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# An Experimental Study on Axial Stress-Strain Behaviour of FRP-Confined Square Lightweight Aggregate Concrete Columns

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**Abstract**. This article presents the results of a research project that aimed to evaluate how the number of fiber-reinforced polymer (FRP) layers and the compressive strength of concrete affect the stress-strain behaviors of concrete columns produced from artificial lightweight aggregate with square cross-sectional shapes. Eighteen test specimens were manufactured and wrapped with glass fiber-reinforced polymer (GFRP) material. The specimens were later subjected to concentric compression for experimental evaluation. The experimental results suggest that GFRP efficiently confines square lightweight aggregate concrete columns. Furthermore, the test results indicate that adding FRP layers augments the ultimate stress and strain. Finally, the results suggest that an increase in the compressive strength of concrete leads to a corresponding increase in the ultimate stress. On the other hand, it has been observed that the ultimate strain decreases as compressive strength increases. The research findings reveal the behaviour of FRP-confined square lightweight aggregate concrete columns, which may also be utilized to formulate a new design-oriented model for these columns.

**Keywords**: Fiber Reinforced Polymer, artificial lightweight aggregate, compressive strength, square cross-section, confinement.

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## 1. Introduction

A study [1] show that lightweight concrete's density is below 1950 kg/m3. Due to its diminished mass, lightweight concrete suits region prone to earthquakes such as Indonesia [2]. The utilisation of this particular type of concrete has the potential to decrease the overall weight of the building, hence resulting in a reduction of the seismic load exerted on the structure [1].

One approach to producing lightweight concrete involves the replacement of natural aggregate with artificial lightweight aggregate (ALWA). The necessity of utilising artificial aggregate has arisen due to the detrimental environmental impacts associated with the overutilisation of natural aggregate [3].

In addition to its 30% reduction in weight compared to conventional concrete, lightweight concrete offers other benefits not present in normal (conventional) concrete, including enhanced thermal and acoustic insulation properties [1]. However, the utilisation of this particular type of concrete is hindered by certain limitations, primarily its low ductility and strength [1], [4].

Fiber Reinforced Polymer (FRP) material has been recognised for its ability to enhance and strengthen the structure when it is compromised [5]. Fibre-reinforced polymer is widely recognised for its strength-to-weight ratio, resistance to corrosion, ease of application, and rapid installation [6]. Large number of experimentally study has been carried out on the subject of FRP-confined concrete columns (FCCCs), as documented by Lin and Teng [7]. The results of these studies demonstrate that the utilisation of FRP enhances both the strength and ductility of FCCCs [8]–[14].

A research study investigates the limitations of lightweight concrete columns by implementing FRP as external confinement on FCCCs. The research was conducted by Zhou et al. [15], [16] dan Louk Fanggi et al. [17]–[19]. The results confirm the effectiveness of employing FRP as an external confinement for lightweight aggregate concrete. Nevertheless, the study exclusively examines FCCCs constructed using circular cross-sectional shapes.

The effectiveness of carbon FRP in square FCCCs made of artificial lightweight aggregate is currently the subject of studies by Louk Fanggi et al [20] and Li et al [21]. However, existing studies have focused on confining square lightweight concrete columns with CFRP and BFRP, and no research has documented the behavior of FRP-confined square lightweight aggregate concrete columns with Glass FRP (GFRP) as the confining material.

This study represents an initial attempt to test the effectiveness of confining concrete columns made of artificial lightweight aggregate with a square cross-sectional shape with GFRP. The parameters investigated include the number or quantity of FRP layers and the compressive strength of concrete.

## 2. Methods

### *2.1. Test Specimens*

This study conducted experiments on a total of 18 square FCCCs. These columns had dimensions of 150 mm X 150 mm, had a radius of curvature of corner of 25 mm, and had a height of 300 mm. The columns were constructed using artificial lightweight aggregate and were wrapped with GFRP. The experimental testing continued until the columns experienced failure. The details of each test specimen are presented in Table 1.

