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Effect of the freeze-thaw exposure on the axial behavior of concrete filled fiber-reinforced polymer tubes

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ABSTRACT**:** Previous studies have demonstrated the high performance of the concrete-filled fiber-reinforced polymer (FRP) tubes (CFFT) technique as a stay-in-place formwork and confining system. However, the environmental effects such as freeze-thaw cycles and de-icing salt solutions may affect materials properties, and therefore the structural response of this technique. This paper investigates experimentally the durability short term behavior of a total 24 CFFT cylinders (150×300 mm). Test variables include confined effect of using glass-FRP tubes and effects of the freeze-thaw exposure. Normal strength CFFT cylinders were exposed to 100 freeze-thaw cycles both while saturation in (salt and/or fresh) water and air. Then, uni-axial compressive failure test were conducted to evaluate the change of mechanical properties of the test specimens. The test results revealed that FRP tubes successfully protected the concrete core of the test specimens against the environmental condition presented in this study. The short-term freeze-thaw cycling had almost no effect on the compressive strength of the CFFT cylinders.

1 INTRODUCTION

In the last decade fiber-reinforced polymer (FRP) composites have been successfully used for confinement of reinforced concrete structures. Various experimental results showed that using FRP tubes to confine concrete columns can enhance the ultimate load carrying capacities by 300% (Fam and Rizkalla 2002; Mohamed and Masmoudi 2008; 2010). The concrete-filled FRP tubes (CFFT) act as form work and protective jacket from the environmental effects, also it increases the axial strength and ultimate strain of the concrete columns. Although the CFFT technique has been adapted successfully structural system for different concrete structures, however there is a lack of the experiments regarding the durability effect. Short and long term durability of the CFFT is the most important factor needed for CFFT to become widely accepted for application in new constructions. The majority of research studies regarding the durability of RC structures strengthened or reinforced with FRP composite materials have been conducted with focus on the effect of freeze-thaw cycles. This is because the freeze-thaw action has been thought to be the most harmful to concrete structures and FRP composite materials as well. Problems with deteriorated infrastructures in marine settings and cold regions are mainly due to exposure to salt water and subject to the force of water freezing and expanding into ice.

2 LITERATURE REVIEW

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 (1994) reported a reduction of more than 30% in the ductility of GFRP-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 on them. Test results showed that the specimens exposed to low temperature showed a higher failure load when compared to specimens kept at room temperature. In dry environment the freeze-thaw effect was found to be very low; however only the hoop strain was affected resulting in a more brittle failure mode (Karbhari 2000). Teng (2003) investigated the effect of the freeze-thaw cycles thawing process in water on the performance of columns wrapped with GFRP sheets. Little effect on the overall behavior was reported, however, a decrease in both axial and hoop strain capacities has been observed. Saenz and Pantelides (2006) studied the effect of various environmental exposure conditions (freeze–thaw cycling in saltwater) of FRP-strengthened concrete cylinders. The results showed that the overall stress–strain behavior of specimens did not change fundamentally but different levels of exposure significantly affect its absolute stress–strain curve. Belarbi and Bae (2006) conducted uni-axial compressive failure tests on RC columns strengthened with CFRP and GFRP sheets. The study aimed to evaluate the change of mechanical properties due to effects of a combined environmental cycle (freeze–thaw cycles, high-temperature cycles, high-humidity cycles, saline solutions, and ultraviolet (UV) radiations). The saline solution was found to decrease significantly the failure load and ductility of the GFRP test specimens, whereas CFRP-columns exhibited slight decrease in failure load. Touanji et al. (2007) highlighted their observation that the concrete confined with FRP and PVC-FRP hybrid composite significantly protected the concrete when subjected to harsh environmental condition (freeze-thaw and wet-dry). Micelle and Myers (2008) conducted experimental axial tests on exposed GFRP-confined columns to environmental cycles condition (freeze-thaw, moisture and high-temperature cycles) and immersion in NaCl solution. The test results indicated that more than 40% loss in the ductility and moderate decrease in the ultimate strength were observed. Also cylinders immersed in NaCl solution lost about 30% of their axial strain. A recent study by El-Hasha et al. (2010) investigated the axial behavior of thirty-six CFRP-confined concrete cylinders subjected to freeze-thaw cycles after exposure to heating and cooling cycles (23 to 45°C). The test results indicated that no significant difference was found in strength between the wrapped cylinders which were subjected to heating and cooling and the specimens that were kept at room temperature. In addition, freezing-thawing exposure as well as fresh and salt water immersion had a slightly negative effect on the compressive strength of both, unwrapped and wrapped cylinders.

