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**Research Article**

# Structural Stability and Strength Analysis of Lightweight Cellular Concrete

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**ABSTRACT**

**Introduction**: Concrete is most important construction materials. Concrete is a material used in building construction, consisting of a hard, chemically inert particulate substance, known as an aggregate that is bonded together by cement and water. Lightweight concrete maintains its large voids and not forming laitance layers or cement films when placed on the wall. This research was based on the performance of aerated lightweight concrete. Lightweight Cellular Concrete (LCC), known for its low density and thermal insulation properties, is increasingly used in modern construction. However, concerns remain regarding its structural stability and mechanical strength, especially when modified with foam agents and recycled materials. The incorporation of waste crushed CLC (Cellular Lightweight Concrete) blocks as a partial replacement for fine aggregates presents a sustainable solution to construction waste, but its impact on the structural performance of LCC is not fully understood. This study aims to analyze the structural stability and strength characteristics of LCC modified with varying proportions of foam agent and crushed CLC waste, to determine optimal mix ratios that balance sustainability with performance.

**Keywords:** CLC, Lightweight Cellular Concrete, waste, foam agents, Concrete, Compressive Strength.

## INTRODUCTION

The most crucial construction material is concrete. A solid, chemically stable material known as an aggregate is combined with cement and water to create concrete, a material frequently used in building. The demand for building, road, and airport development has increased globally in recent years, resulting in a reduction in the supply of aggregate and other raw materials used in concrete.[11] The widespread use of these materials has exhausted local supplies in certain areas with large aggregate deposits, making the importation of resources from other areas necessary. As a result, cellular lightweight concrete is being used in the building and civil engineering construction industries in a novel way. [8]

When lightweight concrete is placed to a wall, it does not form cement films or laitance layers and maintains its expansive spaces. The performance of aerated lightweight concrete was the main focus of this investigation.[6] To produce enough cohesiveness between cement and water, however, the proper water-to-cement ratio is essential. Concrete's strength may decline as a result of a lack of cohesiveness between its particles caused by inadequate water. In a similar vein, too much water can cause cement to flow off from aggregates, creating weak laitance layers. [5]

### CLC Waste Block

One kind of lightweight concrete is called cellular light weight concrete, or foam concrete. Under typical climatic circumstances, cellular lightweight concrete (clc), a lightweight concrete, is manufactured in a manner similar to that of regular concrete. A cement slurry is mixed with additional ingredients to make cement blocks, which are a robust and long-lasting bonding agent.[2] The density of this lightweight material ranges from 300 to 1800 kg/m3. This was three times lighter than clay brocks or fly ash. It is environmentally beneficial. In order to reduce the production process's negative effects on the environment, ecologically friendly resources like fly ash and other industrial waste

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are used to make foam concrete.[4] No hazardous materials are released into the air, water, or land during the manufacture or use of foam concrete.[10]

Fig 1 CLC Waste Block

**Concrete Foaming Agent**

A chemical called a concrete foaming agent is used to create foam in concrete, which makes the material lighter and more insulating. Usually, the foaming ingredient is combined with water and air to generate the foam, which is then added to the concrete mixture.[2] While preserving the concrete's structural integrity and offering further advantages like thermal and acoustic insulation, this procedure aids in lowering the material's overall weight. A particular brand of concrete foaming agent called Marjanol is intended to produce foamed concrete that is both lightweight and long-lasting. It is utilized to create foam, which is mixed with concrete to lower its density while preserving crucial qualities like strength and insulation, just like other foaming agents.[1]


Fig 2 Marjanol Foaming Agent- (389 Rs / liter)

## REVIEW OF LITERATURE

Zdenek P. Bazant et. al. (2000). Elastic and inelastic behavior, static and dynamic responses, linear and nonlinear systems, energy methods, thermodynamic considerations, creep, and instability brought on by damage or fractures are just a few of the many topics covered in this paper's thorough review of structural stability. It quickly covers the field's evolution and emphasizes the importance of stability analysis across several engineering and scientific areas. Key accomplishments are outlined, with an emphasis on new developments in the analysis of fracture-related instability and damage localization. A well chosen set of references is included in the article to bolster the debate.[1]

Dhiraj Bhople et. al. (2021) The subject of this essay is Cellular Lightweight Concrete (CLC), sometimes referred to as Foamed Concrete, which is becoming more and more popular in construction because of its many benefits over conventional concrete. Portland cement, sand (with or without fly ash), and a stable foam are combined to create CLC, which has a density that is much lower than that of ordinary cement (between 300 and 1850 kg/m³). By distributing millions of tiny holes or air bubbles throughout the concrete, the foam makes it lightweight while preserving its quality on par with ordinary concrete blocks. Densities of CLC vary, usually ranging from 400 kg/m³ to 1,800 kg/m³. This study investigates the possible cost savings in structural design, specifically in terms of dead load reduction, by examining CLC blocks that are thinner than conventional blocks. Because CLC blocks are lighter—the shaft section of the construction weighs just 8.635 kg—the study also finds that there are considerable reductions in the amount of steel used.[2]

