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DURABILITY OF CONCRETE CONFINED WITH GFRP TUBE

مدى تحمل اسطوانات الألياف الزجاجية الممتلئة بالخرسانه

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خلاصة

إستخدام المواسير البولمرية الممتلئة بالخرسانة أصبحت من أكثر التطبيقات انتشارا، سواء بإستخدام مواسير الألياف الكربونية أو الزجاجية بسبب الوفر الكبيرفي التكاليف والأيدى العاملة وسهولة التنفيذ وكذلك عدم القابلية للصدأ مما يزيد من العمر الافتراضى للمنشأت و قد خضعت هذة المواد بمختلف أنواعها للعديد من الدراسات المعملية والنظرية السابقة. وهذة الدراسة تستعرض مدى تحمل المواسير البولمرية الزجاجية المملوة بأنواع مختلفة من الخرسانة والخاضعة للأحمال. وقد تم من خلال هذة الدراسة المعملية إختبار العديد من الإسطوانات الخرسانية و الإسطوانات البولمرية الزجاجية المملوة سواء بالخرسانة العادية أوالخرسانة خفيفة الوزن والمصنوعة من الركام خفيف الوزن ذو المسامية وذلك حتى حمل الإنهيار وقد تم عمل عدة مقارنات لنتائج العينات المختلفه من حيث الإنفعالات والإجهادات والحمل الكلى وكذلك طراز الإنهيار وقد أظهرت الدراسة بشكل عام تطور كبير فى أداء الإسطوانات البولمرية الزجاجية من حيث الزيادة الكبيرة فى حمل الإنهيار مقارنة مع الإسطوانات الخرسانية وكذلك كان لدرجات الحرارة المنخفضة تأثيركبير على تدهور أداء الإسطوانات الخرسانية فى حين أوضحت النتائج المعملية للإسطوانات البولمرية الزجاجية المملوة سواء بالخرسانة العادية أوالخرسانة خفيفة الوزن كفاءة عالية فى الأداء.

ABSTRACT

One promising innovative structural system is concrete-filled fibre reinforced polymer (FRP) tubes, which provide many unique advantages. The FRP tube acts as a stay-in-place structural formwork to contain the fresh concrete, which may save the costs of formwork and labour used by cast-in-place or pre-cast industries. At the same time, the FRP tube acts as a non-corrosive reinforcement for the concrete for flexure and shear. More importantly, the FRP tube provides confinement to the concrete in compression, which significantly improves the strength and ductility. The contained concrete is protected from severe environmental effects and deterioration resulting from moisture intrusion. This thesis presents results of an experimental study on the durability performance of concrete cylinders confined with glass-FRP (GFRP) tubes. The study includes 40 plain and FRP-confined concrete specimens of which 16 specimens were standard 150 x 300 mm concrete cylinders and 24 specimens consisted of 167 x 334 mm concrete-filled GFRP tubes. The concrete filled GFRP tubes are mainly considered for new structures and not for rehabilitation purposes. One half of the specimens were made of normal weight concrete while the other half was made of lightweight concrete. For each type of concrete, two groups of identical specimens were kept inside the environmental chamber, with and without sustained axial compression load and subjected to 150 cycles of freeze-thaw as in actual structures, which may have a synergetic effect. Also, two similar groups of specimens were kept at room temperature. All the specimens were tested to failure under axial compression and the effect of different variables on the ultimate strength, stress – strain behaviour and mode of failure were discussed.

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INTRODUCTION

For new construction of columns, piles and bridge piers exposed to corrosive environments, the application of concrete-filled FRP tubes has been explored by several researchers (1-7). There is a great demand for columns and piles to be constructed using more durable materials in comparison to traditional construction materials. The new products have to withstand aggressive corrosive environments, such as the splash zone in the case of marine piles (8).

