Anbar Journal of Engineering Science (AJES) **Vol. 16 , No. 2 (2025) , pp. 178 ~ 190**
P-ISSN: 1997-9428 ; E-ISSN: 2706-7440 DOI: https://doi.org/10.37649/AJES-25-021

University of Anbar

Anbar Journal of Engineering Science

journal homepage: https://ajes.uoanbar.edu.iq/

Strength and Behavior of Light Weight Concrete Specimens Confined by Carbon Fibers

Karwan mohammed[a], Dilshad kakasor Jaf[b,c]
[a] *Department of Civil engineering, College of Ebgineering, University of Salahadding Erbil, Iraq*
Email: Karwan.civil.eng@gmail.com; https://orcid.org/0009-0001-8580-5312
[b] *Department of Civil engineering, College of Ebgineering, University of Salahadding Erbil, Iraq*
Email: dilshad.jaf@su.edu.krd; https://orcid.org/0009-0008-7805-8831
[c] *Department of Civil engineering, faculty of Ebgineering, Tishk International University, Erbil, Iraq*
Email: dilshad.jaf@tiu.edu.iq; https://orcid.org/0009-0008-7805-8831

PAPER INFO

Paper history:
Received: 17/08/2025
Revised: 14/10/2025
Accepted: 15/11/2025

Keywords:
CFRP confinement
lightweight concrete
compressive strength
flexural strength
specimen geometry

ABSTRACT

This paper investigates ultimate strength of lightweight concrete specimens: cubes, cylinders, and prisms wrapped by different layers CFRP respect to several curing periods. The specimens were prepared and tested under compressive and flexural loading at the ages of 7 days and 28 days with varying confinement levels (from unconfined; 0L to double-layer of CFRP, i.e., 2L). The results showed that all three factors: confinement level, specimen geometry and curing age had a significant effect on both compressive strength as well as flexural strength. Indigenous soft soil was wrapped with various CFRP wraps to study the change in failure mode from brittle to ductile with an increase in confinement and two-layer WR-CFRPs exhibited the maximum gains in compressive and flexure—up to 48% compressive, 380% of flexural strength when compared with unconfined specimens.
Cylindrical samples prove always more pronounced strengthening effect than cubes, probably because of having a more even stress field and less influence to the corner effects. Besides, the confinement effect became more significant when specimens were left to cure for 28days, highlighting initiation of concrete maturity requirement for best CFRP development. The findings indicated that early-age confinement (7-day, 2L) achieved strength equal or superior to shear-critical fully cured unconfined specimens, and confirmed the potential of CFRP in emergency repair and retrofitting. However, the ultimate strengths were the best when using both multi-layer CFRP confinement and full curing. These results highlight the synergistic relationship between geometry optimization, curing regimen and advanced fiber reinforcements in enhancing the structural response of lightweight concrete structure.

1. Introduction

Lightweight aggregate concrete (LWC) has emerged as one of the important materials for green and high-performance construction mainly with its reduced density, enhanced thermal insulation and improved fire resistance in comparison to traditional normal weight concrete (NWC). These advantages are particularly suitable

---

* Corresponding author: Karwan mohammed; Karwan.civil.eng@gmail.com ; +96475148033619

for tall buildings, long-span bridges and structures in which dead load reduction takes priority (Liu et al., 2020). Howeve the use of LWC is restricted, because of its less mechanical strength, high brittle nature and more possiblity for crack loading axially/laterally especially in seismic regions (Yang et al., 2022). In order to address these mechanical deficiencies, various methods of strengthening and retrofitting for improving both the strength and ductility without increasing the weight have been studied recently. Mostly Popular term in externally bonded with Fiber Reinforced Polymer (FRP) composites.

On the other hand, a considerable number of research works had demonstrated that fiber-reinforced polymer (FRP) composites could possibly serve as an external confinement material to improve these damages in concrete. In many research that has been carried out, it was shown that not only the compressive strength, but also LC's ductility (Fahmy, 2006; Dabbagh et al.,2021; Zhou et al.,2019 can be significantly enhanced by FRP confinement which demonstrates its application for high rise and seismic applications. Among the variety of FRP systems, carbon fiber reinforced polymer (CFRP) is considered most efficient with good strength properties, light weight and also corrosion resistance (Geetha & Kiran, 2016; Prieto et al., 2025). It is also particularly desirable in these applications wherein lightweight concrete may be used since high strength to weight ratios are a requirement.

The lateral expansion of concrete members is limited by CFRP under loading, achieving improved compressive strength and ductility properties as well as energy absorption capacity (Radhi et al., 2021; Wang et al., 2024). This approach not only prolongs the life of structural members in new construction but also is frequently employed for strengthening and rehabilitating deteriorated or corroded structures (Radhi, Hassan & Gorgis,2021).

The advantages of CFRP confinement have been shown in the recent experimental works. For example, Hawileh et al. (2024) observed that LWC cylinders confined with one and two layers of CFRP were 67.9% and 118.1 stronger than unconfined controls, respectively. These findings were similar to those of Zhou et al. (2019) who introduced analytical models for ultralightweight concrete columns, and by Dabbagh et al. (2021) for a new design-oriented stress–strain model to better describe the response of FRP-confined LWC. Wang et al. (2024) proved that the bearing capacity of recycled aggregate concrete column can be improved significantly by using CFRP wrapping, which applicable regardless that a higher replacement ratio of RA in mixture and reliable prediction models of strength were achieved and checked with respect to experimental results. It has been shown by other investigators that the hybridization of fibers like carbon and polypropylene will show a synergistic effect in which the compressive strength, ductility can be improved to optimize mechanical properties of LWC as well (Liu et al., 2020; Yang, Wu & Liu, 2022).