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Devansh Jain et. al. (2019) The new material known as Cellular Lightweight Concrete (CLWC) has densities ranging from 300 kg/m³ to 1850 kg/m³ and is created by mixing foam into a cement-based mixture. Because it is lightweight but less strong than traditional concrete, it is frequently utilized in non-load bearing components, insulation, and partition walls. Materials such as fly ash and silica fume are added to increase its strength. By altering the fly ash percentage (between 50% and 80%) and decreasing the cement concentration (between 50% and 20%), this study investigates the mechanical and physical characteristics of CLWC, such as dry density, water absorption, and compressive strength. To get desired densities, the amount of foam is changed, and silica fume is added to improve the mix's qualities even further.[3]

Anubhav Kumar Hindoriya et. al. (2016) The technique of lightweight cellular concrete is not new; it was initially used in the early 1920s. Because little is known about its stability and characteristics, its uses are restricted. A form of aerated concrete with cellular structure that makes it lighter and an excellent insulator of sound and heat is called lightweight cellular concrete. This essay focuses on examining the characteristics, uses, and manufacturing process of lightweight cellular concrete.[4]

Gagandeep et. al. (2019) Because of its many benefits, such as lower dead load, smaller structural member dimensions, and lighter pre-cast parts that are less expensive and simpler to handle, cast, and transport, lightweight concrete is being employed more and more in a variety of structural applications. Additionally, it increases useable area, reduces the possibility of seismic damage, and improves fire and heat resistance. The qualities of cellular lightweight concrete blocks—which are composed of 35% cement and 65% fly ash—with a 1.5% foam content by weight are the main subject of this dissertation. Up to 30% of the fly ash is replaced with sand and quarry dust at 5% intervals to increase its strength.[5]

Vikash Bhatt et. al. (2023) The greatest option for the building construction sector is provided by the use of cellular lightweight concrete blocks in civil engineering. A better way to lessen the building's dead weight is with CLC Blocks. Based on varying proportions of their composite components, this work attempts to investigate the distinctive strength of CLC and suggests its potential usage in the building sector. Additionally, it provides an understanding of the Ratio and Density that may be used to characterize CLC in accordance with IS2185 (PART-4) 2008.[6]

Riyal Yadav et. al. (2023) Foam concrete is a cement-based slurry that contains at least 20% foam by volume blended into the plastic mortar. It is sometimes referred to as lightweight cellular concrete or low-density cellular concrete. Since it is made without the use of coarse materials, its density usually ranges between 400 and 1600 kg/m³. By substituting foam for some or all of the fine aggregate, the density may be regulated. With a compressive strength between 6 and 14 MPa, foam concrete lowers the dead weight of buildings. As the concrete cures and hardens, the air bubbles created while mixing increase its strength. Reduced structural dead load, energy saving, lower labor and manufacturing costs, and simpler transportation are just a few advantages of foam concrete. In order to answer consumer concerns and encourage broader use of foam concrete in civil engineering, this study offers a thorough assessment of the material, including its components, preparation, and important characteristics including drying shrinkage, compressive strength, and durability.[7]

Susan Tighe et. al. (2020) One important area of research is protecting the pavement subgrade to increase the lifespan of road pavements. Because of its low weight and simplicity of use, lightweight cellular concrete (LCC), a sustainable material created from industrial byproducts, has become a possible substitute for pavement subbases. With an emphasis on crucial characteristics such modulus of elasticity, compressive and tensile strength, water absorption, and freeze-thaw resistance, this research examines the possible use of LCC as a subbase material. It also looks at how it's used in Canada, taking into account regional design techniques. The study highlights shortcomings and inadequacies in the way LCC is now used in pavements and offers suggestions for enhancing both its functionality and utilization. The assessment comes to the conclusion that although LCC exhibits promise as a subbase material, more investigation into its mechanical characteristics—specifically, its fatigue life—as well as a comparative field study to track performance are required for a deeper comprehension and broader acceptance.[8]

**Summary and Gap Identification**

According to a thorough literature survey, several earlier researchers have investigated the substitution of different cement types for cement in an effort to increase the compressive strength of concrete. In earlier research, foaming

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agents were exclusively utilized in CLC block casting; in subsequent studies, they should be employed in conjunction with a small amount of cement to produce light-weight concrete using a traditional concrete mix design. In order to prevent needless concrete demolition and disposal in fertile land, recycled aggregate has been the subject of several previous research. The authors discovered that as the rate of change of all water cement levels increased, the density of recycled concrete dropped. Consequently, the CLC recycled aggregate will be combined with cement paste for that test, let to dry for two to three days, and then used as a substitute.

### Objectives

1. To check Feasibility of the cellular lightweight concrete for the RCC structure with varying voids %.
2. To check Strength and density of concrete after replacement of aggregate with waste CLC blocks.

