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Behavior of Lightweight Aggregate Concrete with FRP Confinement: Experimental Insights for Structural Applications

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Abstract. Lightweight aggregate concrete reduces structural dead load but generally exhibits lower compressive strength and ductility than normal-weight concrete. This study experimentally evaluates the effectiveness of carbon-fibre-reinforced polymer (CFRP) confinement for low-density lightweight aggregate concrete, an area in which data for square sections remain limited. Twelve 300-mm-high specimens with a density of approximately 1550 kg/m³ were tested under monotonic concentric compression. The investigated parameters were concrete compressive strength (15 and 28 MPa), cross-sectional shape (square and circular), and number of CFRP layers (one and two). Failure occurred through localized, extensive, or hoop rupture of the CFRP. The confined specimens exhibited approximately bilinear stress–strain responses and substantial improvements in strength and deformation capacity. For square specimens with 15 MPa concrete, two CFRP layers increased the average strength ratio to 2.27 and the strain ratio to 23.39. Circular specimens developed greater confinement efficiency, reaching an average strength ratio of 3.76 with two layers. Lower-strength concrete showed larger relative ductility gains than higher-strength concrete. These findings demonstrate that CFRP confinement can substantially reduce the brittle response of low-density lightweight concrete and support its use in lightweight, resilient, and earthquake-resistant structural applications.

Keywords: Lightweight concrete, confined with CFRP, compressive strength, stress–strain behavior, failure modes, mechanical properties, structural reinforcement, and sustainability in construction materials.

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1. Introduction

Due to its lower density, lightweight concrete has become more common in modern construction. The reduction of dead loads, the improvement of foundations, and the reduction of the size of structural elements primary benefits the increased use of lightweight concrete[1–4]. Nonetheless, the lower compressive strength and ductility of lightweight concrete negatively impact the use of this material in high-performance structures [5–8].

The performance of lightweight concrete has been enhanced through various means. The use of artificial lightweight aggregates, mineral admixtures, and mix variations has been proven to improve the mechanical properties of lightweight concrete [6,8–10]. In addition, external concrete strengthening with Fibre Reinforced Polymer (FRP) improves the compressive capacity and ductility of lightweight concrete as well as normal concrete. Many studies have shown that FRP confinement significantly improves the concrete's stress-strain characteristics, often resulting in a ductile bilinear curve [11–15]. While there has been a substantial focus on FRP-confined concrete, most of the published work has been on normal concrete and high-density lightweight concrete.

Research on square-section lightweight concrete has also noted the limited impact of FRP owing to stress concentration at corners of the columns [13,14,16]. Moreover, there has been little comprehensive reporting on the effect of lower-density lightweight concrete on the stress–strain behavior [7], [13], [14]. For instance, lightweight concrete around 1550 kg/m³ has distinctly different properties from concrete of higher density, such as 1850 kg/m³. Concrete of lower density has higher porosity and lower compressive strength, yet it shows greater deformability than higher-density concrete. Consequently, to evaluate the extent to which CFRP confinement will impact performance ergonomically for structures that need to be seismic resistant and assess the trade-off between strength and ductility, the performance of low-density lightweight concrete needs to be investigated.

This paper investigates the gaps in experimental research on CFRP confined, square-section, low-density lightweight concrete. The investigated parameters include the number of FRP layers, concrete strength, shape of the cross-section, and concrete density. The study focusses on addressing the effectiveness of CFRP confinement in square lightweight concrete columns of low density.

To the compressive strength, ductility, and failure modes of CFRP-confined lightweight concrete, this study aims to deliver insights on the quantity of FRP layers, concrete strength, cross-sectional shape, and unit weight. The results are expected to improve the understanding of FRP applications in lightweight, earthquake-resistant structures and to support the design of more efficient and sustainable constructions [17,18].

2. Methods

2.1. Specimens

In this work, twelve lightweight concrete specimens were used, designed with both square and circular cross-sections. The square specimens were 150 mm x 150 mm with a 25mm corner radius, and the circular specimens had a 150 mm diameter. All specimens had a height of 300 mm.

In order to assess the influence of the key parameters, the specimens were varied with respect to the number of FRP layers (one and two layers), the concrete compressive strength (15 MPa and 28 MPa), cross-section shape (square and circular), and concrete unit weight. Additional detail on the specimens is provided in Table 1. It is important to note that the concrete strain value ($\mathcal{E}_{co}$) as presented in Table 1 was not measured directly but was estimated using the equation proposed by Tasdemir et al. [19].