Although a number of studies have been conducted on the durability performance of FRP-wrapped concrete cylinders, there is currently a lack of understanding the performance of CFTT under the same conditions. This paper presents the first phase of an on-going experimental program conducted at the Sherbrooke University to investigate the performance of CFFT columns under the effects of freeze-thaw cycles. The freeze-thaw exposure was conducted in three sets, two of them were meanwhile submerged in (salt and/or fresh) water and the other set was in air. This study is focused only on the behavior of the unreinforced CFFT specimens.

3 EXPERIMENTAL WORK

3.1 Materials

3.1.1 GFRP Tubes

FRP tubes with an internal diameter of 152 mm were used in the experimental program. The FRP tubes were fabricated using the filament winding technique; E-glass fiber and Epoxy resin were utilized for manufacturing these tubes. The split-disk and coupon tensile tests were performed on five specimens according to the ASTM D-2290-08 and ASTM D 638-08 standard to determine the strength and Young's modulus in the axial and transverse directions. Table 1 shows the details, dimensions and the mechanical properties the used FRP tubes.

Table 1. Dimension and mechanical properties of FRP tubes

Diameter (mm)	Thickness (mm)	Stacking sequence	Hoop			Axial		
			Young's modulus (MPa)	Ultimate strength (MPa)	Ultimate Strain	Young's modulus (MPa)	Ultimate strength (MPa)	Ultimate Strain
152	2.65	$[\pm 60]_3$	10385	348	0.0388	12808	60.10	0.009328

3.1.2 Concrete

All specimens were constructed from the same batch of normal strength ready mix concrete. Water reducing admixture with super plasticizer was used to increase the workability of the concrete mix. Ten plain concrete cylinders (152×305 mm) were tested at 28-days under axial load. The average concrete compressive strength for ten cylinders was found 33±0.4 MPa.

3.2 Specimens Details and Preparation

Twenty-four (152×305 mm) plain concrete and CFFT cylinders were prepared and tested in this study. The specimens were divided into four groups; each group consists of 6 specimens: 3 CFFT cylinders and three control plain concrete cylinders (PCC). The first group was used as reference and kept at room temperature for a period equivalent to the 100 freeze-thaw (F/T) cycles. The other groups were exposed to 100 freeze/thaw cycles inside an environmental chamber. The second group was submerged in fresh water. The third group was kept in salt water to simulate the environment of de-icing conditions of the infrastructures. The fourth group was kept in air. Table 2 shows the test matrix and provides the number of specimens according to how they were utilized in the experimental program. In this study the ends of conditioned cylinders were not exposed by protecting them with epoxy. This is attributed to the fact that, in field applications, columns ends are connected in the superstructure. The objective of doing so was to permit the diffusion of the saturated F/T exposure only permitted through the FRP tube. In addition, some specimens were cast with thermocouples inside the concrete core, which help determine the appropriate thermal cycle to be used for controlling the environmental chamber.

