FINAL PROJECT

THE EFFECT OF PARTIAL SUBSTITUTION OF CEMENT WITH COAL FLY ASH ON THE PHYSICAL AND MECHANICAL PROPERTIES OF CELLULAR LIGHTWEIGHT CONCRETE (CLC)

Submitted to Universitas Islam Indonesia Yogyakarta as a Fulfilment of the Requirement to Obtain a Civil Engineering Bachelor's Degree

Yunda Aliefia Bianita
21511023

CIVIL ENGINEERING STUDY PROGRAM
INTERNATIONAL UNDERGRADUATE PROGRAM
FACULTY OF ENGINEERING DESIGN INNOVATION
UNIVERSITY OF ISLAM INDONESIA
2026

FINAL PROJECT

THE EFFECT OF PARTIAL SUBSTITUTION OF CEMENT WITH COAL FLY ASH ON THE PHYSICAL AND MECHANICAL PROPERTIES OF CELLULAR LIGHTWEIGHT CONCRETE (CLC)

Arranged by:

Yunda Aliefia Bianita

21511023

Has been accepted as the requirement for obtaining
a Bachelor's degree in Civil Engineering

Has been evaluated and reviewed on August 27th, 2026

By The Board of Examiners

Lecturer Supervisor :

Ir. Jafar, S.T., MURP., M.T.
NIK: 185111305

Date : 01-09-2026

Examiner I :
Anggit Mas Arifudin, S.T., M.T.
NIK: 185111304

Date : 04-09-2026.

Examiner II:
Astriana Hardawati, S.T., M.Eng.
NIK : 165111301

Date : 01.09.2026

Authorized,

Head of the Civil Engineering Undergraduate Study Program

UNIVERSITAS ISLAM INDONESIA
FAKULTAS
TEKNIK DESAIN INOVASI

Dr.-Eng. Ir. Faizul Chasanah, S.T., M.Sc.
NIK: 14511010

PLAGIARISM-FREE STATEMENT

Hereby, I declare that this final project, which I have arranged as one of the requirements for obtaining a Bachelor's Degree in the International Undergraduate Program of the Civil Engineering Study Program, Faculty of Engineering Design Innovation, Universitas Islam Indonesia, is my original work. As for the parts in the writing of the final project that I cited from other people's creations, the sources have been mentioned clearly in accordance with the norms, rules, and ethics of scientific writing. Suppose in the future it is found that all or part of this final project is not my work, or there is plagiarism in certain parts. In that case, I am willing to accept sanctions, including revocation of my student status under applicable laws.

Yogyakarta, September 1st 2026

The Declarant,



Yunda Aliefia Bianita

21511023

PREFACE

All praise and gratitude to Allah SWT., for His mercies and blessings, so that the author can complete the Final Project entitled *The Effect Of Partial Substitution Of Cement With Coal Fly Ash On The Physical And Mechanical Properties Of Cellular Lightweight Concrete (CLC)* as the requirements for obtaining a Bachelor's Degree in International Undergraduate Program of the Civil Engineering Study Program, Faculty of Engineering Design Innovation, Universitas Islam Indonesia, Yogyakarta.

In the process of arranging and compiling this Final Project, the author encountered many challenges. But due to the advice, criticism, and encouragement from various parties, Alhamdulillah, this Final Project can be completed. In this regard, the Author would like to express his deepest gratitude to:

1. Dr.-Eng. Ir. Faizul Chasanah, S.T., M.Sc, as the Head of the Civil Engineering Undergraduate Study Program,
2. Ir. Jafar, S.T., MURP., M.T., as the Supervisor, thank you for continuous guidance, patience, and direction, through the entire research process.
3. Anggit Mas Arifudin, S.T., M.T., as the Examiner Lecturer I, for the valuable feedback, constructive criticism, and suggestions provided throughout the examination process, which have helped improve and refine the content of this final project.
4. Astriana Hardawati, S.T., M.Eng., as the Examiner Lecturer II, for the valuable feedback, constructive criticism, and suggestions provided throughout the examination process, which have helped improve and refine the content of this final project.
5. *Ummi Bapak*, Daeny Septi Yansuri, S.T., M.T., and Ir. Subianto, S.T., M.T., who have worked tirelessly to give me an education and bring me to where I am today. Thank you for every prayer, every sacrifice, and all the trust you have given me. I can never fully repay it.

6. My Little Sister, Dinda Aristawidya Bianita, who has always been ready to listen whenever I felt stressed out during this thesis research. Thank you for always being there for me.
7. The 21st Batch of Civil Engineering, especially the International Program, I am so grateful to have met all of you. Thank you for the countless experiences, for making my years of study more meaningful, and for giving me a place to keep growing. Thank you for being my home away from home.
8. My closest friends, *ES CEH*, *Terserah*, *Kecebong Hanyut*, Shafa, Muthi, Lili, Dito, Rangsat, Idam, Dika, Zalika, and everyone else whose names I could not mention one by one, thank you for staying by my side while I worked on this thesis from start to finish. Thank you too for being my motivation and inspiration to keep going until this research was done.
9. Someone with the NIM of 21511065, I am truly grateful that we met at the right time. Even though the time we spent together was short, and we will soon go our separate ways to chase our own dreams, I want to thank you for your patience with me throughout this journey, and for the support and company that helped me finish what I had started.

Finally, the Author hopes that this Final Project can be useful to all parties who read it.

Yogyakarta, September 1st 2026
Author,



Yunda Alietia Bianita
21511023

TABLE OF CONTENTS

Title Sheet i
Approval Page ii
PLAGIARISM-FREE STATEMENT iii
PREFACE iv
TABLE OF CONTENTS vi
LIST OF TABLES ix
LIST OF FIGURES xi
LIST OF APPENDIXES xiii
ABSTRACT xiv
CHAPTER I INTRODUCTION 1
1.1 Background 1
1.2 Problem Formulation 4
1.3 Purpose 5
1.4 Advantage 5
1.5 Limitation 5
CHAPTER II LITERATURE REVIEW 7
2.1 Overview 7
2.2 Comparison of Previous Research 10
2.3 Originality of Research 19
CHAPTER III THEORETICAL BASIS 20
3.1 Lightweight Concrete 20
3.2 Lightweight Concrete Specification and Testing 20
3.2.1 Density and Water Absorption Test 22
3.2.2 Compressive Strength Test 23
3.3 Component Materials of Lightweight Concrete 24
3.3.1 Portland Cement 24
3.3.2 Fine Aggregate 25
3.3.3 Water 26

3.3.4 Foam Agent 28
3.4 Partial Replacement Materials of Cement 29
3.4.1 Coal Fly Ash 29
CHAPTER IV METHODOLOGY 32
4.1 Overview 32
4.2 Research Location 32
4.3 Research Variables 32
4.4 Tools Used 33
4.5 Used Materials 39
4.6 Test Object 41
4.7 Stages of Research Execution 42
4.7.1 Preparation 43
4.7.2 Material Testing 43
4.7.3 Fabrication and Curing of Test Object 43
4.7.4 Testing of Test Object 44
4.7.5 Data Analysis 46
4.8 Flowchart of Research 48
CHAPTER V ANALYSIS AND DISCUSSION 51
5.1 Overview 51
5.2 Material Testing 51
5.3 Mix Design Calculation 59
5.3.1 Calculation of the Mix Proportions for Lightweight Bricks 59
5.4 Specimen Preparation Process 63
5.4.1 Material Preparation 63
5.4.2 Mixing Process 63
5.4.3 Casting and Molding 64
5.4.4 Curing 65
5.4.5 Specimen Cutting 65
5.5 Specimen Testing 66
5.5.1 Density and Water Absorption Testing 66
5.5.2 Compressive Strength Test 73

5.5.3 Statistical Analysis 76
5.6 Discussion of Test Results 83
5.6.1 Test Results 83
5.6.2 Reflection and Evaluation of Test Results 91
CHAPTER VI CONCLUSION 96
6.1 Conclusion 96
6.2 Suggestion 98
BIBLIOGRAPHY 99
APPENDIXES 102

LIST OF TABLES

Table 2.1 Comparison of Previous Research 11
Table 3.1 Physical Requirements for Lightweight Concrete CLC 21
Table 3.2 Classification of Lightweight Concrete CLC 21
Table 3.3 Classification of Common Sizes of Lightweight Concrete 22
Table 3.4 Aggregate Gradation 26
Table 3.5 Comparison of Chemical Content between Class F and C Fly Ash 30
Table 3.6 Chemical Content of Fly Ash from PLTU Sumsel-8 31
Table 4.1 Amount of CLC Testing 42
Table 4.2 Composition of Lightweight Bricks Material 42
Table 5.1 Recapitulation of Compacted Fine Aggregate Volume Test 52
Table 5.2 Recapitulation of the Loose Fine Aggregate Volume Test 52
Table 5.3 Recapitulation of Specific Gravity and Water Absorption Fine Aggregate Testing 54
Table 5.4 Recapitulation of Sieve Analysis Fine Aggregate Testing 56
Table 5.5 Gradation of Fine Aggregate 57
Table 5.6 Results of Silt Content Test (No. 200 Sieve Test) 58
Table 5.7 Recapitulation of Used Materials 62
Table 5.8 Test Results of the Density Test 67
Table 5.9 Results of the Water Absorption Test 69
Table 5.10 Recapitulation of Density and Water Absorption Test 71
Table 5.11 Results of Compressive Strength Test 73
Table 5.12 Recapitulation of Compressive Strength Test 75
Table 5.13 The Results of Normality Test Shapiro-Wilk 78
Table 5.14 The Results of Homogeneity Test Levene's Test 79
Table 5.15 Summary of Normality and Homogeneity Test 80
Table 5.16 Mean Rank of Compressive Strength 81
Table 5.17 Statistics of Kruskal-Wallis Test 81
Table 5.18 Pairwise Comparisons of Variation (Bonferroni-Adjusted) 82

Table 5.19 Results of One-Way ANOVA 82
Table 5.20 Recapitulation Test accordance with SNI 8640:2018 90

LIST OF FIGURES

Figure 4.1 Scales 33
Figure 4.2 Oven 34
Figure 4.3 Tube and Stick 34
Figure 4.4 Sieve 35
Figure 4.5 Pycnometer 35
Figure 4.6 Pan 35
Figure 4.7 Bucket 36
Figure 4.8 CLC Block Mould 36
Figure 4.9 Compressor 37
Figure 4.10 Foam Tank 37
Figure 4.11 Cut-off Grinder 38
Figure 4.12 UTM 38
Figure 4.13 Fine Aggregate 39
Figure 4.14 OPC 40
Figure 4.15 Water 40
Figure 4.16 Foam Agent 41
Figure 4.17 Fly Ash 41
Figure 4.18 Flowchart 49
Figure 5.1 Bulk Density Test Process 54
Figure 5.2 Gradation Curve for Fine Aggregates in Region II 57
Figure 5.3 Sieve Analysis Test Process 58
Figure 5.4 Mixing Process 64
Figure 5.5 Casting and Molding Process 64
Figure 5.6 Curing Process 65
Figure 5.7 Specimen Cutting 66
Figure 5.8 Specimen Oven-Dry Density Box Plot 68
Figure 5.9 Density Test 68
Figure 5.10 Water Absorption Test Process 69

Figure 5.11 Specimen Water Absorption Box Plot 70
Figure 5.12 Chart of Oven-Dried Density Test 71
Figure 5.13 Chart of Water Absorption Test 72
Figure 5.14 Specimen Compressive Strength Box Plot 74
Figure 5.15 Chart of Compressive Strength Test 76
Figure 5.16 Compressive Strength Test Process 76
Figure 5.17 Oven-dry Density and Compressive Strength Correlation 77

LIST OF APPENDIXES

Appendix 1 – Compressive Strength Test Report for Cellular Lightweight Concrete (CLC) Bricks 103

ABSTRACT

The construction industry faces major challenges in adopting sustainable practices, as cement production accounts for around 8% of global CO_2 emissions. Cellular Lightweight Concrete (CLC) bricks offer a lightweight, energy-efficient wall material, yet their production still relies heavily on cement as the primary binder. Class F fly ash, an industrial by-product from the PLTU Sumsel–8 power plant, possesses pozzolanic properties that make it a promising partial cement substitute. This study aims to determine the effect of fly ash substitution on the physical and mechanical properties of CLC bricks, to identify the optimum percentage among variations of 0%, 10%, 20%, 30%, and 40%, and to analyse the correlation between bulk density and compressive strength.