GFRP tubes are exceptional fibre reinforced polymers especially with regards to hybrid construction such piling, poles, bridge component and overhead signs. These tubes perform well in aggressive environments and areas where there are high lateral forces, like the ones experienced by marine piles (9). A wide variety of benefits are gained from the use of GFRP tubes, such as, high strength, high stiffness, high-energy absorption, and enhanced stability and ductility (10). GFRP tubes can also act as a protective jacket, confinement, formwork, and shear and flexural reinforcement where GFRP-T helps to reduce shear in the concrete and gives additional strength and flexural stiffness (11). GFRP tubes are much more suitable for the confinement of concrete than steel, due to their orthotropic behaviour (12). The tube maybe cross-ply or angle-ply laminates with hoop and axial component for any fibre orientation. Mirmiran and Shahawy tested 24 concrete filled GFRP tubes, with three distinct jacket thicknesses, 6, 10, and 14. The end result was an effective confinement of the concrete that caused a significant increase in ductility and strength. They also studied the dilation characteristics of concrete confined by GFRP tubes. They found that the confining jacket stiffness was the governing factor for dilation of the confined concrete. Lightweight concrete has a lower density and a higher insulating capacity, which distinguishes it from ordinary normal weight concrete. The properties of the Lw concrete depend on the aggregates used for producing them. Lightweight aggregates usually fall into two groups, those that occur naturally and are ready for use and those that are produced from industrial bi-products through thermal treatment. The low density of these aggregates will reduce the dead weight significantly in high-rise buildings.

EXPERIMENTAL WORK

The following sections provide details of the steps required to achieve these goals, including concrete mix designs, sustained loading, concrete filling of prefabricated GFRP tubes, environmental chamber used to apply freeze-thaw cycles and testing to failure. Other technical details and instrumentation and testing preparations are also described.

General

The experimental program consisted of testing 24 specimens confined by GFRP tubes and 16 plain concrete cylinders. Details of tested specimens are shown in Table 1. All the specimens were tested to failure under axial compression. The experimental program is intended to prepare and test concrete cylinders confined by GFRP tube after being exposed to freeze-thaw cycles with and without sustained axial compression loads. The effective mechanical properties of the prefabricated GFRP tubes used in this study are summarized in Table 2. Both normal weight concrete

(NWC) and lightweight concrete (LWC) have been used. For each type of concrete, two groups of identical specimens were kept at room temperature, with and without sustained axial compression load. Also, two similar groups of specimens were kept inside the environmental chamber and subjected to 150 cycles of freeze-thaw, according to ASTM C666 (American Society of Testing and Material Standards, 1997). One of these two groups was subjected to the sustained axial compression load and one was not. The sustained axial load was equivalent to 50 % of the confined concrete strength. Environmental chamber was used in this study to fulfill the requirements of ASTM standard C 666 – 97, "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing(13)." This standard provides guidelines for subjecting the concrete specimens core to a temperature range of + 5 °C to – 18 °C and back to + 5°C within a period of 5 hours, which is considered as one freeze-thaw cycle. At the end of the exposure period, all specimens were tested to failure to obtain their axial compressive and compare the results.

Concrete Mixes

Two types of concrete were used to fabricate test specimens, namely lightweight and normal weight concrete. Mixes were prepared in the laboratory using a mechanical drum mixer. A total of 24 GFRP tubes were prepared, of which 12 were filled with normal weight concrete and 12 with light weight concrete. The relatively low concrete compressive strength used in this study was intended to fully utilize the confining effect of the fibre reinforced polymer jackets. These concrete mixes had no air-entrainment, in order to maximize the damaging effect of freeze-thaw cycles. The aggregates used for the LWC specimens were from industrial slag, technically known as palletized slag. These light aggregates have a higher moisture absorption rate than regular natural aggregates because of their high level of porosity, and therefore, have to be pre soaked in water for seven days prior to mixing. The average tested strength at 28 days and details of concrete mixes are shown in table 3.

Preparation of Concrete-Filled GFRP Tubes

The prefabricated GFRP tubes were cut such that the diameter to length ratio was 1:2 (167mm x 334mm) (Figure 1). The inside of the tubes had a paper-based non structural layer that had to be soaked in water for at least two hours for easy removal. During concrete filling, a wooden base was affixed to one end of the tube to prevent concrete from leaking out when being poured (Figure 1). The base to tube connection was temporary sealed with latex epoxy corking to prevent water draining from the tube. A total of 24 GFRP tubes were prepared, of which 12 were filled with normal weight concrete and 12 with light weight concrete. The tubes were filled with concrete at the same time. The tubes were filled in three layers, each layer tapped 25 times with a tapping rod to ensure adequate compaction and to reduce or eliminate any trapped air. After seven days of room temperature curing, the wooden base was removed and then the tubes were stored (Figure 1).