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

Conditions			No. of Specimens	
			PCC	CFFT
Room temp 22.5°C		Group (1)	3	3
100 F/T cycles	Submerged in fresh water	Group (2)	3	3
	Submerged in salt water	Group (3)	3	3
	In air (dry)	Group (4)	3	3

3.3 Freeze-Thaw Exposure

Four isolated wooden tanks as shown in Figure 1 were fabricated; two are in size of (2400×1220 mm) and the other is in size of (1220×1220 mm) to fit in the environmental chamber. The dry freeze-thaw specimens were placed in the freeze-thaw chambers. Whereas, those for saturated freeze-thaw were left in either fresh or salt water bath and placed in the same environmental chamber using the isolated wooden tanks. According to the different types of environmental conditions (freeze–thaw cycles in dry, fresh and salt water) existed inside the same environmental chamber, it was hard to reach the same temperature inside the saturated and non-saturated specimens. Therefore, a temperature acquisition system was used to monitor the temperature during cycling (see Figure 2). The freezing cycles consisted of lowering the temperature in the middle of the saturated specimens from 4.4 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 specimens from -17.8 to 4.4°C. Those freeze-thaw hours were sufficient to vary the temperature of non-saturated specimens between (+28°C to -28°C) as shown in Figure 3. Thus, the specimens underwent one freeze-thaw cycles per 27 hours, rather than in accelerated shorter cycles, for a total of about 117 days. This procedure which followed to practice this type of exposure was considered to simulate the winter effect. Conservatively, this represents a minimum of 3 years of outdoor exposure, in order to determinate the resistance of CFFT cylinders subjected to repeated cycles of freezing and thawing.

Figure 1. Specimen in wooden tanks inside the chamber.

Figure 2. Monitoring the chamber during F/T cycles.

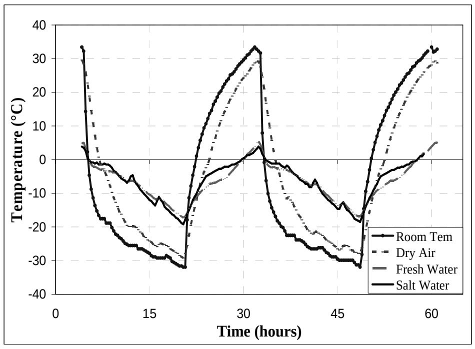
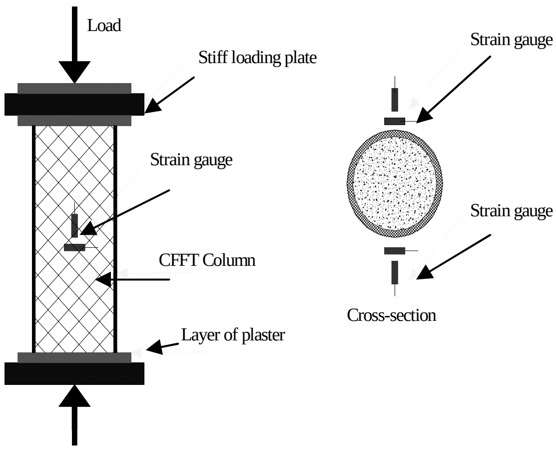


Figure 3. Temperature variation inside the specimens during two complete F/T cycles.

3.4 Test Procedure for Compression Tests

All specimens were brought to room temperature before being tested. Uniaxial compression tests were conducted until failure. Before testing, two axial and two hoop electrical strain gauges were mounted at the mid height, 180 degree apart, along the hoop direction on the external surface of the specimens. Strain gauges of 6 mm length were used to monitor the strain distribution of the GFRP tubes. 30 mm strain gauges were bonded on the surface of the plain cylinders. The axial displacement for each cylinder was measured by two linear variable displacement transducers (LVDTs) 180 degrees apart along the hoop direction of the specimen. All specimens were prepared before the test by a thin layer of the high strength sulfur capping on the top and bottom surfaces to insure the uniform stress distribution during the test. The specimens were tested using a 6,000 kN capacity FORNEY machine, where the CFFT cylinder 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. The loading rate range was 2.0 to 2.50 kN/s during the test by manually controlling the loading rate of the hydraulic pump. Figure 4 illustrates the experimental test setup used in this study.



(a) Instrumentations

(b) Overview of test setup.

Figure 4. The instrumentations and test setup.

