Performance of Concrete Cylinders Confined with Carbon Fiber Reinforced Polymers under Axial Load

Rania F. Abo-Dagher [1], Hazem M. Abd El-Latif [2], Lamiaa E. Sadek [3]

[1, 3]Lecturer, October High Institute for Engineering & Technology, 6th October City, Egypt

[2]Prof. of Strength of Materials, Housing and Building National Research Center, Egypt

Corresponding Author: raniaabodagher15@gmail.com

ABSTRACT

A total number of 18 standard concrete cylinders were manufactured and tested in this study under axial static compression loading, to assess the influence of CFRP confinement on their performance. The specimens were divided into two groups according to two cement grades used. Each of the two Groups consisted of 9 concrete cylinders, eight of which were CFRP fully or partially confined. The last cylinder of each group was without CFRP wrapping, used as control specimen for comparison. The used CFRP strips were from two different Sources (1) and (2) applied to cylinder surface using either one of two epoxy resin Sources (a) and (b).

Two systems of the application of CFRP with epoxy resin were adopted. System (1) using CFRP Source (1) with epoxy resin Source (a). System (2) using CFRP Source (2) with epoxy resin Source (b). Each application system was adopted for 8 cylinders using each of the two cement grades. Four schemes of CFRP wrapping, either fully or partially confined, were used.

Based on obtained test results, conclusions are presented regarding the parameters affecting the ultimate compressive load of tested concrete cylinders, which are the cement grades chosen, the CFRP confinement schemes adopted, and the epoxy resin types used.

Keywords: Axial compression test, CFRP Confinement effectiveness, CFRP wrapping, Fiber-reinforced polymer (FRP), Epoxy resin.

1. INTRODUCTION

Due to the advantages of Carbon Fiber Reinforced Polymers (CFRP), such as light weight, high strength, and corrosion resistance, many studies were developed in order to increase the structural capacity of concrete to resist the stresses to which it is subjected.

Adafer S., et al (2022) presented experimental axial stress strain cyclic responses and clarified that confinement has a favorable impact on strength and deformability. Cylindrical specimens are better at achieving this containment than prismatic ones the residual strain and stiffness deterioration for both geometric shapes are independent of the confinement rate. In contrast, the dissipated and restored energy are strongly influenced by the addition of CFRP layers

Adheem A. H. et al (2021) replaced the organic matrix (such as epoxy) with an inorganic one, fiber reinforced cementitious mortar (FRCM) enhances the performance of fiber-reinforced polymer (FRP), creating a more environmentally friendly solution with significantly increased fire resistance. A design-oriented model for FRCM-confined concrete was presented and numerical specimens acquired by FE analysis. It was utilized to investigate the impact of the following factors: height-to-diameter ratio (H/D), type of FRP fabric, number of FRCM layers (n), compressive strength of unconfined concrete (fco), and mortar compressive strength (fm) and thickness (tm). Findings demonstrated that for all tested n, fco, and (H/D) values, the confined concrete strength (fcc) rises linearly as fm and tm increase. Had significantly higher statistical performance and results correlation than previous models and had a unique coefficient for the effects of mortar qualities.

Benzaid R. et al (2010) presented experimental results from plain- and reinforced concrete (RC) cylinders strengthened with (CFRP). All the test specimens were loaded to failure in axial compression. The results showed that the CFRP wrap increases the strength and ductility of plain and reinforced concrete cylinders significantly.

Babba R. & Merdas A. (2019) focused on how fiber-reinforced polymer affects concrete columns and how different variables, such as the distance between strips, the number of layers, the starting strength of the concrete, and the degree of conflation, effect specific results. The results of an experimental examination into the performance of regular concrete cylinders with layers of carbon fiber-reinforced polymer (CFRP) reinforcement were presented. Assessing the impacts of CFRP composite reinforcement strip width is the main objective of this work, it is evident that this study has shown a perfect configuration and an adequate distribution of CFRP composite materials in order to minimize the consumption of the latter and so utilize it to its greatest strength and carry out the ultimate limit state design.

Cao Q. et al (2019) presented experimental results from the axial compression performance of CFRP-confined self-stressing high-strength concrete cylinders. The parameters included the CFRP layers and the level of prestress (with or without prestress). The results showed intersected stress, inflection stress and peak stress of the self-stressing specimens which were all higher than those of the non-prestressed specimens. They indicated that with the application of prestress, the utilization ratio of CFRP increases.

Cao Y. et al (2020), examined the mechanical behavior of concrete cylinders contained in FRP when compressed uniaxial at various strain rates. According to test results, the strain rate influences failure modes, stress-strain curves, and compressive strength. Based on the test findings from this study, a stress-strain model, a compressive strength model, and an ultimate strain model were suggested. The test data gathered from the literature and from other models is compared to the model predictions. According to the assessment results, the proposed model performs well and can be used to forecast the stress-strain behavior of circular concrete cylinders that are contained in FRP.