Tabel 1. Characteristics of the specimen

Specimen ID	Number of FRP layer	Strength of concrete, f'_{co} (MPa)	Strain at peak stress, $\mathcal{E}_{co}$ (%)	Cross Section Shape	Number of FRP specimens
SC-15-1-1&2	1	15	0.15	Square	2
SC-15-2-1&2	2				2
SC-28-1-1&2	1	28	0.19	Square	2
SC-28-2-1&1	2				2
CC-15-1-1&2	1	28	0.19	Circular	2
CC-15-2-1&2	2				2

2.2. Materials

The specimens were produced using artificial lightweight aggregates, both fine and coarse, manufactured by heating shale rock in a rotary kiln at temperatures ranging from 500–1200 °C [20]. Silica fume and superplasticizer were added at 10% and 0.8% of the cement weight, respectively. The physical properties of coarse lightweight aggregates are depicted in Figure 1, and the detailed attributes of the fine and coarse lightweight aggregates are captured in Table 2.

Figure 1. Artificial lightweight coarse aggregate

Also, the carbon fiber utilized in this research has a tensile strength of 4 GPa, an elastic modulus of 230 GPa, and a nominal diameter of 0.17 mm. Due to its lightweight nature, high strength-to-weight ratio, and remarkable corrosion resistance, this material is appropriate for external confinement of lightweight concrete.

Tabel 2. Characteristics of lightweight aggregates

Lighweight Aggregates	Specific gravity (SSD)	Volume Weight (kg/m^3)	Water content (%)	Absorption (%)
Fine	1,84	844,10	0,20	5,00
Coarse	1,40	768,57	0,20	14,00

The mix proportions are based on previous research on lightweight concrete using artificial aggregates and mineral admixtures [8,11,17]. Due to its ability to improve particle packing, decrease porosity, and enhance the interfacial transition zone, a 10% of silica fume was chosen in concrete mix.

The dosage of 0.8% superplasticizer was adopted to achieve sufficient workability without segregation, following recommendations from ACI and ASTM guidelines.

The chosen target compressive strengths of 15 MPa and 28 MPa correspond to low- and medium-grade lightweight concretes, which allows for evaluation of CFRP confinement across a practical range of strengths for structural use. Moreover, these concrete strength levels have been utilized in other investigations [17,21], which similarly employed 15 MPa and 28 MPa concrete strengths, hence ensuring comparability and easy integration within the established framework of experimental research.

2.3. Preparation and Testing of Specimens

The specimens were cast and then wrapped with CFRP utilizing the wet lay-up technique. For uniform load distribution, the cross-sectional surfaces at each end of the specimens were caps of gypsum with a compressive strength of 42 MPa.

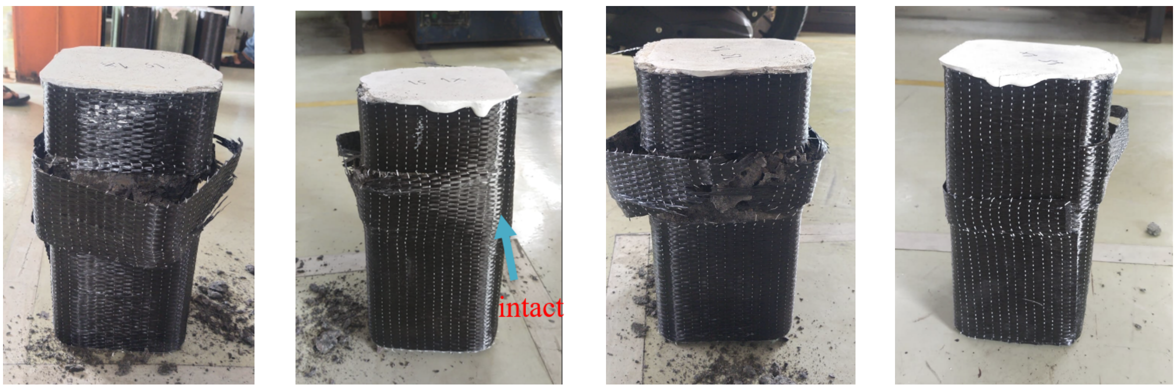
A servo-hydraulic universal testing machine with a maximum capacity of 2000 kN was used for the tests. The load application was monotonic and concentric, to the point of failure, at a 3 kN/s constant rate. This approach was taken to align with previous work on FRP confinement, [14,17,21], and in alignment with the standard ASTM C39 for compressive testing. For concentric loading, CFRP confinement was used to cover the confinement testing, thus removing the complexities of eccentric or cyclic loading.