The research was conducted experimentally at the Construction Materials Laboratory of Universitas Islam Indonesia. Block specimens measuring 60×20×10 cm were cast for each variation, then cut according to SNI 8640:2018 into specimens for compressive strength (10×10×10 cm), density, and water absorption (20×20×10 cm) testing. Testing was performed at 28 days of age using a Universal Testing Machine (UTM), referring to SNI 8640:2018.

The results show a non-monotonic trend, with the 20% fly ash variation as the optimum point, yielding the highest oven-dry density (824,55 kg/m³), the lowest water absorption (17,07%), and the highest compressive strength (0,6045 MPa). At 30% and 40%, all properties declined due to additional voids from unreacted fly ash. However, all compressive strength values remained below the SNI 8640:2018 minimum requirement (2 MPa), indicating the need for further development. A positive correlation was found between oven-dry density and compressive strength of CLC bricks, with a coefficient of determination $R^2 = 0,9425$.

Keywords: CLC Bricks, Fly Ash, Oven-Dry Density, Compressive Strength

CHAPTER I
INTRODUCTION

1.1 Background

The construction industry is facing a major challenge in adapting to sustainable principles amid global environmental issues such as climate change and natural resource depletion. The cement production process involves chemical and thermal combustion, which means that cement is a major source of carbon dioxide *(CO_2)* emissions, which accounts for around 8% of total CO_2 emissions in the world. Every year, more than 4 (four) billion tonnes of cement are produced (Lucy Rodgers, 2018). In response to this global challenge, the concepts of Green Construction and Green Buildings have emerged as alternatives. This concept not only focuses on energy savings during the operational phase of a building, but also emphasises sustainability in the selection and use of recycled materials, minimisation of waste (zero waste), and utilisation of other industrial by-products, which are the main pillars. These concepts create a high sense of urgency for researchers and practitioners who are more environmentally friendly to reduce the ecological footprint produced. One material innovation that addresses this challenge is Cellular Lightweight Concrete (CLC) or CLC lightweight bricks.

In this development, lightweight bricks are generally divided into two types based on the curing process, namely Autoclaved Aerated Concrete (AAC), which undergoes a high-pressure steam curing process (autoclave), and Cellular Lightweight Concrete (CLC), which undergoes a conventional air curing process. Although AAC has more consistent strength due to the autoclave process, this process requires a significant investment of energy and costs. Therefore, for this final project research, the author chose to focus on CLC lightweight bricks. As a wall material, lightweight bricks offer various advantages, such as light weight, good energy efficiency as thermal insulation, and ease of installation. The performance of CLC lightweight bricks is generally evaluated through their physical and mechanical properties. The physical properties refer to characteristics

that describe the internal structure and condition of the material, namely density (bulk density and oven-dry density), which represents the mass of the brick per unit volume as an indicator of its lightness and compactness, and water absorption, which reflects the porosity of the brick and its ability to absorb water. Meanwhile, the mechanical property refers to the ability of the brick to withstand loads, which is represented by compressive strength as the primary indicator of its structural capacity. These physical and mechanical properties are interrelated and become the main parameters used to assess the quality of CLC lightweight bricks. However, their production still depends on cement as the main binder. The innovation that the author researched is the use of coal ash (fly ash) as a partial substitute for cement in the mixture for making CLC lightweight bricks, which is expected to not only improve the mechanical and physical properties of the bricks but also address the challenge of sustainability through the utilisation of waste and reduction of the carbon footprint of the cement industry.

On the other hand, innovations in sustainable construction materials are encouraging the use of industrial waste, one of which is coal fly ash. As a by-product of coal combustion in power plants, large amounts of fly ash often become waste that causes environmental problems. However, technically, this material has pozzolanic properties, meaning it can react with calcium hydroxide in cement in the presence of water to form compounds that have binding properties. It is this property that underlies its use as a partial substitute for cement in concrete mixtures, including CLC lightweight bricks, which can reduce dependence on Portland cement. Fly ash, as a pozzolanic material rich in amorphous silica and alumina, is a high-value by-product of coal combustion that can be utilised for innovation in construction materials. These pozzolanic properties enable it to react with *Ca(OH)2* released during cement hydration, forming additional Calcium Silicate Hydrate (C-S-H), which substantially increases the compressive strength and durability of concrete. Based on the ASTM C618 standard, fly ash is classified into two types, namely Class C and Class F, which are distinguished by the source of coal and CaO content. In this study, the focus was on Class F Fly Ash, which comes from bituminous coal and has a low CaO content (10%). The selection of Class F is

highly relevant because it is less directly cementitious and more stable than Class C, resulting in more controlled pozzolanic reactivity, which has been proven effective in reducing hydration heat and ensuring superior long-term durability in concrete products (Thomas, 2007). Therefore, the strategy of partially substituting cement with Class F Fly Ash in CLC lightweight brick mixtures offers dual potential: creating more sustainable construction products through waste utilisation and enhancing the technical performance of lightweight bricks. However, the success of optimising physical and mechanical properties, such as the ideal combination of lightness and strength, will greatly depend on determining the percentage variation of Class F Fly Ash substitution to be tested in depth.

The use of fly ash as a partial replacement for cement, particularly Ordinary Portland Cement (OPC), is based on complementary chemical synergies in the hydration process. When OPC cement begins to react with water to harden, it not only produces strength but also leaves behind a reaction residue in the form of calcium hydroxide, which is actually a "weak point" because it is brittle and easily soluble. This is where fly ash comes in to complement this deficiency. Fly ash works by binding the cement reaction residue and converting it back into an additional binder *(C-S-H)* that is much stronger. This synergy makes the combination of the two not just a simple mixing of materials, but an effort to improve the internal structure of CLC lightweight bricks to make them denser, sturdier, and less porous.

In its application to CLC lightweight bricks, the combination of these two materials brings several anticipated results that need to be anticipated. On the positive side, this mixture is expected to make the bricks more durable and resistant to water seepage because their pores are closed by the solid fly ash reaction. In addition, the round and smooth texture of fly ash grains will make the CLC mixture easier to mix and flow, so that the expanding foam can be distributed more evenly without breaking easily. However, there are also challenges or negative aspects that may arise, namely that the brick hardening process tends to be slower in the early days compared to using pure cement. This occurs because Class F fly ash takes longer to start reacting, so if the percentage is too high without proper calculation, there is a concern that the bricks will take a long time to reach their maximum

strength or even risk shrinkage. However, the effectiveness of this substitution also depends heavily on the chemical and physical characteristics of the fly ash itself, as well as its proportion or percentage variation in the mixture. The variation in the substitution percentage to be studied is crucial in determining the optimum point at which the mechanical and physical properties of CLC lightweight bricks can be maintained or even improved, while maximising waste utilisation and reducing the carbon footprint.

Based on previous research, Rahmayanti et al. (2023) stated that the compressive strength value was optimised at a percentage of 30%, while Aziz (2025) found that a 10% variation in fly ash met SNI 8640:2018. On the other hand, Kaselle (2020) concluded that although the use of 40% fly ash is included in type 2 quality according to SNI 03-0349-1989, the increase in strength is not yet significant compared to normal bricks, so further research is needed to find the right composition. The inconsistency between the optimal results and the recommendations for further study prompted me to conduct further research on CLC lightweight bricks with fly ash as a cement replacement mixture. Therefore, in this study, fly ash percentages of 0%, 10%, 20%, 30%, and 40% will be used to analyse their effect on the mechanical and physical properties of lightweight bricks.

1.2 Problem Formulation

The problem of this final project can be formulated as follows.

1. How does the substitution of cement with fly ash affect the physical and mechanical properties of CLC lightweight bricks compared to normal CLC lightweight bricks (without any admixtures)?
2. What is the optimal percentage of fly ash variation (0%, 10%, 20%, 30%, and 40%) that can produce the best characteristics in terms of density and water absorption, and compressive strength test?
3. What is the relationship (correlation) between the density and compressive strength test in CLC lightweight bricks for each variation in the percentage of partial fly ash substitution?

1.3 Purpose

The purposes of this final project can be explained as follows.

1. To determine the comparison of the physical and mechanical properties of CLC lightweight bricks in each variation of fly ash substitution compared to normal CLC lightweight bricks.
2. Determining the optimal percentage of fly ash variation (0%, 10%, 20%, 30%, and 40%) capable of producing the best physical and mechanical characteristics, in terms of compressive strength, bulk density, and water absorption.
3. Analysing the relationship (correlation) between the weight value and compressive strength value of CLC lightweight bricks for each variation in fly ash substitution percentage.

1.4 Advantage

This research is expected to provide technical benefits by determining the optimal formulation of CLC lightweight bricks using fly ash as a cement substitute, thereby reducing dependence on Portland cement without compromising physical and mechanical properties.

1.5 Limitation

The limitations of this research aim to simplify the research process, enabling the author to focus on the issues to be studied. The limitations of the research are as follows.

1. The research will be conducted at the Construction Materials Technology Laboratory of the Universitas Islam Indonesia.
2. The fly ash to be used comes from PLTU Sumsel–8, using Type F fly ash.
3. The cement used is Ordinary Portland Cement (OPC) from Bima Semen.
4. The water and fine aggregate (sand) used came from the Engineering Construction Materials Laboratory (BKT), Department of Civil Engineering, Faculty of Civil Engineering and Planning, Universitas Islam Indonesia.