4 RESULT AND DISSECTIONS

4.1 Effect of Confinement: Virgin Specimens

Confining using the GFRP tubes showed a large increase in the compressive strength, axial and hoop strain in comparison with unconfined specimens, as a result of the confinement in the radial direction. Figure 5 showed that the average axial stress-axial and hoop strain relationships of the six test specimens (3 CFFT and 3 PCC). The stress-strain curve of CFFT specimens is essentially composed of three parts; elastic and plastic regions with a transition zone in between; the initial part of the curve is referred to the elastic region in which the stiffness is similar to the behavior of plain concrete. In this region the elastic radial pressure exerted by the GFRP tube is negligible. During the transition zone, the concrete core exhibits cracks and the core lateral expansion become limited by the elastic pressure of the FRP tubes. Also, a sharp transition between the first and second region of the stress-strain curve could be noted. In the third stage, the tube was fully activated to confine the concrete core presenting the hardening stage on the curve. The figure confirms the fact that improvements in compressive strength, ductility and absorption capacity were observed, as measured by increases in level of axial failure strain, 0.03 mm/mm. Also, as can be observed from Figure 4, the same stress level the axial strain of CFFT was higher than that one of the hoop strain. Table 3 presents the test results of PCC kept in room temperature and environmental chamber under different conditions. As can be observed from Figure 5 and Table 3, significant enhancement of the strength as well as the ductility for the CFFT cylinders were achieved by confinement action. The average ratio of confined to unconfined concrete strength (*f′cc/f′c*) was 2.2. The average confined strength of the unconditioned CFFT cylinders was 71 MPa, representing 33% increases over the unconfined strength of plain concrete cylinders. The maximum confined concrete strength for confined specimen using a GFRP tube reached up to 74 MPa.

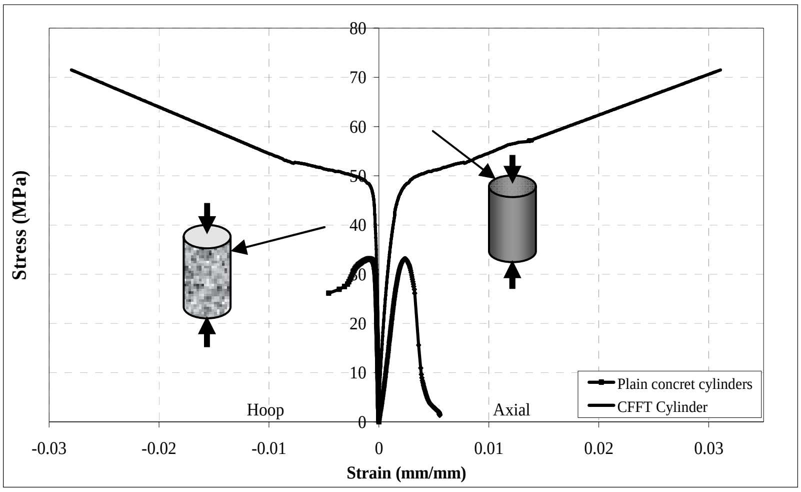


Figure. 5 Typical stress strain curve of unconfined and confined specimens.

4.2 Effects of Freeze- Thaw Cycles

4.2.1 Compressive Strength

It is important that we review results here to explain the effects of freezing and thawing on the confined concrete. During the freeze cycle water in the pores turns into ice and increases in volume by approximately 9%. Thus, stress is induced on the surrounding concrete. Similar pressure will be generated if water is present in spaces between the FRP tubes and the confined concrete core. However, during the thaw cycles this induced stress is released. If the stress induced during the freeze cycles is higher than the tensile strength of the concrete, with increasing the freeze thaw cycles, damage such as cracks in the concrete occurs. Thus, as long as the F/T cycles are repeated more damage will happen due to water penetration into the cracks.