Dang Z., Feng P., Yang J., Zhang Q., (2020), suggested to use an unique hybrid component with ductile engineered cementitious composite (ECC) as the confining material and linear elastic fiber-reinforced polymer (FRP) as the core material. On ECC cylinders that were contained in FRP, a number of axial compressive tests were performed. The test findings showed that FRP-confined ECC specimens had compression hardening behavior comparable to that of FRP-confined normal concrete specimens in the axial stress-strain curve. The stress-strain response and failure mode were significantly impacted by the "self-confinement" effect of ECC and the confinement stiffness of FRP. A failure mechanism was put out for FRP confined cement-based materials under compression based on the FRP strain distribution. During compression, FRP-confined ECC cylinders went through three separate stages: micro crack formation, multiple crack formation, and significant crack formation and propagation. A qualitative model for FRP constrained ECC was created, which explains why the hoop rupture strain is lower than the ultimate tensile strain of FRP and shows the influence of various tensile characteristics of cement-based materials on the failure mode. Moreover, fitting equations for forecasting the compressive strength and ultimate strain of FRP-confined ECC cylinders there at ultimate state were presented.

Demir C. et al (2010) investigated concrete cylinder specimens cast using medium strength concrete and exposed to either uniaxial compression at different loading rates, or sustained axial stresses after being jacketed externally with carbon-fiber-reinforced polymer CFRP sheets. Results showed that the stress-strain behavior of CFRP confined concrete was affected by the change in loading rate. Also the strength improvement was clear for specimens loaded at higher strain rates, while specimens loaded at slower strain rates recorded better deformability. Results obtained from short-term monotonic loading tests were also compared with the results of two analytical approaches originally developed for plain concrete. The results of residual strength tests showed that specimens did not have any strength loss due to sustained loading.

Huang L. et al., (2022) examined the impact resistance of FRP-confined ultra-high-performance concrete (UHPC) included in carbon fiber-reinforced polymer (CFRP) under splitting loads. The CFRP jackets covering the UHPC cylinders ranged in thickness from one to three plies. The specimen’s dynamic behaviors were examined and contrasted with those under quasi-static loading. According to the findings, UHPC's splitting characteristics showed a considerable dependence on strain rate; however, the confinement of CFRP decreased UHPC's sensitivity to strain rate. Under dynamic splitting loads, the failure of CFRP-confined UHPC was caused by the CFRP rupturing after UHPC cracking. Although the CFRP confinement ratio could enhance the quasi-static splitting tensile strength about linearly, the effect of the CFRP confinement diminished with increasing strain rate. To forecast the splitting tensile strength of CFRP-confined UHPC under impact loading, a novel model that takes into account the impacts of confinement ratio and core concrete inertia was presented.

Huang L., et al (2021) Studied the compressive behavior of enclosed ultra-high performance concrete UHPC with carbon fiber-reinforced polymer FRP sheets when compressed axially repeatedly. The cyclic stress-strain response of fiber-reinforced polymer-confined ultra-high performance concrete UHPC was further studied using modelling. Analyses were done on the stress-strain curve, plastic strain, stress degradation ratio, and secant modulus in relation to confinement ratio and cyclic loading mode. The results for the stress-strain behavior of conventional concrete confined with FRP and UHPC confined with FRP were compared .A stress-strain model for FRP-confined UHPC under cyclic axial compression was provided based on the interpretation of the test findings from this work and a thorough evaluation of cyclic stress-strain models created for FRP-confined conventional concrete. The findings demonstrate that the suggested model can predict the stress-strain reactions of FRP-confined UHPC quite well.

Hussain Q. et al (2020) investigated the effectiveness of fiber rope reinforced polymer (FRRP) composites, a new, affordable, and environmentally friendly reinforcing method in order to improve the axial compressive strength, strain, and deformability of concrete specimens by external wrapping. According to experimental findings, FRRP external confinement is a very efficient way to increase the ultimate strength, strain, and deformability of concrete.

Ismail R. et al. (2019) presented fully, partly horizontal, and helicoidally CFRP-confinement strip. Results from both partial CFRP confinement modes were compared to full confinement and unconfined specimens using strip spacing's of 60, 40, and 20 mm. An acceptable load capacity (80.56 MPa) was obtained with partial horizontal CFRP strip confinement at 20 mm strip spacing and 71% strength increase. Consequently, it is demonstrated that partial CFRP containment using a horizontal strip is enough.

Jirawattanasomkul T. et al (2019) conducted to get a thorough understanding of the compressive behaviour of concrete contained in inexpensive natural fiber reinforced polymer (NFRP). To determine the tensile characteristics of the Jute, Hemp, and Cotton NFRP, a coupon test was performed. A number of concrete cylinders encased in NFRPs made of cotton, jute, and hemp were constructed and put to the test using a uniaxial compression test. The findings demonstrate that NFRP, particularly Jute-NFRP, is efficient and suited for enhancing the confinement effect of concrete.