Sustained Loading of Specimens

A maximum of Three GFRP were stacked together in each of the steel frames in a series parallel to the floor.

The first step was to find an area on the floor that was almost perfectly smooth and flat, where the frames could be placed. Three wooden chairs were first placed longitudinally within the frame with only three of the threaded rods in place. The Tubes were then individually placed in the frame, sitting on the wooden chairs. A level was used to ensure that they were perfectly levelled to avoid any form of eccentricity. After all the cylinders were placed in the frame; the fourth threaded bar was put in place. The nuts were then carefully tightened, resulting in the two end plates gripping the cylinders in place. In order to apply the required load 50% of the concrete confined strength, a load cell was placed in the frame, behind one of the end plates, followed by a hydraulic ram, as shown in Figure 1. An additional 50 mm thick metal plate was then placed at the end of the frame, behind the ram, in order to jack against.

Instrumentation and Testing to Failure

The specimens were carefully coded according to their type of concrete core and the sustained loading condition. Each specimen was instrumented with two100 mm displacement-type strain gauge transducers (PI Gauge) in the axial direction to measure the average axial strain. The PI gauges were placed circumferentially on two opposite sides of the cylinder at mid-height. In addition to the two PI gauges, two 5 mm electric-resistance strain gauges were also placed circumferentially on two opposite sides of the cylinder for measuring the average hoop strain (Figure 1). The specimens were then tested under axial compression, using a 5000 kN MTS testing machine, at a 0.3 mm per minute rate of loading.

EXPERIMENTAL RESULTS

Unconfined Normal weight Concrete Specimens

All plain concrete cylinders were tested under loading, at a rate of 0.3 mm/min. The average compressive strength of the cylinders tested after 28 days was 25 MPa. The average ultimate axial and hoop strains for the URC cylinders were 0.16 % and 0.06 % respectively. All the plain concrete cylinders that were placed in the environmental chamber during freeze-thaw cycling were completely disintegrated after 100 cycles due to the lack of air-entrainment. Ideally much better performance would be expected for plain concrete after freeze-thaw exposure if they were air entrained.

Unconfined Lightweight Concrete Specimens

All lightweight concrete cylinders were tested similarly to the normal weight cylinders. The average compressive strength of the cylinders tested after 28 days was 28 MPa . The axial and hoop strains were approximately 0.24 % and 0.06 % respectively. URC-Lw cylinders broke into two halves through shear plains at ultimate stress. The lightweight plain concrete cylinders placed in the environmental chamber were totally disintegrated after 150 freeze-thaw cycles, which showed an improvement over the normal weight cylinders that were disintegrated at 100 cycles. This may be attributed to the porous nature of the Lw aggregates used to cast the concrete.

NW Concrete-Filled GFRP Tubes

Two of these cylinders were tested to failure, initially, to determine the suitable level of sustained loading. The concrete-filled GFRP tubes exhibited exceptional increase in strength with respect to the strength of unconfined concrete, due to the larger thickness of tubes (5 mm). The strength increase due to confinement with the GFRP tubes was approximately 189 %. The ultimate strength of the concrete-filled GFRP tubes, sustained-loaded, and subjected to freeze-thaw (GFS-T) and the concrete-filled GFRP tubes subjected to sustained load at room temperature (GRS-T) were 69.9MPa and 71.1MPa, respectively, which lead to a slight decrease in strength after freeze-thaw cycling of 1 %. The average axial and hoop strains for GFS-T were 1.47 % and 0.96 %, and for GRS-T, were 1.83 % and 1.01 %, respectively. An insignificant reduction in strength was noted for control cylinders subjected to freeze-thaw (GFC-T), when compared with control cylinders at room temperature (GRC-T). The average strength of GFC-T cylinders was 60.2 MPa, compared to 63.7 MPa for GRC-T, which indicates a 6.0 % reduction due to freeze-thaw. The average axial and hoop strains for GFC-T and GRC-T cylinders were (1.94 % and 0.96 %) and (1.34 % and 0.94 %), respectively. Figures 2 and 3 show the stress-strain curves for the normal weight concrete-filled GFRP tubes subjected to freeze-thaw and those at room temperature. A bilinear response, in both axial and hoop directions, in the stress-strain curves of the tested normal weight cylinders was observed. The transition point of the bilinear response was observed at 40% of the ultimate load. This is attributed to the fact that, once the concrete reaches its unconfined strength, it starts to dilate excessively due to the development of a uniform network of internal micro cracks and the tube becomes fully activated in confinement. The strains increase rapidly as evident from the second slope of the stress-strain curve.