## METHODOLOGY

The approach for lightweight cellular concrete (CLC) focuses on analyzing how different proportions of waste CLC as aggregate and foaming agent affect important mechanical qualities. As described below, the study uses a systematic method that involves experimental tests to ascertain the influence on density and compressive strength.

1. **Preparation of CLC Mixes:**

- **Foaming Agent (%)**:The following seven percentages of foaming agents are taken into consideration: 0%, 0.25%, 0.5%, 0.75%, 1%, 1.25%, and 1.5%. To ensure that the foam is evenly dispersed throughout the mix, varying volumes of foaming agent are added to the cement-based slurry to create each sample.

Table 1 Mix proportion for Foaming Agent- Cube

| Percentage of Foaming agent (%) | Cement (kg) | Sand (kg) | Aggregates (kg) | Water ml | Foaming agent ml |
|---|---|---|---|---|---|
| **0%** | 1.8 | 2.85 | 5.82 | 810 | 0.00 |
| **0.25%** | 1.8 | 2.85 | 5.82 | 808 | 2.03 |
| **0.50%** | 1.8 | 2.85 | 5.82 | 806 | 4.05 |
| **0.75%** | 1.8 | 2.85 | 5.82 | 804 | 6.08 |
| **0.1%** | 1.8 | 2.85 | 5.82 | 809 | 0.81 |
| **1.25%** | 1.8 | 2.85 | 5.82 | 800 | 10.13 |
| **1.5%** | 1.8 | 2.85 | 5.82 | 798 | 12.15 |

- **Waste CLC as Aggregate (%)**:Waste CLC is utilized as aggregate in seven different percentages: 0%, 10%, 15%, 20%, 25%, 30%, and 35%. To evaluate its impact on the concrete's overall performance, waste CLC is used in part to substitute natural aggregates.

Table 2. Mix proportion for Waste CLC- Cube

| Percentage of Waste CLC as Agg (%) | Cement (kg) | Sand (kg) | Aggregates (kg) | Waste CLC as Agg Approx Kg | Water ml |
|---|---|---|---|---|---|
| **0%** | 1.8 | 2.85 | 5.82 | 0 | 810 |
| **10%** | 1.8 | 2.85 | 5.238 | 0.582 | 810 |
| **15%** | 1.8 | 2.85 | 4.947 | 0.873 | 810 |
| **20%** | 1.8 | 2.85 | 4.656 | 1.164 | 810 |
| **25%** | 1.8 | 2.85 | 4.365 | 1.455 | 810 |
| **30%** | 1.8 | 2.85 | 4.074 | 1.746 | 810 |
| **35%** | 1.8 | 2.85 | 3.783 | 2.037 | 810 |

2. **Mix Design:**

- **Cement and Fly Ash**: In order to offer a similar matrix for comparison among the different foam and waste CLC aggregate content, the base mix is composed of a fixed ratio of cement to fly ash.

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- **Water-to-Cement Ratio**: All mixtures maintain the same water-to-cement ratio, guaranteeing that the hydration process is the same for every sample.
- **Preparation of Foam**: A foaming agent diluted in water is used to create foam, guaranteeing consistent uniformity for precise testing.

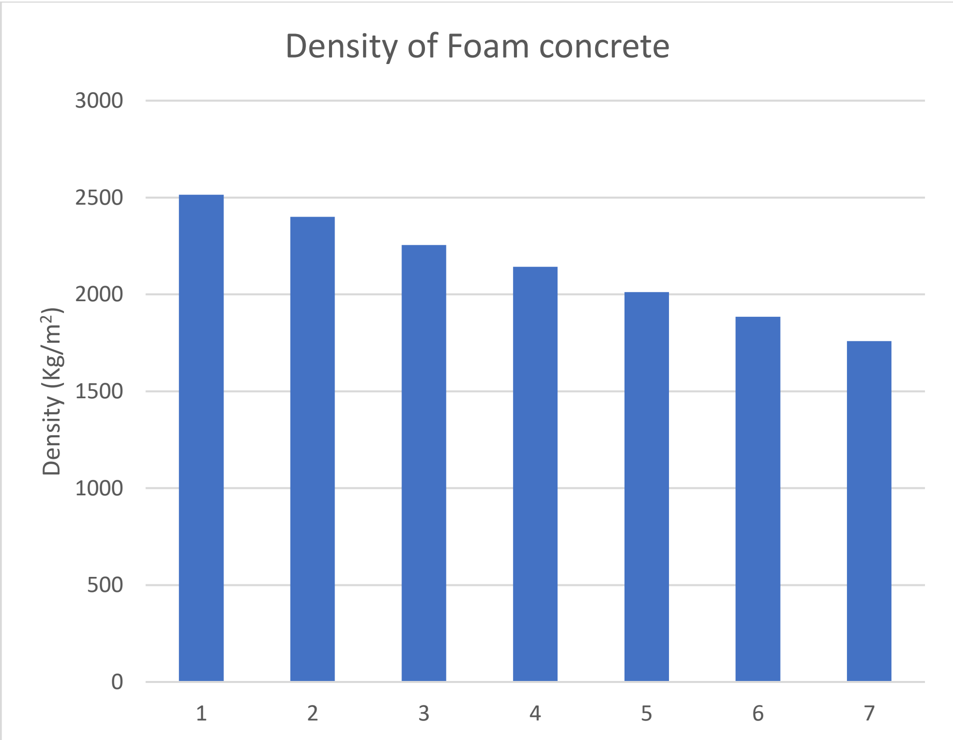
3. **Casting of Samples:**
   - The various foam and waste CLC aggregate contents are used to cast cubes and cylinders. The samples are cast in standard-sized molds (such as 150mm cylinders for various tests and 100mm cubes for compressive strength testing).
   - The samples are allowed to cure for 28 days under carefully monitored circumstances (ambient temperature and humidity).
4. **Testing and Evaluation:**
   - **Density Test**: The weight-to-volume ratio is used to quantify the samples' dry density in order to evaluate the effects of waste CLC and foaming agent.
   - **Compressive Strength Test**: A compression testing equipment is used to impart axial load to the concrete samples in order to measure their compressive strength. Compressive strength is computed using the cross-sectional area and the failure load is noted.