5. The size of the CLC lightweight bricks that the author will examine complies with SNI 8640:2018: Specifications for Lightweight Bricks for Wall Construction, namely 60 x 20 x 10 cm.
6. The fly ash variations to be used are 0%, 10%, 20%, 30%, and 40%.
7. The Water-Cement Ratio used is 1:0,5, and the Water-Foam Agent Ratio used is 1:0,4.
8. The target dry density of this research is 900 kg/m^3.
9. The tests to be conducted are Density and Water Absorption, and Compressive Strength Test.
10. Specimen Testing will be conducted when the test object reaches 28 days.
11. The size of the test specimen refers to SNI 8640:2018, namely for testing the Density and Water Absorption, measuring 20 × 20 × 10 cm. Then, for testing compressive strength, specimens measuring 10 × 10 × 10 cm are used.
12. The number of test specimens used for the Density Test is 3 specimens, for the Water Absorption Test is 2 specimens, and for the Compressive Strength Test is 5 specimens.

CHAPTER II
LITERATURE REVIEW

2.1 Overview

In order to discuss this literature review, it is necessary to find out about previous studies related to the research to be conducted. The existence of previous studies is expected to serve as a reference for this research and provide information that can be used during the course of this study. The following are some previous studies that can be used as references for this research.

1. Kaselle (2020)

This study discusses *Pengaruh Subtitusi Fly Ash Terhadap Kuat Tekan dan Penyerapan Bata Beton Ringan Seluler (Cellular Lightweight Concrete)*, with the aim of determining compressive strength, specific gravity, and water absorption. The percentage of fly ash used varied between 0% and 40% of the cement weight, and the foam agent was 1.5% of the fly ash mixture weight. Test specimens will be cast in the form of blocks measuring 60 × 10 × 20 cm, as well as cylinders with a diameter of 10 cm and a height of 20 cm, with two specimens for each type and variation of testing. All tests were conducted after 28 days of examination and maintenance in the laboratory.

The results of this study obtained compressive strengths of 10.26 MPa and 8.12 MPa with variations of 0% and 40%, respectively. For density testing, the average brick density was 1.3863 g/cm^3. In addition, the water absorption value was 29.61% at a variation of 0% and 28.5% at a variation of 40%. Therefore, this study concludes that the use of a 40% fly ash variation is included in the quality level of type 2 solid concrete bricks based on SNI 03-0349-1989.

2. Sugianto (2022)

This study, titled *Pemanfaatan Fly Ash dan Kapur Alam Sebagai Bahan Pengganti Semen Terhadap Karakteristik Bata Ringan Cellular Lightweight Concrete (CLC)*, aims to determine compressive strength, bulk density, and water absorption. The percentage of fly ash used varied between 10% and 40% of the

cement weight, and natural lime was added at 5% for each variation. Test specimens were cast as blocks measuring 60 × 10 × 20 cm, with 35 specimens per type and test variation. All tests were conducted after 28 days of curing and maintenance in the laboratory.

The results of this study yielded compressive strengths of 2.02 MPa and 0.70 MPa for the 10% and 40% variations, respectively. For bulk density testing, the results showed a maximum density of 889.608 kg/m³ and a minimum density of 575.326 kg/m³. Additionally, the water absorption values ranged from 16.86% to 40.38% across all variations. Therefore, this study concludes that the use of a 10% fly ash and 5% natural lime mixture constitutes the optimal blend, which falls within the quality grade for non-structural lightweight bricks, Class IIA, as per SNI 8640:2018.

3. Rahmayanti, et al. (2023)

This study is entitled *Pemanfaatan dan Pengaruh Fly Ash Batu Bara Sebagai Subtitusi Sebagian Semen Terhadap Nilai Kuat Tekan Bata Ringan Jenis Cellular Lightweight Concrete (CLC)*, which aims to determine the benefits and effects of coal fly ash as a partial substitute for cement on the compressive strength of CLC bricks. The CLC lightweight brick test specimens were made in sizes of 15 × 15 × 15 cm. The percentage variations used consisted of 0%, 20%, 30%, 40%, and 50% of the cement weight. The tests conducted for this study were compressive strength tests when the curing age had reached 28 days.

Based on the experiments conducted, the maximum compressive strength value obtained for the 30% fly ash variation was 8.539 MPa, and the minimum compressive strength value for the 50% fly ash variation was 5.351 MPa. Therefore, the optimum percentage of fly ash as a partial substitute for cement to obtain the maximum compressive strength of CLC lightweight bricks was found to be 30%.

4. Putra, et al. (2024)

This research, entitled *Studi Eksperimental Sifat Mekanis Bata Ringan CLC Dengan Penambahan Fly Ash*, aims to determine the optimum fly ash content for lightweight bricks with maximum compressive strength through an experimental study of the mechanical properties of CLC lightweight bricks. This study used

variations in fly ash content of 0%, 5%, 10%, 15%, 20%, and 25% of the cement weight in cube samples with a side length of 10 cm. Compressive strength testing was carried out at 7, 14, and 28 days. Deformation (settlement) testing was conducted at 28 days. The compressive strength and settlement results were used to analyse the strain and stress values in lightweight bricks.

Based on the results of this experiment, the highest compressive strength was obtained in the 10% variation, which was 10.20 kg/cm2 at 28 days of age, with a decrease of 9.440 mm, strain of 0.094, and stress of 1.20 N/mm2. From these results, it can be concluded that the addition of 10% fly ash can increase the compressive strength of lightweight bricks, thus providing a recommendation to lightweight brick manufacturers for the optimal composition of lightweight brick mixtures using fly ash.

5. Aziz (2025)

The study entitled *Pengaruh Fly Ash sebagai Subtitusi Sebagian Semen pada Bata Ringan CLC (Cellular Lightweight Concrete)* aims to analyse the effect of fly ash on the mechanical and physical properties of CLC lightweight bricks, such as compressive strength, split tensile strength, shear strength, dry bulk density, and water absorption, as well as to determine the optimal percentage of fly ash according to the SNI 8640:2018 standard. In this study, test specimens in the form of cubes measuring 10 cm × 10 cm × 10 cm will be made for compressive strength and splitting tensile strength testing, while for shear strength, bulk density, and water absorption testing, moulds in the form of beams measuring 30 × 10 × 10 cm will be used. The variations in fly ash proportion used are 0%, 5%, 10%, 15%, and 20% of the cement weight.

Based on the results of this research experiment, the highest average compressive strength value obtained was 2.267 MPa at a variation of 10%, and the lowest compressive strength value was 1.533 MPa at a variation of 20%. Furthermore, the highest splitting tensile strength value was 0.354 MPa at a variation of 10%, and the lowest splitting tensile strength value was 0.212 MPa at variations of 0% and 20%. Furthermore, the highest shear strength value was 0.800 MPa at a variation of 10%, and the lowest shear strength value was 0.475 MPa at a

variation of 20%. Then, the highest dry weight value was 698.6 kg/m³ at a variation of 10%, and the lowest dry weight value was 671.3 kg/m³ at a variation of 20%. The highest water absorption test value was 24.9% at a variation of 20%, and the lowest water absorption test value was 21.5% at a variation of 10%. This study concluded that fly ash as a partial cement substitute in CLC lightweight bricks can be used to improve the mechanical and physical performance of CLC lightweight bricks and provide an environmentally friendly solution for sustainable development.

2.2 Comparison of Previous Research

Based on previous studies as described above, there are differences and similarities between the studies that the author will examine. A comparison of previous studies can be seen in Table 2.1 on the next page.

Table 2.1 Comparison of Previous Research

No	Description	Previous Research					Current Research
		Kaselle (2020)	Sugianto (2022)	Rahmayanti, et al. (2023)	Putra, et al. (2024)	Aziz (2025)	
1	**Title**	Pengaruh Subtitusi Fly Ash Terhadap Kuat Tekan dan Penyerapan Bata Beton Ringan Seluler (Cellular Lightweight Concrete)	Pemanfaatan Fly Ash dan Kapur Alam Sebagai Bahan Pengganti Semen Terhadap Karateristik Bata Ringan Cellular Lightweight Concrete (CLC)	Pemanfaatan dan Pengaruh Fly Ash Batu Bara Sebagai Substitusi Sebagian Semen Terhadap Nilai Kuat Tekan Bata Ringan Jenis Cellular Lightweight Concrete (CLC)	Studi Eksperimental Sifat Mekanis Bata Ringan CLC Dengan Penambahan Fly Ash	Pengaruh Subtitusi Fly Ash Terhadap Kuat Tekan dan Penyerapan Bata Beton Ringan Seluler (Cellular Lightweight Concrete)	The Effect of Partial Substitution of Cement with Coal Fly Ash on the Physical and Mechanical Properties of Cellular Lightweight Concrete (CLC)
2	**Purpose**	This study aims to determine the effect of fly ash substitution in CLC lightweight bricks in terms of compressive strength, density, and absorption capacity.	To determine the characteristics of CLC lightweight bricks by adding fly ash and natural lime as cement substitutes.	This study aims to obtain the optimum percentage of compressive strength of lightweight bricks, determine the characteristics of coal fly ash as a partial substitute for cement in CLC lightweight brick mixtures, and determine the differences in compressive strength values of CLC lightweight bricks for each variation in the percentage of coal fly ash as a partial substitute for cement.	By adding fly ash to the lightweight brick material mixture, this study aims to determine the optimum fly ash content in determining lightweight bricks with maximum compressive strength through experimental studies of the mechanical properties of CLC lightweight bricks in the form of compressive strength, stress, and strain values of lightweight bricks, and reducing fly ash waste produced by industries using coal.	This study aims to analyse the effect of fly ash on the mechanical and physical properties of CLC lightweight bricks, such as compressive strength, splitting tensile strength, shear strength, dry bulk density, and water absorption. In addition, this study also aims to determine the optimal percentage of fly ash in accordance with the SNI 8640:2018 standard.	This study aims to evaluate the physical and mechanical properties of CLC lightweight bricks with various fly ash substitution levels by comparing them to normal CLC lightweight bricks. It also seeks to determine the optimal percentage of fly ash variation (0%, 10%, 20%, 30%, and 40%) that can produce the best physical and mechanical characteristics, particularly in terms of compressive strength, bulk density, and water absorption. In addition, the study analyzes the relationship (correlation) between bulk density and compressive strength of CLC lightweight bricks for each level of fly ash substitution.

