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MECHANICAL PERFORMANCE OF CELLULAR LIGHTWEIGHT CONCRETE USING FLY ASH AS PARTIAL CEMENT REPLACEMENT

*Reni Suryanita[1], Yohannes Firzal[1], Harnedi Maizir[2] and Raihan Arditama Harnedi[3]

[1]Faculty of Engineering, Universitas Riau, Indonesia; [2]Department of Civil Engineering, Sekolah Tinggi Teknologi Pekanbaru, Indonesia; [3]PT. Dynamic Testing Indonesia, Indonesia

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ABSTRACT: Cellular Lightweight Concrete (CLC) is widely recognised for its low density and good thermal insulation performance; however, its relatively low compressive strength limits broader engineering applications. This study investigates the effect of fly ash as a partial cement replacement on the physical and mechanical properties of CLC mortar. CLC specimens were prepared with fly ash replacement levels of 0%, 10%, and 15% by mass of cement using a protein-based foaming agent. The specimens were tested at curing ages of 7, 14, 28, and 56 days to evaluate density, compressive strength, and deformation behaviour. The experimental results show that the incorporation of fly ash significantly influences the strength development of CLC. The 10% fly ash mixture achieved the highest compressive strength of 0.960 MPa at 56 days, exceeding both the control mixture (0.852 MPa) and the 15% fly ash mixture (0.720 MPa). The improvement in strength at the 10% replacement level is attributed to enhanced pozzolanic reactions and improved matrix densification, resulting in a more uniform pore structure. In contrast, a higher replacement level of 15% led to reduced strength development, likely due to dilution of the cementitious content and delayed hydration. Within the investigated range, a 10% fly ash replacement provides an optimal balance between compressive strength and density, indicating its suitability for non-structural to semi-structural lightweight applications. The findings demonstrate the potential of fly ash-based CLC as a more sustainable construction material by reducing cement consumption while maintaining acceptable mechanical performance.

Keywords: Cellular lightweight concrete (CLC), Fly ash, Compressive strength, Physical properties, Sustainable construction materials

1. INTRODUCTION

The construction industry is increasingly challenged to develop materials that meet technical performance requirements while simultaneously addressing environmental sustainability. Conventional concrete production relies heavily on Portland cement, whose manufacturing process is energy-intensive and contributes significantly to global carbon dioxide emissions. In parallel, modern construction practices demand materials that can reduce structural dead load, improve thermal efficiency, and simplify on-site construction. These combined challenges have accelerated interest in lightweight and resource-efficient construction materials.

Cellular Lightweight Concrete (CLC) is one such material that has attracted growing attention in recent years. CLC is produced without coarse aggregates and incorporates preformed foam to generate a system of uniformly distributed air voids within a cementitious matrix. This cellular structure results in a material with relatively low density [1], good thermal insulation properties [2,3], and ease of handling [4]. Consequently, CLC has been widely applied in non-structural and semi-structural components, such as partition walls, lightweight blocks, and infill materials. However, despite these advantages, the low compressive strength of CLC remains a significant limitation that restricts its broader application in construction [5–7].

The mechanical performance of CLC is strongly governed by its density, pore structure, and binder composition. While reducing density improves lightweight characteristics and insulation performance, it also reduces load-bearing capacity. Previous studies have shown that optimising the cementitious matrix is essential to improving the strength of CLC without compromising its lightweight nature. This has led researchers to explore the use of supplementary cementitious materials as partial replacements for cement in CLC mixtures [8].

At the same time, fly ash—an industrial byproduct of coal combustion in thermal power plants—continues to accumulate and pose environmental challenges when inadequately managed [9,10]. Large quantities of fly ash continue to accumulate worldwide, posing environmental and disposal challenges. Interestingly, fly ash contains significant amounts of silica and alumina, which exhibit pozzolanic properties. This reaction contributes to the formation of additional calcium silicate hydrate, which can enhance matrix densification and long-term strength while reducing cement consumption and associated carbon emissions. The incorporation of fly ash into lightweight and foamed concrete systems has been reported to improve workability, refine pore structure, and enhance durability-related properties, particularly at moderate replacement levels. In the context of CLC, fly ash may play a dual role: improving the microstructural integrity of the cementitious matrix while contributing to more sustainable material production. However, the presence of a highly porous structure in CLC introduces additional complexity. Excessive fly ash replacement may dilute the cement content and delay early-age strength development, while insufficient replacement may limit its pozzolanic benefits. As a result, determining an optimal fly ash content for CLC remains a critical issue.