## RESULTS AND DISCUSSION

**Results for Density of Foam concrete**.

Table 3 Density of Foam concrete

| Percentage Replacement | **0%** | **0.25%** | **0.50%** | **0.75%** | **0.10%** | **1.25%** | **1.50%** |
|---|---|---|---|---|---|---|---|
| M20 (Kg/m²) | 2515 | 2400 | 2255 | 2142 | 2012 | 1885.6 | 1759.2 |




Graph 1 Density of Foam concrete

The density of Foam concrete decreases with the increase in percentage addition of foaming agent by 8-12%. Hence Foam concrete can be considered as light weight concrete which results in smaller dead loads. There is Need to check strength of the cube for better understand.

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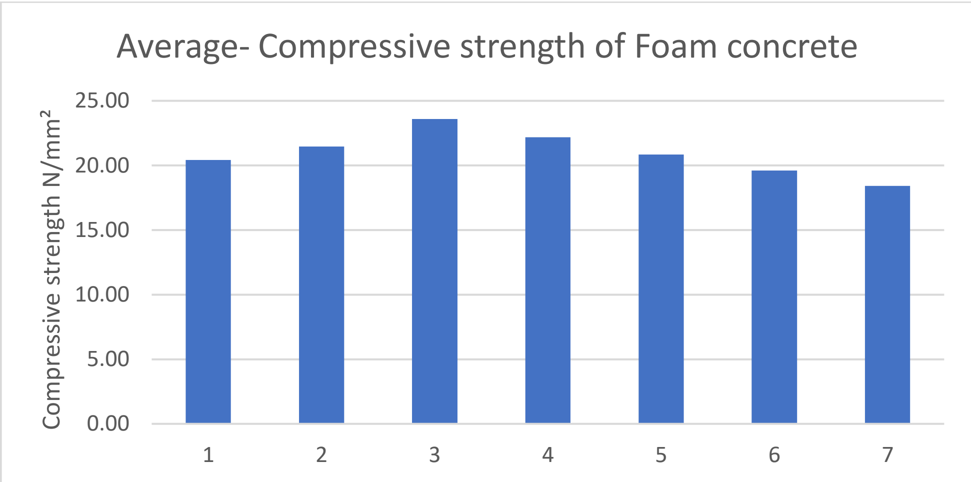
**Compressive strength of Foam concrete**

Table 4. Compressive strength of Foam concrete

| Percentage Replacement | 0% | 0.25% | 0.50% | 0.75% | 0.10% | 1.25% | 1.50% |
|---|---|---|---|---|---|---|---|
| Specimen 1 | 20.5 | 21.53 | 23.68 | 22.26 | 20.92 | 19.67 | 18.49 |
| Specimen 2 | 20.09 | 21.96 | 24.15 | 21.81 | 21.34 | 20.06 | 18.12 |
| Specimen 3 | 20.71 | 20.88 | 22.97 | 22.48 | 20.30 | 19.08 | 18.67 |
| Average | 20.43 | 21.46 | 23.60 | 22.19 | 20.85 | 19.60 | 18.43 |




Graph 2 Average- Compressive strength of Foam concrete

The average compressive strength of foam concrete specimens at different percentages of foam content (0%, 0.25%, 0.50%, 0.75%, 1.0%, 1.25%, and 1.5%) is shown in the following graph. The graph shows that up to 0.5% foam concentration, the compressive strength of foam concrete improves gradually. This suggests that adding foaming agent up to this point improves the performance of the concrete, most likely because it makes the concrete easier to work with and distributes fine air gaps more evenly without sacrificing structural integrity.