LW Concrete-Filled GFRP Tubes

All prefabricated GFRP glass concrete-filled tubes performed exceptionally well under all the various conditions. Two of these cylinders were tested to failure, initially, to determine the suitable level of sustained loading. The gain in strength for prefabricated GFRP glass lightweight concrete-filled tube was 74 %. GFS-T-Lw specimens had an average strength of 71.0 MPa, while GRS-T-Lw had an average strength of 70.0 MPa, which lead to an increase in strength after freeze-thaw cycling of 1.5 %., which is rather unexpected. Since these values are obtained based on average of three tests only, a conclusion related to the strength gain may not be justified in this case. GFC-T-Lw specimens had an average compressive strength of 68.8 MPa, while GRC-T-Lw specimens had an average stress of 70.1 MPa. Thus the reduction due to freeze-thaw was calculated as 2 %. This was similar to what had occurred to normal weight concrete specimens but with relatively smaller percentage. According to Figures 4 and 5, show a bilinear response, in both axial and hoop directions, in the stress-strain curves of the tested light weight cylinders. The transition point of the bilinear response was observed at higher stress levels for light weight cylinders than those of normal weight cylinders, the bilinear transition occurs at a load about 30 % higher than the normal weight cylinders. However, there isn't much difference in stress-strain behaviour for cylinders subjected to freeze-thaw and those left in room temperature. Figures 6 and 7, show stress and axial strain comparison for both normal weight and light weight concrete cylinders.

Failure Modes

The failure modes for the normal weight concrete-filled GFRP tubes were quite similar for all the various conditions under which they were tested. Failure started with crushing of the tube at mid-height, at about 70 % of the ultimate load, and was followed by a longitudinal fracture due to the hoop tensile stresses. The failure modes for light weight concrete-filled GFRP tubes were similar to those filled with normal weight concrete. At about 60 –70 % of the tube-strength during compression, they could hear sounds that could be attributed to aggregates shifting and micro cracking of the concrete. Before failure, the tubes would produce white patches at the mid-height of the cylinder, which would gradually extend to the top and bottom of the tube as the failure load increased.

The axial compressive stresses were due to the direct axial loading on the tube, while the hoop tensile stresses resulted from confinement of the dilating concrete under high axial stresses. Inspection of the test specimens after failure revealed that only two or three major internal cracks had developed. On the other hand, a large network of micro cracks uniformly distributed within the concrete mass was formed. However, all tested concrete-filled GFRP tubes gave some warning signs as it approaches failure. Figure 8 shows modes of failure for different tested specimens.

CONCLUSIONS

The following conclusions are drawn based on the experimental results:

1- The lightweight plain cylinders placed in the environmental chamber were totally disintegrated after 150 freeze-thaw cycles, which showed an improvement over the normal weight cylinders that were disintegrated at 100 cycles. This may be attributed to the porous nature of the aggregates used to cast the concrete. Ideally much better performance would be expected for plain concrete after freeze-thaw exposure if they were air entrained

2- Concrete-filled GFRP tubes showed the highest level of confinement and highest resistance to freeze-thaw compared with unconfined specimens. They had the lowest level of degradation due to freeze-thaw. This is possibly due to the larger jacket thickness and bi-directional fibres, which lead to significant enhancement in strength and ductility.

3- Concrete cylinders confined with prefabricated GFRP tubes performed exceptionally well when subjected to sustained loads and freeze-thaw cycles, when compared to the unstrengthened cylinders. Prefabricated GFRP concrete-filled tubes experienced slight reduction (6.0 % with NWC & 1.88 % with LWC) in strength due to freeze-thaw cycling with out sustained loads.

4- The transition point of the bilinear response was observed at higher stress levels for light weight cylinders than those of normal weight cylinders, the bilinear transition of light weight cylinders occurs at a load about 30 % higher than the normal weight cylinders. However, there isn't much difference in stress-strain behaviour for cylinders subjected to freeze-thaw and those left in room temperature.