Mortazavi AA & Jalal M. (2014) conducted experiments on 12 FRP confined concrete cylinders wrapped with FRP materials and subjected to both monotonic and cyclic loading, FRP materials which were carbon fibers (CFRP) and glass fibers (GFRP) were used for the construction of the FRP jackets.

They examined the effect of the type of confinement material, the reinforcement ratio based on the jacket stiffness, and the type of loading. They concluded that the effectiveness of confinement increases with an increase in the lateral jacket stiffness.

Panjehpour M. et al (2016) presented experimental results on damaged high-strength concrete cylinders repaired using CFRP sheets. They found that the energy absorption of the damaged specimens confined with CFRP was approximately three times more than that of the undamaged specimens without confinement.

Ostrowski K.A., & Furtak K. (2021), stated that the load capacity of high-performance, self-compacting, fiber-reinforced concrete (HPSCFRC) is essential for understanding the impact of concrete surface preparation on the efficacy of CFRP reinforcement. A few variables that affect the stress-strain characteristics of concrete that is contained by CFRP laminates were explored in this study. The technique used to prepare the surface and the amount of CFRP layers were thought to be important factors that greatly affect the features of the load-bearing capacity of reinforced parts. Three distinct types of concrete surfaces: ground, sanded, and unfinished were presented. The Abbott-Firestone profile material share curve was then thoroughly studied after the shape of each of the concrete surfaces was clearly identified. They carried out 40 cylindrical concrete examples were wrapped in one, two, or three layers of CFRP for this study, and they were then put through a uniaxial compressive test. The obtained findings demonstrated that the load-bearing capability of HPSCFRC reinforced with CFRP is significantly influenced by the form of the concrete surface. The grinded concrete surface was characterized by the best cooperation with the composite reinforcement

Raza A., et al (2021) examined how the various compressive strength CS of the hybrid fiber reinforced concrete HFRC are affected by carbon fiber reinforced polymer CFRP confinement. The experimental results showed that the axial compressive strain, and CS of low strength HFRC specimens were all greatly increased by the lateral confinement of concrete in CFRP. Improvements of 115.7% and 130.7% for single and double CFRP layers, respectively, were seen in the CS of 12.5 MPa group. Similar improvements of 37.4% and 112.6% for single and double CFRP layers respectively occurred in the CS of 16.5 MPa group. In terms of axial CS and axial compressive strain, low strength HFRC is therefore better confined by CFRP than high strength HFRC.

Sivasankar S. et al (2020) examined RC cylinders both un- and reinforced specimens Results stated that the application of aramid fiber reinforced polymer (AFRP) boosted the load bearing capability of the cylindrical specimens and that excellent interment of AFRP textiles was seen. Following the experimental inspections, the results were compared to the specimens that had not been reinforced, and the characteristics of the members were then examined by drawing load-deflection curves, load-stiffness curves, and axial stress-strain curves.

Toska K. et al (2023), stated that bond aspects may significantly influence the effectiveness of Fiber Reinforced Cementitious Matrix (FRCM) jackets as confining system. An experimental campaign was run on cylindrical specimens reinforced with two layers of carbon-based FRCM and subjected to cyclic axial stress (CFRCM). The analysis included failure modes, the axial stress-strain curve, degradation of strength and stiffness, and plastic strains. The best results were obtained when epoxy-coated carbon fibers were employed in the confining jackets, according to experimental data. It should be noted that for the application to be practical, a relatively large mesh size and a low degree of coating impregnation should be utilized for the textiles.

Touhari M. & Mitiche-Kettab R. (2016) investigated the behavior of FRP confined concrete cylinders subjected to axial compressive loading. Carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP) were tested under monotonic axial compression, using several parameters such as unconfined concrete strength, type of FRP composite and number of FRP layers. Results showed that CFRP reinforced cylinders provide a significant increase in ultimate compression stress compared to the GFRP reinforced ones.

UsmaN M.,et al (2020) examined samples underwent axial compression testing. Results showed that while adding steel fiber to concrete had little impact on its compressive strength, it considerably increased its ductility and improved its post-peak behavior. The compressive strength increased dramatically as a result of the confinement. The use of steel fibers in conjunction with confinement in concrete columns may be seen as being very advantageous since it not only boosts the concrete's compressive strength but also significantly resolves the problem of brittle failure.

Based on the findings of the literature review, this study was conducted to assess the axial compression performance of 16 CFRP- confined concrete cylinders. The main variables of the experimental program include the cement grade, CFRP strengthening schemes, and confinement effectiveness of CFRP jackets based on type of epoxy resin. No steel reinforcement was taken into account because the main aim is to determine the performance of CFRP-confinement only.