But beyond 0.5%, there is a discernible drop in compressive strength. The presence of excessive air gaps lowers the concrete's density and strength when the foam content rises over this threshold, producing weaker specimens. Thus, for applications where compressive strength is a crucial requirement, the use of foaming agents in foam concrete is best up to 0.5% and is not advised above this proportion.

**Split Tensile Test for Foam Concrete**

Table 4.6 Split Tensile Test Result for Foam Concrete

| Foaming Agent (%) | Specimen 1 | Specimen 2 | Specimen 3 | Average |
|---|---|---|---|---|
| 0 % | 2.9 | 2.95 | 2.88 | 2.91 |
| 0.25% | 2.96 | 2.98 | 2.94 | 2.96 |
| 0.50% | 3.02 | 3.05 | 3 | 3.02 |
| 0.75% | 2.8 | 2.78 | 2.76 | 2.78 |
| 1.00% | 2.5 | 2.55 | 2.48 | 2.51 |
| 1.25% | 2.15 | 2.18 | 2.1 | 2.14 |
| 1.50% | 1.85 | 1.9 | 1.82 | 1.86 |

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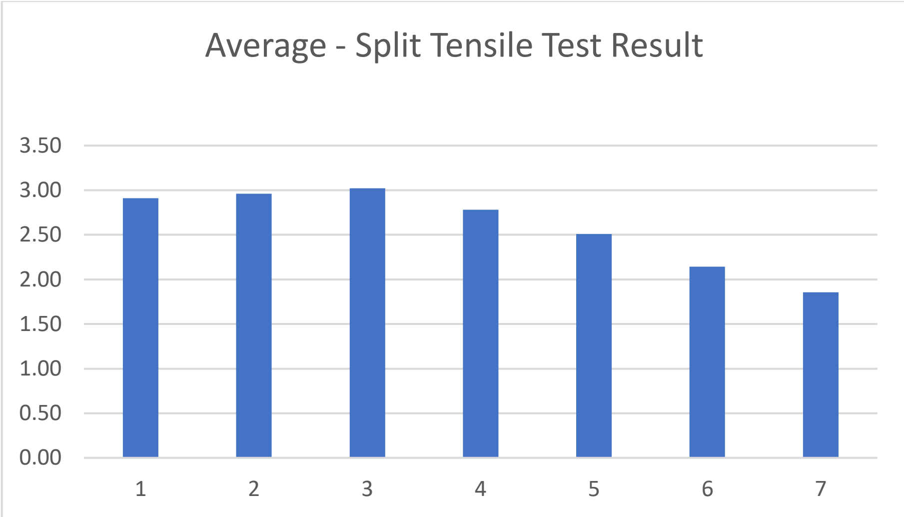


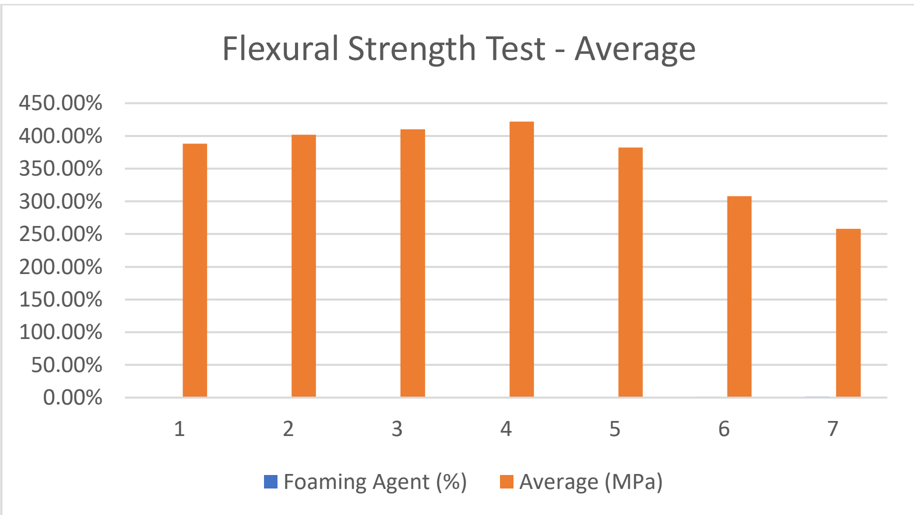

Graph 3 Average - Split Tensile Test

The split tensile strength values for foam concrete with different amounts of foaming agent are shown in the above result. The findings demonstrate that moderate foaming improves strength, as the tensile strength rises marginally from 2.91 MPa at 0% foaming agent to a high of 3.02 MPa at 0.50%. The strength, however, steadily declines after 0.50% and reaches its lowest value of 1.86 MPa at 1.50%, indicating that using too much foaming agent weakens the concrete structure.