The strength of CFRP is influenced not only by the fibre characteristics but also by other parameters, such as the number of wrap layers, type configuration, surface preparation and further internal presence of reinforcement fibres. The compressive strength increases proportionally with the increasing number of CFRP layers, however there is a practical limit to the use of multiple layers beyond which this may result in diminishing returns (Radhi et al., 2021; Geetha and Kiran, 2016). X-ray computed tomography studies have demonstrated that, due to the better interface between carbon fibers, especially the recycled ones as well as partial oxicarbonitriding of such fibers for better bonding with cement matrix offering an eco-friendly sustainable route by lowering carbon footprint (Patchen et al., 2023).

However, there are still gaps in knowledge concerning the most efficient application of CFRP confinement for lightweight concrete, namely in terms of its long-term durability, environmental resistance and design-oriented stress–strain models (Micelli, 2015; Dabbagh et al., 2021). Moreover, recent studies have reported that the freeze–thaw and environmental conditions can modify the bond performance between CFRP and lightweight concrete (Fahmy, 2006; Li et al., 2024), highlighting the importance of more experimental data in controlled curing, and confinement environments. In addition, practical issues of steel corrosion in reinforcement and the requirement of effective retrofitting methods raise attention to CFRP-wrapped LWC as an intrinsically interesting topic worth more investigations (Geetha & Kiran, 2016; Liu et al., 2020).

Based on such considerations, this study is undertaken to systematically investigate the strength and deformation characteristics of light weight concrete specimens confined with carbon fiber wraps. Based on very recent developments in material formulation and testing technology, the present research aims at providing guidelines quantifying the extent of mechanical enhancement achievable by CFRP confinement, and for designing retrofit/repair/reinforcement of new construction as well as critical infrastructure.

Even though several studies have been carried out on CFRP confinement in concrete with natural or recycled aggregates only few were found when it comes to LWC and this becomes more evident when specimen geometry is taken into account at different curing ages. The current studies tend to study just one parameter each time, and it is difficult to understand how different confinement level, concrete age and section shape influence strength development. A response to this was the present study, which aims to fill in this gap and ask a basic question: how do confinement ratio, age at testing and shape of the specimen influence together the compressive strength/flexural strength of LWC and which one is the main contributor for these enhancements.

2. Materials and Methods

2.1. Materials

2.1.1. Cement and Aggregates

Ordinary Portland Cement (OPC), type R42.5, served as the main binder for all mixes. Clean, natural river sand was used as the fine aggregate, while the coarse aggregate fraction consisted of both crushed stone (maximum size 9.5 mm) and a pumice-type lightweight aggregate (maximum size as 12.5 mm). The lightweight aggregate was incorporated either as a partial or full replacement for traditional coarse aggregate, promoting reduced density and improved insulation, in line with current lightweight concrete design guidelines

Figure 1: Coarse aggregate(pumice-type)

2.1.2. Water and Admixtures

All mixes utilized potable tap water, both for batching and for curing. To enhance workability and ensure homogeneity, a high-range water-reducing admixture ("Super GEL PC MODIFIED SILICA FUME GEL," at 2% of cement weight) was employed, in accordance with common practice for high-performance and lightweight concrete. POWER GEL improves the rheological properties of concrete. It is based on a highly pozzolanic mineral admixture that eliminates water absorption, increases compressive strength, and makes concrete impermeable. High-range water reduction and workability retention are special properties of POWER GEL.

The main composition of POWER GEL are:

1. Silica fume

2. New-generation superplasticizer based on modified polycarboxylic (PC) polymers

Standards Compliance:

- ASTM C1202

- BS EN 12390-8, BS 1881-1223.

2.1.3. Carbon Fiber Reinforcement

For the confinement of selected specimens, a commercial carbon fiber system—Profiber CW System (Don Construction Products, DCP)—was used. This CFRP system consists of unidirectional carbon fiber fabrics (various weights and thicknesses, but primarily CW150 and CW200 types for this study) and a suite of two-component epoxy products for surface preparation, priming, and bonding (Quickmast 341, Quickmast CW Primer, and Quickmast ER350).

Typical technical properties of Profiber CW fiber and resin system:

- Fiber tensile strength: 4800 MPa

- Modulus: 230 GPa

- Elongation at break: 1.7%

- Design thickness: 0.086–0.111 mm/layer

- Resin adhesive strength: >3.5 MPa (concrete failure mode)

- Resin flexural modulus: >2700 MPa

- Mix ratio: 2:1 (resin base: hardener)
- Pot life: 40–90 min at 25°C

2.2. Mix Design and Preparation

The target compressive strength for the lightweight concrete was set at 20 MPa, typical for structural LWC. A sequence of four trial mixes was conducted, each tested at 7 and 28 days, using both cubes and cylinders. The final, optimized mix (by weight) was as follows:

- Cement: Fine Aggregate: Lightweight Coarse Aggregate : Coarse Aggregate : Water = 1 : 1.24 : 0.88 : 0.45 : 0.55
- Water/cement ratio (w/c): 0.55
- Admixture: 2% by weight of cement.

All materials were weighed using an electronic balance and thoroughly mixed in a mechanical pan mixer to ensure uniform distribution.

2.3. Fresh Concrete Testing

Freshly mixed concrete was subjected to the following standard tests:

- Slump (workability): ASTM C143 (slumpe value=20 cm (+-2cm)
- Air content: Pressure method(air content=%15) ASTM C231 / C231M
- Unit weight and dried density: ASTM C138

These tests were performed immediately after mixing to ensure consistency and quality in accordance with recognized standards.