2. EXPERIMENTAL PROGRAM

2.1 Concrete Mixes

Two mixes of self-compacting concrete (SCC) with two Portland cement grades were used conforming to the European Norms EN 197-1. The specimens were divided into two groups (A) and (B) according to cement grade; Group A (CEM I 42.5 N) and Group B (CEM I 52.5 N). **Table 1** shows the concrete mix proportions used.

Table 1 Concrete Mix proportions (in m^3)

Code Mix	Cement		Aggregate		Water	Silica fume (kg/m^3)	Chemical admixtures	
	Grade	Weight (kg)	Sand (kg)	Gravel (kg)			Type	Weight (kg)
M1	52.5	500	845	845	185	0	G	13
M2	42.5	360	864	864	209	40	G	12

The fine aggregate was natural siliceous sand that conforms to the requirements of EN12620. The nominal maximum aggregate size of the used coarse aggregate was 19 mm. The used silica fume was dark grey. High range water-reducing Type G admixture with dark brown color were used conforming to ASTM C494. Slump flow diameter, as well as the flow time for SCC mix reaching diameter of 650 mm, T50, were measured as shown in **Fig. 1**, where the slump flow T50 = 6 seconds for 50cm.

All specimens of the identical Group of concrete (A) or (B) were cast with the same batch of specified mix proportions, and for both CFRP Source (1) with epoxy resin type (a) or CFRP Source (2) with epoxy resin type (b). The Self-Compacting Concrete was cast in cylindrical moulds, without needing mechanical vibration, and left to harden for 24 hours after which the moulds were dismantled and the hardened concrete cylinders were submerged in a fresh water curing tank for 120 days, then removed from the curing tank to be tested after their preparation as indicated in what follows. The cylinders preparation procedure took 3 additional days before testing.

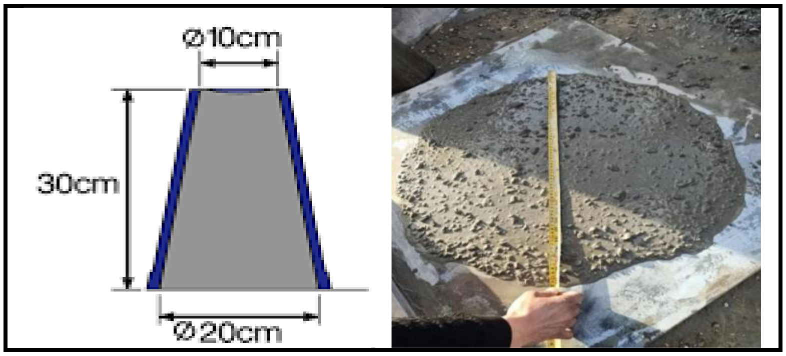


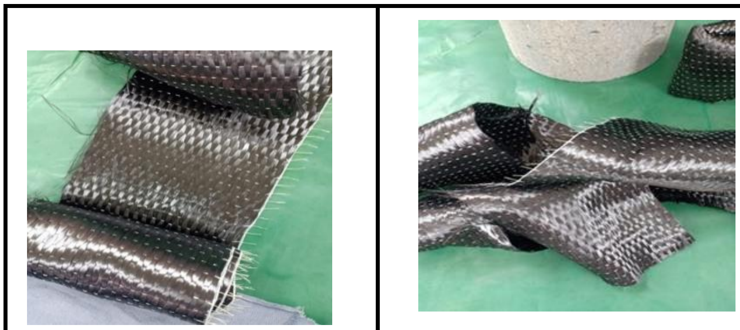
Fig. 1 Slump Flow Test

2.2 CFRP Composites

Strips of CFRP from two different Sources (1) and (2) were used, as shown in **Fig. 2,** where they have identical mechanical characteristics. Both CFRP Source (1) and (2) used had a tensile strength of 4900 N/mm^2 for dry fabric, with a tensile E-modulus of 230000 N/mm^2 and elongation at break of 2.1%. For the laminate, width 500 and fiber weight of 322 Kg/m^2 (CFRP + epoxy), the ultimate tensile load is 480 KN/m width.

Two sources of Epoxy resin were used, as shown in **Fig. 3** Source (a) was Master Brace Sat 4500, with mix proportions of 2.5 part of component A to 1 part of component B, viscosity=3100 MPa, Color (Transparent blue). Source (b) was Sikadur - 330, with mix proportions of 4 part component A to 1 part component B, Density=1.31 kg/lit, Color (component A is white and component B is grey).

Two systems of the application of CFRP with epoxy resin were adopted. System (1) using CFRP Source (1) with epoxy resin Source (a). System (2) using CFRP Source (2) with epoxy resin Source (b). Each application system was adopted for 8 cylinders using each of the two cement grades. Since the CFRP strips from the two Sources (1) and (2) had identical mechanical characteristics, then the comparison of results between the two application systems would be actually based on only the type of epoxy resin whether from Source (a) or (b).