5–However, lightweight concrete is rarely or never used for construction of regular concrete columns, the study showed that light weight concrete can be used in cases of concrete-filled GFRP tubes.

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Table 1: Details of tested specimens

Loading Condition	NWC		LWC	
	GFRP-Tube	URC-Nw	GFRP-Tube	URC-Lw
Freeze-Thaw / Sustained loaded	3 GFS-T	0	3 GFS-T-Lw	0
Freeze-Thaw / Control	2 GFC-T	3	2 GFC-T-Lw	3
Room Temperature / Sustained load	3 GRS-T	0	3 GRS-T-Lw	0
Room Temperature / Control	2 GRC-T	3	2 GRC-T-Lw	3
Preliminary strength testing	2	2	0	2
Sub-total	12	8	12	8

URC – Unconfined cylinder

Lw -- Light weight concrete

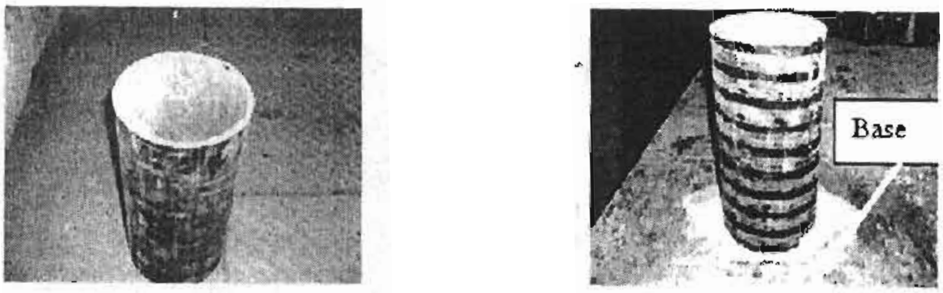
Nw--Normal weight concrete

Table 2: Mechanical properties of GFRP tube

Properties	GFRP tube
Hoop tensile strength (MPa)	401
Longitudinal compressive strength[#] (MPa)	343
Elastic Modulus in the hoop direction (GPa)	23.5
Elastic Modulus in the axial direction (GPa)	21.7
Ultimate tensile strain in the hoop direction (%)	1.97
Poisson's ratio due to axial loading	0.09

Table 3: Details of concrete mixes

Mix. Type	NWC	LWC
Cement (kg/m^3)	385	385
Water (kg/m^3)	218	218
Coarse Agg.(kg/m^3)	1072	580
Sand (kg/m^3)	661	530
W/C ratio	0.57	0.57