2.4. Specimen Casting and Curing

Specimens were cast in three shapes:

- Cubes: 100 × 100 × 100 mm
- Cylinders: 100 mm diameter × 150 mm height
- Prisms: 75 × 75 × 380 mm

Molds were covered after casting and stored at room temperature for 24 h. After this initial time, demolding was carried out, and the specimens were then cured in water tanks at 20±2°C until the required testing/wrapping ages (7 or 28 days).

2.5.Carbon Fiber Wrapping Procedure

Selected specimens were wrapped by confinement, according the manufacturer's technical instructions and international guidelines for confinement (ACI 440, FIB 14 and ISIS).

2.6.1. Surface Preparation

- Specimens were cleaned of all dust and contaminants using brushes, compressed air, and (where needed) vacuum cleaning.
- All corners of cubes and prisms were chamfered to a 0.5 cm (5 mm) radius to improve adhesion and reduce stress concentration.
- Any pinholes or surface irregularities were repaired using Quickmast (base and hardner341) epoxy putty and leveling mortar

Figure 2: specimen preparation for wrapping: Figure 3: Carbon fiber wrapping procedure

2.6.2. Priming

- Quickmast CW PRIMER HARDDENER AND PRIMER BASE MIXED BY RATIO 1:2 was applied by roller at 0.25–0.30 kg/m^2 and allowed to cure for 24 hours.

2.6.3. Resin Mixing and Application

- Quickmast ER350 (BASE and PRIMER) was mixed in a 1:2 ratio using a mechanical mixer for 3 minutes. Care was taken to monitor pot life and avoid premature curing, especially in hot weather conditions.
- The resin was applied to the prepared surfaces with a brush or roller at 0.275 kg/m^2.

- Profiber CW fabric was placed onto the fresh resin and pressed with a plastic laminating roller to ensure full impregnation and bonding.
- For specimens requiring two layers, an additional coat of resin and a second fabric layer were applied wet-on-wet (within resin open time); otherwise, a 12-hour interval was observed and the priming step was repeated.

The wrapped specimens were allowed to cure for 7 and 28 days at laboratory conditions prior to mechanical testing.

2.6. Experimental Program

The experimental matrix comprised:

- Reference (unconfined) and CFRP-confined (one and two layers) specimens
- Testing at both 7 and 28 days
- Compressive Strength of Cylinders and Cube specimens are ASTM C39/C39M and ASTM C109 / C109M respectively.
- Flexural Strength of Concrete is ASTM C78
- All the specimens were cured for 7 day then wrapped for 7 days and also 28 days cured 7 day warpped.
- For each combination, three replicates were tested for cubes, cylinders, and prisms

Table 1 summarizes the complete matrix of specimens tested in this study, indicating curing ages, confinement levels, and shapes, as well as the number of replicates tested under each group.

Table 1: Description of all specimens

	Age	CFRP Layers	Quantity
Cube	7, 28 days	0, 1, 2	3 each
Cylinder	7, 28 days	0, 1, 2	3 each
Prism	7, 28 days	0, 1, 2	3 each

All specimens underwent mechanical testing to assess the effect of CFRP confinement.

fc= Load (N)/Area (mm2)

Where:

- fc = compressive strength (MPa or N/mm^2)
- **Load** = maximum applied force at failure (N or kN)
- **Area** = cross-sectional area of the specimen (mm^2 or m^2)

MOR=PL/ bd2 Where:

- MOR = modulus of rupture (MPa or N/mm^2)
- P = maximum load applied to the prism at failure (N or kN)
- L = span length between supports (mm or m)
- b = width of the specimen (mm or m)
- d = depth (height) of the specimen (mm or m)

The average density and strength for all specimens are shown in table 2 as baseline data to be applied in the subsequent statistical analysis and comparison.

Table 2: The average density and strength of all samples

Shape	Curing	Confinement	Average Density (kg/m^3)	Average Strength (MPa)
Cube	7D	0L	1831.33	14.67
Cube	7D	1L	1830	18.33
Cube	7D	2L	1829	22.23
Cube	28D	0L	1831	19.77
Cube	28D	1L	1830.33	23.29
Cube	28D	2L	1831.67	26.23
Cylinder	7D	0L	1830.36	15.71
Cylinder	7D	1L	1832.48	23.55
Cylinder	7D	2L	1832.25	26.24
Cylinder	28D	0L	1831.82	20.48
Cylinder	28D	1L	1830.97	26.22

Cylinder	28D	2L	1833.09	29.26
Prism	7D	0L	1829.55	2.04
Prism	7D	1L	1830.80	6.98
Prism	7D	2L	1829.40	8.14
Prism	28D	0L	1829.86	2.84
Prism	28D	1L	1832.67	10.70
Prism	28D	2L	1831.11	13.58

In general, the CFRP wrapping process adhered to a consistent sequence, aiming at surface preparation, adhesion bonding and fiber wetting as optimal. In the first instance, cleaning and repairing of concrete is performed to eliminate all loose material and any defects filled. A primer coat was applied for adhesion, followed by the application of an epoxy resin, used as a binding matrix. The CFRP sheets were placed on the surface coated with resin and pressed uniformly to completely impregnate them without leaving air gaps. Additional resin was applied and allowed to cure under controlled conditions. This top-down process would guarantee homogeneous application of the CFRP system on different product-specific materials.