Continuation Table 2.1 Comparison of Previous Research

No	Description	Previous Research					Current Research
		Kaselle (2020)	Sugianto (2022)	Rahmayanti, et al. (2023)	Putra, et al. (2024)	Aziz (2025)	
3	**Methodology**	The manufacture of lightweight bricks was carried out experimentally by adding 10-40% fly ash with a 10% increase and 5% natural lime in each variation. The test specimens were 10 cm x 20 cm x 60 cm in size for each variation.	The experimental study on the production of CLC lightweight bricks using a mixture of fly ash and lime was conducted at the Volcanic Materials Innovation Laboratory of the Islamic University of Indonesia. The lightweight bricks were produced experimentally by adding 10–40% fly ash in 10% increments and 5% natural lime in each variation. The test specimens produced measured 10 cm x 20 cm x 60 cm for each variation.	The research method used was an experimental method that substituted part of the cement with coal fly ash. The substitution percentage varied from 0%, 20%, 30%, 40%, and 50% of the cement weight. The compressive strength of the lightweight bricks was tested when the curing period had reached 28 days.	The study used variations in composition with fly ash content of 0%, 5%, 10%, 15%, 20%, and 25% of the cement weight in cube samples with a side length of 10 cm. Compressive strength testing was carried out at 7, 14, and 28 days. Deformation (settlement) tests were conducted at 28 days. The compressive strength and settlement results were used to analyse the stress and strain values in lightweight bricks.	The research method used was an experimental method supported by literature studies, material examination, and test specimen testing. The fly ash proportion variations used were 0%, 5%, 10%, 15%, and 20% of the cement weight. In this study, test specimens in the form of cubes measuring 10 cm × 10 cm × 10 cm will be made for compressive strength and split tensile strength testing, while for shear strength, bulk density, and water absorption testing, moulds in the form of beams measuring 30 × 10 × 10 cm will be used.	The research method used was an experimental method that substituted part of the cement with Class F coal fly ash sourced from PLTU Sumsel-8. The substitution percentage varied from 0%, 10%, 20%, 30%, and 40% of the cement weight. Test specimens were cast as blocks measuring 60 cm × 20 cm × 10 cm and, in accordance with SNI 8640:2018, each block was cut into 10 pieces of 10 cm × 10 cm: 5 specimens for compressive strength testing, 3 for density testing, and 2 for water absorption testing. All tests were conducted after the specimens had cured for 28 days. The test results were then analysed statistically. The normality of the compressive strength data was examined using the Shapiro-Wilk test and the homogeneity of variance using Levene's test. Because the

Continuation Table 2.1 Comparison of Previous Research

No	Description	Previous Research					Current Research
		Kaselle (2020)	Sugianto (2022)	Rahmayanti, et al. (2023)	Putra, et al. (2024)	Aziz (2025)	
							normality assumption was not satisfied in all groups, the non-parametric Kruskal-Wallis test was used for hypothesis testing, followed by Bonferroni-adjusted pairwise comparisons, with a One-Way ANOVA computed as a sensitivity check. The relationship between oven-dry density and compressive strength was analysed using simple linear regression.
4	**Analysis and Discussion**	1. **Density Testing** The testing was conducted on lightweight bricks that had undergone a 28-day curing period by spraying water on their surfaces. Based on the results of the density testing analysis in Table 5.8, the results varied, with the highest density being 889.6 kg/m^3 and the lowest being 575.3 kg/m^3. Based on SNI 8640:2018, the density value of each test specimen	**1. Density Testing** The highest density value of 889.6 kg/m³ was obtained for Variation 1, and the lowest of 575.3 kg/m³ for Variation 5. **2. Compressive Strength Test** The highest average value was obtained from variation 2 at 2.02 MPa, while the lowest value was found in variation 5 at 0.70 MPa. **3. Water Absorption Testing**	Based on this study, the average density of CLC lightweight bricks decreased with each increase in fly ash percentage, so it can be concluded that the use of fly ash as a partial cement substitute reduces the weight of the resulting lightweight bricks. The CLC lightweight bricks in this study had a density above 1000 kg/m^3 and below 2000 kg/m^3, so the CLC lightweight bricks produced in this study are classified as high-density lightweight bricks. The compressive strength value of CLC	1. The lowest density mixture was found in the 15% fly ash mixture with a density value of 0.817 t/m3, while the highest density value was found in the 0% fly ash mixture with a density value of 1.065 t/m3. 2. The test specimen was aged for 14 days, and the maximum compressive strength was found in the 10% fly ash mixture with an average weight of 1008 grams and a compressive strength of 10.13 kg/cm2. 3. The maximum compressive strength	**1. Compressive Strength Test Results** The compressive strength value of lightweight bricks with a 0% fly ash proportion used as a control produced an average compressive strength value of 1.733 MPa. When fly ash was added with variations in proportion of 5%, 10%, and 15%, there was an increase in compressive strength of 15.4%, 30.8% and 7.7% with average compressive strength values of 2 MPa,	**1. Density Testing** The oven-dry density increased from 806,88 kg/m³ (0%) to a peak of 824,55 kg/m³ at the 20% variation, then dropped sharply to 758,41 kg/m³ (30%) and 751,98 kg/m³ (40%). Referring to SNI 8640:2018 (acceptable range approx. 800–1000 kg/m³), the 0%, 10%, and 20% variations met the standard, while the 30% and 40% variations fell below it. **2. Water Absorption Test** Water absorption decreased from 23,11% (0%) to a minimum of 17,07% at the 20%

Continuation Table 2.1 Comparison of Previous Research

No	Description	Previous Research					Current Research
		Kaselle (2020)	**Sugianto (2022)**	**Rahmayanti, et al. (2023)**	**Putra, et al. (2024)**	**Aziz (2025)**	
		variation meets the requirements for class IIA non-structural bricks. The results show that substituting cement with fly ash results in a decrease in density. 2. **Compressive Strength Test** Similar to the density test, this test was conducted on test specimens that were 28 days old. This test aims to determine the strength value of lightweight bricks based on the load applied per surface area. The test results show that the average compressive strength meets the requirements for non-structural bricks in SNI 8640:2018 of 2 MPa and is classified as a lightweight brick with a quality level of IIA only in variation 2.	Water absorption values ranged from 16.86% to 40.38%. According to SNI 8640:2018, the maximum water absorption value for Class IIA is 25%, so only variation 2 met this requirement. Variations 3, 4, and 5 did not meet the requirement.	lightweight bricks obtained reached the planned compressive strength, which was more than 1.4 MPa. Variations in the percentage of fly ash caused the compressive strength value of CLC lightweight bricks to decrease. The compressive strength values of CLC lightweight bricks at fly ash variations of 0%, 20%, 30%, 40%, and 50% were 14.361 MPa, 8.510 MPa, 8.539 MPa, 5.535 MPa, and 5.351 MPa, respectively.	was found in the 10% fly ash mixture aged 28 days, with an average weight of 1008 grams and a compressive strength of 10.20 kg/cm2. 4. The 0% fly ash mixture from day 7 to day 28 experienced an increase in compressive strength of 2.38 kg/cm² from 7.64 kg/cm² at 7 days to 10.02 kg/cm² at 28 days. The 5% fly ash mixture from day 7 to day 28 experienced an increase in compressive strength of 1.19 kg/cm2 from 8.89 kg/cm2 at 7 days to 10.08 kg/cm2 at 28 days. The 10% fly ash mixture from day 7 to day 28 experienced an increase in compressive strength of 0.17 kg/cm² from 10.03 kg/cm² at 7 days to 10.20 kN at 28 days. The 15% fly ash mixture from day 7 to day 28 experienced an increase in compressive strength of 0.72 kg/cm² from 5.32 at 7 days to 6.04	2.267 MPa, and 1.867 MPa. At a variation of 20% fly ash, there was a decrease in the compressive strength of lightweight bricks of -11.5% with an average compressive strength of 1.533 MPa. **2. Split Tensile Strength Test Results** The split tensile strength test results without fly ash addition obtained a split tensile strength of 0.212 MPa, which was used as a control in this study. The addition of 5%, 10%, and 15% fly ash increased the tensile strength by 33.5%, 67%, and 11.3%, with tensile strength values of 0.283 MPa, 0.354 MPa, and 0.236 MPa. When adding a 20% fly ash proportion, the splitting tensile strength value of 0.212 MPa was the same as the initial value without fly ash.	variation, then rise sharply to 26,91% (30%) and 30,00% (40%). Based on SNI 8640:2018 (maximum 25%), the 0%, 10%, and 20% variations complied with the standard, while the 30% and 40% variations exceeded it. **3. Compressive Strength Test** The compressive strength followed the same optimum-then-decline pattern, rising from 0,5748 MPa (0%) to a peak of 0,6045 MPa at the 20% variation, then falling to 0,5127 MPa (30%) and 0,4606 MPa (40%). Compared with the SNI 8640:2018 minimum of 2 MPa for non-structural bricks, all variations fell short of this requirement, so the resulting material cannot yet be recommended for structural or non-structural applications, although the 20% variation remains the best-performing composition among those tested. **4. Statistical Analysis**

Continuation Table 2.1 Comparison of Previous Research

No	Description	Previous Research					Current Research
		Kaselle (2020)	Sugianto (2022)	Rahmayanti, et al. (2023)	Putra, et al. (2024)	Aziz (2025)	
		3. **Water Absorption Test** Based on the above analysis, the absorption values ranged from 16.86% to 40.38%. In SNI 8640:2018, the maximum water absorption value for class IIA is 25%, so the lightweight brick samples that meet this requirement are only in variation 2. The water absorption value in lightweight bricks is not only influenced by their porous surface but also by the composition of the materials in the mixture. Fly ash and natural lime, which are used as cement substitutes, cumulatively cause the structure of lightweight bricks to be more fragile when viewed from the compressive strength value, which also decreases.			kg/cm² at 28 days. The 20% fly ash mixture from day 7 to day 28 experienced an increase in compressive strength of 0.25 kg/cm² from 4.70 kg/cm² at 7 days to 4.95 kg/cm² at 28 days. The 25% fly ash mixture from day 7 to day 28 experienced an increase in compressive strength of 0.28 kN from 2.82 kg/cm² at 7 days to 3.10 kg/cm² at 28 days.	**3. Shear Strength Test Results** The shear strength value of lightweight bricks with a 0% fly ash proportion used as a control produced an average shear strength value of 0.600 MPa. When fly ash was added with variations in proportion of 5%, 10% and 15%, it resulted in an increase in splitting tensile strength of 16.7%, 33.3% and 4.2% with average shear strength values of 0.700 MPa, 0.800 and 0.625 MPa. At a fly ash proportion of 20%, there was a decrease of 20.8% with an average shear strength of 0.475 MPa. **4. Dry Weight Test Results** Lightweight bricks without fly ash added as a cement substitute had an average dry weight of 678.9 kg/m^3, which was used as the control in the dry weight test.	The Shapiro-Wilk test showed that FA30 was not normally distributed, so the non-parametric Kruskal-Wallis test was used. The result (H = 22,338; Asymp. Sig. < 0,001) confirmed significant differences between variations, with Bonferroni-adjusted pairwise comparisons showing significance only between the high-replacement groups (FA30, FA40) and the moderate-replacement groups (FA10, FA20). The regression between oven-dry density and compressive strength produced y = 0,0017x – 0,831 with R^2 = 0,9425.

