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THE PERFORMANCE OF LIGHTWEIGHT CONCRETE CONFINED BY FIBER COMPOSITES

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Degradation of infrastructure due to overloading and corrosion is a major concern. FRP materials are now increasingly being used in the construction industry. Confinement of circular concrete members using FRP is a popular application. As such, studying the performance of concrete members confined by FRP jackets is quite important for both rehabilitated and new structures. This thesis presents results of an experimental study on the performance of concrete cylinders confined with glass-FRP (GFRP) sheets, carbon-FRP (CFRP) sheets. While the subject of FRP-confinement of circular concrete columns has been extensively studied experimentally and analytically, more emphasis has typically been put on the characteristics of the FRP jackets in comparison to the concrete core properties. In this paper, the performance of the lightweight concrete core on FRP jackets is explored in order to simulate the worst case scenario in old structures that were built several decades ago, and maximize the damaging effect of concrete durability. This study simulates wrapping of circular columns with FRP sheets for retrofitting applications; concrete core with different strengths has been used to evaluate the different levels of confinement induced by GFRP and CFRP jackets of different thicknesses, specimens were tested to failure under axial compression, the study showed that wraps provide substantial increase in strength and ductility of different lightweight concretes. However, increasing the strength of concrete core shows a decreasing in the confined strength gain of tested specimens with any improvement in ductility.

***KEY WORDS**: fiber composite sheets, confinement, concrete, column repair, rehabilitation, strengthening.*

INTRODUCTION

Deterioration of reinforced concrete columns due to corrosion of the reinforcing steel and spalling of concrete has been a major problem for the aging infrastructure [1]. The most common methods for repair and retrofit of RC columns are concrete jacketing, steel jacketing, and fiber-wrapping. Concrete jacketing requires formwork and considerable increase in the weight and cross-section of the column, steel jacketing is also labor intensive and costly, on the other hand, Fiber-wrapping, offers a high strength, low-weight, and corrosion-resistant jacket with easy and rapid installation and minimal change in the column geometry. Also, fiber-wrapping does not require the use of heavy equipment, contrary to the other two methods. The wrap enhances shear strength, axial strength and ductility of the column [2]. Design of fiber-wrapped concrete has evolved from the application of steel-based models such as that of Mander et al. [3] recognizing that such models fail to capture the true behavior of FRP-confined concrete [2, 4].Mainly due to the unique dilation characteristics of concrete when confined by linear-elastic and non-yielding materials such as FRP [5], confinement models must account for the stiffness of the jacket. Many efforts have since been targeted at developing improved numerical and theoretical approaches such as Mirmiran et al. [6, 7] and Xiao and Wu [8]. Good progress has been achieved, leading to the publication of design codes and recommendations, but no unified approach has emerged and many questions remain to be answered. The parameters, commonly studied, included thickness of the FRP jackets, governed by the number of plies, laminate structure in terms of orientation of fibers in each ply, types of fibers and resins, and slenderness of the columns [9, 10].This work reports on an experimental investigation that tries to shed light on the performance of light weight concrete wraps on the compression behavior of confined concrete cylinders. The application of CFRP and GFRP wrapping in discontinuous bands along the longitudinal axis varying the strengths of concrete core were considered.

EXPERIMENTAL PROGRAM

The experimental program consisted of testing 48 concrete cylinders, including 36 cylinders wrapped with CFRP and GFRP sheets and 12 plain concrete cylinders. Cylinders were wrapped with one layer of glass-FRP (GFRP) sheet, two layers of GFRP sheet or one layer of carbon-FRP (CFRP) sheet. All the specimens were tested to failure under axial compression. This section provides a description of the FRP sheets used in this study. The various lightweight concrete mixes used to achieve different concrete strengths are also presented.