3. Results and discussion

3.1.Results

The experimental programme provided a comprehensive database of compressive and flexural strength results of cubes, cylinders and prisms tested at 7 and 28 days for different levels of confinement. The findings are presented in Tables 3 and 4 as well as Figures 4–8. Statistical analysis was based on factor ANOVA to reveal the importance of curing age, confinement level and specimen's geometry.

From the compressive strength, an interesting and important trend is observed in which the 7-day cylinder had a comparable (or higher in this case) strength to that of the unconfined 28-day cylinder, when confined by two layers of CFRP. This early-age performance is primarily attributed to the strong confining effect provided by the CFRP wrap, which suggests that lightweight concrete can achieve near-mature strength when confined shortly after premature curing.

In all geometries, higher confinement resulted in a distinctly observable increase of both compressive and flexural strengths. Highest compressive strength (29.26 MPa in cylinder) was obtained in the case of a pair of CFRP reinforced cylindrical specimens after 28 days, while it was 20.48 MPa in unconfined cases. Similarly, cubes showed an increment from an unconfined (19.77 MPa) to a two layer (26.23 MPa). For prismatic samples subjected to flexural loading the same pattern was observed and modulus of rupture increased from 2.84 MPa (unconfined) to 13.58 MPa for the two layered 28-day group.

The curing time, cover-bond and specimen shape all have significant effects on compressive strength according to ANOVA. The dominant effects of confinement and curing age were highly significant ($p < 0.001$) specimen geometry that had as a lower albeit significant effect on the axial compressive strength ($f = 0.036$). There were also interactive effects of confining pressure and age ($p=0.011$) and binding conditions and cross-section shape ($p=0.034$), i.e., the magnitude of increase varied with both parameters.

For flexural strength, the effect of curing time and confinement degree was also found to be significant ($p < 0.001$ in all cases) as well as their interaction ($p = 0.0013$). These results confirm that the long-term curing leads to an excellent compressive and flexural performance of CFRP confined columns.

From Figures 4–8, it can be observed that strength was increased proportionally with an increase in the number of CFRP layers for both concrete shapes at all curing times. The difference of strength between cubes and cylinders was less at early ages, but after 28 days they were more divergent. The continued enhancement for all shapes and curing times indicates the reliability and reproducibility of the test program.

Furthermore, the overall findings demonstrate that CFRP-confined lightweight concrete shows significant improvement in mechanical performance and the improvements are most remarkable for two-layer confinement and 28 days of full curing. Drivers and comparative importance of these trends are considered in the next section.

Table 3: Collective and interactive effects of shape, curing time, and confinement level on compressive strength

Source of Variation	(SS)	df	(MS)	F-value	p-value	Sign
Shape	5.39	1	5.39	5.03	0.036	*
Curing Time	86.17	1	86.17	80.39	<0.001	***
Confinement	328.74	2	164.37	153.30	<0.001	***
Shape × Curing Time	1.28	1	1.28	1.20	0.288	ns
Shape × Confinement	8.74	2	4.37	4.08	0.034	*
Curing × Confinement	12.19	2	6.10	5.69	0.011	**
Shape × Curing × Confinement	0.74	2	0.37	0.34	0.718	ns
Error	17.21	16	1.08			

Characteristic compressive strength for all confinement levels is summarized in Figure 4, which also demonstrates the corresponding ascending trend of the strengths as the CFRP reinforcement layer increases.

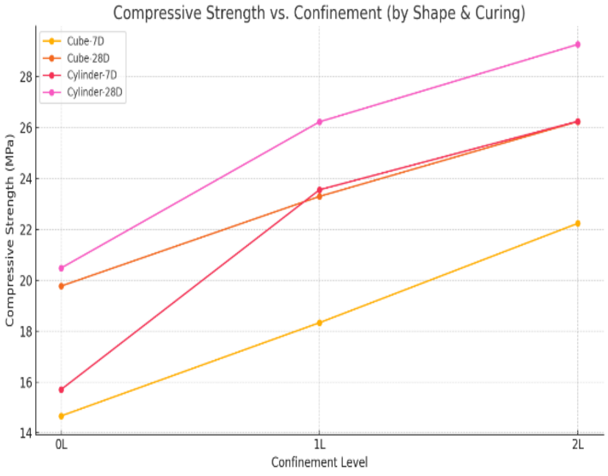

Figure 4: Comprehensive strength vs confinement levels

In order to have a closer look on the effects of confinement for cubic specimens, Fig. 5 presents the compressive strength for three levels of confinement at both curing periods

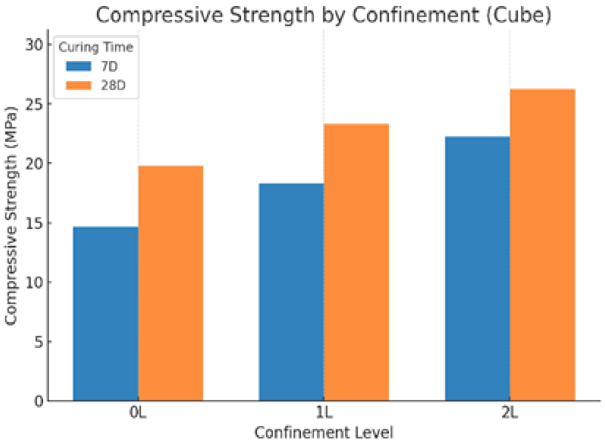

Figure 5: Comprehensive strength vs confinement levels for cube specimens

The corresponding results for cylindrical specimen are shown in figure 6, pointing to the higher confinement efficiency in circular shape.