The experimental results of the freeze-thaw effect in terms of the average unconfined compressive strength (f'_c) are presented in Table 3. The unconditioned control plain concrete cylinders (unconfined) were tested after the total period and it gave an average strength of 33.2 MPa. In comparison with the unconfined conditioned control cylinders, a reduction in (f'_c) by 10.3%, 7% and 28% of the unconfined strength after exposure to F/T cycles in air, fresh water and salt water, respectively, were observed. It should be noted at this point that the reduction occurred although air entrainment concrete was used in this study to reduce the freeze-thaw effect as much as possible. In comparison with the reference CFFT specimens kept at room temperature, the CFFT specimens tested after exposure to the dry F/T cycles showed insignificant increase in the average compressive strength. On the other hand, the CFFT cylinders exposed to saturated F/T cycles in (fresh and salt) water exhibited a slight decrease in the average compressive strength by 2.6 and 2.7%, respectively, as compared with the CFFT specimens kept in room temperature (see Figure 6). Table 4 illustrated the test results of the CFFT specimens subjected to different environmental condition.

The test results indicated that the CFFT specimens subjected to freeze-thaw cycling in air condition showed a slight increase in the confined strength as compared with the specimens kept in room temperature. However, the CFFT specimens subjected to freeze-thaw cycling in fresh and salt water exhibited to an insignificant decrease in the confined strength. These results highlighted the fact that the FRP tubes protected the concrete core from the exposed harsh environmental condition over the 100 freeze-thaw cycles.

Table 3 Test results of unconfined concrete cylinders

Plain Concrete	Room Temperature	F/T in Air	F/T in Fresh Water	F/T in Salt Water
Average failure load (kN)	602	540	560	436
(f'_c) Average strength (MPa)	33	30	31	24
(f'_c) Reduction after exposure (%)	-	10.3	7	28

Table 4 Test results of CFFT cylinders subjected to different environmental condition

Specimen code	Condition	Failure Load kN	f'_{cc} (MPa)	ε_a	ε_h
R-30	Room temperature	1297	72	0.038	0.032
D-30	F/T in air	1301	72	0.031	0.030
F-30	F/T in fresh water	1264	70	0.036	0.033
S-30	F/T in salt water	1263	70	0.031	0.029

ε_a is the axial strain, ε_h the hoop strain.
Each of the values presented in table 3-4 is the average of three tested specimens.

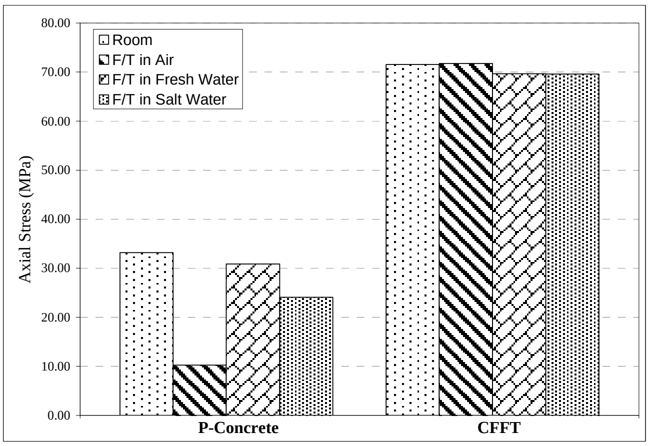


Figure 6. Compressive stress of unconfined and confined (conditioned and unconditioned) specimens.