Continuation Table 2.1 Comparison of Previous Research

No	Description	Previous Research					Current Research
		Kaselle (2020)	**Sugianto (2022)**	**Rahmayanti, et al. (2023)**	**Putra, et al. (2024)**	**Aziz (2025)**	
		Meanwhile, this decrease is also followed by an increase in the water absorption value. From this explanation, the relationship between the water absorption value and the compressive strength value of lightweight bricks can be determined. The greater the water absorption value, the lower the compressive strength value of lightweight bricks.				When fly ash was added in proportions of 5% and 10%, there was an increase in the average dry weight to 688 kg/m^3 and 698.6 kg/m^3, respectively. At variation proportions of 15% and 20%, there was a decrease in the average dry weight of 675.9 kg/m^3 and 671.3 kg/m^3. **5. Water Absorption Test Results** The water absorption value of lightweight bricks with fly ash variations of 0%, 5%, and 10% decreased with average water absorption values of 23.4%, 22.3%, and 21.5%. At fly ash proportions of 15% and 20%, there was an increase in the average water absorption value of 24.2% and 24.9%.	
5	**Conclusion**	1. Variations in mixtures with fly ash and natural lime in lightweight bricks resulted in a decrease in compressive	1. The use of different mixtures of fly ash and natural lime in lightweight bricks results in a decrease in	The chemical characteristics of fly ash have an SO3 content of 0.81% – 2.92% and meet the requirements of SNI 15-7064-2004, namely that a material to be used	1. This study shows that the maximum addition of fly ash is 10%. Adding more than that reduces the compressive strength. For deformation	1. The addition of 10% fly ash provides the best mechanical performance in lightweight bricks for compressive strength, split tensile strength,	1. The substitution of cement with fly ash affected the physical and mechanical properties of CLC lightweight bricks in a non-monotonic

Continuation Table 2.1 Comparison of Previous Research

No	Description	Previous Research					Current Research
		Kaselle (2020)	**Sugianto (2022)**	**Rahmayanti, et al. (2023)**	**Putra, et al. (2024)**	**Aziz (2025)**	
		strength and density, while water absorption increased compared to normal mixtures. 2. Mixtures with variations in fly ash and natural lime were able to produce lightweight bricks similar to those in normal mixtures without experiencing breakage before testing. 3. Based on all tests conducted, lightweight brick variation 2 with a mixture of 10% fly ash and 5% natural lime is the optimal mixture for use. 4. Based on compressive strength, density, and water absorption tests, only the variation with 10% fly ash and 5% natural lime meets the requirements of SNI 8640:2018, making this	compressive strength and density, while water absorption increases compared to lightweight bricks made with a standard mixture. 2. Despite the use of different mixtures of fly ash and natural lime, the resulting lightweight bricks still formed well, similar to the standard mixture, and did not suffer damage or breakage prior to testing. 3. Based on the results of all tests conducted, the mixture consisting of 10% fly ash and 5% natural lime is the most optimal composition for use in lightweight brick production. 4. The results of the compressive strength, density, and water absorption tests indicate that only	for general construction purposes must have a maximum SO3 content of 4%. The compressive strength value of CLC lightweight bricks without the addition of coal fly ash as a partial cement substitute was a higher value than the compressive strength value of CLC lightweight bricks with the addition of coal fly ash as a partial cement substitute. The variation in fly ash addition caused the compressive strength value of CLC lightweight bricks to decrease from the 0% fly ash variation. The compressive strength values obtained for fly ash variations of 0%, 20%, 30%, 40%, and 50% were 14.361 MPa, 8.510 MPa, 8.539 MPa, 5.535 MPa, and 5.351 MPa, respectively.	values, the greater the compressive strength, the greater the deformation value, and if the compressive strength is small, the deformation value will also be smaller. 2. The stress-strain value is highly dependent on the compressive strength and deformation values. The greater the compressive strength, the greater the stress value, and the greater the strain value. 3. In this study, the addition of 10% fly ash resulted in a compressive strength of 10.20 kg/cm² after 28 days, with a strain of 0.094 and a stress of 1.20 N/mm². 5. Based on this study, it can be seen that fly ash as a pozzolanic material can improve the bonding properties in lightweight brick mixtures at certain levels, thereby increasing the overall compressive strength. However, if the optimal level is	shear strength, bulk density, and water absorption tests. The addition of more than 10% fly ash tends to reduce the mechanical performance of lightweight bricks, while a proportion of 20% fly ash produces the lowest values in all types of testing. 2. Based on the results of research on variations in fly ash mixtures as an optimal cement substitute for lightweight bricks, a variation of 10% fly ash can meet the standards set out in SNI 8640:2018 for compressive strength, dry bulk density, and water absorption.	manner. Up to the 20% replacement level, oven-dry density increased (806,88 to 824,55 kg/m³), and compressive strength increased (0,5748 to 0,6045 MPa), while water absorption decreased (23,11% to 17,07%). Beyond 20%, all three properties reversed direction, with the 30% and 40% variations performing worse than even the normal (0%) brick. 2. The 20% fly ash variation was found to be the optimal percentage among the five variations tested (0%, 10%, 20%, 30%, and 40%), producing the highest oven-dry density (824,55 kg/m³), the lowest water absorption (17,07%, within the SNI 8640:2018 limit of 25%), and the highest compressive strength (0,6045 MPa). Nevertheless, the compressive strength of all

Continuation Table 2.1 Comparison of Previous Research

No	Description	Previous Research					Current Research
		Kaselle (2020)	Sugianto (2022)	Rahmayanti, et al. (2023)	Putra, et al. (2024)	Aziz (2025)	
		mixture effective as a partial cement substitute.	the mixture containing 10% fly ash and 5% natural lime meets the requirements of SNI 8640:2018. Therefore, this composition is considered effective as a partial substitute for cement in lightweight brick mixtures.		exceeded, the strength of the lightweight bricks tends to decrease. The results of this study reflect the same trend, confirming that the addition of 10% fly ash is the optimal level for achieving structural integrity.		variations remained far below the 2 MPa minimum required by SNI 8640:2018 for non-structural lightweight blocks, so the material cannot yet be recommended for structural or non-structural building applications. 3. There is a positive correlation between oven-dry density (weight of content) and compressive strength across the fly ash variations, as density increased from 0% to 20% fly ash, compressive strength increased accordingly, and as density decreased at the 30% and 40% variations, compressive strength decreased as well, reaching its lowest value at 40% fly ash.

2.3 Originality of Research

Based on several previous studies, the author declares that this research on CLC lightweight bricks with fly ash substitution is original work and not plagiarized. The differences lie in the object and methodology of the research. This study specifically investigates the optimal composition of CLC lightweight bricks by partially substituting cement with fly ash sourced from the PLTU Sumsel–8 at variation percentages of 0%, 10%, 20%, 30%, and 40% to analyze its effect on compressive strength, density, and water absorption. The fly ash, obtained directly from PLTU Sumsel-8, represents local industrial waste classified as Class F per ASTM C618 standards, making it highly relevant for Indonesian construction applications. These variations are designed to address the inconsistencies in the optimal findings of previous studies and to find a clearer optimum point. With an experimental approach and a planned age of 28 days, the author is responsible for the originality of this study.

CHAPTER III
THEORETICAL BASIS

3.1 Lightweight Concrete

Lightweight bricks are a modern wall construction material widely recognized for their low weight and ease of installation. In general, there are two main types of lightweight bricks, namely Autoclaved Aerated Concrete (AAC), which is cured under pressurized steam, and Cellular Lightweight Concrete (CLC). In this study, the main focus is on CLC lightweight bricks. CLC is defined as porous lightweight concrete produced by mixing a stable foam agent into a mixture of cement, water, and fine aggregate, so that the drying process can be carried out naturally without the need for an autoclave. The lightweight concrete is shown in Figure 3.1 below; this image provides a visual view of the cellular lightweight concrete (CLC) blocks I produced, illustrating their overall appearance, texture, and relative size.



Figure 3.1 Lightweight Concrete CLC

3.2 Lightweight Concrete Specification and Testing

CLC lightweight bricks meet the physical property requirements of SNI 8640:2018, as shown in Table 3.1. The table lists the measured parameters used for conformity assessment, including the Minimum Average Compressive Strength, the Minimum Individual Compressive Strength, the Maximum Water Absorption, and the Minimum Thickness.

Table 3.1 Physical Requirements for Lightweight Concrete CLC

Physical Requirements	Unit	Structural Bricks		Non-structural Bricks	
		Exposed to the Env. (Outdoor)	Not Exposed to the Env. (Indoor)	Exposed to the Env. (Outdoor)	Not Exposed to the Env. (Indoor)
Type	-	IA	IB	IIA	IIB
Average Compressive Strength, min.	MPa	6	4	2	
Individual Compressive Strength, min.	MPa	5,4	3,6	1,8	
Water Absorption, max.	% Vol	25	-	25	-
Thickness, min.	mm	98		98	73

(Source: SNI 8640:2018)

To ensure quality, even though CLC is produced without an autoclave, the general quality specifications refer to SNI 8640:2018, as shown in Table 3.2 below.

Table 3.2 Classification of Lightweight Concrete CLC

	Weight Category	Structural Bricks		Non-structural Bricks	
		Exposed to the Env. (Outdoor)	Not Exposed to the Env. (Indoor)	Exposed to the Env. (Outdoor)	Not Exposed to the Env. (Indoor)
Type	-	IA	IB	IIA	IIB
Oven Dry Weight (kg/m^3)	500			400-600	
	700		600-800	600-800	
	900	800-1.000	800-1.000	800-1.000	
	1.000	1.000-1.200	1.000-1.200	1.000-1.200	
	1.300	1.200-1.400	1.200-1.400	1.200-1.400	

(Source: SNI 8640:2018)

In addition, SNI 03-0349-1989 stipulates product dimensions and tolerances, whereby lightweight bricks must have precise dimensions. The following is a general classification of the weight and size of lightweight bricks in accordance with the standards shown in Table 3.3 on the next page.

Table 3.3 Classification of Common Sizes of Lightweight Concrete

Size (mm)			Size Tolerance (mm)
Length	Width	Thick	
600 + 3	200 + 3	75	± 2
600 - 5	200 - 5	100	
		125	
		150	

(Source: SNI 03-0349-1989)

3.2.1 Density and Water Absorption Test

The unit weight and water absorption test on CLC lightweight bricks is conducted in an integrated manner according to SNI 8640:2018 with the research objective of determining the material density under oven-dry and water-saturated conditions as well as the ability of the lightweight brick to absorb water, which affects durability and wall performance, so that it can be evaluated whether the physical quality of CLC lightweight bricks meets the standard requirements according to the SNI 8640:2018.