CFRP Source (1) **CFRP Source (2)**

Fig. 2 Strips of CFRP Source (1) and Source (2)

Epoxy resin Source (a) **Epoxy resin Source (b)**

Fig. 3 Epoxy resin Source (a) and Source (b)

2.3 Wrapping Schemes

Four schemes of CFRP wrapping were used, as shown in **Fig. 4**. The first was by fully wrapping the total length of the cylinder of 30 cm with strips surrounding the cylinder perimeter. The second scheme was by partial wrapping with two strips of width 10 cm spaced at 10 cm and surrounding the cylinder perimeter. The third scheme was by partial wrapping with three strips of 5 cm width each surrounding the cylinder perimeter, with 7.5 cm spacing between adjacent strips. The fourth scheme was by partial wrapping with four strips of 5 cm width each surrounding the cylinder perimeter, with 3.3 cm spacing between adjacent strips.

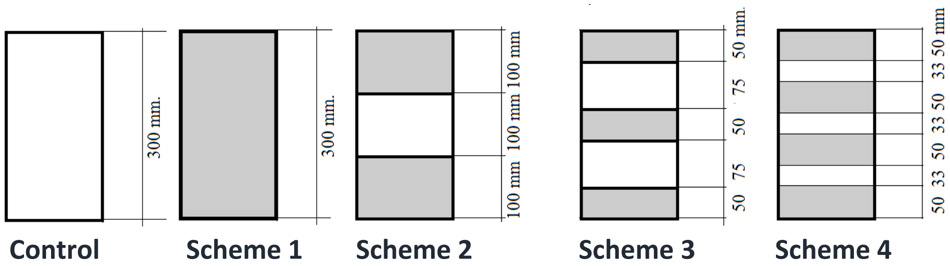


Fig. 4 Four Schemes of Cylinder Wrapping with CFRP

2.4 Preparation of Specimens

The strengthening procedure of the tested cylinders included surface preparation by grinding then application of a priming adhesive layer and bonding of the CFRP strips. Before bonding, special consideration was given to the surface preparation. Uniform mechanical grinding was employed to remove the outer weak surface of the concrete until the aggregates were exposed. The surface of the cylinders was then cleaned with compressed air to remove any loose particles. The epoxy resins were mixed as per the manufacturer's instructions until the mixture had a uniform color. CFRP strips were cut exactly according to the specified dimensions and placed over the cylinder specimens according to the wrapping schemes, as shown in **Figs. 4, 5, and 6**. **Table 2** lists the details of control and CFRP-Wrapped Cylinders.

Application System (1) CFRP Source (1) + Master Brace Sat 4500			
Group (A) CEM I 42.5 N		Group (B) CEM I 52.5N	
 Scheme 1	 Scheme 2	 Scheme 1	 Scheme 2
 Scheme 3	 Scheme 4	 Scheme 3	 Scheme 4

Fig. 5 Strengthening Schemes of test Specimens with Application System (1) Using CFRP source (1) + Master Brace Sat 4500

Application System (2) CFRP Source (2) + Sikadur-330 Component			
Group (A) CEM I 42.5 N		Group (B) CEM I 52.5N	
 Scheme 1	 Scheme 2	 Scheme 1	 Scheme 2
 Scheme 3	 Scheme 4	 Scheme 3	 Scheme 4

Fig. 6 Strengthening Schemes of test Specimens with Application System (2) Using CFRP source (2) + Sikadur-330 Componen

2.5 TEST RESULTS

The values of ultimate crushing load for Control and CFRP Confined concrete test cylinders are presented in **Table 3** for both grades of cement and the four wrapping schemes, as well as the two sources of both CFRP strips and epoxy resin. The corresponding failure modes of the tested groups of CFRP confined concrete cylinders are shown in **Figs. 7, 8, 9 and 10**. The two control cylinders without confinement tested in compression are shown in **Fig. 11**.

Cylinder S-A-1 | **Cylinder S-A-2** | **Cylinder S-A-3** | **Cylinder P-A-4**

Fig. 7 Failure modes of CFRP Confined Cylinders Group (S-A) Cast with Cement Grade (CEM I 42.5 N) &Wrapped with CFRP Source (1) + Epoxy Resin Source (a)

Cylinder P-A-1 | **Cylinder P-A-2** | **Cylinder P-A-3** | **Cylinder P-A-4**

Fig. 8 Failure modes of CFRP Confined Cylinders Group (P-A) Cast with Cement Grade (CEM I 42.5 N) &Wrapped with CFRP Source (2) + Epoxy Resin Source (b)