Specimen casting and curing are potential sources of experimental error. During testing, the wet lay-up of CFRP had minor defects (e.g., air bubbles or misaligned fibers) along with uneven gypsum capping which may have affected stress distribution. While extensive quality control procedures were implemented during preparation, the uncertainties mentioned cannot be completely eliminated, thus likely contributing to the scatter observed in the experimental results.

3. Results and Discussion

3.1. Failure Modes

The ultimate failure of all specimens was attributed to the rupture of the FRP layers. This failure was progressive and was first signaled by faint tearing sounds that grew louder until the specimen dramatically and violently ruptured and collapsed. The ruptured condition of the FRP layers is depicted in Figure 2.



a. Significant tear b. Intact fibre c. Significant tear d. Less tear

Figure 2. FRP rupture at several locations of specimen

Figure 2 illustrates the condition of the specimens with 15 MPa initial concrete strength wrapped with a single FRP layer. The most severe rupture was at one of the cross-section corners with the square cross-section and then ran along the adjacent sides. In the end some areas of the ruptured section the concrete was covered and the fibers were intact suggesting they were held in place. This suggests the corners of square sections were the areas of concentration of the undamaged surrounding concrete that led to failure and thus triggering the fragility. This phenomenon corresponds to localized rupture, which is constant with observations of Al-Salloum [16].

a. 1 layer   b. 2 layers   c. Circular specimen

Figure 3. Condition of specimen after testing

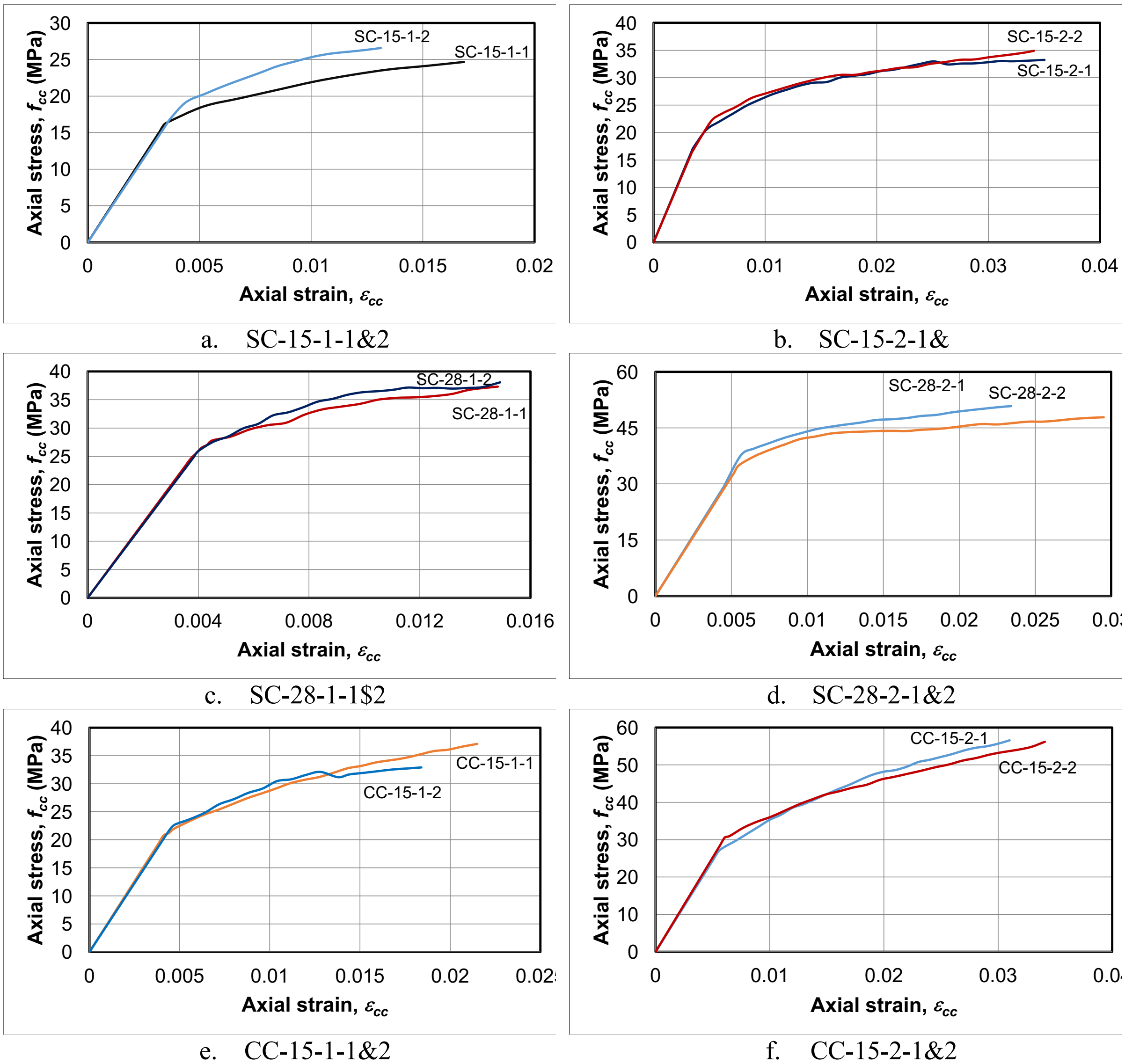
Figure 3 shows specimens with 28 MPa concrete strength exhibited wider and more severe ruptures than those with 15 MPa concrete strength. This suggests that higher compressive strength leads to worse ruptures. In addition, the 28 MPa specimens failed with more audible fracturing than the 15 MPa specimens. Thus, higher compressive strength concrete corresponds to greater energy release upon failure. This can be categorized as extensive rupture.