Concrete's strength and durability can be increased by adding more binding chemicals through a chemical reaction between fly ash and the calcium hydroxide generated during cement hydration [11]. In addition to lowering dependency on Portland cement, whose manufacture significantly increases CO2 emissions, using fly ash in concrete provides a practical way to recycle industrial waste [12].

Recent studies have demonstrated that partially replacing cement with fly ash in CLC mixtures can improve microstructural density, resistance to aggressive environments, and long-term compressive strength [13–15]. However, there is still a lack of specific research on how fly ash affects the physical and mechanical properties of lightweight CLC blocks, particularly regarding optimal mix proportions, dry density, water absorption, and compressive strength. On the other hand, the use of high-volume fly ash must also be evaluated for its practicality and consistency in delivering quality results.

Although numerous studies have examined fly ash in conventional concrete and foamed concrete, experimental investigations specifically focused on fly ash-based cellular lightweight concrete with controlled low-strength targets remain limited. In particular, systematic evaluations of how fly ash replacement levels influence density, compressive strength development, and deformation behaviour of CLC at different curing ages are not yet well established. This gap underscores the need for experimental data to support practical mix design recommendations for sustainable CLC applications.

Therefore, the study focuses on experimentally investigating the physical and mechanical properties of CLC incorporating fly ash as a partial cement replacement. The effects of different fly ash replacement levels on density, compressive strength, and deformation characteristics are evaluated at various curing ages. The novelty of this study lies in identifying an optimal fly ash content that enhances the mechanical performance of low-density CLC while maintaining its lightweight characteristics, providing experimental evidence that supports the practical use of fly ash-based CLC in sustainable construction. This study aims to address two critical issues: improving the technical performance of CLC blocks and reducing the environmental impact of fly ash disposal. By evaluating the effect of fly ash as a partial replacement for cement in CLC mixtures, this research aims to identify an optimal formulation that balances strength, durability, and material efficiency. The findings are expected to support the development of greener, more sustainable, and resource-efficient construction practices.

2. RESEARCH SIGNIFICANCE

This research contributes to both engineering practice and environmental sustainability by evaluating the role of fly ash in improving the performance of CLC. By identifying an optimal fly ash replacement level that enhances compressive strength without significantly increasing density, the study provides practical guidance for designing low-strength CLC suitable for non-structural and semi-structural applications. In addition, the utilisation of fly ash as a partial cement replacement supports waste valorisation, reduces cement consumption, and lowers the carbon footprint of construction materials. The findings offer experimental insights that can assist engineers and material designers in developing more sustainable, resource-efficient lightweight concrete systems.

3. MATERIALS AND METHODS

3.1. Materials

The chemical composition of the Portland Composite Cement (PCC) and fly ash used in this study was determined using X-Ray Fluorescence (XRF) analysis. The chemical composition of the PCC used in this study is dominated by oxides, including CaO (62.3%), SiO_2 (min. 20%), and Al_2O_3 and Fe_2O_3 (max. 6%), as typically reported in technical data sheets of domestic cement manufacturers. This type of cement contains a blend of clinker, gypsum, and supplementary cementitious materials. According to ASTM C 150-04, the chemical composition of cement must include a minimum concentration of CaO, SiO2, Al2O3, and Fe2O3. XRF testing of PCC cement showed that the CaO, SiO_2, Al_2O_3, and Fe_2O_3 content in the cement met the ASTM C 150-04 standard. The XRD results for the PCC showed a diffraction pattern indicating that the dominant phases in the material were calcite (CaCO3) and monoclinic calcium silicate (Ca3SiO5).