**Table 1.** Detail of test specimen

| Specimen | Applied layer of FRP number | Compressive strength of concrete, $f'_c$ (MPa) | Concrete strain at peak stress, $\varepsilon_{co}$ (%) | Number of specimens |
|---|---|---|---|---|
| S G-15-1-1&2 | 1 | | | 2 |
| S G-15-2-1&2 | 2 | 15 | 0,15 | 2 |
| S G-15-3-1&2 | 3 | | | 2 |
| S G-28-1-1&2 | 1 | | | 2 |
| S G-28-2-1&1 | 2 | 28 | 0,19 | 2 |
| S G-28-3-1&2 | 3 | | | 2 |
| S G-38-1-1&2 | 1 | 38 | | 2 |
| S G-38-2-1&2 | 2 | | 0,21 | 2 |
| S G-38-3-1&2 | 3 | | | 2 |

The strain values ($\mathcal{E}_{co}$) presented in this table were derived from calculations using the formula proposed by Tasdemir et al. [22].

*2.2. Materials*

The test specimens were manufactured using three different concrete mixtures. The detail of the mixtures can be seen in Table 2.

**Table 2.** Detail of concrete material composition

| Concrete Strength (MPa) | Water ($kg/m^3$) | Cement ($kg/m^3$) | River Sand ($kg/m^3$) | Lightweight Coarse Aggregate (ALWA) ($kg/m^3$) | Silica Fume ($kg/m^3$) | Superplasticizer ($kg/m^3$) |
|---|---|---|---|---|---|---|
| 15 | 207,65 | 305,36 | 943,79 | 394,20 | - | - |
| 28 | 207,65 | 432,60 | 816,56 | 394,20 | 43,26 | 34,61 |
| 38 | 207,65 | 519,12 | 730,04 | 394,20 | 51,91 | 41,53 |

Artificial lightweight coarse aggregate, ALWA as presented in Figure 1, typically has a maximum particle size of 10 mm. The physical examination of the specific gravity, volume weight, water content, and absorption rate of ALWA is 1.40, 768,57 $kg/m^3$, 0.2%, and 13.12%, respectively.

**Figure 1.** Shape of ALWA

*2.3. Specimen Preparation, Instrumentation, and Testing*

One week before the test day, the test specimens, which possess a dry surface, are wrapped in layers of GFRP. The procedure for applying FRP to the test specimens use the Wet Lay-Up technique. GFRP has a tensile strength of 3.24 GPa and a tensile modulus of 72.4 GPa. The test specimen is capped with gypsum at both ends before testing to distribute the loading uniformly. Subsequently, the test specimen is equipped with several lateral strain gauges (SG) and linear variable differential transformers (LVDT). The test specimen has strain gauges mounted to each corner, as depicted in Figure 2. The strain gauge data will be subsequently analysed for information regarding the horizontal strain's magnitude upon the test specimen's destruction.

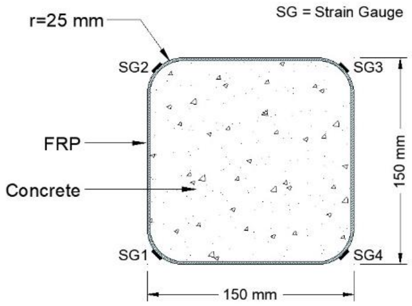



**Figure 2.** Location of lateral strain gauges

A cage LVDT frame, depicted in Figure 3, was attached to the middle part of the test specimen, having four Linear Variable Differential Transformers (LVDTs). The placement of LVDTs is centred on each side of the flat surface of the test specimen. The strain data along the middle part of the test specimen was obtained using the four LVDTs. The strain data along the height of the test specimen is acquired using the Linear Variable Differential Transformer (LVDT) installed on the Universal Testing Machine (UTM). The overall strain experienced by a test specimen can be determined by combining strain data from the LVDT frame and UTM machine. This approach allows for the analysis of strain behaviour throughout the entire curve, including the elastic and non-elastic regions, until the point of failure. Louk Fanggi dan Ozbakkaloglu employed this methodology in their study [23].

