at the matrix-fibre interface (Schutte 1994; Kumar and Gupta 1998). In addition to the previously concern, test results give evidence that the further cycles continue the more degradation recorded resulting in strength reduction, in other words, the level of decrease in strength caused by 300 F/T cycling is greater than that caused by the 100 F/T cycling. This emphasized that the deleterious effect of coupled moisture and freeze-thaw cycling.

4. PROPOSED ENVIRONMENTAL REDUCTION FACTOR BASED ON THE EXPERIMENTAL RESULTS

It is known that the number of freeze-thaw cycles seen in the field could differ substantially based on geographic location. Barnes (1990) estimated that 2,000 cycles was a conservative estimate for all temperature cycles in a worst-case scenario for 50-year building life for cycling from cold to warm using a rather large temperature range of 16 to -7. Pando et al. 2002 reported that on an average in Virginia there were 30 freeze-thaw cycles yearly. Gomez and Castro 1996reported reductions in flexure strength and modulus in their study on composites after 300 cycles, which were used to simulate the structure's life. Based on this literature, the 100 and 300 cycles used in the current study, each over a full period of 24 h rather than in an accelerated shorter cycle, conservatively represent a minimum of 3-4 and 8-9 years of outdoor exposure. In this section, an Environmental Reduction Factor (ERF), $\phi_{env,}$ was proposed in an attempt to consider the environmental effects when predicting the confined compressive strength of CFFT cylinder. ϕ_{env} is presented in three different forms: ϕ_{env-f} and ϕ_{env-s}. Whereas, ϕ_{env-f} consider the effects of freeze-thaw cycles in fresh water and ϕ_{env-s} accounts for the effects of freeze-thaw cycles in salt water. The compressive strength f'_{cc} of the CFFT cylinders obtained from the experimental results is presented in Tables 4 to 7. The three factors are developed based on the test results (by obtain the ratio of the average f'_{cc} of conditioned specimens, to the control room temperature counterparts).

4.1 Environmental Reduction Factor, (Fresh water-condition- ϕ_{env-f})

The Environmental Reduction Factor (ϕ_{env-f}), was determined based on the test result provided in Tables 4 and 5, which present the compressive strength, f'_{cc}, of the CFFT cylinders cast in GFRP tubes at room temperature, and the CFFT cylinders conditioned to either 100 or 300 freeze-thaw cycles while submerged in fresh water, respectively. Table 4 presents the ratio of the average compressive strength, $f'_{cc,}$ of CFFT cylinders, A-F, conditioned to 100 freeze-thaw cycles in fresh water, to those of control room temperature counterparts, A-R. As shown, the ratios were 0.97, for cylinders. Thus, the reduction factor, ϕ_{env-f} , of 0.97 had to be assigned to the CFFT cylinders. However conservatively, the value of 0.95 was assigned to CFFT cylinders after 100 freeze-thaw cycles in fresh water. Table 5 presents the ratio of the average compressive strength, $f'_{cc,}$ of CFFT cylinders, A-F, conditioned to 300 freeze-thaw cycles in fresh water, to those of control room temperature counterparts, A-R. As shown, the average ratio was 0.84. Thus, the reduction factor, ϕ_{env-f} , of 0.85 was assigned to both CFFT cylinders conditioned to 300 freeze-thaw cycles in fresh water.

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Table 4. Environmental Reduction Factor, (Fresh water-condition- ϕ_{env-f})

	Specimens	Compressive Strength f'_{cc} (**Fresh water -condition**)				Ratio	$0 < \phi_{env-f} < 1.0$
		1	2	3	Average		
100 cycles	A-R	71.50	72.10	72.30	71.60	0.97	0.95
	A-F	72.31	65.85	70.82	69.67		

Table 5. Environmental Reduction Factor, (Fresh water -condition- ϕ_{env-f})

	Specimens	Compressive Strength f'_{cc} (**Fresh water -condition**)				Ratio	$0 < \phi_{env-f} < 1.0$
		1	2	3	Average		
300 cycles	A-R	71.50	72.10	72.30	70.00	0.84	0.85
	A-F	49.10	56.10	61.20	58.7		

5. PROPOSED SERVICE-LIFE ENVIRONMENTAL REDUCTION FACTOR (75 YEARS)

The present test results of the 100 and 300 freeze-thaw cycles are used to predict the service life environmental reduction factor for design new structure up to 75 years. As mentioned before, 100 and 300 cycles used in the current study, represent a minimum of 3-4 and 8-9 years of outdoor exposure, respectively. In this section, the test results of the Environmental Reduction Factor for the 100 and 300 freeze-thaw cycles are presented in a logarithmic-scale for the three different exposure conditions (see Figure 1). Presentation of data on a logarithmic-scale was intended to predict the Service-Life Environmental Reduction Factor (SERF) for 75 years exposure time, using the regression analysis. Also, Table 8 summarizes the predicted values of the Service Life Environmental Reduction Factor for 75 years. The long-term predictions revealed that the effect of freeze-thaw cycles in salt water–condition could be more significant on SERF than on specimens conditioned in fresh water. Figure 1 show that the trend lines of SERF versus the conditioning time for the specimens conditioned in in fresh water.