**Flexural strength Test for Foam Concrete**

Table 4.7 Flexural strength Test Result for Foam Concrete

| Foaming Agent (%) | Specimen 1 (MPa) | Specimen 2 (MPa) | Specimen 3 (MPa) | Average (MPa) |
|---|---|---|---|---|
| 0.00% | 3.9 | 3.85 | 3.88 | 3.88 |
| 0.10% | 4 | 4.05 | 4.02 | 4.02 |
| 0.25% | 4.1 | 4.12 | 4.08 | 4.1 |
| 0.50% | 4.25 | 4.2 | 4.22 | 4.22 |
| 0.75% | 3.85 | 3.8 | 3.82 | 3.82 |
| 1.25% | 3.1 | 3.05 | 3.08 | 3.08 |
| 1.50% | 2.6 | 2.55 | 2.58 | 2.58 |




Graph 4 Flexural Strength Test – Average

The flexural strength data for foam concrete with varying foaming agent percentages are displayed above. According to the findings, the foaming agent raises flexural strength by up to 0.50%, peaking at an average of 4.22 MPa. Following this, the strength decreases, reaching 2.58 MPa at 1.50%, indicating that although tiny levels of foaming agent increase strength, larger concentrations have a detrimental effect on the flexural performance of the concrete.

**Results for Waste Clc Blocks.**

**Preparation of Crushed Waste CLC Blocks**

The crushed waste CLC blocks that were gathered from the local residential and commercial building sites as well as the CLC block production business are a significant component of this study. Analyze the sieve and choose crushed blocks up to 20 mm in size. The CLC recycled aggregate will be combined with cement paste and allowed to dry for two to three days before being used as a substitute because Waste CLC Blocks are extracted from a location and have a high ability to absorb water. Crushed Waste CLC Blocks are covered with a 1: 4 cement slurry (a ratio of cement to water) to make up for excessive water absorption.

(a)

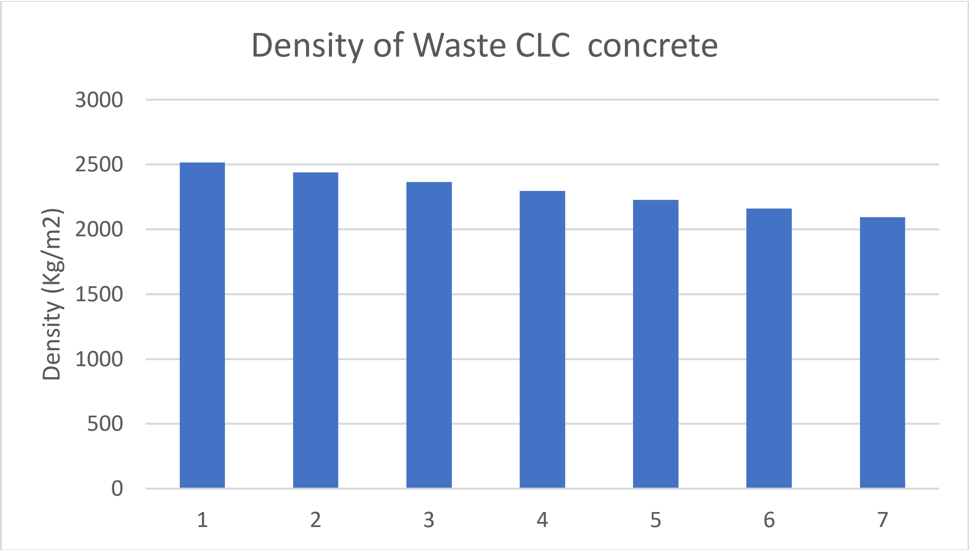
(b)

Fig 3. a) Collection of Crushed Waste CLC Blocks b) Coated with a 1: 4 cement slurry

**Density of Waste CLC concrete**

Table 5 Results For Density of Waste CLC concrete

| Percentage Replacement | 0% | 10% | 15% | 20% | 25% | 30% | 35% |
|---|---|---|---|---|---|---|---|
| M20 (Kg/m²) | 2515 | 2439.55 | 2366.36 | 2295.37 | 2226.51 | 2159.72 | 2094.92 |




Graph 3 Density of Waste CLC concrete

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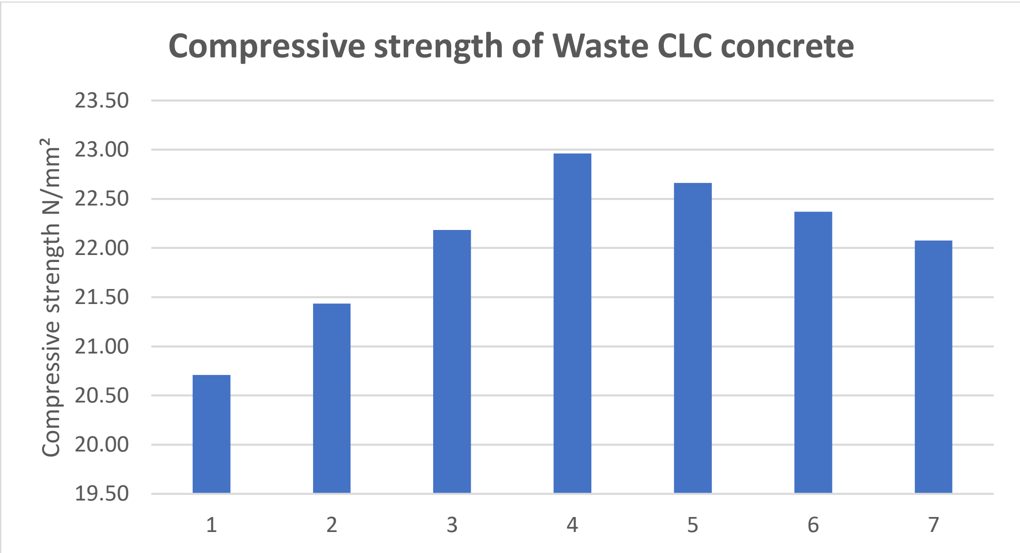
As the percentage addition of Waste CLC increases by 5–6%, the density of Waste CLC concrete drops. As a result, waste CLC concrete may be thought of as lightweight concrete that produces lower dead loads. To further comprehend, the cube's strength must be checked.