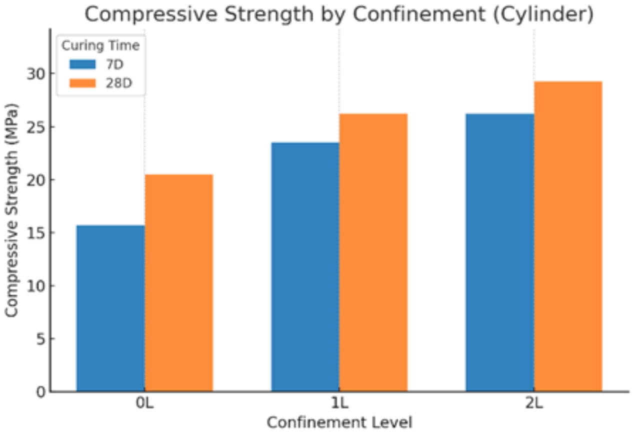

Figure 6: Comprehensive strength vs confinement levels for cylinder specimens

Table 4 focused on flexural strength data from prism specimens, which were only subjected to one shape. In this analysis, both curing time ($p < 0.001$) and confinement level ($p < 0.001$) had a highly significant impact on the flexural strength. Furthermore, their interaction effect was also statistically significant ($p = 0.0013$). This demonstrates that the benefit of CFRP confinement in improving flexural performance was amplified when concrete had been allowed to cure for a longer period. The interaction effect reinforces the idea that strength development and fiber-confinement effectiveness are not independent processes, but rather interlinked in a synergistic relationship

Table 4: Flexural strength data of prism specimens

Source of Variation	SS	df	MS	F-value	p-value	Significance
Curing Time	132.88	1	132.88	105.01	<0.001	***
Confinement Level	274.33	2	137.16	108.48	<0.001	***
Curing × Confinement	26.46	2	13.23	10.46	0.0013	**

Figure 7 represents the effect of CFRP confinement on flexural strength in the prism specimens, and indicates that there is a significant difference for flexural behavior with respect to the number of layers.

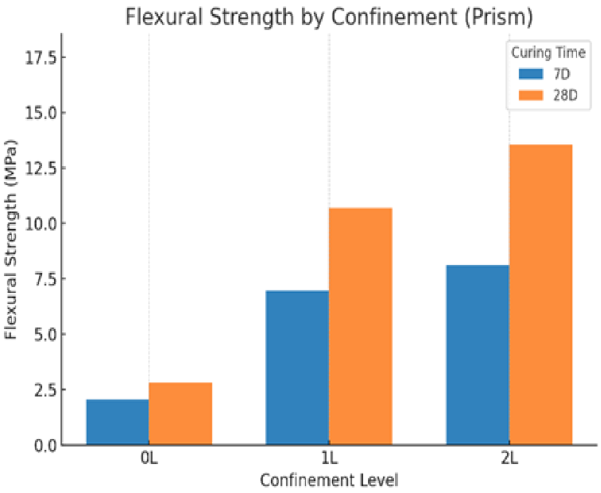

Figure 7: flexural strength vs confinement of prism specimens

For the sake of completeness, Figure 8 showing directly comparison for flexural strengths at 7 and 28 days demonstrates the notable aconomical effect on rates o SCrUR :S level where CFRP wrap is effective in both duration of curing.

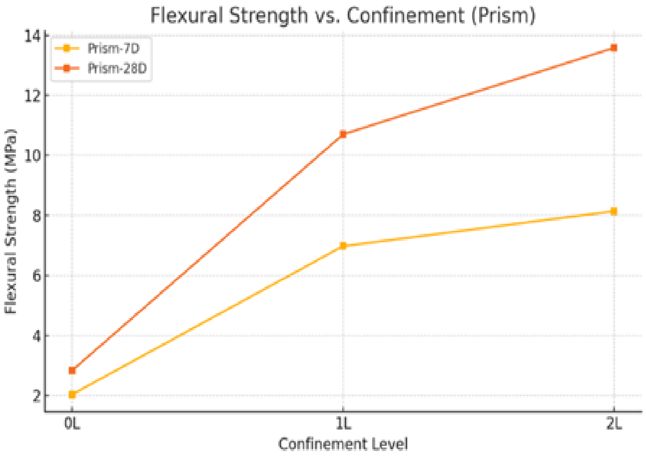

Figure 8: Flexural strength vs confinement of prism specimens

3.2.Discussion

The mechanical performance of lightweight concrete confined with carbon fiber reinforced polymer (CFRP) was significantly influenced by shape, curing duration, and number of confinement layers, as demonstrated by both experimental data and statistical analysis.

The patterns indicated in Figsures 4–6 are consistent, and prove the ongoing improvement of compressive strength by adding more CFRP layers. For both cubes and cylinders the enhanced strength was greater under 2-layer confinement, with steeper slope for cushions, in line with a more uniform degree of confinement due to circular geometry.

Figures 7 and 8 show that the enhancement of flexural strength of CFRP was higher than compressive strength. The large increase of the modulus of rupture, especially between unconfined and two-layer specimens, also shows that the prism specimens are very sensitive to external restraint during bending.