For the circular specimens, the FRP rupture was nearly uniform along the perimeter, particularly in the mid-height region of the specimen. Ruptures in circular specimens were more extensive than those in square specimens. This failure pattern can be described as a hoop rupture, confirming that circular cross-sections distribute stress more evenly across the perimeter, while square cross-sections concentrate stress at the corners [16].

Furthermore, the failure patterns in this study are in accordance with other studies regarding FRP-confined lightweight concrete. Zhou et al. [11] explained that FRP rupture occurs abruptly after reaching the ultimate strain, while cross-sectional geometry predominantly guides the damage distribution. More recent studies by Li et al. [14] also verified that lightweight concrete columns with square sections exhibit earlier failures than their circular counterparts due to corner stress concentrations. These outcomes are consistent with the findings of de Diego et al. [13], who showed that the effectiveness of FRP confinement in square columns is relatively limited with few FRP layers. For this reason, exploring failure modes becomes critical in understanding the constraints and possible enhancements of FRP confinement in lightweight concrete structures.

3.2. Stress-Strain Behaviour

The stress-strain responses of all specimens are shown in Figure 4. The results indicate that the stress-strain profiles of lightweight concrete with square and circular cross-sections approached a bilinear form. This suggests that FRP confinement had a substantial confining effect, which promoted an increase in the lightweight concrete's deformation capacity.



a. SC-15-1-1&2
b. SC-15-2-1&
c. SC-28-1-1$2
d. SC-28-2-1&2
e. CC-15-1-1&2
f. CC-15-2-1&2

Figure 4. Stress-strain behavior of tested specimens

Table 3 shows that ultimate stress and ultimate strain increased more than 100% after confinement with FRP. This confirms that FRP wrapping improves not only the compressive capacity of lightweight concrete, but also its ductility. Thus, the effectiveness of employing FRP for lightweight concrete has met the practical goal of minimizing its greatest drawback, which is the material brittleness.

Tabel 3. Ultimate condition of confined concrete

Specimen	f_l/f'_c	f'_{cu} (MPa)	Avg. f'_{cu} (MPa)	f'_{cu}/f'_c	Avg. f'_{cu}/f'_c	ε_{cu} (%)	Avg. ε_{cu} (%)	$\varepsilon_{cu}/\varepsilon_{co}$	Avg. $\varepsilon_{cu}/\varepsilon_{co}$
SC-15-1-1	0.28	24.66	25.62	1.64	1.71	1.68	1.50	11.37	10.12
SC-15-1-2	0.28	26.58		1.77		1.31		8.87	
SC-15-2-1	0.57	33.25	34.09	2.22	2.27	3.50	3.46	23.70	23.39
SC-15-2-2	0.57	34.92		2.33		3.41		23.09	
SC-28-1-1	0.15	37.30	37.69	1.33	1.35	1.48	1.48	7.81	7.83