**Compressive strength of Waste CLC concrete**

Table 6 Compressive strength of Waste CLC concrete

| Percentage Replacement | 0% | 10% | 15% | 20% | 25% | 30% | 35% |
|---|---|---|---|---|---|---|---|
| M20 ($N/mm^2$) | 20.71 | 21.43 | 22.19 | 22.96 | 22.66 | 22.37 | 22.08 |




Graph 4 Compressive strength of Waste CLC concrete

The compressive strength of waste CLC (cellular lightweight concrete) concrete at various replacement levels—0%, 10%, 15%, 20%, 25%, 30%, and 35%—is depicted in the following graph. The data clearly shows that Waste CLC concrete's compressive strength gradually rises up to 20% replacement, reaching its peak performance at this point. This implies that adding up to 20% waste material to the CLC mix enhances strength qualities, most likely as a result of improved internal structure and particle packing. There is a modest drop in compressive strength after 20% replacement. However, the compressive strength is still higher than that of conventional concrete even at higher replacement levels (25–35%), demonstrating Waste CLC concrete's ongoing structural viability.

**Split Tensile Strength of Waste CLC concrete**

Table 7 Split Tensile Strength of Waste CLC concrete

| Percentage of Waste CLC as Agg. (%) | Specimen 1 | Specimen 2 | Specimen 3 | Average |
|---|---|---|---|---|
| 0% | 2.9 | 2.95 | 2.88 | 2.91 |
| 10% | 3.02 | 3.05 | 3.01 | 3.03 |
| 15% | 3.1 | 3.12 | 3.08 | 3.10 |
| 20% | 3.18 | 3.2 | 3.17 | 3.18 |
| 25% | 3.15 | 3.17 | 3.13 | 3.15 |
| 30% | 3.08 | 3.06 | 3.09 | 3.08 |
| 35% | 3.02 | 3 | 3.01 | 3.01 |

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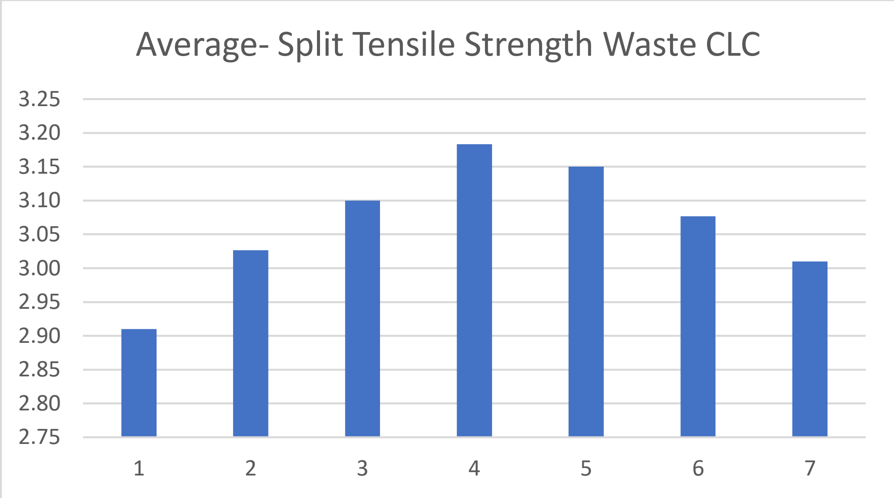