Concrete Mixes

A total of 48 (100 x 200) mm cylinders were cast using four mixes of lightweight concrete LWC to achieve the desired range of unconfined concrete strength. The relatively low concrete compressive strength was intended to fully utilize the confining effect of the fiber reinforced polymer (FRP) jackets. These concrete mixes had no air-entrainment, in order to simulate the worst case scenario in old structures that were built several decades ago, and maximize the damaging effect of concrete durability. Mixes were prepared in the laboratory using a mechanical drum mixer and were used for the concrete cylinders wrapped with FRP sheets. Details of concrete mixes are shown in **Table 1**. The aggregates used for the LWC cylinders were from industrial slag, technically known as palletized slag. Lightweight concrete typically has lower density and higher insulating capacity that distinguishes it from ordinary normal weight concrete. 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 (LWC) batch was prepared at the laboratory and poured in the plastic moulds. The moulds used to form the concrete cylinders were filled in three layers, **Fig. 1**, each layer tapped 25 times with a tapping rod to ensure adequate compaction and to reduce or eliminate any trapped air in the concrete. The concrete was poured and left in air cure in a secure environment for one week. The concrete had maximum light aggregate size of 10 mm. The average tested strength at 28 days and details of concrete mixes are shown in **Table 1**. The cylinders were demolded 24 hours after casting and subjected to moist-cured for three weeks and then air dried in the laboratory before being wrapped with the FRP sheets. As such, any concrete shrinkage has mostly occurred before wrapping.

Table1. Details of concrete mixes.

Mix No.	4	3	2	1
Concrete strength, (Mpa)	66	51	38	29
High early cement, (kg/m^3)	520	469	440	385
Water (kg/m^3)	174	208	229	218
Silica fume (kg/m^3)	100	50	-	-
C. Agg., (kg/m^3)	580	580	580	580
F. Agg., (kg/m^3)	530	530	530	530
W/C ratio	0.28	0.40	0.52	0.57

Fig. 1: Casting of tested specimens.

Fabrication of Test Specimens

The following sections describe the fabrication process of the concrete cylinders wrapped with FRP sheets. Carbon and E-glass fiber sheets were used to wrap the concrete cylinders, where the fibers were all oriented in the hoop direction. The thicknesses of the cured CFRP and GFRP sheets were 0.8 mm and 1.3 mm, respectively. The effective mechanical properties of the prefabricated GFRP and CFRP sheets used in this study are summarized in **Table 2**. A total of 36 LWC cylinders were

Table 2. Properties of FRP.

Properties	GFRP	CFRP
Hoop tensile Strength (MPa)	575	784
Elastic Modulus in the hoop direction (GPa)	26.1	47
Elastic Modulus in the axial direction (GPa)	4.64	3.57
Ultimate tensile strain in the hoop direction (%)	2.2	1.67
Poisson's ratio due to axial loading	0.055	0.025

externally wrapped with both CFRP and GFRP sheets. Both the carbon and glass fiber fabrics were cut, such that each would completely wrap the concrete cylinder circumferentially, and have an overlap length of 100 mm. The same epoxy was used for impregnating the carbon and glass fabric. The cylinder surfaces had to be carefully cleaned before the epoxy could be applied. The two components of the epoxy were mixed thoroughly for approximately 5 minutes. The wet lay-up method was employed for applying the sheets to the cylinders. Using a paint brush, the epoxy was applied to the fabric and care was taken to ensure complete saturation of the sheets with epoxy. The concrete cylinders were then lightly coated with epoxy to fill any surface voids and to ensure adequate bonding. During the rolling process, the FRP sheet was continuously pressed and gently stretched to release any trapped air between the FRP sheet and the concrete. After completely wrapping the cylinders with the FRP sheets, they were left to cure in the same spot for 24 hours, and then they were removed and stocked for a minimum of one week, until the epoxy gain its full strength before any testing. The cylinders were used to produce 16 sets of specimens S1 - S4, SG1 - SG4, SGG1 - SGG4 and SC1 - SC4 for unconfined, one layer GFRP, two layer GFRP and one layer CFRP. Details of test specimens are shown in **Table 3.** Generally, each set contains three identical specimens, tested to provide reliable average values for the test results.