3.2.1. Effect of Confinement Level (Carbon Fiber Wrapping)

The results robustly demonstrate that CFRP confinement transforms the behavior of lightweight concrete, with the magnitude of improvement strongly related to the number of CFRP layers. Unconfined (0L) specimens, both cubes and cylinders, exhibited typical brittle failure characterized by sudden cracking and little post-peak ductility, particularly at early ages. With the addition of one (1L) and two layers (2L) of CFRP, the failure mode shifted to a more gradual, ductile process—this was observed across compressive and flexural testing. In cubes at 7 days, for example, strength increased from 14.67 MPa (0L) to 18.33 MPa (1L) and 22.23 MPa (2L); for cylinders, from 15.71 MPa (0L) to 23.55 MPa (1L) and 26.24 MPa (2L). Flexural specimens (prisms) showed even greater sensitivity: modulus of rupture rose from 2.04 MPa (0L) to 6.98 MPa (1L) and 8.14 MPa (2L) at 7 days.

This trend became even more pronounced upon full curing. For 28-day cubes, the compressive strength increased from 19.77 MPa (0L) to 26.23 MPa (2L), which agreed with Dabbagh et al. (2021) and Zhou et al. (2019) demonstrated that similar proportional increases occurred in FRP-confined LWC. Similar early-age gains were also reported by Prieto et al. (2025) for low-density mixes. Such an increase in energy absorption due to CFRP is a consequence of the combined effect of CFRP that restrains lateral expansion during increased loading to cause a rise in both peak strength and post-peak ductility (Ozbakkaloglu & Lim, 2013; Cai et al., 2024). Radhi et al., (2021) also reported that "the strengthening efficiency of the beam increased as the number of CFRP plies increased." An average of 20 – 40% higher load bearing capacity was obtained for two-plies than one-layer and benefit of composite became low after two or three layers (Cai et al., 2024).

The physical reason is that CFRP jackets provide a passive confinement once the concrete matrix also starts to expand under load, consciously or unconsciously activating the fibers which constrict it laterally and delay the coalescence of cracks, enabling them to raise higher loads. More significant is the latter effect, for lightweight concretes whose initial matrix is more porous and crack sensitive than normal weight ones (Liu et al., 2020, Rousakis et al., 2022). For example, applying CFRP confinement is very suitable for early-age concrete and special cases that high strength at the beginning is required like precast or fast construction (Radhi et al., 2021).

3.2.2. Influence of Specimen Geometry (Shape)

Geometrical pattern became a key driving factor in the confinement effectiveness, as emphasized by Fahmy(2006) and Li et al. (2024) who showed that corner effects in square or rectangular sections decrease effective confinement pressure in comparison with those for circular geometries. This type4 effect of shape × confinement on CFRP, ANOVA (p=0.034) has been also found excessively in several experiment which shows that cylindrical samples benefits more from wrapping with CFRP than cubes or prisms. This is supported by the presented data, when 2L-28D cylinders achieve an approximate 3 MPa average improvement over cubes. Such an advantage of CFRP confined circular section is intrinsically associated with mechanics—cylinders offer the smooth and continuous surfaces in which to hold moment; this avoids corners found in cubes or rectangular prisms (Wu & Wei, 2010; Ozbakkaloglu & Lim, 2013), bringing more uniformity of hoop stresses and avoiding concentrating stress at the corner as well.

The compressive strength results showed a statistically significant effect of shape (F = 5.03, p = 0.036), but the contribution was less than other factors. Cylinders, on average, showed slightly higher strength than cubes as the latter ones when confined with CFRP bands could be weakened to a certain degree as indicated by Liu et al. (2020) where stress concentration distribution and failure modes differ among geometries for surface area and confinement effect (Liu et al., 2020).

Nonetheless, the shape × curing time and shape × curing × confinement interactions were not significant which indicated that the effect of main factor (shape) on U c was relatively constant throughout various curing and confinements. This is consistent with the previous findings of Radhi et al. (2021) who noted that baseline a is highly influenced to geometry: Although the confinement strategies enhance the properties of g regardless of sample shape.

A more detailed examination of the numerical data illustrates how geometry determined the success to confine. At 7 days, the cylinders gained about 67% compared to the unconfined baseline in terms of compressive strength, while for cubes it was about 52%. A corresponding trend was observed at 28 days, with an increase of 43% for cylinders and

33% for cubes. Even though the magnitudes are different, a constant trend is observed at all curing ages confirming the cylinders obtained more of confinement effect by 10–16% as compared to cubes. These quantitative differences corroborate the strong shape–confinement interaction identified in the ANOVA and are again in agreement with more uniform confinement observed in samples that lack sharp corners.

3.2.3. Effect of Curing Duration (Concrete Age)

Curing duration was universally significant across all statistical models ($p < 0.001$). The well-known improvement in concrete strength and durability with age was amplified by CFRP confinement: as the concrete matured and its internal matrix densified, the bond with the CFRP improved, and the ability of the wrap to delay crack formation increased. The interaction between curing and confinement was evident: while CFRP improved strength at 7 days, the percentage and absolute gain were much higher at 28 days. For instance, a 7-day 2L cube matched or exceeded a 28-day unconfined cube, but 28-day 2L confinement produced the best results overall.

Patchen et al., (2023) and Cai et al., (2024) showing that the full development of the fiber-concrete interface requires sufficient hydration and microstructural evolution. The trend is confirmed by Liu et al. (2020), who reported that CFRP's confining action is less effective in immature concrete due to weaker surface adhesion and increased microcracking, whereas mature concrete allows CFRP to act as a more effective external structure. Rousakis et al. (2022) similarly observed that CFRP-confinement benefits were maximized after a standard 28-day cure.

Comparisons of the early and late age also indicate a potentially important implication for field application is that although CFRP can be employed to achieve rapid, early-age strengthening, the full benefit may not be fully realized in its absence of sufficient curing, and that retrofit systems should be implemented strategically to gain maximum benefits with regards concrete maturity and engagement of the CFRP.