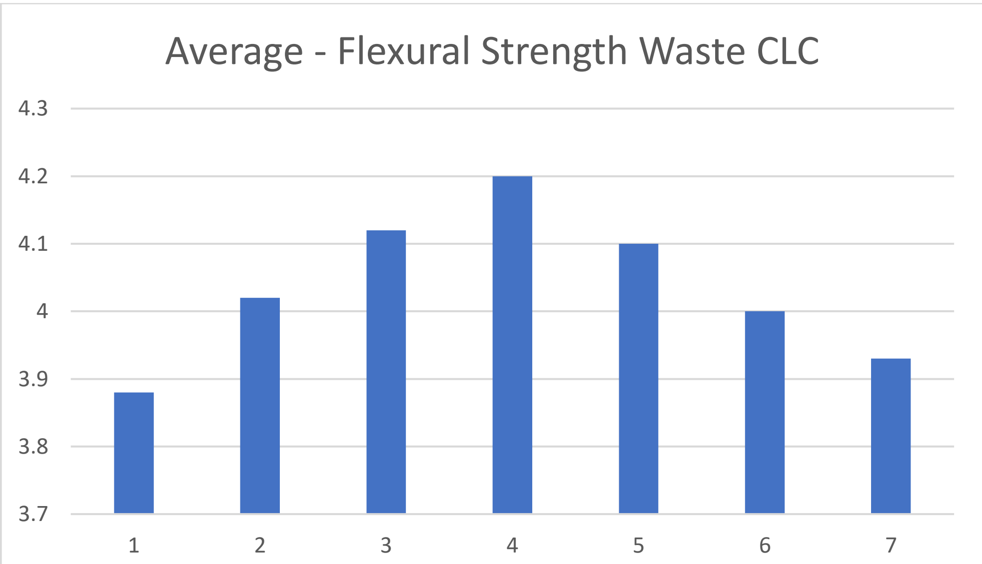
Graph 5 Average Split Tensile Strength of Waste CLC concrete

The split tensile strength values for concrete using different amounts of waste CLC as aggregate are shown above. The strength rises from 2.91 MPa at 0% to a high of 3.18 MPa at 20% replacement, suggesting that modest waste CLC utilization improves bonding and structural integrity. Strength starts to decrease at 20% and reaches 3.01 MPa at 35%, indicating that too much waste CLC may lower the concrete's tensile performance because of inferior aggregate characteristics.

**Flexural Strength of Waste CLC concrete**

Table 8 Flexural Strength of Waste CLC concrete

| Percentage of Waste CLC as Agg (%) | Specimen 1 | Specimen 2 | Specimen 3 | Average (MPa) |
|---|---|---|---|---|
| 0% | 3.9 | 3.85 | 3.88 | 3.88 |
| 10% | 4.00 | 4.05 | 4.02 | 4.02 |
| 15% | 4.12 | 4.15 | 4.1 | 4.12 |
| 20% | 4.2 | 4.18 | 4.22 | 4.2 |
| 25% | 4.1 | 4.08 | 4.12 | 4.1 |
| 30% | 4.000 | 4.02 | 3.98 | 4.00 |
| 35% | 3.95 | 3.92 | 3.93 | 3.93 |



Graph 6 Flexural Strength of Waste CLC concrete

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The flexural strength of concrete with varying amounts of waste CLC used as aggregate is seen in the above graph. With moderate waste CLC utilization, the flexural strength increases from 3.88 MPa at 0% to a high of 4.20 MPa at 20% replacement, demonstrating improved performance. However, the strength steadily declines beyond 20%, reaching 3.93 MPa at 35%, indicating that the flexural capacity of the concrete may be compromised by a larger waste CLC content.

## CONCLUSION

- The goal of the experimental investigation on lightweight cellular concrete (LCC) was to compare the compressive strength and structural stability of two varieties of LCC: waste CLC concrete and foam concrete. The following important findings are reached once the test data have been analyzed:
- Waste CLC concrete offers a better balance of strength, stability, and sustainability, making it more appropriate for light structural applications.
- Waste CLC concrete exhibits superior compressive strength and structural reliability, even though both foam concrete and Waste CLC concrete offer the advantages of reduced density.
- Foam concrete is still useful for some applications, such partition walls, insulation layers, and places with little structural weight.As the foam percentage climbs to 0.5%, foam concrete's compressive strength increases, suggesting better internal structure and workability. 0.5% is found to be the ideal foam percentage for preserving structural stability while attaining decreased density.
- The findings demonstrate that moderate foaming improves strength, as the tensile strength rises marginally from 2.91 MPa at 0% foaming agent to a high of 3.02 MPa at 0.50%.
- According to the findings, the foaming agent raises flexural strength by up to 0.50%, peaking at an average of 4.22 MPa. The strength decreases after this.
- Results of split tensile strength for concrete using different proportions of waste CLC as aggregate. When significant waste CLC is used, the strength improves from 2.91 MPa at 0% to a high of 3.18 MPa at 20% replacement, showing increased bonding and structural integrity.
- The concrete's flexural strength at varying aggregate percentages of waste CLC. with 0%, the flexural strength is 3.88 MPa; with 20% replacement, it peaks at 4.20 MPa.
- In a variety of applications where sustainability, sufficient strength, and decreased weight are sought, lightweight cellular concrete can successfully replace traditional concrete.
- Waste CLC concrete is suggested for wider structural use out of the two, especially when optimized at 20% replacement.
- More research is encouraged to examine LCC's long-term performance, durability, and cost-effectiveness in actual building situations.

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