The test specimens underwent testing utilising a Universal Testing Machine (UTM) with servo-hydraulic control with a maximum load capacity of 2000 kN. The experiment applied displacement control, maintaining a consistent load with a 0.003 mm/second velocity.

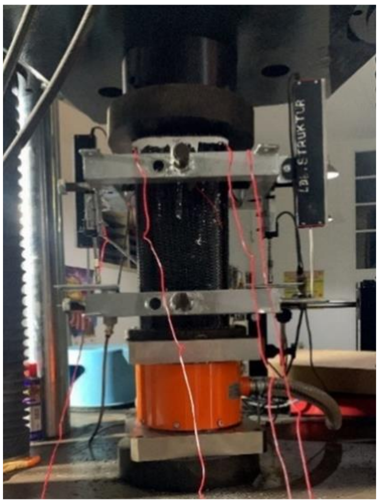
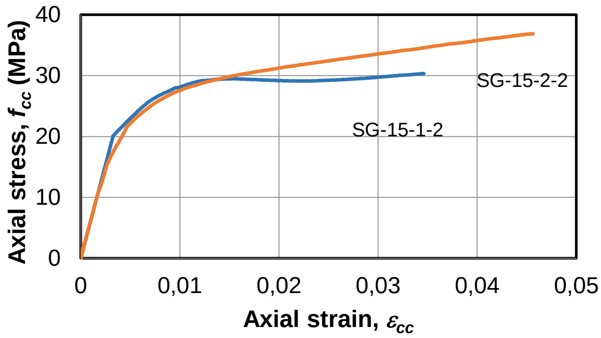


**Figure 3.** Cage LVDT

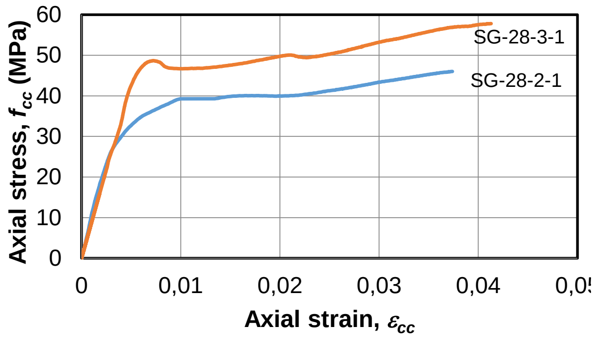
## 3. Results and Discussion

### *3.1. Impact of Number of FRP layers*

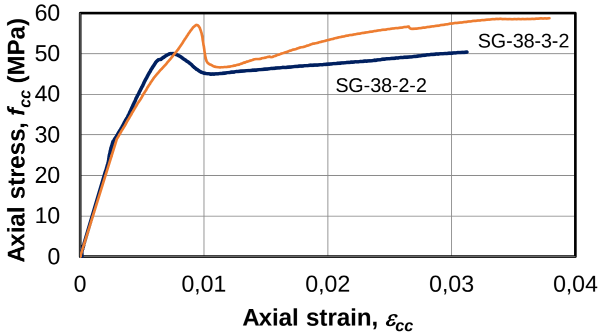
The impact of the number or quantity of GFRP layers employed in wrapping the test specimen is illustrated in Figure 4. The impact of the number of layers of 1, 2, and 3 GFRP layers with compressive strength of 15 MPa ($f'_c$=15 MPa) is illustrated in Figure 4a. The impact of the number of layers of 2 and 3 GFRP layers with a compressive strength of 28 MPa ($f'_c$ = 28 MPa) is illustrated in Figure 4b. The impact of the number of layers 1 and 2 of GFRP with compressive strength of 38 MPa ($f'_c$ = 38 MPa), is depicted in Figure 4c.




a.




b.




c.

**Figure 4.** Impact of numbers of FRP layers: (a) 15 MPa square FCCCs with 1 and 2 layers of FRP, (b) 28 MPa square FCCCs with 2 and 3 layers of FRP, and (c) 38 MPa square FCCCs with 2 and 3 layers of FRP.