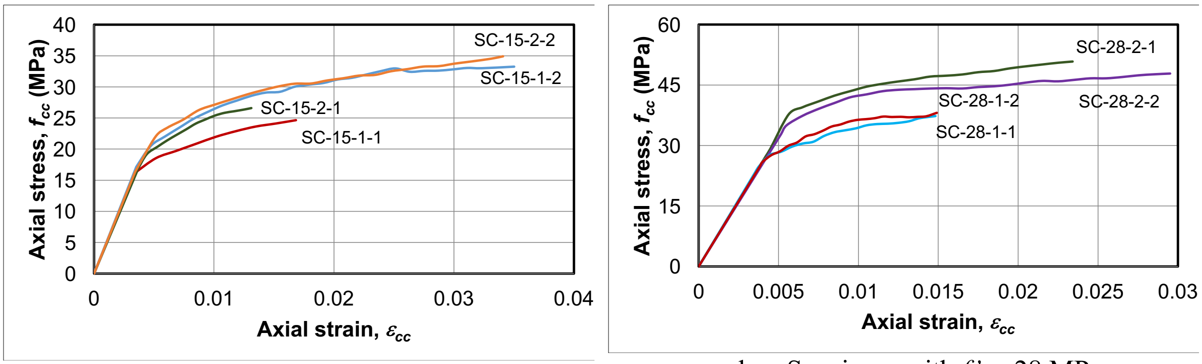
SC-28-1-2	0.15	38.08		1.36		1.49		7.86	
SC-28-2-1	0.30	50.83	49.33	1.82	1.76	2.34	2.65	12.34	13.95
SC-28-2-2	0.30	47.82		1.71		2.95		15.56	
CC-15-1-1	0.61	37.09	38.46	2.47	2.56	2.15	1.75	14.56	11.85
CC-15-1-2	0.61	39.83		2.66		1.35		9.14	
CC-15-2-1	1.22	56.59	56.40	3.77	3.76	3.10	3.26	20.99	22.04
CC-15-2-1	1.22	56.21		3.75		3.41		23.09	

The findings of this study agree with findings of Zhou et al. [11] . Zhou et al. [11] focuses in the behavior of confined FRP on circular lightweight concrete. Zhou et al. [11] confirms increase in the capacity of load and ultimate strain for concrete having FRP confinement. According to Zhou et al. [11], the stress-strain response of FRP-confined lightweight concrete primarily exhibits a bilinear response, initially exhibiting unconfined concrete behavior, then developing the FRP confined behavior, as noted with the present study where transition from elastic to plastic phase took longer due to FRP confinement. Subsequent studies have further examined the effects of lightweight aggregate characteristics, confinement configurations, stress–strain modelling, composite structural systems, and design-oriented prediction models for FRP-confined concrete [22–25].

Choosing both 15 MPa and 28 MPa concrete strengths helped provide a reasonable contrast between the low and medium grade lightweight concretes. The stress-strain curves highlights the difference as a result of varying the designed concrete mixes thus confirming the difference in design aimed at varying confinement effectiveness at different concrete strengths as noted in previous works [17,21].

3.3. *Influence of number of FRP Layers*

The influence of the number of FRP layers on lightweight concrete is shown in Figure 5. For both concrete strengths of 15 MPa and 28 MPa, specimens exhibited increases in stress and strain with the number of FRP layers and this is because of the increased levels of confinement that additional FRP layers provide. Similar improvements in strength and deformation capacity resulting from increased confinement have also been reported for FRP-confined lightweight aggregate concrete [17,21–23].



a. Specimens with f'_{co}=15 MPa

b. Specimen with f'_{co}=28 MPa

Figure 5. Influence of number of FRP layer

Table 3 indicates the ratio of f'_{cu}/f'_c increased by adding FRP layers. For specimens with an initial concrete strength of 15 MPa, the average f'_{cu}/f'_c value when two FRP layers were used was 2.27, which was significantly higher than the 1.71 recorded for single-layer confinement. In specimens of strength 28 MPa, a similar trend was observed as two FRP layers resulted in an average f'_{cu}/f'_c value of 1.76, while the single FRP layer provided a value of 1.35. These results show the added FRP layers improved the compressive strength of the tested lightweight concrete in direct proportion, a finding also reported by Li et al. [14]. Furthermore, the adaptability of lightweight concrete, evidenced by the ratio of $\varepsilon_{cu}/\varepsilon_{co}$, was markedly enhanced with the incorporation of FRP layers. For specimens exhibiting an initial strength of 15 MPa, the $\varepsilon_{cu}/\varepsilon_{co}$ ratio escalated from 10.12 with a single FRP layer to 23.39 with two layers.