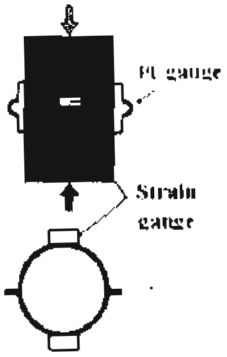


Hollow specimen

Wooden base

Stored specimens

Steel frame



Instrumentation of specimens

FIG. 1 Fabrication and instrumentation of test specimens

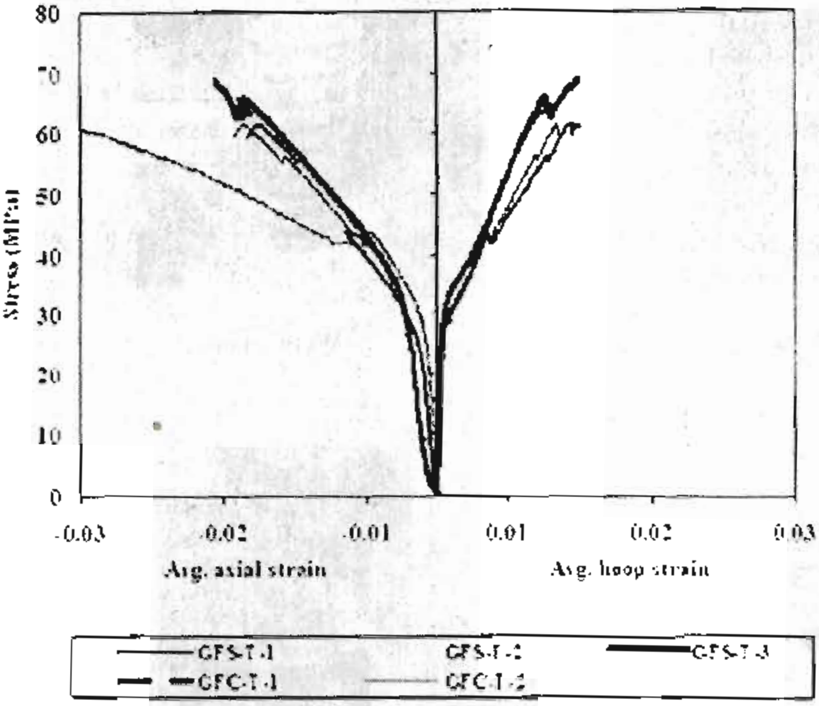


FIG. 2: Stress-strain curves for normal weight concrete-filled GFRP tubes subjected to 150 freeze-thaw cycles

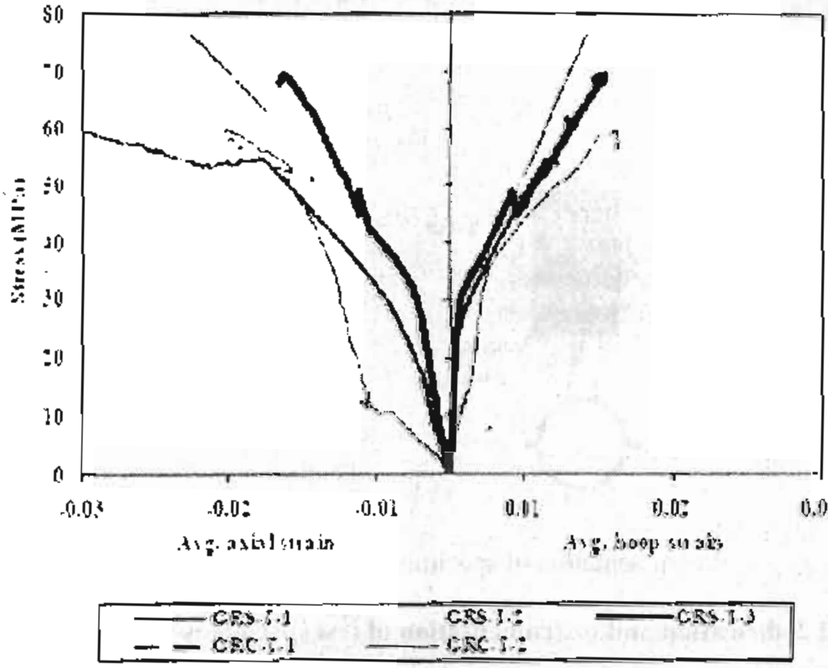


FIG. 3: Stress-strain curves for normal weight concrete-filled GFRP tubes at room temperature.

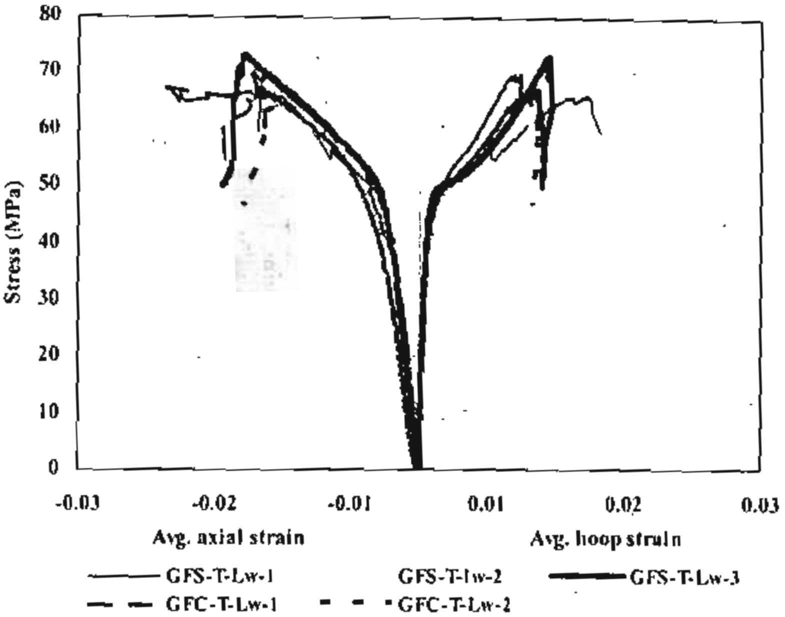


FIG. 4: Stress-strain curves for lightweight concrete-filled GFRP tubes after 150 freeze-thaw cycles