The major constituents of the fly ash (Fig.1) include silicon dioxide (SiO_2) at 53.74%, followed by aluminium oxide (Al_2O_3) at 22.568%, and iron oxide (Fe_2O_3) at 9.251%. Fly ash characteristics were tested using X-Ray Fluorescence (XRF) to determine chemical characteristics and X-Ray Diffraction (XRD) to identify atomic and oxide content in fly ash. XRF test results showed that fly ash contained 85.559% SiO2 + Al2O3 + Fe2O3 and met ASTM class C specifications.

Based on the XRD test results, fly ash material shows a diffraction pattern with the dominant phase identified as the quartz (Q) crystal phase at an angle between (20-30) for the silica (SiO_2) structure and the mullite crystal phase at angles between 30-40, 40-45 and 60-65 for the alumina (Al_2O_3) structure. The highest relative-intensity peak for silica occurs at $2\theta \approx 26.62\,°$ in the quartz crystalline phase. Furthermore, the alumina (Al_2O_3) structure has an orthorhombic crystal system with a $2\theta \approx 26.27°$ for the mullite phase. The XRF testing results indicate that silica (SiO_2) has the highest composition, followed by alumina (Al_2O_3) as the second-largest component.

To create the cellular structure of the lightweight concrete, a protein-based foaming agent was used. The foaming agent was selected for its ability to produce stable, consistent bubbles, resulting in a uniform pore distribution and improved mechanical performance. The foaming agent was diluted with water and mechanically pre-foamed using a high-speed mixer before being incorporated into the concrete mix. Clean tap water was used in all mixes for hydration and foam preparation, ensuring no impurities that could interfere with the chemical reactions.

Additionally, silica sand with a particle size passing 1.18 mm was included in selected mixtures to enhance packing density, reduce segregation, and improve particle interlocking in the matrix. All materials were stored in dry conditions and brought to room temperature before use.

Their selection and proportions were based on preliminary trials and previous literature to ensure the CLC blocks' practical relevance and optimal performance.

Fig.1 Fly Ash

3.2. Methods

The experimental program evaluated three fly ash replacement levels—0%, 10%, and 15% by mass of cement. Prior to mix design, fine aggregate characterisation included moisture content, bulk density, specific gravity, organic impurities, silt content, and particle-size distribution, as per relevant ASTM procedures. For each replacement level, five CLC mortar cubes (100 mm) were prepared and cured for 7, 14, 28, and 56 days prior to testing (Table 2). All aggregate tests were conducted in accordance with standard ASTM procedures [16,17].

The design strength of the CLC mortar mixture is 1 MPa with a wet density of 1.013 t/m³. After curing, the CLC mortar specimens exhibited a distinct cellular structure and uniform geometry, reflecting the effectiveness of the protein-based foaming agent in producing stable pore distribution within the cementitious matrix. The physical appearance of representative CLC mortar cubes prepared in this study is shown in Fig. 2, which illustrates the surface texture, shape integrity, and overall quality of the specimens prior to mechanical testing.

Table 1. Composition of CLC mortar mixture

Variation of Fly ash (%)	Water (kg)	Sand (kg)	Foam (kg)	Cement (kg)	Fly Ash (kg)
0	1.01	3.45	0.29	2.03	0.00
10	1.01	3.45	0.29	1.82	0.10
15	1.01	3.45	0.29	1.72	0.20

Table 2. Total of CLC mortar specimens

Variation of Fly ash (%)	(Testing Day)				Total of each variation	Total of Specimen
	7	14	28	56		
0	5	5	5	5	20	60
10	5	5	5	5	20	
15	5	5	5	5	20	

Fig.2 Cellular Lightweight Concrete (CLC) mortar

Compressive strength testing and surface settlement measurements of the test specimens were conducted after preparing a set of testing equipment, including a loading frame, according to the setup shown in Fig. 3.

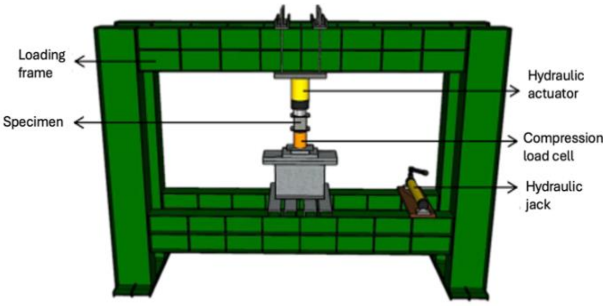

Fig. 3 Loading Frame

Compressive strength testing was conducted on steel plates at the centre of a flat-loading frame, ensuring the load was evenly distributed. A load cell was used to apply vertical pressure to the specimen during compressive strength testing. Meanwhile, CLC surface deflection testing was measured using a linear variable displacement transducer (LVDT) installed vertically on the specimen.