With the parameters shown in Table 3.1 for Water Absorption and Table 3.2 for Oven-dry Weight, the density test can be calculated using the following equation.

$$\text{Density of Contents } (\rho) = \frac{\boldsymbol{W}}{\boldsymbol{V}} \tag{3.1}$$

$$\text{Nominal content weight (BI)} = \left(\frac{\boldsymbol{Ba}}{\boldsymbol{V}}\right) \times 10^6 \text{ kg/m}^3 \tag{3.2}$$

$$\text{Oven dry weight } (BI_o) = \left(\frac{\boldsymbol{Bk0}}{\boldsymbol{V}}\right) \times 10^6 \text{ kg/m}^3 \tag{3.3}$$

$$\text{Water saturation weight } (BI_a) = \left(\frac{\boldsymbol{Bssd}}{\boldsymbol{V}}\right) \times 10^6 \text{ kg/m}^3 \tag{3.4}$$

$$\text{Water Absorption} = \frac{\boldsymbol{BIa - BI0}}{\boldsymbol{A}} \times 100\% \tag{3.5}$$

Where,

ρ = Test Object Weight (kg/m^3)

W = Test Object Weight (kg)

V = Test Object Volume (m^3)

BI = Nominal Weight (gram)

B_a = Initial Weight (gram)

Bk_0 = Oven-dried weight (gram)

BI_a = Water saturation weight (kg/m^3)

B_{ssd} = Saturated Water Weight (kg/m^3)

3.2.2 Compressive Strength Test

The compressive strength test on CLC lightweight bricks is conducted with the research objective of determining the ability of the lightweight brick to withstand compressive load until failure and to establish the characteristic compressive strength value of the material, so that it can be ascertained whether the produced CLC lightweight bricks have adequate structural quality and comply with the quality classification specified in the lightweight brick standard, namely SNI 8640:2018. Based on the parameters in Table 3.1, compressive strength tests can be calculated using the following formula.

$$\text{Compressive Strength } (\sigma) = \frac{\boldsymbol{P}}{\boldsymbol{A}} \qquad (3.6)$$

Where,

Compressive Strength (σ) = Compressive Strength (MPa or N/mm^2)

P = Maximum Load (N)

A = Cross-sectional Area of Test Object (mm^2)

The sketch of the Density and Water Absorption Test, and Compressive Strength Test used in this study is shown in Figure 3.2.

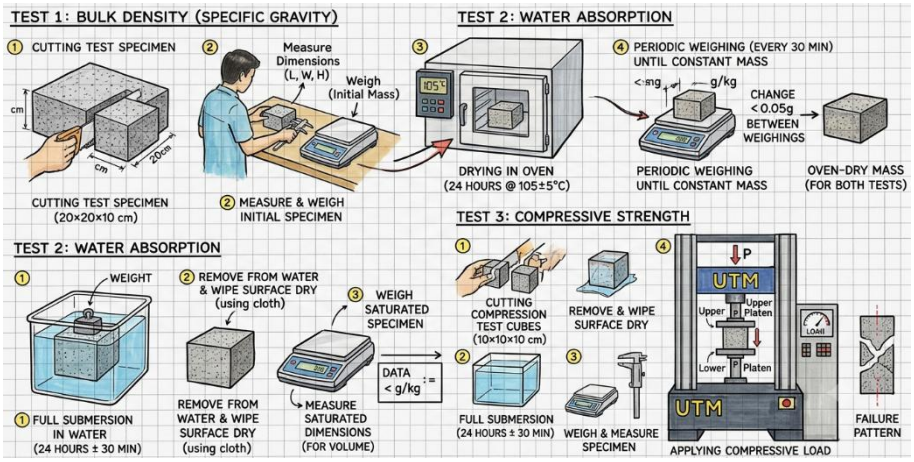


Figure 3.2 Sketch of Specimen Test

(Source: Sketch by *Gemini.google.com*)

The use of CLC lightweight bricks offers several significant advantages on construction sites. One of the main advantages of lightweight concrete is that it weighs less than conventional concrete, thereby significantly reducing the dead load on structures and potentially reducing the dimensions of structural elements and the load on foundations (Agrawal, et al., 2021). In addition, lightweight concrete with high air porosity has superior thermal insulation and soundproofing properties compared to regular concrete due to its hollow structure (Benjeddou, et al., 2023). However, CLC lightweight bricks also have limitations. One limitation of CLC lightweight bricks is their relatively low compressive strength compared to conventional concrete, as their highly porous structure tends to reduce mechanical strength. Therefore, CLC lightweight bricks are generally more suitable for non-structural applications such as partition walls (Putra, et al., 2024). The process of installing lightweight bricks tends to be more efficient when carried out by skilled workers using the right techniques, as precise dimensions and the use of instant mortar will increase productivity and reduce material waste and implementation time (Pramesti & Priyanto, 2023).

3.3 Component Materials of Lightweight Concrete

The materials used to make lightweight bricks are cement, fine aggregate, water, foam agent, and coal fly ash as a partial substitute for cement. The following is an explanation of these materials.

3.3.1 Portland Cement

Portland cement is a fundamental hydraulic binder in construction, and the type used in this study is Ordinary Portland Cement (OPC) Type I. OPC is defined as cement produced from grinding Portland cement clinker and gypsum, together with additional inorganic materials (fillers) that can comprise up to 35% of the cement mass. According to SNI 2049:2020 concerning Portland Cement, Semen Kasturi Portland (SKP) has functional properties equivalent to Type I Cement, making it the standard for general construction applications that do not require special resistance. SNI 2049:2020 regulates in detail the technical specifications of SKP, including chemical and physical properties, and most crucially, the

compressive strength of cement. This standard stipulates that SKP must achieve adequate compressive strength at a certain age (e.g., 40.0 MPa at 28 days) to ensure consistent and reliable material quality as a structural binder.

The decision to use Type I Portland Cement (OPC) is supported by three compelling reasons. First, Portland Composite Cement (PCC) is one of the most widely used types of cement today. However, before PCC became popular in the market, the cement commonly used in construction work was Ordinary Portland Cement (OPC), especially in Indonesia (Prameswari, et al., 2023). Secondly, optimal performance, whereby Type I OPC cement offers a good rate of strength development and is highly suitable for the strength requirements of concrete and mortar in civil engineering projects in general. Third, Ordinary Portland Cement (OPC) is a type of cement that is still commonly used in concrete mixtures in Indonesia. Compared to composite cement such as PCC, OPC shows significant differences in compressive strength. The use of OPC in this study provides a strong practical basis so that the results of the analysis can be more easily applied to general concrete construction practices in the field (Mariatul Kiptiah & Giarto, 2025).

3.3.2 Fine Aggregate

Fine aggregate, more commonly known as sand, is one of the fundamental components in construction, particularly as the main filler in cement, concrete, and mortar mixtures, including in the manufacture of CLC lightweight bricks. Sand is defined as a natural granular material derived from the disintegration of rock, with a grain size of less than 5 mm. In CLC lightweight concrete, the use of fine aggregates in larger proportions can fill the air voids formed by foam, making the product more compact. The mechanism of filling voids/reducing pore volume with fine sand has also been reported to reduce drying shrinkage in cement-based materials (Pah, et al, 2021). To ensure the quality and performance of materials, fine aggregates must meet the quality requirements set by national standards. Based on SNI 03-6820-2002, fine aggregates are classified based on their gradation or particle size distribution, which is measured through sieve analysis. Good gradation will ensure optimal mortar density and reduce air voids. The ideal gradation

requirements are regulated by the percentage weight pass limits of the aggregate on each standard sieve size, as specified in the SNI standard table. The gradation requirements for fine aggregates used in this study must comply with SNI 03-6820-2002 to ensure that the fine aggregates used are based on the sieve numbers that pass, as shown in Table 3.4 below.

Table 3.4 Aggregate Gradation

Sieve	Percentage Passed	
	Maximum	**Minimum**
No. 4 (4,76 mm)	100	-
No. 8 (2,36 mm)	99	100
No. 16 (1,18 mm)	70	100
No. 30 (0,6 mm)	40	75
No. 50 (0,3 mm)	10	35
No. 100 (0,15 mm)	2	15
No. 200 (0,75 mm)	0	3

(Source: SNI 03-6820-2002)

Aggregates that pass within these limits are considered to have good gradation, which is very important because improper gradation can increase water and cement requirements and reduce the strength and workability of CLC mortar. Therefore, strict control of the size and gradation of fine aggregates is a crucial step in ensuring the quality of the CLC lightweight brick products produced.

3.3.3 Water

Water is defined as a liquid that plays a crucial role in construction, particularly as a medium for chemical reactions and as a solvent. In CLC lightweight concrete, water is one of the ingredients in the mixture (along with cement and fine aggregate), and the main purpose of using water is to cause hydration, which is a chemical reaction between cement and water that causes the mixture to harden after a certain period of time (Anggraini, et al., 2022). In addition, water also serves to provide workability to the mortar, allowing it to be mixed and moulded easily. Given its vital role in the hydration reaction, the quality of the water used must meet certain standards to avoid adverse effects on the strength and durability of the material. The quality requirements for water used in mortar mixing are regulated in SNI 03-2847-2002, which refers to the requirements for water that

can be used for concrete production. In general, SNI requires that the water used must be free from harmful substances such as oil, acid, alkali, salt, organic matter, or other substances that can damage the cement hydration process or cause corrosion. This standard often concludes that potable water is considered suitable for cement mortar production, including for CLC lightweight bricks, because it has sufficient purity.

1. Water-Cement Ratio (WCR)

The Water-Cement Ratio (WCR), often referred to as *Faktor Air Semen (FAS)*, is the ratio between the weight of water and the weight of cement in a concrete mixture. Fundamentally, FAS is a key indicator in determining mortar quality, means that the lower the FAS value, the higher the compressive strength of the concrete tends to be because fewer capillary pores are formed during water evaporation. On the other hand, the quality of CLC lightweight bricks is also influenced by the stability of air bubbles and the homogeneity of the mixture related to the foam system (e.g., the selection of foaming agents and the use of admixtures), so controlling the proportion of water in the mixture is important to maintain foam stability during the mixing process (Naifah, et al., 2025).

In CLC production, FAS plays a crucial role in determining the workability or ease of handling the mixture before foam is added. If the FAS is too low, the mixture becomes too stiff and can damage the air bubbles, while if it is too high, the mixture becomes too runny, causing the bubbles to float to the surface and leading to segregation or separation of materials.

2. Water-Foam Agent Ratio (WFR)

Unlike WCR, which focuses on mortar strength, Water-Foam Agent Ratio, also known as *Faktor Air Foam (FAF)*, plays a direct role in determining the quality and stability of air bubbles (bubble stability). The right FAF ensures that the foam produced has sufficient rigidity (not too liquid and not too dry) so that it does not break easily when mixed with cement and sand. In the manufacture of CLC lightweight bricks, foam agents, which are surfactants or stable organic foams, serve to form air bubbles so that pores are formed in the mixture. After the mortar hardens, the addition of foam agent produces evenly distributed and stable pores,

making foam stability an important factor that affects the quality of the porous structure and the final density of lightweight bricks (Syapawi, et al., 2022). The main role of FAF in the CLC system is to maintain the integrity of the mortar volume, meaning that mortar with too high a ratio (too much water) will produce weak foam that shrinks quickly, while too low a ratio can cause the foam to be too thick and difficult to mix homogeneously. The accuracy of the FAF value is key to ensuring that lightweight bricks have a low specific gravity while still meeting the required compressive strength standards.