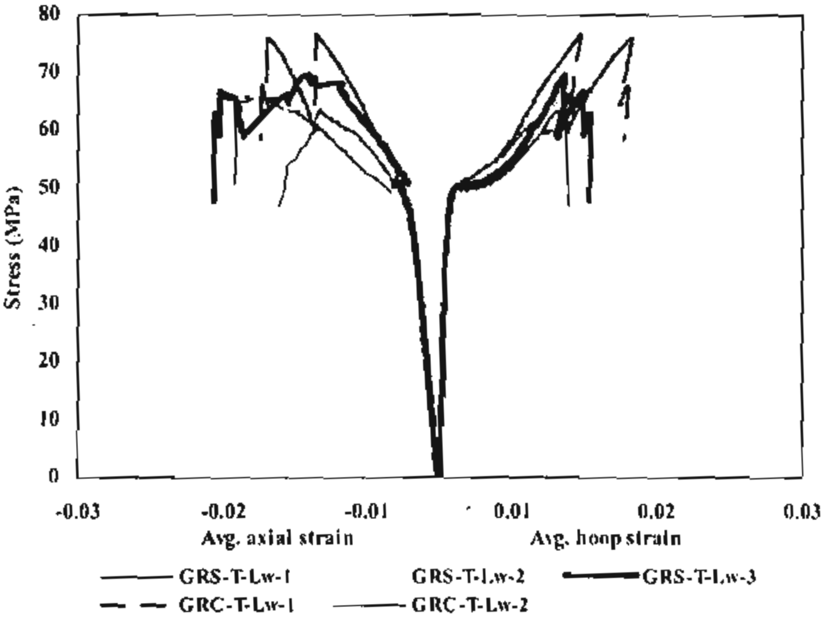


FIG. 5: Stress-strain curves for lightweight concrete-filled GFRP tubes at room temperature

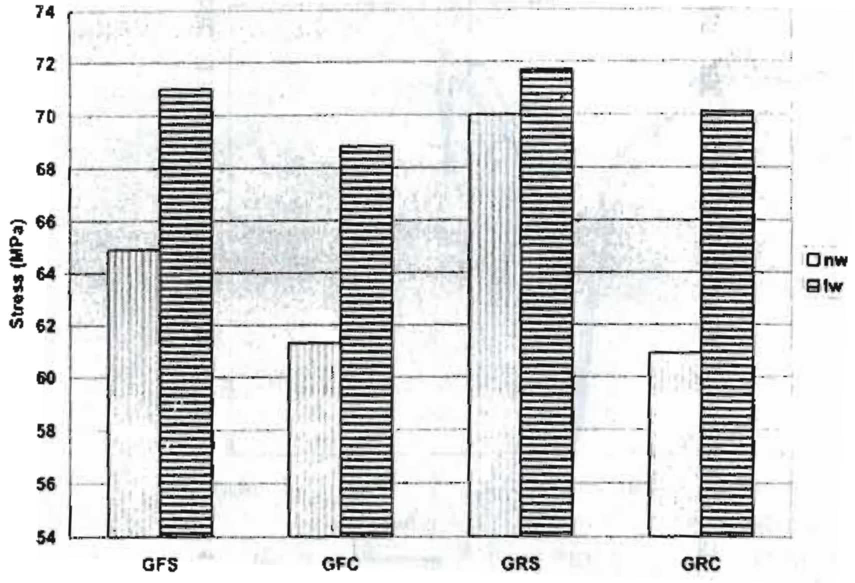


FIG.6: Stress comparison for NWC and LWC cylinders.