EXPERIMENTAL RESULTS

Prior to testing, all the FRP-wrapped cylinders as well as the plain concrete cylinders were capped with sulfur mortar at both ends as shown in **Fig. 2**. The deformations were measured using high precision gauges placed circumferentially and vertically on the middle portion of the specimen (**Fig. 2**). Measurements were taken during the compressive tests, and results were recorded and plotted. The specimens were tested using a 1300 kN Riehle testing machine, under displacement control mode with a constant rate of 0.3 mm/min. The load was applied to the entire cross-section, including the concrete core and the FRP jacket. The overall performance of the lightweight wrapped concrete cylinders was very good. In the following sections, the test results are presented, including the different stress-strain responses of the confined concrete, effect of concrete strength, effect of FRP wrapping and failure modes are also discussed.

Table3. Details of the test specimens.

Specimen	Concrete mix	f'_c MPa	Material of jacket
S4	4	66	-
SG4			1 Layer GFRP
SGG4			2 Layers GFRP
SC4			1 Layer CFRP
S3	3	51	-
SG3			1 Layer GFRP
SGG3			2 Layers GFRP
SC3			1 Layer CFRP
S2	2	38	-
SG2			1 Layer GFRP
SGG2			2 Layers GFRP
SC2			1 Layer CFRP
S1	1	29	-
SG1			1 Layer GFRP
SGG1			2 Layers GFRP
SC1			1 Layer CFRP

Fig. 2: Sulfur capping of specimens & Positions of high precision gauges.

General Behavior of Stress - Strain Curves

Figure 3 shows the measured stress-strain curves for the FRP-wrapped cylinders. The specimens include cylinders wrapped with one or two layers of GFRP sheets, or one layer of CFRP sheet. The experimental curves representing the average behavior of three identical specimens tested for each case. For medium strength concrete, mix 1&2, the stress-strain curves showed a typical bi-linear trend with strain hardening, similar to that observed by other researchers [11, 12]. However, in high strength concrete, mix 3&4 as the unconfined concrete strength increases, the second part of the bi-linear curve gradually shifts from strain hardening to a flat plateau, and eventually to a sudden strain softening with a drastically reduced ductility. It is also important to note