The compressive strength test at 56 days was intended to observe the trend in the development of the specimen's compressive strength values. The compressive strength values were calculated based on Eq. (1) as follows.

$$f'_c = \frac{P}{A} \tag{1}$$

where:
f'c = Compressive Strength of CLC Mortar (MPa)
P = Axial Load (N)
A = Specimen Surface Area (mm^2)

4. RESULTS AND ANALYSIS

4.1. Material Characteristics

The results of fine aggregate testing have met the ASTM C136, C40, and C33 standards [18]. The results of fine aggregate properties testing are shown in Table 3.

The fine aggregate utilized in this study was subjected to a series of standard laboratory tests to evaluate its suitability for use in construction materials. The results are summarized in Table 3. The aggregate's water content was measured at 3.43%, within the acceptable range of 3–5%. The mud content was recorded at 1.11%, which is well below the maximum allowable limit of 3%, indicating the material's good cleanliness. The organic impurities test yielded a value of 2, which complies with the maximum permissible limit of No. 3, ensuring minimal organic contamination. The bulk density was determined under two conditions: 1470.26 g/cm³ in a dry state and 1679.15 g/cm³ in a compacted state. These values are within the standard range of 1400–1900 g/cm³, confirming that the material has appropriate packing characteristics.

Table 3. The Results of Fine Aggregate Properties Test

No.	Testing	Specification Standard	Results
1	Water content (%)	3-5	3.43
2	Mud rate (%)	<3	1.11
3	Organic Impurities	Max No.3	2
4	Volume weight (g/cm^3)		
	a. Dry condition	1400-1900	1470.26
	b. Solid condition	1400-1900	1679.15
5	Specific Gravity		
	a. Apperent Specific Gravity	2.58-2.83	2.80
	b. Bulk Specific Gravity on Dry	2.58-2.84	2.65
	c. Bulk Specific Gravity on SSD	2.58-2.85	2.71
	d. Absorption	2-7	2.01
6	Finess Modulus	1.5-3.8	2.65

Specific gravity tests revealed that the apparent specific gravity was 2.80, while the bulk specific gravity in dry and saturated surface-dry (SSD) conditions was 2.65 and 2.71, respectively. These values comply with the typical specification range of 2.58–2.85. The absorption capacity was 2.01%, within the standard 2–7% range, suggesting a moderate absorption potential suitable for concrete applications.

Additionally, the aggregate fineness modulus was determined to be 2.65, within the standard range of 1.5–3.8. The aggregate has a moderate grain size distribution, which contributes to balanced workability and strength development in mortar or concrete mixes.

These test results indicate that the fine aggregate meets the required standards and is suitable for the production of lightweight or conventional concrete materials.

4.2. Physical Properties

Lightweight mortar bricks are manufactured using a job mix design that achieves the target quality, as specified by the density and compressive strength of the specimen. The wet density of the mixture was determined before mixing and is in accordance with the standard requirements, which is 1.013 t/m³. Figure 4 illustrates the failure modes of CLC mortar specimens incorporating 0%, 10%, and 15% fly ash after compressive strength testing at 28 days of curing. The visual evidence demonstrates distinct differences in crack propagation and structural integrity across fly ash contents.

In Fig. 4(a), the specimen without fly ash (0%) exhibits brittle failure, characterised by multiple vertical cracks and partial collapse of the upper edge. A typical fracture pattern for lightweight cementitious materials with limited tensile strength and moderate cohesion. In Fig. 4(b), the specimen with 10% fly ash substitution exhibits a relatively cohesive failure surface, characterised by fewer visible cracks and a more intact shape post-failure. The specimen exhibits enhanced microstructural bonding and matrix densification, resulting from the pozzolanic reaction of fly ash, which improves the material's integrity under axial load. In contrast, Fig. 4(c) shows the specimen with 15% fly ash, where more distributed but shallow cracks are visible, indicating a reduced load-bearing capacity. The surface remains largely intact, but the internal structure appears to have experienced microcracking, suggesting that excessive fly ash may hinder early strength development and compromise the internal matrix.