A similar trend was seen in the 28 MPa specimens, where the ratio increased from 7.83 to 13.95. This demonstrates the fact that the additional FRP layers does not only increase the compressive strength, but also greatly improves the deformation capacity of the concrete prior to failure, which is crucial in the case of earthquake resistant structures. This is in line with the findings of de Diego et al. [13], where the number of FRP layers was shown to have a direct impact on the ductility of confined concrete.

3.4. Influence of Concrete Strength

Figure 6 shows the stress and strain relationships for 15 MPa and 28 MPa specimens, with one FRP layer. Specimens exhibiting elevated concrete strength demonstrated increased ultimate stress, although reduced ultimate strain. This pertains to the brittleness of concrete, as concrete with higher compressive strength exhibits more resistance to plastic deformation [18]. A number of studies have also shown the same trend, as in the work of Louk Fanggi et al. [17,21].

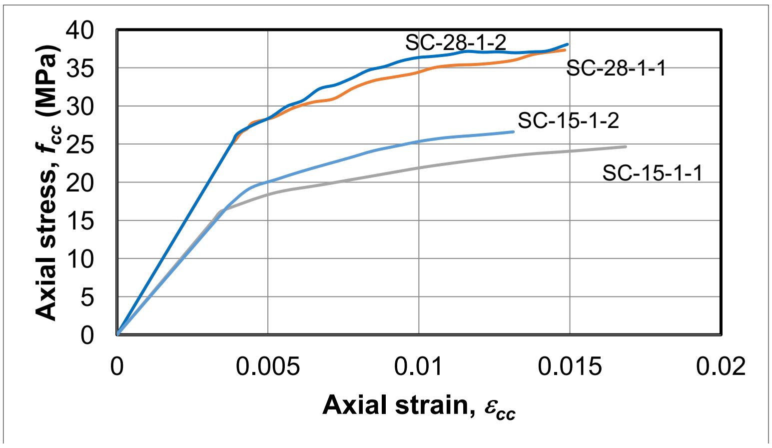


Figure 6. Influence of concrete compressive strength (f'_{co})

According to the data in Table 3, specimens with an initial compressive strength (f'_{co}) of 15 MPa confined with two FRP layers achieved an average ultimate stress (f'_{cu}) of 34.09 MPa, which is a 127% increase from the unconfined strength. On the other hand, the specimens with an initial strength of 28 MPa and 2 FRP layers attained an average f'_{cu} of 49.33 MPa, equating to an increase of 76 %. This demonstrates that even though concrete of a higher strength class does indeed gain the benefits of FRP confinement, the improvement in the concrete strength class has a less percentage gain than the improvement in lower strength concrete. This is also in agreement with Zhou et al. [7], which described that FRP has a greater improvement in compressive capacity only on lower strength classes of lightweight concrete.

Considering the strain, the specimens with f'_{co} = 15 MPa and 2 FRP layers attained an average ultimate strain (ε_{cu}) of 3.46 %. This is an increase of more than 20 times the initial strain of ε_{co} = 0.15 %. However, the specimens with f'_{co} = 28 MPa and 2 FRP layers attained an average ε_{cu} = 2.65 %, which is about 14 times the initial ε_{co} = 0.19 %. This shows that even though there is a remarkable increase in compressive capacity of higher strength concrete, the range of deformation capacity still remains less than lower-strength concrete. This is also described by Wu et al. [18], where the increased brittleness of higher strength concrete is which and the higher compressive strength of concrete is the most probable explanation.

3.5. Influence of Cross-sectional shape

Figure 7 demonstrates the influence of the cross-sectional shape on lightweight concrete confined with FRP. Compared to the square specimens, the circular specimens endured higher stress and strain. This can be explained by the more uniform confinement distribution for circular cross-sections. For square sections, confinement becomes concentrated at the corners [16]. This concentration of stress at the corners results in premature failure and ineffective confinement of the FRP on the square sections. The influence of confinement geometry and the more uniform distribution of lateral pressure in circular sections have also been incorporated into design-oriented models for FRP-confined concrete [25].