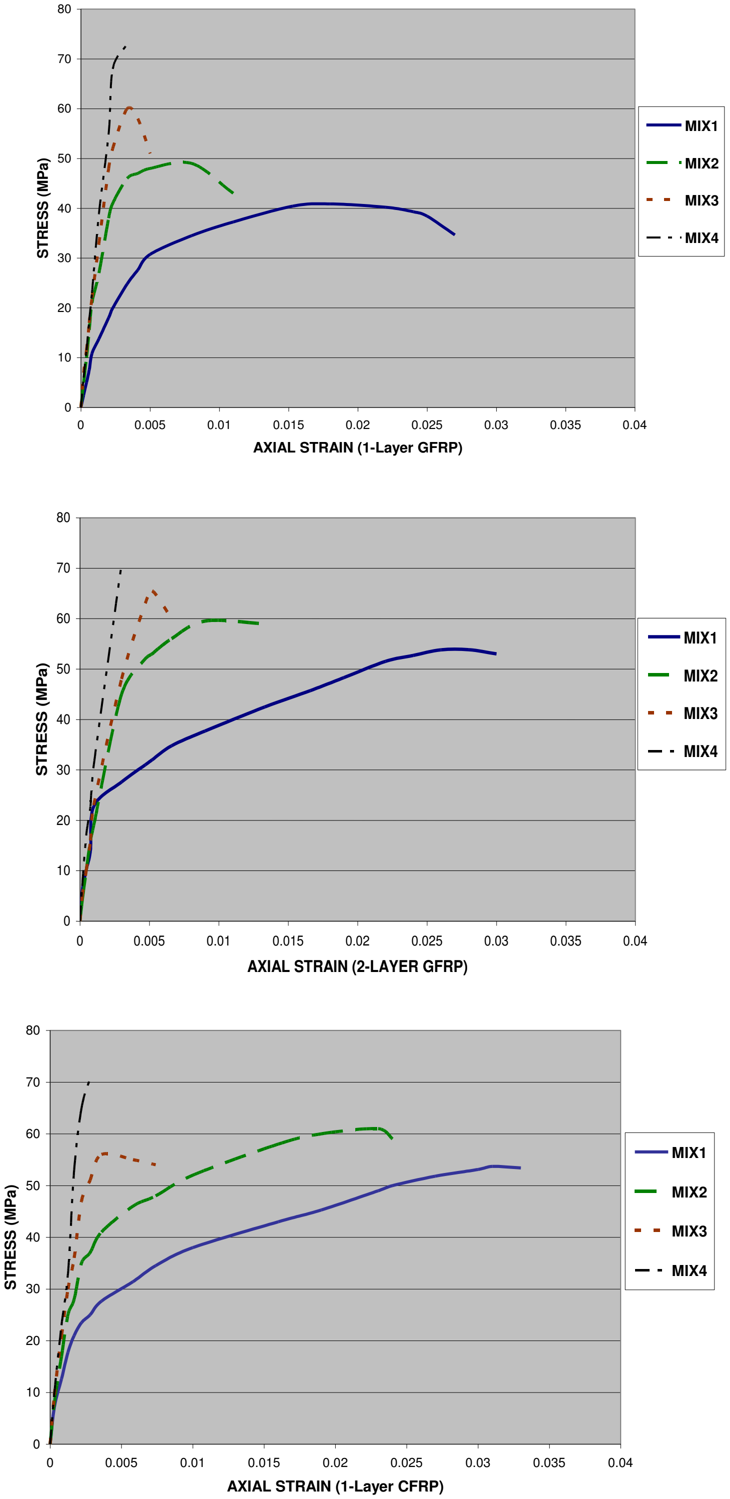


Fig. 3: Stress – Strain curves for Tested Specimens.

that in medium strength concrete, confining the cylinders with FRP sheets lead to significant increase in both strength and ductility, but in high strength concrete, although a minor increase in strength may occur, no significant enhancement in ductility can be expected. The modulus and thickness of the confining material significantly influence the strength of confined medium strength concrete. However, they have little effect on the strength of confined high strength concrete.

Effect of FRP Layers and the Type of Fibers

Figures 4 & 5 show the effect of FRP layers and the type of fibers on the axial strain**.** The experimental study clearly demonstrates that FRP composite wrapping can significantly enhance the structural performance of lightweight concrete, durability, ductility and compressive strength. The effects of different FRP- wrapped on the compressive strength of tested specimens are shown in **Fig. 6**. It should be noted that, the percentage increase in strength for the SG1, SGG1& SC2 (mix1) concrete cylinders was 43, 88& 86 % respectively. While the percentage increases in strength for SG2, SGG2 & SC2 (mix2) specimens was 30, 75 & 61 % respectively. On the other hand, the average gain in strength value for SG3, SGG3& SC3 (mix3) was found to be 13, 34 & 15 % respectively, which lead to a decrease in its confined strength comparing with the mix 1 & 2 specimens strength. In addition, specimens of mix4 followed the same behavior of mix 3 specimens. It should be noted that gain of compressive strength for two layer GFRP wrapped specimens was nearly twice the effect of one layer GFRP wrapped specimens, while the specimens of CFRP wrapped showed approximately the same increase in compressive strength of two layer GFPP wrapped specimens for mix1, the other specimens of CFRP wrapped exhibited a continuous decrease in its confined % gain in strength comparing with the two GFRP wrapped specimens. Especially for high strength concrete mixes 3 & 4.