The presented figures demonstrate a clear correlation between the increase in GFRP layers and the corresponding increases in ultimate stress ($f'_{cu}$) and strain ($\mathcal{E}_{cu}$). A similar observation is also evident in Table 3. This finding demonstrates a positive correlation between the number of layers and the resulting ultimate stress ($f'_{cu}$) or ultimate strain ($\mathcal{E}_{cu}$). This phenomena is associated with the confinement effect of Fiber Reinforced Polymer (FRP), where increasing the number of layers results in higher pressure applied to the concrete. This has been extensively documented by earlier investigations [17-20]. Previous studies undertaken by Zhou et al. [15, [16] dan Louk Fanggi et al. [16]–[20] also confirm the same findings. It can also be seen from the figures that when the number of FRP layers increases, the slope of the ascending second portion also increases.

The data also shown in Figure 4 demonstrates that the specimens possessing a compressive strength of 15 MPa (SG-15-1) display an ascending trend in the second portion of their stress-strain curve. However, it is evident that the curve has a near-flat shape, suggesting that the confinement ratio surpasses the minimum threshold. Lam and Teng [24] established that a minimal value of 0.07 applies to rectangular FCCCs constructed with normal concrete. According to the data presented in Table 3, the confinement ratio value for test specimen SG-15-1-1 is 0.4. This suggests that in the case of lightweight concrete, a higher confinement ratio is required in order to achieve an ascending second part. The observed bi-linear lines indicate that applying GFRP wrapping improves the stress and strain capacity of the square FCCCs made from the artificial lightweight aggregate.

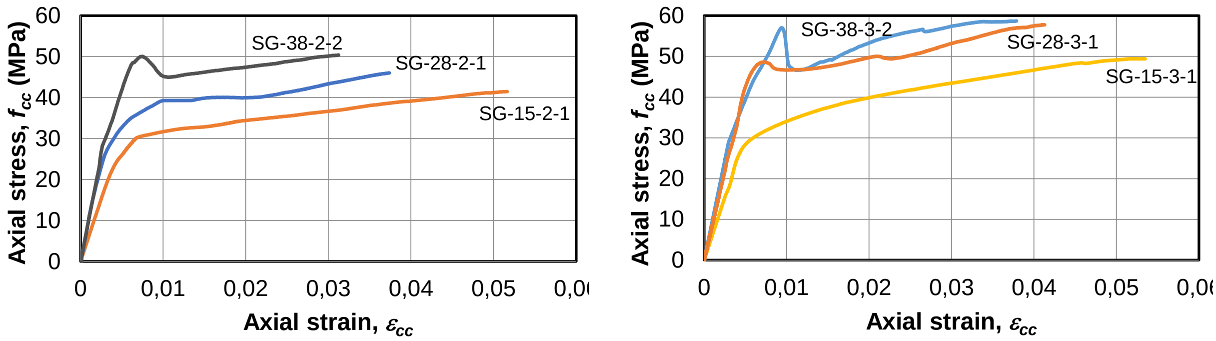
**Table 3.** Ultimate conditions of the tested specimens