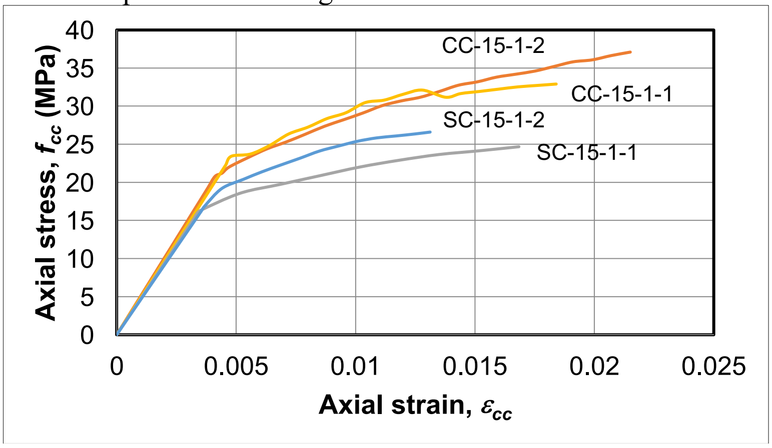


Figure 7. Influence of cross sectional shape

As indicated in Table 3, circular specimens, at 15 MPa compressive strength and with two FRP layers, reached an average ultimate stress (f'_{cu}) of 56.40 MPa. This is also higher than the square specimens at the same conditions, which reached 34.09 MPa. This 22.31 MPa difference validates that the circular cross-sections more effectively distribute FRP confinement around the column cross-section. This is also supported by Valasaki and Papakonstantinou [12] which showed the stark improvement of circular sections on the compressive strength of FRP-confined concrete.

From the deformation standpoint, the ultimate strain (ε_{cu}) of two FRP layers and 15 MPa strength circular specimens was 3.26% and square specimens was 3.46%. Even though the absolute strain of square specimens appears to be greater, the literature suggests that circular cross-sections should be able to sustain greater deformation than square ones [12,13]. This is most likely a result of technical issues related to the preparation of the circular specimens, like defective casting, or inconsistencies in the FRP wrapping that may have limited the specimens from achieving their maximum deformation potential. It is reasonable to assume that, regardless of the overall numerical value derived in this study, circular sections are still dominantly accepted in practice as having the greatest deformability.

It is still appreciated that the shape of a cross-section is a functional geometric factor in the effectiveness of FRP confinement. This is evident as lightweight concrete with circular sections has shown not only increased compressive capacity, but also increased ductility, and limited deformation. This indicates that reinforced structures that require a balance of high strength and high ductility will be best served with circular cross-sections.

3.6. Influence of Concrete unit weight

Table 4 includes the effect of unit weight on the stress–strain behavior of lightweight concrete. In this research, concrete specimens had a density of 1550 kg/m³ while Louk Fanggi et al [21] had a density of 1850 kg/m³ concrete specimens. All other parameters remained the same, including the type of FRP, number of layers, cross-sectional dimensions, and concrete strength. As such, this ensures that the differences explained interspersed unit weight was not the same concrete absence. This gives a basis for understanding the role of concrete density and the use of CFRP in concrete confinement. Previous investigations involving full lightweight aggregate concrete and FRP-based composite confinement systems have likewise demonstrated that aggregate characteristics and concrete density influence the resulting strength and deformation response [22,24].

In the numerical analysis, the compression strength of low density concrete stated in the f'_{cu}/f'_c ratio clearly articulated low density concrete had a relative reduction within the compressive capacity. For the specimens with an initial strength of 15 MPa and a reduction in density from 1850 to 1550 kg/m³, the f'_{cu}/f'_c ratio for single-layer confinement dropped from 2.02 to 1.71 and for double-layer confinement dropped from 3.59 to 2.27. A similar trend was recorded for the 28 MPa specimens with smaller differences from 1.43 to 1.35 for one layer and from 1.95 to 1.76 for two layers. This indicates that higher-density lightweight concrete has a greater response to FRP confinement in the concrete compressive strength than lower-density lightweight concrete. Contrarily, the ratio of the $\varepsilon_{cu}/\varepsilon_{co}$ showed other values in the deformation.