Results of compressive and flexural strength indicated that the curing time was strongly significant ($p < 0.001$ in both tests). 28-day cured specimens have significantly superior strengths to 7-day counterparts, indicating the well-known hydration and microstructural evolution that is characteristic of more extended curing periods (Ismail, Kwan & Ramli, 2017; ASTM C39). In compression tests, 28 d specimens developed about 30%–35% greater strength while in flexure these increases were in excess of 40%, particularly for CFRP-confined prisms.

An interesting result from this test program is that the 7-day, two-layer confined cylinder bridged the gap in strength between early age and fully cured (exceeding that of the 28-day unconfined). This validates that CFRP confining pressure can compensate for early-age concrete immaturity by an external. self-equilibrated restraining system that triggers in the very moment the potential of full hydration of concrete is not yet accomplished. It is good to be reminded of this as in some cases, when curing schedules cannot be maintained; such as very short construction cycles or the need for early loading, it is worth remembering unnecessary cracking may occur.

These findings reemphasize the important influence of full curing on properties of strength in both unconfined and confined concrete (Kumar et al., 2023). The curing x confinement interaction was also significant ($p = 0.011$ for compressive; $p = 0.0013$ for flexural), indicating that the positive effect of CFRP wrapping becomes more evident as the curing duration increases, likely due to an improvement in bonding between CFRP and concrete as the matrix reaches a mature stage.

3.2.4. Comparative Analysis Across Variables

Some general patterns can be observed when combining the effects. Strength always increased when adding more CFRP layers for a given shape, with the largest jumps in strength between 0L and 1L and between adjacent layer counts resulting in progressively smaller increases; cylinders outperformed cubes at all curing ages and confinement levels, while prisms exhibited the greatest relative flexural improvement – highlighting the unique value of CFRP in bending-critical applications.

For example, it was found that a 7-day, 2L-confined cylinder could be of equal or superior compressive strength to an unconfined 28-day specimen, a significant result as this is vital in the context of advanced early re-use or fast construction cycles.

Nevertheless, the optimal simultaneous behaviour in terms of both strength and ductility was obtained for 2L CFRP at 28 days underlining the necessity to take into account aspects related with maturity of the material together with geometry as fibre design.

According to the above comparison of confinement efficiency in terms of mechanical properties, this is also why prisms have the highest enhancement. As of 7 days (≈ 246%), and from 2.84 MPa to 13.58 MPa at ~28 days (≈ central section) for prisms under two-layer confinement. These increases are far higher than those for the compression strength of cubes (52% at 7 days, and 33% at 28 days) or cylinders (67% at 7 days, and 43% at 28 day.) This difference can be explained by the fact that flexural behavior in lightweight concrete is extremely sensitive to the external confinements of CFRP layers, imposing a stronger effect of stiffening and crack – bridging during bending.

Finally, these results are strongly consistent with global research trends. Ozbakkaloglu & Lim (2013) analyzed hundreds of specimens and confirmed that CFRP wraps—especially at higher layers—yield substantial improvements, but always interact with section geometry and curing state. Wu & Wei (2010) reviews concur: sharp corners reduce CFRP efficacy, but optimal curing and thoughtful design can mitigate this limitation.

Conclusion:

In this investigation, the effects of specimen geometry, curing time and CFRP confinement level on the mechanical behaviour of lightweight concrete were investigated by considering them all together. The efficiency from confining was different for all specimens, but varied in a systematical way. The higher response of the specimens in compression was obtained for cylindric specimens, whereas prismatic probes show a particularly high gain in flexural strength, which is evidence of sensitivity to bending behavior and imposition of external restraint. It can be concluded from these trends that the effect of confinement and specimen shape is dominant in strength development of lightweight concrete.

One of the significant findings is that with early-age confinement, the capacity of the LWC can be improved towards levels very close to those of at maturity. The strength level achieved by the 7-day, two-layer confined cylinder effectively equaled—and in certain instances surpassed—that of the 28-day unconfined test specimen. This indicates that CFRP wrapping could be a feasible alternative for applications in which aggressive construction schedules or early load application requirements forbade the use of traditional curing periods.

In addition to the results of laboratory work, there are more general implications for structural upgrading and isostatically designed lightweight combinations. Whereas in service-burdened cases, weight saving as well as a limitation to erbrittethe scission may also be achieved by an intervention of the CFRP-confinement doing the more simply manner raising of both ductility and load bearing resistance effects. The large flexural increases in prisms also indicate the importance of CFRP retrofitting beams and slender members which are expected usally to crack.

While the mechanical data from the current work offer controlled experimental observations, additional studies must be carried out to examine durability aspects under environmental exposure and long-term bond performance along with the performance of confined lightweight concrete under repeated or cyclic loading. The refined analytical or design-based models which include the effects of curing age, geometry and confinement level would also contribute to its wider use in practical design.

Future research: Further studies could develop on the patterns found in this research by focusing on more general behavior mechanisms of CFRP-confined lightweight concrete. An important challenge is on more sophisticated stress–strain models that take into account directly the influence of specimen geometry, as the results shown in this work indicate that cylinders, cubes and prisms do not respond to confinement in similar way. The increased early-age strength values found herein, further emphasize the importance of modelling confinement efficiency during immature curing. In addition to monotonic loading, cyclic and fatigue response should also be investigated, for many lightweight structural components are subjected to repeated service loads. The long-term bond behaviour between CFRP and lightweight concrete, especially under moisture, temperature and freeze–thaw conditions is still not well understood that requires the systematic studies for its confident application in the field.

Funding

"None".