Effect of Concrete Core Strength

The average values of % gain in strength for confined specimens are shown in **Fig. 6**. For medium strength concrete such as Mix 1, the strength of the confined concrete was found to increase by 43, 88 & 86 percent over its unconfined strength for one layer of GFRP, two layers of GFRP and one layer of CFRP sheets, respectively. However, for high-strength concrete such as Mix 4, the increase in strength was only 14.5, 25.5 &18 percent, respectively. In this case, it is clear that the number of FRP layers and the type of fibers do not have much influence on the strength gain. **Figure 5** shows a plot of the confinement % strength gain comparing with the unconfined concrete strength for one and two layers of GFRP wrap and one layer of CFRP wrap. It is evident that, as the unconfined concrete strength increases, the confinement strength decreases. The FRP-wrapped cylinders with the lowest unconfined strength show the maximum increases in confined strength for tested specimens. **Figure 5** shows the effect of concrete strength on the peak strain of the confined concrete, confined strain is always taken at the peak strength of confined specimens, whether the specimens show strain hardening or strain softening behavior, the experimental trend in **Fig. 5** shows that, similar to the confining effect, the confined strain is reduced as the unconfined concrete strength increases reflecting, the reduction of ductility effectiveness of FRP wraps in high strength concrete.

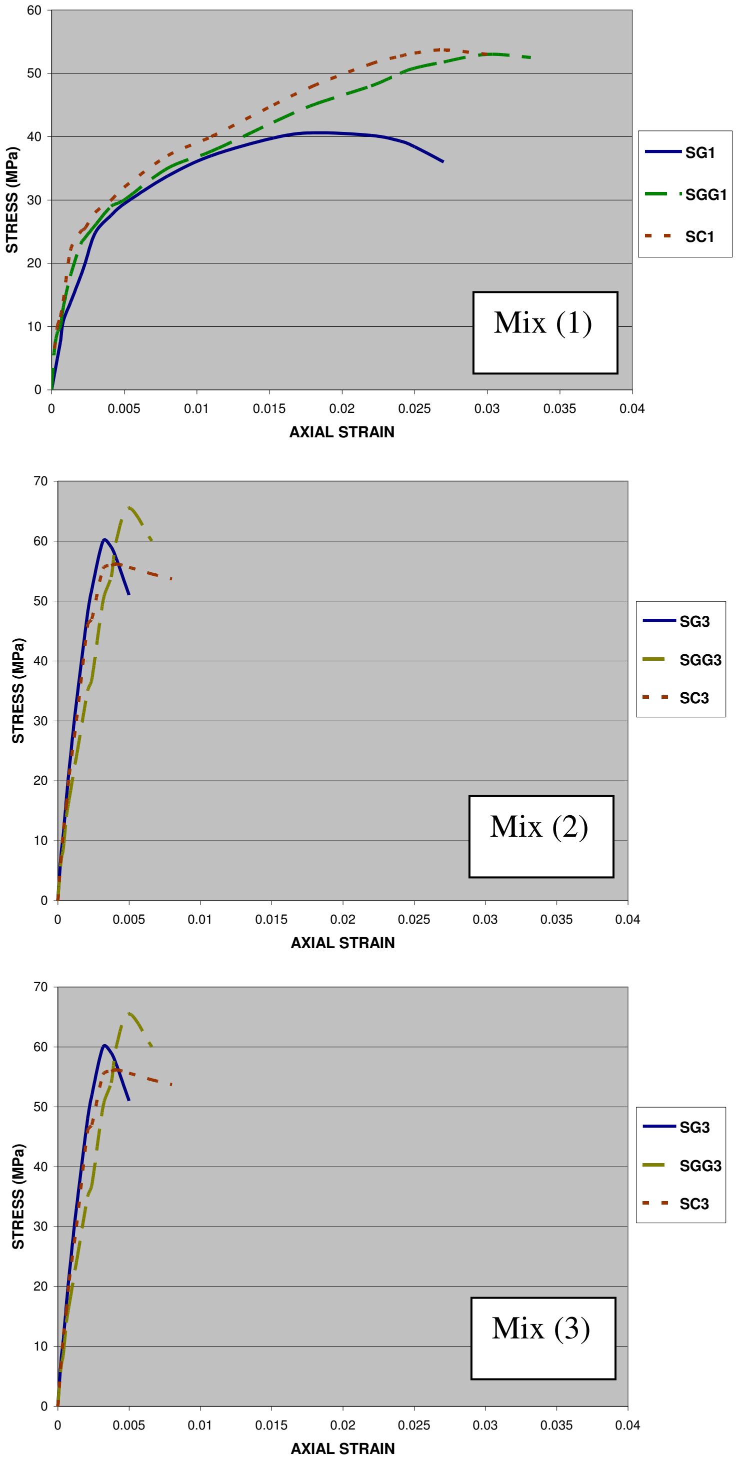


Fig. 4: Effect of FRP on the Stress - Strain Behavior.

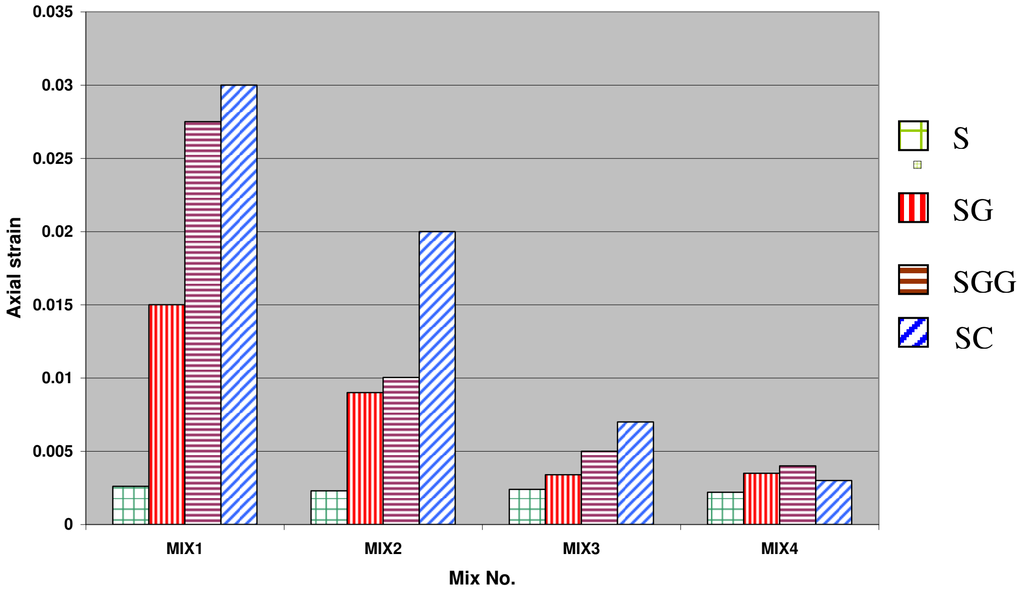


Fig. 5: Effect of FRP layers and the type of fibers on the axial peak strain.