Table 2 List of Control and CFRP Wrapped Cylinders

Specimen Code	CFRP Wrapping Scheme	Application System		Number of CFRP Strips	Strip Width (cm)
		Epoxy Resin Source	CFRP Source		
C-A	Without confinement	Control cylinder without confinement			
S-A-1	Fully wrapped	Source (a)	Source (1)	1	30
S-A-2	Partially wrapped	Source (a)		2	10
S-A-3	Partially wrapped	Source (a)		3	5
S-A-4	Partially wrapped	Source (a)		4	5
P-A-1	Fully wrapped	Source (b)	Source (2)	1	30
P-A-2	Partially wrapped	Source (b)		2	10
P-A-3	Partially wrapped	Source (b)		3	5
P-A-4	Partially wrapped	Source (b)		4	5
C-B	Without confinement	Control cylinder without confinement			
S-B-1	Fully wrapped	Source (a)	Source (1)	1	30
S-B-2	Partially wrapped	Source (a)		2	10
S-B-3	Partially wrapped	Source (a)		3	5
S-B-4	Partially wrapped	Source (a)		4	5
P-B-1	Fully wrapped	Source (b)	Source (2)	1	30
P-B-2	Partially wrapped	Source (b)		2	10
P-B-3	Partially wrapped	Source (b)		3	5
P-B-4	Partially wrapped	Source (b)		4	5

Table 3 Ultimate Crushing Load for Control and CFRP Confined Concrete Test Cylinders

Cylinder Specimen Code	CFRP Wrapping Scheme		Application System	Ultimate Load	
	CFRP Wrapping Percentage	Number/ Width of CFRP strips		KN	% of the Control Specimen
C-A	0.0 %	Control cylinder without confinement		320	100 %
S-A-1	100 %	1 / 30 cm	CFRP Source (1) + Epoxy Resin Source (a)	1010	316 %
S-A-2	66.7 %	2 / 10 cm		640	200 %
S-A-3	50.0 %	3 / 5 cm		690	216 %
S-A-4	66.7 %	4 / 5 cm		775	242 %
P-A-1	100 %	1 / 30 cm	CFRP Source (2) + Epoxy Resin Source (b)	1440	450 %
P-A-2	66.7 %	2 / 10 cm		660	206 %
P-A-3	50.0 %	3 / 5 cm		690	216 %
P-A-4	66.7 %	4 / 5 cm		1145	358 %
C-B	0.0 %	Control cylinder without confinement		460	100 %
S-B-1	100 %	1 / 30 cm	CFRP Source (1) + Epoxy Resin Source (a)	1320	287 %
S-B-2	66.7 %	2 / 10 cm		845	184 %
S-B-3	50.0 %	3 / 5 cm		840	183 %
S-B-4	66.7 %	4 / 5 cm		990	215 %
P-B-1	100 %	1 / 30 cm	CFRP Source (2) + Epoxy Resin Source (b)	1650	359 %
P-B-2	66.7 %	2 / 10 cm		865	188 %
P-B-3	50.0 %	3 / 5 cm		850	185 %
P-B-4	66.7 %	4 / 5 cm		960	209 %

Cylinder S-B-1	Cylinder S-B-2	Cylinder S-B-3	Cylinder S-B-4

Fig. 9 Failure modes of CFRP Confined Cylinders Group (S-B) Cast with Cement Grade (CEM I 52.5 N) &Wrapped with CFRP Source (1) + Epoxy Resin Source (a)

Cylinder P-B-1	Cylinder P-B-2	Cylinder P-B-3	Cylinder P-B-4

Fig. 10 Failure modes of CFRP Confined Cylinders Group (P-B) Cast with Cement Grade (CEM I 52.5N)&Wrapped with CFRP Source (2) + Epoxy Resin Source (b)

Fig. 11 Failure modes for the Two Tested Control Cylinders without CFRP Confinement, (C-A) with Cement Grade (CEM I 42.5 N) & (C-B) with Cement Grade (CEM I 52.5 N)

2.6 Effect of Compressive Strength

As shown in table 3, all unconfined control or CFRP confined cylinders cast with cement Grade (CEM I 52.5 N), whether using Application System (1) or (2), gave ultimate compressive loads higher than the corresponding cylinders cast with cement Grade (CEM I 42.5 N), which is natural. Except for Cylinder P-B-4 cast with the higher cement grade, which gave lower compressive load of 960 KN while the corresponding Cylinder P-A-4 gave a value for ultimate compressive load of 1145 KN. This may be due to an error in manufacturing or testing Cylinder P-B-4.

However, the percentage increases in ultimate compressive load, as compared to the corresponding strength of control unconfined cylinder, was higher for all the CFRP confined cylinders cast with cement grade (CEM I 42.5 N). For example, cylinder S-A-1 fully CFRP confined and cast with cement grade (CEM I 42.5 N) gave a percentage increase of 316% as compared to Cylinder S-B-1 fully CFRP confined and cast with cement Grade (CEM I 52.5 N), giving a percentage increase of only 287%.