| Specimen | $f_l/f'_c$ | $f'_{cu}$ (MPa) | Avg. $f'_{cu}$ (MPa) | $f'_{cu}/f'_c$ | Avg. $f'_{cu}/f'_c$ | $\mathcal{E}_{cu}$ (%) | Avg. $\mathcal{E}_{cu}$ (%) | $\mathcal{E}_{cu}/\mathcal{E}_{co}$ | Avg. $\mathcal{E}cu/\mathcal{E}co$ |
|---|---|---|---|---|---|---|---|---|---|
| S G-15-1-1 | 0,40 | 29,50 | 29,92 | 1,97 | 1,99 | 1,49 | 2,48 | 10,09 | 16,76 |
| S G-15-1-2 | 0,40 | 30,33 | | 2,02 | | 3,46 | | 23,42 | |
| S G-15-2-1 | 0,81 | 41,50 | 39,18 | 2,77 | 2,61 | 5,17 | 4,99 | 35,00 | 33,78 |
| S G-15-2-2 | 0,81 | 36,85 | | 2,46 | | 4,81 | | 32,56 | |
| S G-15-3-1 | 1,21 | 49,38 | 48,55 | 3,29 | 3,24 | 5,35 | 5,46 | 36,22 | 36,93 |
| S G-15-3-2 | 1,21 | 47,71 | | 3,18 | | 5,56 | | 37,64 | |
| S G-28-1-1 | 0,22 | 40,41 | 39,53 | 1,44 | 1,41 | - | - | - | - |
| S G-28-1-2 | 0,22 | 38,64 | | 1,38 | | - | | - | |
| S G-28-2-1 | 0,43 | 46,01 | 46,49 | 1,64 | 1,66 | 3,74 | 3,74 | 19,73 | 19,73 |
| S G-28-2-2 | 0,43 | 46,96 | | 1,68 | | - | | - | |
| S G-28-3-1 | 0,65 | 57,79 | 57,39 | 2,06 | 2,05 | 4,13 | 4,13 | 21,78 | 18,72 |
| S G-28-3-2 | 0,65 | 56,99 | | 2,04 | | 2,97 | | 15,66 | |
| S G-38-1-2 | 0,16 | 40,59 | 39,70 | 1,07 | 1,04 | - | - | - | - |
| S G-38-1-2 | 0,16 | 38,80 | | 1,02 | | - | | - | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| S G-38-2-1 | 0,32 | 45,51 | 47,96 | 1,20 | 1,26 | 3,44 | 3,28 | 16,06 | 15,31 |
| S G-38-2-2 | 0,32 | 50,41 | | 1,33 | | 3,12 | | 14,56 | |
| S G-38-3-1 | 0,48 | 58,70 | 56,84 | 1,54 | 1,50 | 3,79 | 3,07 | 17,69 | 16,01 |
| S G-38-3-2 | 0,48 | 54,97 | | 1,45 | | 3,07 | | 14,33 | |

### *3.2. Impact of concrete strength (f'c)*

Figure 5 illustrates the impact of different changes in compressive strength on test specimens wrapped with GFRP. Figure 5a illustrates the impact of increasing the compressive strength of concrete, ranging from 15 MPa to 38 MPa, on test specimens with a single layer of GFRP. Figure 5b illustrates the impact of increasing the compressive strength of concrete ($f'_c$), ranging from 15 to 38 MPa, on specimens wrapped with two layers of GFRP.




a. b.

**Figure 5.** Impact of compressive strength of concrete: (a) FCCCs with two layers of FRP and compressive strength of concrete of 15, 28, and 38 MPa, (b) FCCCs with three layers of FRP and compressive strength of concrete of 15, 28, and 38 Mpa

The two figures presented demonstrate a positive correlation between the comprrssive strength of concrete ($f'_c$) and the ultimate stress ($f'_{cu}$), as well as a negative correlation between the strength of concrete ($f'_c$) and the ultimate strain ($\mathcal{E}_{cu}$). The findings indicate that an increase in concrete strength ($f'_c$) rises the ultimate stress ($f'_{cu}$) while simultaneously reduces the ultimate strain ($\mathcal{E}_{cu}$). Zhou et al. [15], [16] have also reported a comparable finding. However, it is evident from Table 3 that there is a decrease in the degree of increase in the ultimate stress ($f'_{cu}$) when the compressive strength of concrete ($f'_c$) increase. The aforementioned phenomenon that increase in compressive concrete strength ($f'_c$) rises the ultimate stress ($f'_{cu}$) while simultaneously reduces the ultimate strain ($\mathcal{E}_{cu}$) can be attributed to the natural features of the concrete material. Specifically, it can be noted that concrete possessing a greater compressive strength tends to exhibit a larger degree of brittleness compared to concrete with a lower strength. Consequently, this brittleness leads to an increase in the ultimate stress ($f'_{cu}$) but a decrease in the ultimate strain ($\mathcal{E}_{cu}$). The findings also suggest that an increase in ultimate stress ($f'_{cu}$) and a decrease in ultimate strain ($\mathcal{E}_{cu}$) with increased GFRP layers may exhibit slight discrepancies compared to the specific details provided in Table 3. Specifically, when comparing the ultimate stress ($f'_{cu}$) between specimens SG-28-2-1 and SG-15-2-1&2, it is evident that the $f'_{cu}$ value observed in specimen SG-38-2-1, which possesses a compressive strength of 38 MPa, is marginally lower than the $f'_{cu}$ value observed in specimen SG-28-2-1&2. Similarly, a comparison can be made between test specimens possessing compressive strengths of 38 MPa (SC-38-3-2) and 28 MPa (SG-28-3-1&2). The occurrence of lower or nearly equivalent $f'_{cu}$ values in items with lower compressive strength or differing from the results above might be attributed to defective processes when applying FRP wrapping to the test specimens.