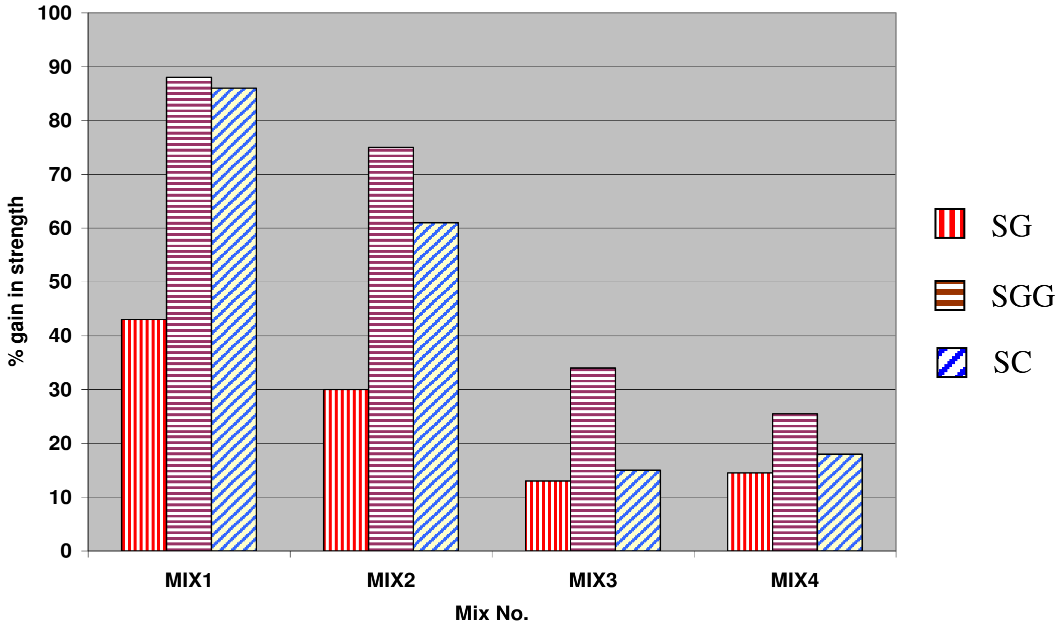
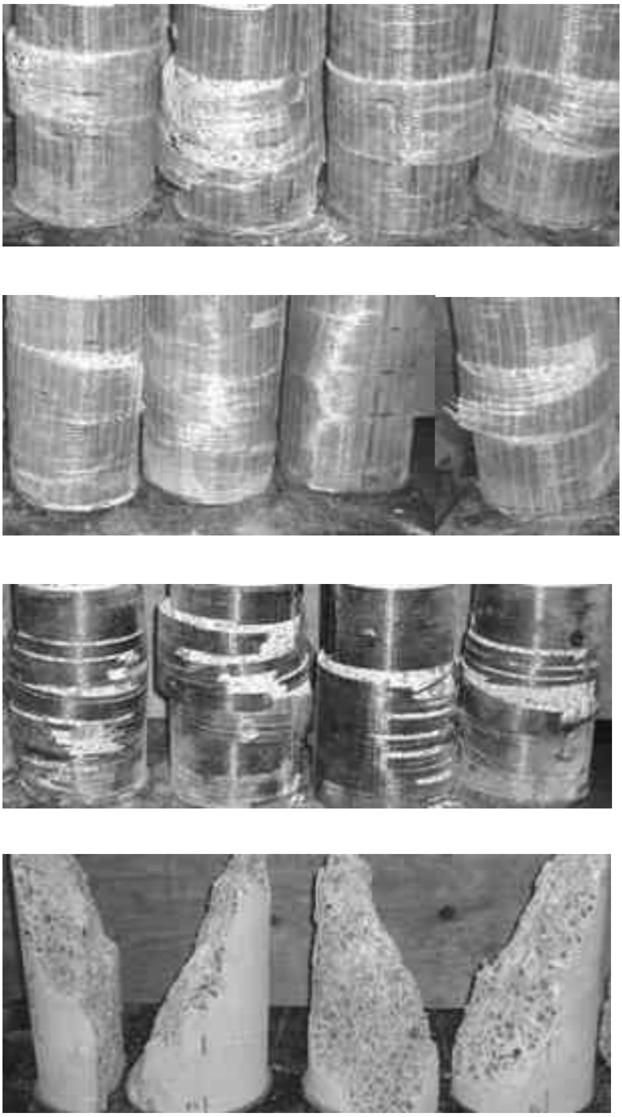


Fig. 6: Effect of unconfined concrete strength on the % gain in strength for confined specimens.

Failure Modes

The unconfined lightweight cylinders exhibited a more aggressive failure mode. The lightweight cylinders would split into two separate rigid bodies at ultimate stress. This observation is likely due to the porous nature of the aggregates and not due to concrete density. The FRP-wrapped concrete cylinders failed by fracture of the FRP wraps under hoop tensile stresses, in the presence of the axial compressive stresses, as shown in **Fig. 7**. None of the specimens has failed at the overlap location of the jacket, which confirmed the adequate stress transfer over the splice. In all the wrapped specimens, noticeable discoloration of the FRP jacket was, observed and large acoustic emission had taken place at the time of failure, especially for the cylinders wrapped with CFRP sheets.