3.3.4 Foam Agent

Foam agents are defined as surfactant chemicals that, when mixed with water and air, produce stable foam. In the context of Cellular Lightweight Concrete (CLC) manufacturing, foam agents play a central role as expanding agents, which are generally divided into two types, such as synthetic-based and protein-based. Synthetic types generally have high expansion power but lower bubble stability against mortar loads, while the type used in this process is protein-based, which is known to have much higher bubble stability and a more rigid pore structure. Foam agents are concentrated surfactant-based solutions that must be dissolved in water before use. With the help of a foam generator, they can produce stable pre-foam for use in the production of mortar or cement mixes containing foam (Husin & Setiadji, 2008). Its main role is to create closed air pore volume within the hardened cement matrix, thereby significantly reducing the specific gravity and improving the thermal insulation properties of CLC lightweight bricks.

The main function of foam agents in CLC lightweight bricks is to provide lightness and porosity. The use of protein-based foam agents is crucial in ensuring that the foam remains stable and does not break before the cement mixture hardens, so that the pores become an integral part of the concrete structure. With the superior bubble stability of protein-based materials, CLC lightweight bricks can achieve a low dry density (usually between 500 and 800 kg/m^3) while maintaining optimal compressive strength. The current applicable standard is SNI 8640:2018, which regulates the final results of foam agent use in terms of dry density and compressive strength parameters. Therefore, the selection of protein-based foam agents is a

strategic step to meet quality criteria in terms of volume, stability (ability to withstand pressure without collapsing), and uniform bubble quality in order to comply with minimum SNI performance specifications.

One of the foam agent products commonly used in the production of CLC lightweight bricks is shown in Figure 3.3



Figure 3.3 Foam Agent

3.4 Partial Replacement Materials of Cement

In this study, the author used fly ash as a partial cement replacement to improve the quality characteristics of CLC lightweight bricks.

3.4.1 Coal Fly Ash

Fly ash is defined as a fine-powdered pozzolanic material produced as a by-product of coal combustion in steam power plants. In the context of construction materials, fly ash acts as a partial cement substitute, utilizing its pozzolanic properties. Although not cementitious on its own, pozzolanic materials can react with calcium hydroxide $Ca(OH)_2$ produced during the cement hydration process to form cementitious compounds or produce additional *C-S-H* compounds that act as binders (Hendrawati, et al., 2018). The use of fly ash as a cement substitute is not only economical but also contributes to the sustainability of construction.

Chemically, fly ash is classified into two main types based on the ASTM C618 standard: Class C Fly Ash and Class F Fly Ash. Class C Fly Ash is produced from lignite or sub-bituminous coal and generally has a high calcium oxide *(CaO)* content, making it cementitious and pozzolanic. Meanwhile, Class F Fly Ash, which

is the focus of this study, comes from the combustion of anthracite or bituminous coal and has a low *CaO* content (<10%).

The comparison of the chemical content between Class F and Class C fly ash is presented in Table 3.5.

Table 3.5 Comparison of Chemical Content between Class F and C Fly Ash

Chemical Content	Class	
	F	C
$SiO_2 + AI_2O_3 + Fe_2O_3$, minimum, %	70,0	50,0
SO_3, maximum, %	5,0	5,0
CaO	<10	>20

(Source: ASTM C-618)

Therefore, Class F Fly Ash is purely pozzolanic and requires $Ca(OH)_2$ formed during cement hydration. The pozzolanic reaction between silica (SiO_2) from pozzolanic materials and free lime $Ca(OH)_2$ resulting from cement hydration produces calcium silicate hydrate gel *(C-S-H)* which acts as an adhesive and also acts as a filler, thereby increasing density and compressive strength at later ages and gradually reducing the amount of free $Ca(OH)_2$ that is easily soluble, especially in aggressive environments (Eniarti, et al., 2025). The effect of fly ash on CLC lightweight bricks is multiple. In the fresh mortar stage, fine-grained fly ash improves the workability of the mixture due to the ball-bearing effect of its spherical particles. During the hardening stage, the use of fly ash as a partial cement substitute tends to reduce compressive strength at an early age (e.g., 28 days), but compressive strength increases significantly at a later age (up to 90 days), and the permeability coefficient to water decreases with increasing hydration age, thereby increasing the impermeability of concrete (Salain, 2021).

In this study, Class F fly ash substitution was carried out with varying percentages of 0%, 10%, 20%, 30%, and 40% of the cement mass used to investigate the optimal percentage that provides the best balance between lightweight characteristics (due to the use of foam agent) and structural strength in CLC lightweight bricks. The following is the chemical content of Fly Ash from PLTU Sumsel-8, as shown in Table 3.6.

Table 3.6 Chemical Content of Fly Ash from PLTU Sumsel-8

No	Parameter	Fly Ash Test Result (%)
1	*Silika* (SiO_2)	52,66
2	*Alumina* (AI_2O_3)	21,42
3	*Besi Oksida* (Fe_2O_3)	8,29
4	*Kalsium Oksida* (CaO)	8,71
5	*Sulfur Trioksida* (SO_3)	3,35

(Source: PLTU Sumsel-8 Document)

CHAPTER IV
METHODOLOGY

4.1 Overview

The method used for this research is an experimental method that aimed to determine the causal relationship (cause and effect) between variables through the process of manipulating independent variables under certain conditions. The implementation of this research was divided into four stages, namely fine aggregate testing, test object fabrication, test object maintenance, and test object testing.

4.2 Research Location

This research will be conducted entirely at the Construction Materials Laboratory of the Civil Engineering Study Program, Faculty of Civil Engineering and Planning, Universitas Islam Indonesia.

4.3 Research Variables

This research is divided into several research variables, which can be seen as follows.

1. An independent variable is a variable that influences, causes changes in, or gives rise to a dependent variable. In this study, it is this variable that will demonstrate its impact. The independent variables in this study are the percentages of partial substitution of cement with coal fly ash, namely 0%, 10%, 20%, 30%, and 40%.
2. The dependent variable is a variable that can be observed or measured to see the results of the influence of the independent variable. The dependent variables in this study are compressive strength, density, and water absorption in the test objects.

3. Control variables are factors that remain constant or unchanged throughout the study. The control variables in this study were the type of cement used, the cement-water ratio, the foam-water ratio, the planned compressive strength, the oven-dried weight, and the 28-day curing period for the test specimen.

4.4 Tools Used

Before conducting this research, it is necessary to prepare the tools that will be used during the research. These tools are as follows.

1. Scales

   Used to weigh raw materials precisely, such as cement, sand, water, and foam agent liquid. The weight consistency of the materials greatly determines the quality and density of the lightweight bricks produced. The scales used in this research are shown in Figure 4.1



Figure 4.1 Scales

2. Oven

   In a laboratory or quality control context, ovens are used to measure the moisture content of sand or to dry brick samples for dry density testing. The oven used in this research is shown in Figure 4.2



Figure 4.2 Oven

3. Tube and Stick

This tool is used to perform a slump test. Its purpose is to measure the viscosity or thinness of the mortar mixture before mixing it with the foam. If it is too thin, the foam will break, and if it is too thick, the foam will not mix evenly. The tube and stick used in this research are shown in Figure 4.3.



Figure 4.3 Tube and Stick

4. Sieve

It is used to sieve the sand to remove large gravel, debris, or soil clumps. The sand used in CLC lightweight bricks must be fine and uniform to ensure that the air-pore structure is properly maintained. The sieve used in this research is shown in Figure 4.4.



Figure 4.4 Sieve

5. Pycnometer

   This tool is used to test the specific gravity and water absorption of fine aggregates. The pycnometer used in this research is shown in Figure 4.5.



Figure 4.5 Pycnometer

6. Pan

   It is used as a container for collecting fresh-mix samples or as a vessel for weighing materials on a small-scale during mix design experiments. The pan used in this research is shown in Figure 4.6.



Figure 4.6 Pan

7. Bucket

It functions as a container for water or other materials used manually, and is also used in the cleaning process to remove residual mix from the equipment. The bucket used in this research is shown in Figure 4.7.



Figure 4.7 Bucket

8. CLC Block Mould

This tool is the primary equipment for shaping the mixture into brick blocks. The mould typically has partitions (dividers) and must be coated with a release oil to ensure that the bricks can be easily removed after hardening, usually after 24 hours. The CLC block mould used in this research is shown in Figure 4.8.



Figure 4.8 CLC Block Mould

9. Compressor

It functions as a source of air pressure. Compressed air from the compressor is supplied to the foam generator tank to convert the mixture of water and foam agent into stable and stiff foam. The compressor used in this research is shown in Figure 4.9.



Figure 4.9 Compressor

10. Foam Tank

    This is where the foam generation process takes place. The foam agent solution is blown with compressed air from the compressor through a filtering medium inside the tank, producing shaving-like foam that is then mixed into the cement–sand slurry. The foam tank used in this research is shown in Figure 4.10.



Figure 4.10 Foam Tank

11. Cut-off Grinder

    A cut-off grinder is used to precisely cut and level CLC lightweight brick specimens, ensuring accurate dimensions and full contact with testing machine platens per SNI 8640:2018, while minimizing micro-damage for

representative test results. The cut-off grinder used in this research is shown in Figure 4.11.



Figure 4.11 Cut-off Grinder

12. Universal Testing Machine (UTM)

This device is used in the final stage or for quality control. After the lightweight bricks reach an age of 28 days, the samples are placed in this machine to be tested until failure. The purpose of this test is to ensure that the bricks meet the required compressive strength standards (N/mm² or MPa). The Universal Testing Machine (UTM) used in this research is shown in Figure 4.12.



Figure 4.12 UTM

4.5 Used Materials

The following are the materials used to support the implementation of this research.

1. Fine Aggregate

   Fine aggregate in the form of sand functions as the primary filler material. The sand provides volume to the brick structure and contributes to compressive strength after the cement has hardened. A uniform particle size is essential to avoid damaging the air-bubble structure. The fine aggregate used in this research is shown in Figure 4.13.



Figure 4.13 Fine Aggregate

2. Ordinary Portland Cement (OPC)

   Cement acts as the binding material. When mixed with water, cement undergoes a hydration process that binds the sand particles and encapsulates the foam bubbles as it hardens. Type I cement (Ordinary Portland Cement, OPC) is the most commonly used due to its ability to provide good early strength. The Ordinary Portland Cement (OPC) used in this research is shown in Figure 4.14.



Figure 4.14 OPC

3. Water

Water has two crucial functions, as follows.

a. As a chemical reactant that initiates the hydration process of cement, enabling it to bind the materials.
b. As a lubricant that provides workability to the mortar mixture, allowing the foam to be mixed homogeneously without collapsing.

The water used in this research is shown in Figure 4.15.



Figure 4.15 Water

4. Foam Agent

This is the “key” material in CLC lightweight bricks. The liquid is concentrated and then converted into a stable foam by a foam generator. Its primary function is to create air voids (air cells) within the concrete, thereby significantly reducing the density compared to conventional concrete. The foam agent used in this research is shown in Figure 4.16.