The figures additionally demonstrate that, for specimens with compressive strengths of exceeding 15 MPa, the stress showed any fluctuation in its second part as shown in figures 5a-b. The noticed phenomenon can be ascribed to the inherent brittleness of lightweight concrete. This brittleness is a result of the increase in concrete strength, which causes a shift in the fracture patterns within the material. Specifically, the transition occurs from distribution of heterogeneous microcracks to the formation of localized macrocracks. This transition eventually results in an accelerated and uncontrolled expansion of the concrete, triggering the mechanism of confinement. It is worth noting that this mechanism is initiated only after a significant level of damage has been inflicted upon the concrete. The phenomen has been described clearly in Ozbakkaloglu [25].

Li et al. [21] characterize the typical stress-strain behavior of FRP-confined lightweight aggregate concrete columns, comprising three phases: elastic, transitional, and stress recovery stages. The study indicated that stress drops after attaining its peak during the transitional phase. By comparing the test data illustrated in Figure 5 with that of Li et al. [21], it is evident that the reduction in stress is particularly noted in specimens with a concrete strength of 38 MPa. This suggests that smoothing the corner edges improves the effectiveness of FRP in confining square lightweight aggregate concrete columns, as described by Al-Salloum [26].

The findings of this study clarify experimentally the influence of the quantity of FRP layers and the compressive strength of concrete on the stress-strain of square concrete columns constructed from artificial lightweight aggregate wrapped in GFRP. In addition to characterising the stress-strain response, the findings of this study can also be utilised to develop a mathematical model for predicting the ultimate condition of square columns constructed from lightweight aggregate and reinforced with fiber-reinforced polymer (FRP) wrapping. In order to thoroughly assess the effectiveness of employing FRP as a external confinement layer for concrete columns composed of artificial lightweight aggregate, additional investigation is required that incorporates both artificial lightweight coarse aggregate and artificial lightweight fine aggregate. In order to conduct a more comprehensive study on the effectiveness of wrapping lightweight concrete columns, it is necessary to consider the weight of the column as the investigated parameter.

## 4. Conclusion

This study investigates the results obtained from 18 test specimens that were produced using artificial lightweight aggregate and then wrapped with glass fiber-reinforced polymer (GFRP) material. The study findings suggest that the performance of square lightweight aggregate concrete columns can be enhanced by wrapping them with glass fiber-reinforced polymer (GFRP). With an increase in the number of Glass Fiber Reinforced Polymer (GFRP) layers, there is a corresponding increase in both the ultimate stress ($f'_{cu}$) and ultimate strain ($\mathcal{E}_{cu}$). Moreover, as the compressive strength ($f'_c$) rises, the ultimate stress ($f'_{cu}$) also increases. Conversely, the ultimate strain ($\mathcal{E}_{cu}$) exhibits an inverse relationship with the compressive strength ($f'_c$), indicating that as the compressive strength ($f'_c$) grows, the ultimate strain ($\mathcal{E}_{cu}$) decreases.

This paper investigates a lack of understanding of the behaviour of FRP-confined square lightweight aggregate concrete columns. Furthermore, the test data may facilitate the development of a new design-oriented model for FRP-confined square concrete columns. Future research may enhance the comprehension of the behaviour of FRP-confined square lightweight aggregate concrete columns by integrating both fine and coarse lightweight aggregates into concrete mixtures.

## 5. Acknowledgements

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