Another example of concrete cylinder P-A-2 partially CFRP confined and cast with cement grade (CEM I 42.5 N) giving a percentage increase of 206% as compared to cylinder P-B-2 partially CFRP confined and cast with cement grade (CEM I 52.5 N), giving a percentage increase of only 188%.

The compressive strength increased more than 3 to 4.5 times compared to control unconfined cylinder in case of fully confinement depending on CFRP source. The partially confinement led to increase in ultimate compressive strength by rang from (2 to 3.6 times) compared to the control cylinder.

In case of CFRP wrapping percentage 66.7%, increasing number of stripes (4stripes with 5cm width) instead of 2 stripes 10 cm width enhanced the ultimate load by about 42%.

This clearly indicates that the effect of CFRP confinement is more effective in concrete with low compressive strength.

2.7 Effect of CFRP Wrapping Scheme

The full CFRP wrapping gave the highest ultimate compressive load in all cases, irrespective of the cement grade or the type of epoxy resin used, which was to be expected. That was conducted with Benzaid R. et al (2010) .

Comparing the wrapping Schemes 2 and 4, having equal CFRP wrapping percentage of 66.7%, it was found that Scheme 4 gave ultimate compressive load of cylinders higher than wrapping Scheme 2 for all cases, irrespective of the cement grade or the type of epoxy resin used. This is attributed to the fact that in Scheme 2 the whole unconfined concrete surface area of 10 cm increases the risk of lateral bulging occurrence during testing cylinders in compression.

In Scheme 4, only unconfined concrete surface area of 3.3 cm exists between every two adjacent CFRP strips lowering the risk of free lateral bulging of concrete.

The fully confined concrete specimens showed an increase in the ultimate compressive stress compared to the control specimens (31%, 32%, 55%, and 66% for W/C ratios of 0.33, 0.36, 0.401, and 0.522, respectively).

RIAD BENZAID (2010) showed that the CFRP wrap increases the strength and ductility of plain- and RC cylinders significantly.

According to Babba (2019), minimizing the space between the CFRP stripes has led to increase in capacity of the used specimen strength.

2.8 Effect of Epoxy Resin

The epoxy resin Source (b) gave ultimate compressive load higher than Epoxy resin Source (a) for all CFRP confined cylinders, irrespective of the cement grade or the CFRP wrapping scheme used. This was except for Cylinder P-B-4, as mentioned before.

In other words, Application System (2) using CFRP Source (2) with epoxy resin Source (b) proved to give ultimate compressive load of CFRP confined cylinders higher than Application System (1) using CFRP Source (1) with epoxy resin Source (a), irrespective of the cement grade or the CFRP wrapping scheme used.

3 CONCLUSIONS

Based on the detailed study and analysis of the obtained experimental results, the following conclusions can be set forth:

1- The percentage increase in ultimate compressive load as compared to the corresponding ultimate load of control unconfined cylinder was higher for all CFRP confined cylinders cast with cement Grade (CEM I 42.5 N), irrespective of the wrapping scheme or the type of epoxy resin used. This clearly indicates that the effect of CFRP confinement is more pronounced in cases of cements of lower grades.

2- Full CFRP confinement of concrete cylinders would give the highest ultimate compressive strength for all cement grades and all types of epoxy resin used. The percentage increase in ultimate compressive strength as compared to the corresponding ultimate strength of control unconfined cylinder can reach 450% for fully wrapping**.**

3- For the same partial CFRP wrapping percentage, the scheme adopting more CFRP strips with smaller spacing between adjacent strips would give the higher ultimate compressive load of cylinders, irrespective of the cement grade or the epoxy type used. This is since the small limited unconfined concrete surface area between adjacent CFRP strips would lower the risk of free lateral bulging of concrete.

4- The Application System (2) using CFRP Source (2) with epoxy resin Source (b) proved to give ultimate compressive load of CFRP confined cylinders higher than Application System (1) using CFRP Source (1) with epoxy resin Source (a), irrespective of the cement grade or the CFRP wrapping scheme used.

ACKNOWLEDGEMENTS

This paper is based on an experimental research program of B.Sc. Graduation Project (2020) of a group of Civil Engineering students at October High Institute for Engineering & Technology; namely: Anas Eltahhan, Mohammed Abu Elnasr, Abdeltawwab Abdeltawwab, Mohammed Elokda, Ahmed Abdelsattar, Ahmed Abdelaziz, Yaser Elghab.

The authors would like to acknowledge with deep appreciation the valuable help and assistance of The Institute Materials Lab staff and technicians in preparing and testing the test specimens

REFERENCES

1. Adafer S., Youcef Y.S., Amziane S., (2022), "Cyclic behaviour of CFRP confined concrete under axial compression", Construction and building materials, 340:127793.