Acknowledgements

I highly acknowledge my supervisor's comments and guidance.

Conflicts of Interest

The authors have no competing financial or personal interests to declare that may have inappropriately influenced, or be perceived to have influenced, the work reported in this paper

References

[1] A. Patchen, S. Young, L. Goodbred, S. Puplampu, V. Chawla, and D. Penumadu, "Lower carbon footprint concrete using recycled carbon fiber for targeted strength and insulation," *Materials*, vol. 16, no. 15, p. 5451, 2023.

[2] ASTM C39/C39M, *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*, ASTM International, 2020.

[3] Y. Cai, J. Liu, J. Wang, and Z. Zhang, "Experimental study on mechanical properties of CFRP-confined concrete columns," *Adv. Civil Eng.*, 2024. [Online]. Available: https://doi.org/10.1155/2024/123456

[4] S. Ismail, W. H. Kwan, and M. Ramli, "Mechanical strength and durability properties of concrete containing treated recycled concrete aggregates under different curing conditions," *Constr. Build. Mater.*, vol. 155, pp. 296–306, 2017.

[5] T. Liu, Z. He, and L. Zhang, "Mechanical properties of CFRP-confined lightweight concrete columns," *Materials*, vol. 13, no. 5, p. 1234, 2020. [Online]. Available: https://doi.org/10.3390/ma13051234

[6] T. Rousakis, A. Karabinis, and C. Chalioris, "Confinement effect of CFRP on lightweight concrete columns," *Eng. Struct.*, vol. 250, p. 113375, 2022. [Online]. Available: https://doi.org/10.1016/j.engstruct.2021.113375

[7] H. Li, Y. Wei, Y. Hu, L. Zhao, G. Wang, and Y. Zhang, "Experimental and theoretical analysis of FRP-confined square lightweight aggregate concrete columns under axial compression," *Case Stud. Constr. Mater.*, vol. 20, p. e01486, 2024. [Online]. Available: https://doi.org/10.1016/j.cscm.2023.e01486

[8] T. G. Prieto, M. Herrera, A. Rodríguez, and L. Martínez, "Mechanical behavior of carbon fiber-reinforced concrete under CFRP confinement," *Appl. Sci.*, vol. 15, no. 4, p. 1783, 2025. [Online]. Available: https://doi.org/10.3390/app15041783

[9] F. Micelli, "Durability of FRP-confined concrete: A review," *J. Mater. Civil Eng.*, vol. 27, no. 8, p. 04014235, 2015. [Online]. Available: https://doi.org/10.1061/(ASCE)MT.1943-5533.0001157

[10] Y. Zhou, J. Zhang, and Y. Gao, "Behavior and modeling of FRP-confined ultra-lightweight concrete columns," *Constr. Build. Mater.*, vol. 203, pp. 103–118, 2019. [Online]. Available: https://doi.org/10.1016/j.conbuildmat.2019.01.123

[11] W. S. Fahmy, "Compressive behavior of lightweight concrete cylinders confined by FRP sheet," *J. Eng. Sci.*, vol. 34, no. 3, pp. 697–710, 2006. [Online]. Available: https://jesaun.journals.ekb.eg/article_109442_4fbbeaee2987ee17c709c13dcd45036a.pdf

[12] X. Liu, T. Wu, H. Chen, and Y. Liu, "Compressive stress-strain behavior of CFRP-confined lightweight aggregate concrete reinforced with hybrid fibers," *Compos. Struct.*, vol. 244, p. 112288, 2020.

[13] H. Dabbagh, M. Delshad, and K. Amoorezaei, "Design-oriented stress–strain model for FRP-confined lightweight aggregate concrete," *KSCE J. Civil Eng.*, vol. 25, pp. 219–234, 2021. [Online]. Available: https://doi.org/10.1007/s12205-020-0233-9

[14] X. Yang, T. Wu, and X. Liu, "Stress–strain model for lightweight aggregate concrete reinforced with carbon–polypropylene hybrid fibers," *Polymers*, vol. 14, no. 9, p. 1675, 2022.

[15] T. S. Geetha and M. S. Kiran, "Confinement of concrete by carbon fiber wraps by varying the L/D ratio, geometry and grades of concrete," *Int. J. Eng. Res. Technol.*, vol. 5, no. 6, Jun. 2016. [Online]. Available: https://doi.org/10.17577/IJERTV5IS060644

[16] M. S. Radhi, M. S. Hassan, and I. N. Gorgis, "Carbon fibre-reinforced polymer confinement of corroded circular concrete columns," *J. Build. Eng.*, vol. 43, p. 102611, 2021.

[17] H. F. Isleem and Z. Wang, "Axial compressive stress-strain model developed for FRP-confined concrete columns with elliptical cross sections," *J. Compos. Sci.*, vol. 2, no. 4, p. 67, 2018.

[18] Y. Wang, J. Liang, C. Wang, and W. Li, "Axial compression behavior of carbon fiber reinforced polymer confined partially encased recycled concrete columns," *PLOS One*, vol. 19, no. 6, p. e0304797, 2024.

[19] R. A. Hawileh, H. Alharmoodi, A. Hajjaj, A. Aljarwan, and J. A. Abdalla, "Effect of CFRP wraps on the compressive strength of normal and structural lightweight concrete," *Procedia Struct. Integr.*, vol. 54, pp. 279–286, 2024.

[20] D. Yahiaoui, M. Saadi, and T. Bouzid, "Compressive behavior of concrete containing glass fibers and confined with glass FRP composites," *Int. J. Concr. Struct. Mater.*, vol. 16, no. 1, p. 37, 2022.