GFRP
1 Layer

GFRP
2 Layers

CFRP
1 Layer

Unconfined

Fig. 7: Modes of failure for confined & unconfined specimens.

CONCLUSIONS

This study was mainly focused on the performance of light weight concrete confined with FRP. The following conclusions are drawn based on the experimental results. In general, the overall performance of the lightweight wrapped concrete cylinders was very good.

1. Unconfined lightweight cylinders exhibited a more aggressive failure mode, the lightweight cylinders would split into two separate rigid bodies at ultimate stress, and this observation is likely due to the porous nature of the aggregates and not due to concrete density.
2. Confined concrete cylinders failed by fracture of the FRP wraps under hoop tensile stresses, in the presence of the axial compressive stresses. None of the specimens has failed at the overlap location of the jacket, reflecting the adequate stress transfer over the splice.
3. The type and thickness of the FRP jacket slightly affect the strength of confined medium strength concrete. However, they have a very limited effect on the strength of confined high strength concrete.
4. Confining of the lowest concrete strength with FRP sheets lead to a significant enhancement in strength and ductility. However, for highest strength concrete, very little enhancement in strength could be observed and no enhancement in ductility can be expected.
5. In all the wrapped specimens, noticeable discoloration of the FRP jacket was observed and large acoustic emission had taken place at the time of failure, especially for the cylinders wrapped with CFRP sheets.

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أداء الخرسانة خفيفة الوزن والمدعمة بالمواد البولمرية

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نظراً للتطور الكبير فى إستخدام المواد البولمريه ومشتقاتها خلال الخمس سنوات السابقة فى تدعيم وزيادة كفاءة المنشأت الخرسانية أوالحديدية بسبب الوفر الكبيرفى التكاليف والأيدى العاملة وسهولة التنفيذ وكذلك عدم القابلية للصدأ مما يزيد من العمر الافتراضى للمنشأت فقد خضعت هذة المواد بمختلف أنواعها للعديد من الدراسات المعملية والنظرية السابقة والتى اهتمت بمدى تأثير مواصفات وخواص هذة المواد على السلوك الإنشائى للقميص المصنوع من المواد البولمرية لتدعيم الأعمدة الخرسانية ومدى تأثير سمك وعدد الطبقات المختلفة وقطاع وطول العمودعلى الأداء الإنشائى للأعمدة ونظرا لعدم وجود دراسات كافية عن مدى تأثيرنوع الخرسانة ومواصفاتها داخل القميص على أداء قميص المواد البولمرية . فان هذة الدراسة المعملية قد اهتمت بدراسة أداء القميص للخرسانة خفيفة الوزن والمصنوعة من الركام خفيف الوزن ذو المسامية العالية لتماثل حالة تدهور الخرسانة فى المنشأت القديمة المتعرضة لدورات من البلل والجفاف أو الجليد والذوبان. وذلك من خلال إختبارالعديد من الإسطوانات الخرسانية المصنوعة من أربع خلطات خرسانية مختلفة حتى حمل الإنهيار مأخوذاً فى الإعتبار تأثير أنواع مختلفة من المواد البولمرية المستخدمة للقميص.وقد تم خلال هذه الدراسة مناقشة وتحليل كافة النتائج المعملية وتأثير المتغيرات المختلفة على الإجهادات والإنفعالات والحمل الكلى وكذلك شكل الإنهيار. وقد أوضحت النتائج المعملية أداءاً جيداً للخرسانة الخفيفة المدعمة بإستخدام المواد البولمريه والذي يتضح من خلال الزيادة فى الحمل الكلى والتطورفى المرونة عند الإنهيار خصوصا فى أضعف أنواع الخرسانات المستخدمة .