4.3. Mechanical Properties

4.3.1. *Compressive Strength*

Table 4 presents the average compressive strength and corresponding densities of CLC mortar specimens incorporating fly ash at substitution levels of 0%, 10%, and 15% by weight of cement. At 7 days, the control mix (0% fly ash) exhibited a compressive strength of 0.660 MPa with a density of 1.062 kg/m³. The inclusion of 10% fly ash slightly improved early strength to 0.696 MPa, despite a reduced density of 1.019 kg/m³. However, a 15% substitution resulted in a notable reduction in strength to 0.510 MPa, indicating a slower early hydration process. On 14 days, the strength continued to improve for both the control and the 10% fly ash mixes, reaching 0.796 MPa and 0.808 MPa, respectively.


(a) (b) (c)

Fig. 4 Collapse of Specimen with 0% (a), 10% (b) and 15% (c) Fly Ash on 28 days

The 15% fly ash mix achieved a lower strength of 0.602 MPa, suggesting that higher fly ash content may delay strength development due to its pozzolanic nature. By 28 days, the compressive strength of the 10% fly ash mix (0.850 MPa) had slightly exceeded that of the control (0.848 MPa), indicating a beneficial long-term pozzolanic reaction. In contrast, the 15% mix remained lower at 0.682 MPa.

After 56 days, the specimen with 10% fly ash achieved the highest strength of 0.960 MPa, followed by the control at 0.852 MPa, while the 15% fly ash specimen reached only 0.720 MPa. The trend indicates that a moderate fly ash content (10%) enhances the long-term strength performance of CLC mortar, whereas excessive replacement (15%) may hinder mechanical development.

Figure 5 illustrates the compressive strength development of CLC mortar at 7, 14, 28, and 56 days as a function of fly ash content (0%, 10%, and 15%).

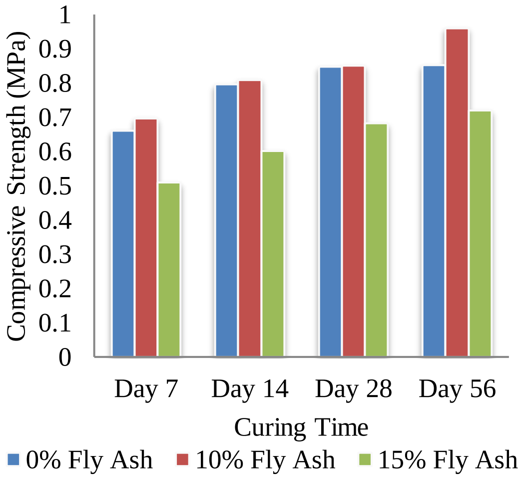

Fig. 5 Compressive Strength with Variation of Fly Ash

The bar chart shows a clear trend in strength performance as a function of the fly ash substitution level over the curing period. At an early age (7 days), the compressive strength was relatively low across all mixes, with the highest value observed for the 10% fly ash mix, followed by the control (0% fly ash), while the 15% mix showed the lowest strength (0.51 MPa). After 14 days, strength values increased for all specimens, with the 10% fly ash mix again exhibiting the highest strength. The condition exhibits an active pozzolanic contribution, which begins to manifest after one week of curing. By 28 days, both the control and the 10% fly ash mixes reached nearly equal compressive strengths (above 0.84 MPa), while the 15% mix continued to lag.

At 56 days, the 10% fly ash mixture outperformed all others, reaching a maximum compressive strength of 0.96 MPa. The condition reflects the long-term pozzolanic reaction benefits, contributing to the continued densification of the matrix. In contrast, the 15% fly ash specimen exhibited delayed strength gain, ultimately resulting in a lower final strength than that of both the control and the 10% mixtures.