In the case of single-layer FRP and concrete specimens of 15 MPa strength, concrete of 1850 kg/m³ density surpassed the results of concrete of 1550 kg/m³ density. However, for double-layer confinement, concrete of lower density showed greater ultimate strain in comparison to specimens of higher density. For 28 MPa concrete, the differences between the densities were less visible for both the single and double layers. Still, the incorporation of FRP layers further accelerated the rate of deformability improvements, which provides evidence that lower density lightweight concrete, despite having lower compressive strength, possesses more ductility potential.

This contrast primarily reflects the differences between high density and low density lightweight concrete. While high density lightweight concrete provides greater compressive strength, low density lightweight concrete provides greater deformability. In a way, this reflects a strength and ductility trade-off, which is an important aspect in structural design. This further confirms the results of Zhou et al. [11] that FRP confinement is also effective in improving the deformability of lightweight concrete, especially lower density concrete which is more susceptible to brittle failure.

Tabel 4. influence of concrete unit weight

Source	Specimen	f'_{cu} (MPa)	Avg. f'_{cu} (MPa)	f'_{cu}/f'_c	Avg. f'_{cu}/f'_c	ε_{cu} (%)	Avg. ε_{cu} (%)	$\varepsilon_{cu}/\varepsilon_{co}$	Avg. $\varepsilon_{cu}/\varepsilon_{co}$	Density (Kg/m^3)
Louk Fanggi et al. [2]	SC-15-1-1	30.18	30.37	2.01	2.02	2.05	2.34	13.88	15.81	1850
	SC-15-1-2	30.56		2.04		2.62		17.74		
	SC-15-2-1	53.34	53.85	3.56	3.59	3.11	3.23	21.05	21.83	
	SC-15-2-2	54.35		3.62		3.34		22.61		
	SC-28-1-1	39.37	39.91	1.41	1.43	1.46	1.46	7.70	7.70	1850
	SC-28-1-2	40.44		1.44		-		-		
	SC-28-2-1	53.26	54.71	1.90	1.95	2.80	2.63	14.77	14.77	
	SC-28-2-2	56.16		2.01		2.46		-		
Present Study	SC-15-1-1	24.66	25.62	1.64	1.71	1.68	1.50	11.37	10.12	1550
	SC-15-1-2	26.58		1.77		1.31		8.87		
	SC-15-2-1	33.25	34.09	2.22	2.27	3.50	3.46	23.70	23.39	
	SC-15-2-2	34.92		2.33		3.41		23.09		
	SC-28-1-1	37.30	37.69	1.33	1.35	1.48	1.48	7.81	7.83	1550
	SC-28-1-2	38.08		1.36		1.49		7.86		
	SC-28-2-1	50.83	49.33	1.82	1.76	2.34	2.65	12.34	13.95	
	SC-28-2-2	47.82		1.71		2.95		15.56		

These outcomes further validate the selection of 15 MPa and 28 MPa as representative strength levels, which not only reflect practical ranges of lightweight concrete but also allow meaningful comparison with earlier investigations [17,21]. This alignment underscores the consistency of the experimental program with established benchmarks in FRP confinement research.

4. Conclusion

The aim of this study was to assess the impact of CFRP confinement on lightweight concrete within the frameworks of several parameters: failure modes, number of FRP layers, concrete strength, cross-sectional shape and unit weight. Regarding the experimental results, the following points are of particular importance:

1. The observations on failure modes showed that square specimens failed more quickly at the corners because of concentrated stresses; in contrast, circular specimens had more uniform rupture failure.
2. The implementation of FRP layers markedly enhanced the compressive strength and ductility of the concrete. The supplementary layers efficiently confined the concrete, allowing it to endure greater loads and elevated deformations at failure.
3. The strength of concrete had an impact on the behavior of the concrete. With low strength concrete, ductility markedly improved more after confinement, while brittle high strength concrete was dominant, despite the increase in compressive capacity.
4. The shape of the cross-section affected the effectiveness of the confinement. The circular cross-section bore uniform confinement while the square cross-section produced corner confinement.
5. The unit weight of concrete had an impact on the concrete's balance between strength and deformability. High-density lightweight concrete possessed greater compressive strength while low-density lightweight concrete offered superior deformability.

Future studies could examine concrete of varying densities, additional FRP layers, and different loading patterns and other structural parameters. Reseach can then focus on the practical use of materials with ductility and material efficiency, potentially advancing the performance and resilience of earthquake-resistant constructions.

Declaration of AI and AI assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT (OpenAI) in order to assist with language editing, sentence restructuring, and improving the clarity and readability of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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