2. Adheem A. H., Kadhim M. M. A., Jawdhari A., Fam A., (2021), "Confinement model for concrete wrapped with fiber reinforced cementitious mortar", Constuction and building materials, 312:125401.

3. Benzaid R., Mesbah H., Nasr Eddine Chikh. (2010),"FRP-confined concrete cylinders: Axial compression experiments and strength model.", Journal of Reinforced Plastics and Composites, 29(16): 2469-88.

4. Babba R. & Merdas A.,(2020) "Width effect of CFRP strips on the compressive behavior of plain concrete cylinders", Iranian journal of science and technology, Transactions of civil engineering, 44(3).

5. Cao Q., Li X., Gao R. (2019),"Axial Compressive Performance of CFRP Confined Self-stressing High-strength Concrete Cylinders.", KSCE Journal of Civil Engineering, 23(9): 4000-9.

6. Cao Y., Liu M., WU Y., (2020), "Effect of low strain rate on the axial behavior of concrete in CFRP-confined circular cylinders", Construction and Building Materials, (255:119351.

7. Dang Z., Feng P., Yang J., Zhang Q., (2020), "Axial compressive behavior of engineered cementitious composite confined by fiber-reinforced polymer", Composite Structures, (243); 112191.

8. Demir C., Kolcu K. & Ilki A. (2010),"Effects of Loading Rate and Duration on Axial Behavior of Concrete Confined by Fiber-Reinforced Polymer Sheets.", Journal of Composites for Construction, 14(2), 146-151.

9. Guo Y, Xiao S., Zeng J. , Zheng Y. , Li X., Liu F., " Fiber reinforced polymer-confined concrete under high strain rate compression: Behavior and a unified dynamic strength model", Construction and building materials, 260, 120460.

10. Huang L., Su L., Xie J., Lu Z., Li P., Hu R., (2022), "Dynamic splitting behaviour of ultra-high-performance concrete confined with carbon-fibre-reinforced polymer", Construction and Building,284, 115-155.

11. Huang L., Xie J., Li L., Xu B., Huang P., Lu Z. (2021), "Compressive behaviour and modelling of CFRP-confined ultra-high performance concrete under cyclic loads", Construction and Building materials, 310, 124-949.

12. Hussain Q., Ruangrassamee A., Tangtermsiriku S., Joyklad P., (2020) "Behavior of concrete confined with epoxy bonded fiber ropes under axial load", Construction and buildings , (263), 120-093.

13. Ismail R., Rashid R.S.M., Wong Chien Chan, Jaafar M. S., Hejazi F., (2019), "Compressive behavior of concrete cylinder fully and partially confined by carbon fibre-reinforced polymer (CFRP)", Construction and building materials, 201, 196-206.

14. Jirawattanasomkul T., Ueda T., Likitlersuang S., Zhang D., Hanwiboonwat N., Wuttiwannasak N., Horsangchai K., (2019), "Effect of natural fibre reinforced polymers on confined compressive strength of concrete", Construction and building materials,223, 156-164

15. Mortazavi AA, Jalal M. (2014),"Investigation of CFRP- and GFRP-confined concrete cylinders under monotonic and cyclic loading.", Science and Engineering of Composite Materials, 21(4), 607-614.

16. Ostrowski K.A.,& Furtak K.,(2021), "The influence of concrete surface preparation on the effectiveness of reinforcement using carbon fibre-reinforced polymer in high-performance, self-compacting, fibre-reinforced concrete", Composite structures, 276, 1145522.

17. Panjehpour M., Farzadnia N., Demirboga R. & Ali AAA. (2016)," Behavior of high-strength concrete cylinders repaired with CFRP sheets.", Journal of Civil Engineering Management, 22(1): 56-64.

18. Raza A. , Rafique U., Masood B., Ali B., Haq F., Nawaz M.A., (2021) "Performance evaluation of hybrid fiber reinforced low strength concrete cylinders confined with CFRP wraps" Structures, 31(2021), 182-189.

19. Sivasankar S., Sankar L.P. , A., Kumar A.P. ,Shunmugasundaram M., (2020), "Compression behavior of cylinder reinforced with aramid fiber reinforced polymer", Materials Today: Proceedings 27, 764-771.

20. Toska K., Faleschini F., Zanini M.A., (2023), " Confinenemt of concrete with FRCM:Influence of bond aspects under cyclic axial loading", Construction and building materials, 368, 130-432.

21. Touhari M. & Mitiche-Kettab R. (2016),"Behaviour of FRP confined concrete cylinders: Experimental investigation and strength model", Periodica Polytechnica Civil Engineering, 60(4), pp. 647-660.

22. Usman M., Farooq S., Umair M., Hanif A., (2020) "Axial compressive behavior of confined steel fiber reinforced high strength concrete", Construction and Building Materials, (230), 117-043.