4.3.2. *Deformation*

This study also examines deformations measured using a Linear Variable Displacement Transducer (LVDT) positioned at the centre of the specimen. The results showed that increasing the fly ash content in the mixture led to greater shrinkage, with the highest deformation observed in the 10% fly ash specimens, which showed a shrinkage of 9.44 mm. However, the specimens with a higher fly ash content (15%) also exhibited shrinkage, with a greater reduction in strength. This indicates that while fly ash improves the workability and sustainability of the mixture, excessive fly ash can reduce the material's resistance to deformation under load.

4.3.3. *Stress-Strain Analysis*

The analysis of the stress-strain behaviour revealed that the 10% fly ash mix strikes the best balance between strength and deformation, as shown in Fig. 6. It exhibited improved ductility compared to the control mix (0% fly ash), allowing it to deform under stress while maintaining high strength. In contrast, the 15% fly ash mix showed significant degradation in both strength and stiffness, making it less suitable for structural applications that require both high strength and low deformation.

The findings also indicate that a moderate fly ash content (10%) yields an optimal stress-strain response in lightweight concrete.

Table 4. The average compressive strength test of CLC mortar specimens

Fly ash (%)	7 Days		14 Days		28 Days		56 Days	
	Avg. Density	Avg. fc’	Avg. Density	Avg. fc’	Avg. Density	Avg. fc’	Avg. Density	Avg. fc’
	kg/m^3	MPa	kg/m^3	MPa	kg/m^3	MPa	kg/m^3	MPa
0	1.061	0.660	1.027	0.796	1.004	0.848	0.998	0.852
10	1.018	0.696	1.003	0.808	0.997	0.850	0.997	0.960
15	1.070	0.510	1.003	0.602	0.999	0.682	0.998	0.720

Table 5. Deformations Value

Fly Ash Content (%)	Sample	
	Load (kN)	Deformations (mm)
0	10.02	5.835
10	10.20	9.440
15	6.04	3.954

In comparison, excessive fly ash content (15%) resulted in a more brittle material with reduced deformation resistance, similar to findings by [12].

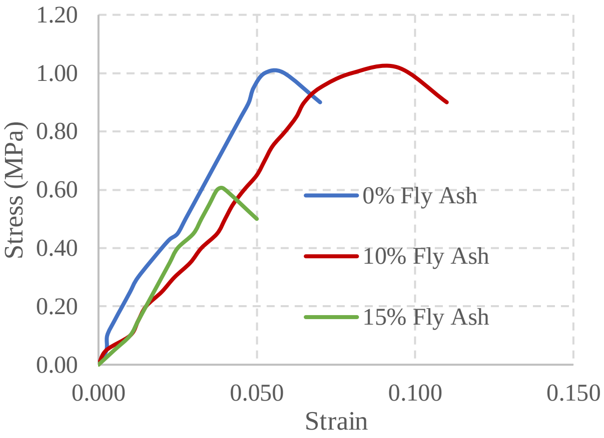

Fig. 6 Stress-Strain Curve Results

5. CONCLUSIONS

This study investigated the physical and mechanical properties of Cellular Lightweight Concrete (CLC) mortar incorporating fly ash as a partial cement replacement at 0%, 10%, and 15% by weight. The fine aggregate used in the mixture met all standard specifications, including water content, mud content, specific gravity, and fineness modulus, indicating its suitability for lightweight concrete applications.

Compressive strength tests conducted at 7, 14, 28, and 56 days demonstrated that a 10% fly ash substitution consistently produced superior performance in both early and long-term strength development compared to the control mix and the 15% fly ash mixture. At 56 days, the 10% fly ash mix achieved the highest strength of 0.96 MPa, confirming the long-term pozzolanic benefit of fly ash.

Visual observations of the specimen failure modes under compressive load revealed that the 10% fly ash specimen exhibited the most cohesive and stable failure pattern. In comparison, the 0% and 15% mixes showed more brittle or inconsistent behavior. This suggests that a 10% fly ash content not only enhances strength but also improves integrity under mechanical stress. Overall, the results indicate that a 10% fly ash substitution provides an optimal balance between strength, durability, and material stability in CLC mortar, making it a promising alternative for sustainable construction materials.

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