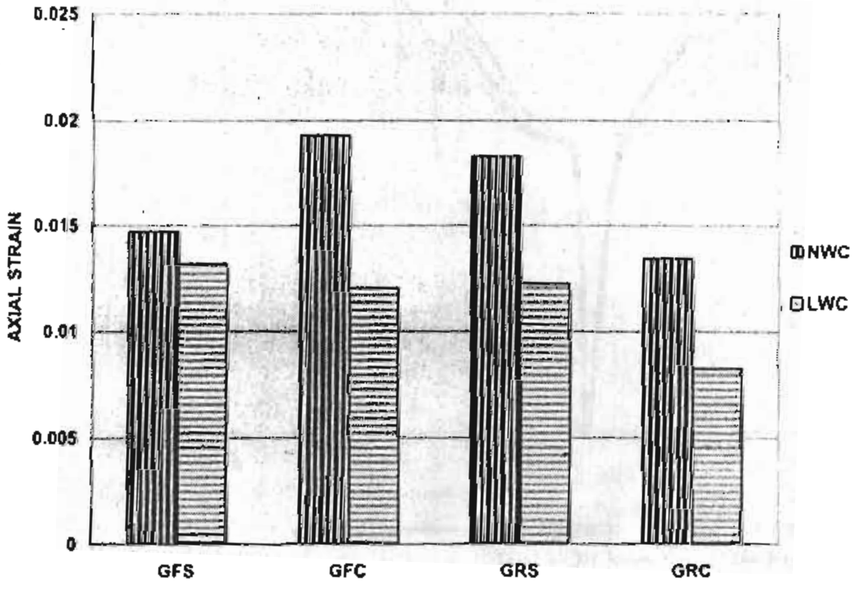
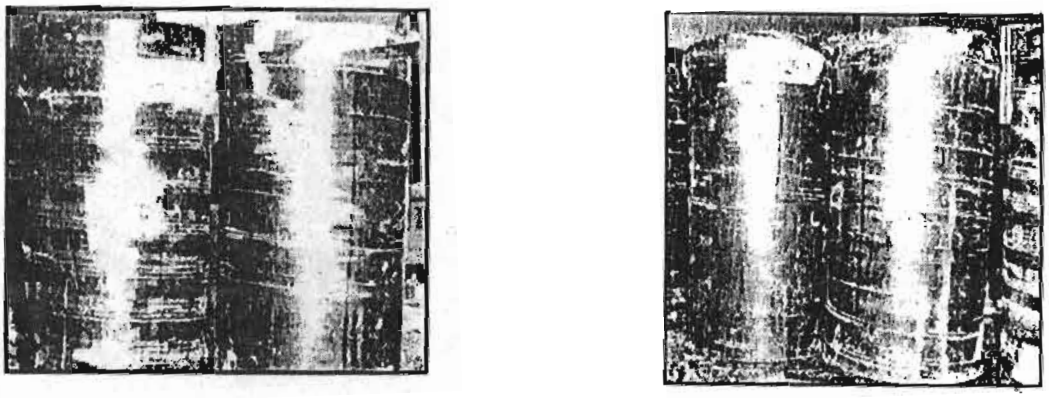
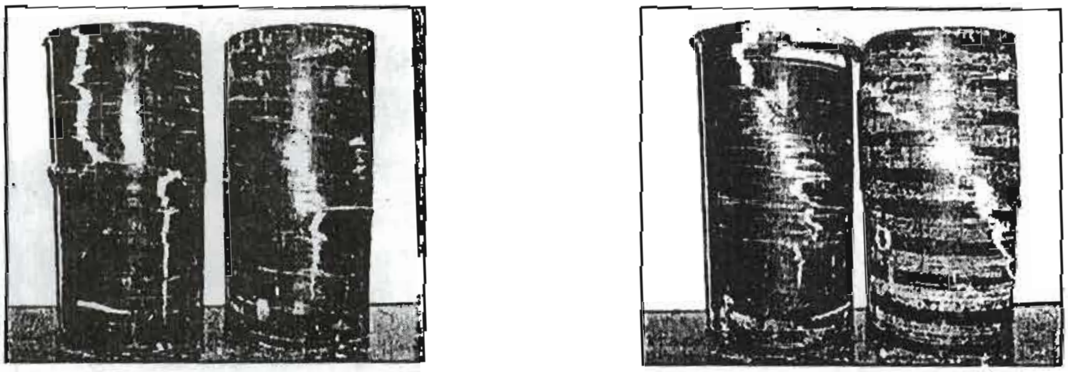


FIG.7: Axial strain comparison for NWC and LWC cylinders.



GFC-T normal weight

GFS-T lightweight



GRC-T normal weight

GRS-T normal weight

FIG.8: Samples of failure mode for concrete-filled GFRP tube specimens