Table 8 indicates that the average SERF for 75 years design purpose based on the regression analysis were 0.96 and 0.93, respectively, for exposure condition in fresh-water and salt-water. These factors are significantly greater than that included in ACI440-2R-08 (Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures). The ACI440-2R-08 environmental reduction factors (0.75, 0.65, 0.50) are introduced for various GFRP systems and exposure conditions: interior exposure, Exterior exposure (bridges, piers, and unenclosed parking garages), aggressive environment (chemical plants and wastewater treatment plants), respectively. It was stated that these factors are conservative estimates based on the relative durability of each fiber type. Also, it stated that as more research information is developed and becomes available, these values will be refined. The methodology regarding the use of these factors, however, will remain unchanged. When available, durability test data for FRP systems with and without protective coatings may be obtained from the manufacturer of the FRP system under consideration (ACI ACI440-2R-08). In Table 8, the SERFs (0.90) was proposed for the design purposes for exposure condition in fresh-water.

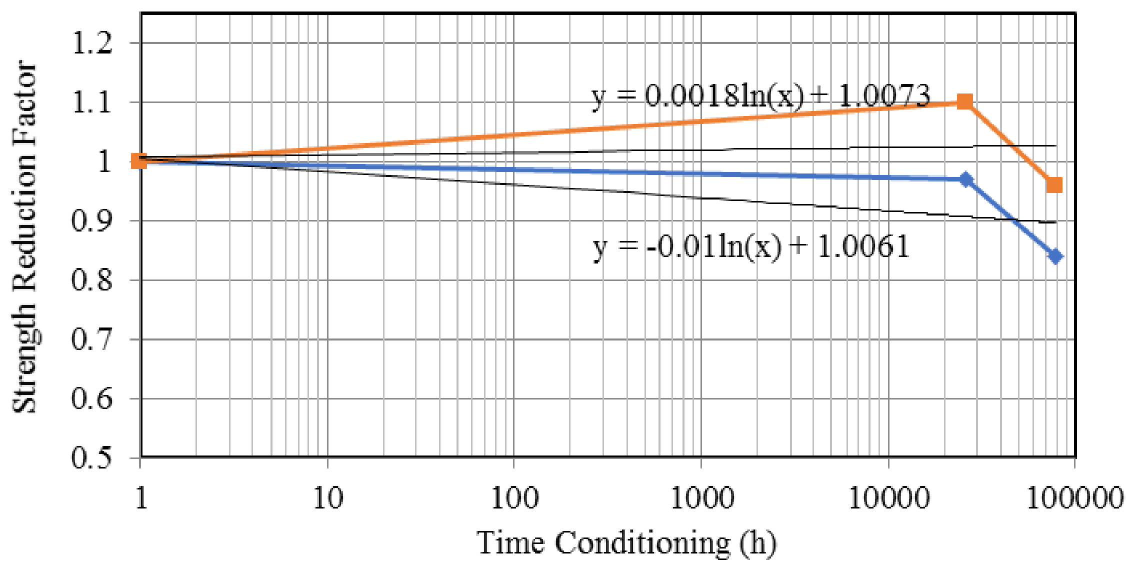

Figure 1. Strength reduction factor versus conditioning time for different exposure condition

Table 8. Predicted Service-life Environmental Reduction Factor (75 years)

	Predicted Service life Environmental Reduction Factor (75 years)	**Average (SD)**	**Proposed**
Fresh water–condition	0.87	0.96 (0.11)	0.90

6. CONCLUSIONS

1- The results of this study come in a line with others, to give experimental evidence that the GFRP tube provided an effective means of protecting the concrete core from sever environmental conditions. Also, significant increase in strength and ductility behavior, in terms of average axial and hoop strain, were achieved for the CFFT cylinders compared to unconfined cylinders.

2- The plain concrete cylinder (PCC) exposed to 100 freeze-thaw cycles in fresh water showed insignificant reduction in the axial compressive strength 7.0 %. The corresponding reductions values were 26.7% after 300 freeze-thaw cycles in fresh water

3- Significant degradation on the strength properties of CFFT cylinders was reflected by increasing the number of freeze-thaw cycles from 100 to 300. The reductions in the average ultimate strength, axial and hoop strains were more pronounced, (much as 16.2, 42 and 21%, respectively), for the sets exposed to freeze-thaw in fresh water. This reduction is attributed to the fiber and fiber-matrix degradation induced by the freeze-thaw cycling in saturated state.

4- Environmental Reduction Factor (ERF), ϕ_{env}, was proposed to account for the environmental effects when predicting the confined compressive strength of CFFT cylinder. ERF (ϕ_{env-f}) accounts for the effects of freeze-thaw cycles in fresh water and ϕ_{env-s} accounts for the effects of freeze-thaw cycles in salt water.

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