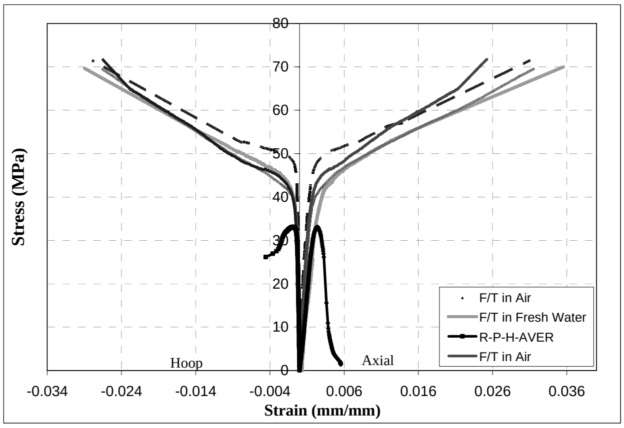
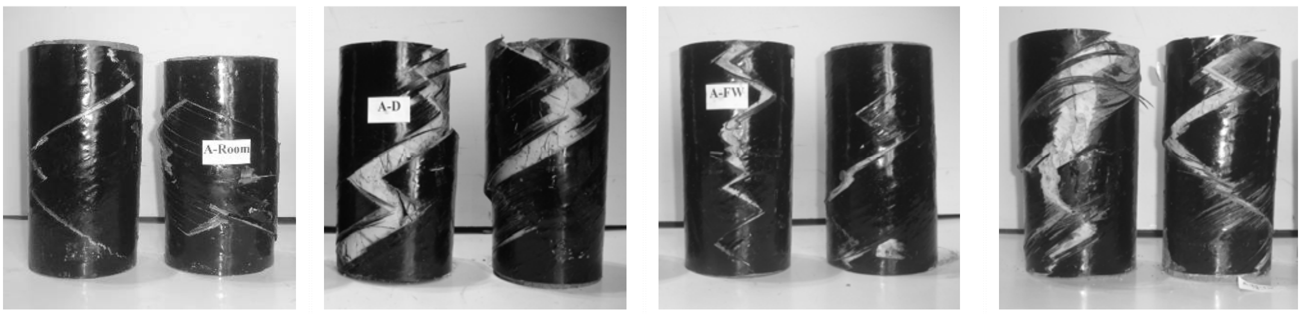


Figure 7. Stress strain curves of conditioned unconditioned CFFT specimens.
Each of the curves presents the average of three tested specimens.

4.2.2 Failure Modes

Figure 8 shows the failure modes of the CFFT cylinders subjected to the four different conditions. In all cases, careful observation showed rupture of the fiber in the hoop direction at the ultimate hoop stress, resulting from the dilation of the concrete. The fracture of the GFRP tubes occurred within the total height of the cylinders started from top or bottom and extended to the opposite direction. The rupture of the tube was very clear for the specimens exposed to F/T in salt water. The shape of the failure was a “zigzag” pattern normal to the direction of fibers in the hoop direction. Popping sounds heard during the early-to-middle stages of loading were referred to the dilation, micro-cracking of concrete and offset of the aggregate and the ultimate failure was very explosive due to rupture of the fibers. Loud sounds were heard at higher levels of confining pressure and the ultimate failure was very explosive. The concrete fell out of the tube in a crushed state, immediately after failure especially for the specimens exposed to F/T in salt water. The room temperature specimens failed in less destroyed behavior between the four conditions.



a- Room temperature b- F/T in air c- F/T in fresh water d- F/T in salt water

Figure 8. Failure modes of conditioned and unconditioned CFFT cylinders.

5 SUMMARY AND CONCLUSIONS

The study presented herein intended to examine experimentally the short term effects of freeze-thaw cycling on the mechanical behaviour of using concrete-filled GFRP tubes technique. In summary, it was found that the confinement using a GFRP tube appear to provide excellent protection against freeze thaw cycles, but different types of freeze thaw cycles appear to affect the hoop and axial strain levels. Based on the test results so far, the following conclusions are drawn:

- Confinement using GFRP tubes was found to enhance the compressive strength to 2.15 times that of plain concrete. Also a significant increase in ductility, in terms of average axial strain, was achieved.
- Regardless of the type of the freeze-thaw cycles on the short term (100 F/T cycles), the freeze-thaw cycles have almost no affect on the average ultimate stress. However, insignificant decrease (2.6 and 2.7%) in the confined strength of the specimens exposed to freeze-thaw in salt and fresh water, respectively, was observed.
- The confined cylinders exposed to freeze-thaw cycles failed in more catastrophic fashion, especially the specimens exposed to freeze-thaw cycles in salt water, than those at room temperature.

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