Figure 4.16 Foam Agent

5. Fly Ash

   Fly ash is a pozzolanic material commonly added as a partial replacement for cement. The fly ash used in this research is shown in Figure 4.17.



Figure 4.17 Fly Ash

4.6 Test Object

This study uses fly ash as a partial cement replacement material with varying percentages of 0%, 10%, 20%, 30%, and 40% of the cement weight. The test specimens will be made in the form of blocks with dimensions of 60 cm × 20 cm × 10 cm. The intact lightweight brick samples will be divided into 10 pieces measuring 10 cm × 10 cm for testing. Based on SNI 8640:2018, compressive strength testing will be conducted on 5 test specimens, bulk density testing on 3 test specimens, and water absorption testing on 2 test specimens. The amount of CLC testing carried out in this research is presented in Table 4.1 on the next page.

Table 4.1 Amount of CLC Testing

No	Specimen Code	Testing			Amount
		Compressive Strength	Density	Water Absorption	
1	FA0 (Normal)	5	3	2	10
2	FA010	5	3	2	10
3	FA020	5	3	2	10
4	FA030	5	3	2	10
5	FA040	5	3	2	10
Total					**50**

To determine the effect of varying fly ash content as a partial cement substitute on the characteristics of CLC lightweight bricks, a mix design was carried out with several fly ash content variations. In this study, fly ash was used as a cement substitute at percentages of 0%, 10%, 20%, 30%, and 40% by weight of cement. Other parameters, such as mould volume, number of test specimens, amount of sand, water, and foam, were kept constant so that the observed effects were solely due to variations in fly ash content. The composition of the CLC lightweight brick mix for each fly ash variation used in this study is presented in Table 4.2 below.

Table 4.2 Composition of Lightweight Bricks Material

No	Specimen Code	Casting Volume (m^3)	Variation of Fly Ash (%)	Cement (kg)	Sand (kg)	Water (L)	Foam (L)	Fly Ash (kg)
1	FA0	0,012	0	43,2	64,8	0,5	0,4	0
2	FA10	0,012	10	38,88	64,8	0,5	0,4	4,32
3	FA20	0,012	20	34,56	64,8	0,5	0,4	8,64
4	FA30	0,012	30	30,24	64,8	0,5	0,4	12,96
5	FA40	0,012	40	25,92	64,8	0,5	0,4	17,28

4.7 Stages of Research Execution

A research project involves several processes or stages, which always begin with preparation, material testing, test object fabrication, test object maintenance, test object testing, data analysis, and finally the compilation of a research report. The following are details of the stages involved in conducting the research.

4.7.1 Preparation

Before conducting research, authors need to prepare several things to support the success of their research. Research preparation starts with a review of references, drawing up a plan for the test objects to be studied, and preparing materials that meet research standards.

4.7.2 Material Testing

The material required for testing before the test piece manufacturing stage is fine aggregate to ensure that the fine aggregate to be used complies with standards. The following is the fine aggregate testing process that must be carried out.

1. Bulk Density (Loose and Compacted)

   The standard used as a reference for this test is SNI 03-4804-1998. This test aims to determine the classification of fine aggregate based on its bulk density.

2. Specific Gravity and Water Absorption Test

   SNI 1970-1990 serves as the reference standard for this test. The objective of this test is to determine the bulk specific gravity, saturated surface-dry (SSD) specific gravity, apparent specific gravity, and the water absorption of fine aggregate.

3. Sieve Analysis Test

   This test uses SNI 1968-1990 as the reference standard. The testing method serves as a benchmark for evaluating the percentage distribution of fine aggregate particles.

4. Silt Content Test

   The standard applied for this test is SNI 4142-1996, which aims to determine the percentage of material in the aggregate that passes the No. 200 sieve (0.075 mm).

4.7.3 Fabrication and Curing of Test Object

After the material testing phase is completed, the next stage is the preparation of test specimens. This research uses CLC lightweight brick specimens in the form of blocks with dimensions of 60 cm × 20 cm × 10 cm, where the cement content will be substituted with fly ash based on percentage variations of 0%, 10%, 20%,

30%, and 40% of the cement weight. Referring to SNI 8640:2018, each whole lightweight brick sample will be cut into 10 sections measuring 10 cm × 10 cm to fulfil the testing requirements, which include 5 specimens for compressive strength, 3 specimens for density, and 2 specimens for water absorption. The following are the stages required in the CLC lightweight brick production process.

1. Ensure the materials to be used have been prepared beforehand, including cement, sand, water, foaming agent, and fly ash.
2. After the materials are prepared, prepare the tools to be used.
3. Next, connect the foam generator to the compressor.
4. Then, weigh the materials to be used based on the planned mix design.
5. Create a mixture of foaming agent and water in a bucket, and stir thoroughly using the foam generator and compressor.
6. After the mixture is homogeneous, add the cement, sand, and water into the bucket containing the foam agent and water mixture. Mix again until uniform.
7. Pour the mixture into the CLC lightweight brick moulds and level the surface.
8. Repeat steps 5 and 6 by incorporating fly ash according to the planned composition, and level it.
9. Let the mixture in the moulds set for 24 hours.
10. After the mixture has hardened completely, remove the specimens from the moulds.
11. Periodically spray lightweight bricks with water during 28 days of curing.
12. On the 28th day, the lightweight bricks are ready for testing.

4.7.4 Testing of Test Object

Lightweight bricks that have been submerged for 28 days can proceed to the next stage, which is specimen testing. The objective of this testing is to determine the physical and mechanical properties of the lightweight bricks. The tests to be conducted are as follows.

1. Density and Water Absorption Testing

   Based on SNI 8640:2018, this test uses 2 specimens with dimensions of 20 × 20 × 10 cm that have been cleaned of dust and weighed. This test aims to

determine the physical properties of the test specimens. The procedure for this test is as follows.

a. Dry the specimens in an oven at a temperature of (105 ± 5) ℃ for a minimum of 24 hours until they reach a constant mass. Constant mass is achieved when the difference between two weighing at a 30-minute interval is no more than 0,05 grams.
b. Weigh the constant mass of the test specimens.
c. Measure the length, width, and thickness to calculate the volume of the specimens.
d. Submerge the weighed specimens in water for 24 hours ± 30 minutes. If the specimen floats, a load must be applied to the surface until the specimen is fully submerged in water.
e. Remove the specimens from the water, wipe them with a damp cloth, and weigh the specimens.

2. Compressive Strength Testing

This test refers to SNI 8640:2018 using 5 specimens with dimensions of 10 × 10 × 10 cm. Clean the specimens of dust, then submerge the specimens fully in water for 24 hours ± 30 minutes. The procedure for this test is as follows.

a. Remove the specimens from the water and wipe them using a damp cloth.
b. Measure the length and width of the specimens to a tolerance limit of 1 mm.
c. Conduct the compressive strength test using a hydraulic compression machine, applying pressure to the flat surface, specifically on the thickness side of the specimen.
d. Apply the load gradually to the specimen until failure occurs, with a loading rate of approximately 0,1 MPa/second.
e. Record the average compressive strength value by dividing the total value by the number of specimens, and also record the maximum and minimum values for each specimen.

4.7.5 Data Analysis

After the testing phase is completed, the process continues to the next stage, which is the data analysis of the results obtained from the conducted tests. This analysis will be discussed in detail as follows.

1. Analysis of Density and Water Absorption

   Following the completion of the compressive strength testing on the lightweight bricks, the subsequent stage involves analysing the density and water absorption capacity of the bricks. This analysis is conducted through a specimen immersion process, followed by weighing to compare the mass before and after immersion, allowing for the determination of the water absorption percentage.

2. Analysis of Compressive Strength

   This analysis calculates the maximum load that the CLC lightweight bricks can withstand until failure, which is then used to determine the compressive strength value. The compressive strength test is performed by applying a gradual load using a compression testing machine until the specimen can no longer sustain the load. The compressive strength value is derived from the ratio of the maximum load sustained to the cross-sectional area of the specimen, thereby illustrating the capacity of the CLC lightweight brick to resist compressive loads.

3. Statistical Analysis

   Statistical analysis in this research is conducted to describe the distribution pattern of the test results and to determine the appropriate hypothesis-testing method for the characteristics of the data obtained from the oven-dry density, water absorption, and compressive strength tests of the CLC lightweight brick specimens with variations in fly ash content (FA0, FA10, FA20, FA30, and FA40). The statistical analysis step will be detailed as follows.

   a. The first step of the statistical analysis is a descriptive analysis using a box plot. A box plot presents the median, the first and third quartiles, the

minimum and maximum values, and any outliers of a data set in a single graphical display (Quraisy, Wahyuddin, & Hasni, 2021). In this research, box plots are constructed for each of the three test results, such as oven-dry density, water absorption, and compressive strength, for every fly ash variation, to provide an overview of the spread, symmetry, and consistency of the specimen data before further statistical testing.

b. Before determining the appropriate method for comparing the means among the fly ash variations, a normality test is required to examine whether the data are normally distributed, since this assumption determines whether a parametric or a non-parametric statistical test should be used (Quraisy, Wahyuddin, & Hasni, 2021). When the compressive strength data do not satisfy the normality assumption, the Kruskal-Wallis test is applied as a non-parametric alternative to the one-way analysis of variance (ANOVA). The Kruskal-Wallis test was first introduced by Kruskal and Wallis (1952) as a rank-based method used to examine whether several independent samples originate from the same population, without requiring the data to follow a normal distribution. In this research, the Kruskal-Wallis test is performed on the compressive strength data of each fly ash variation using the SPSS software, in order to determine whether a significant difference exists among the groups.
c. In addition to the normality test, a homogeneity of variance test is also carried out using Levene's method (Levene, 1960). This test aims to determine whether the variance of the compressive strength data among the fly ash variations is homogeneous, which is an important prerequisite before concluding a parametric comparative test such as ANOVA. This test is likewise performed with the assistance of the SPSS software on the compressive strength data of the CLC lightweight brick specimens.
d. The final stage of the statistical analysis is a correlation and regression analysis between the oven-dry density and the compressive strength of the CLC lightweight brick. This analysis is carried out specifically on these two variables because it is directly related to the problem statement of this

research, namely to determine the extent to which the density of the CLC lightweight brick influences its compressive strength. The correlation analysis is used to measure the strength and direction of the linear relationship between the two variables, while the regression analysis produces a mathematical equation that can be used to estimate the compressive strength value based on the oven-dry density value. Several previous studies have shown that density is one of the dominant factors affecting the compressive strength of foamed or cellular lightweight concrete, where a denser specimen generally produces a higher compressive strength (Othman et al., 2021). This finding is also relevant to research on CLC lightweight bricks with fly ash variation conducted by Bella, Pah, and Ariansyah (2017), which examined the relationship between the physical and mechanical properties of CLC bricks.

4.8 Flowchart of Research

The flowchart of this research can be seen in Figure 4.17 as follows.

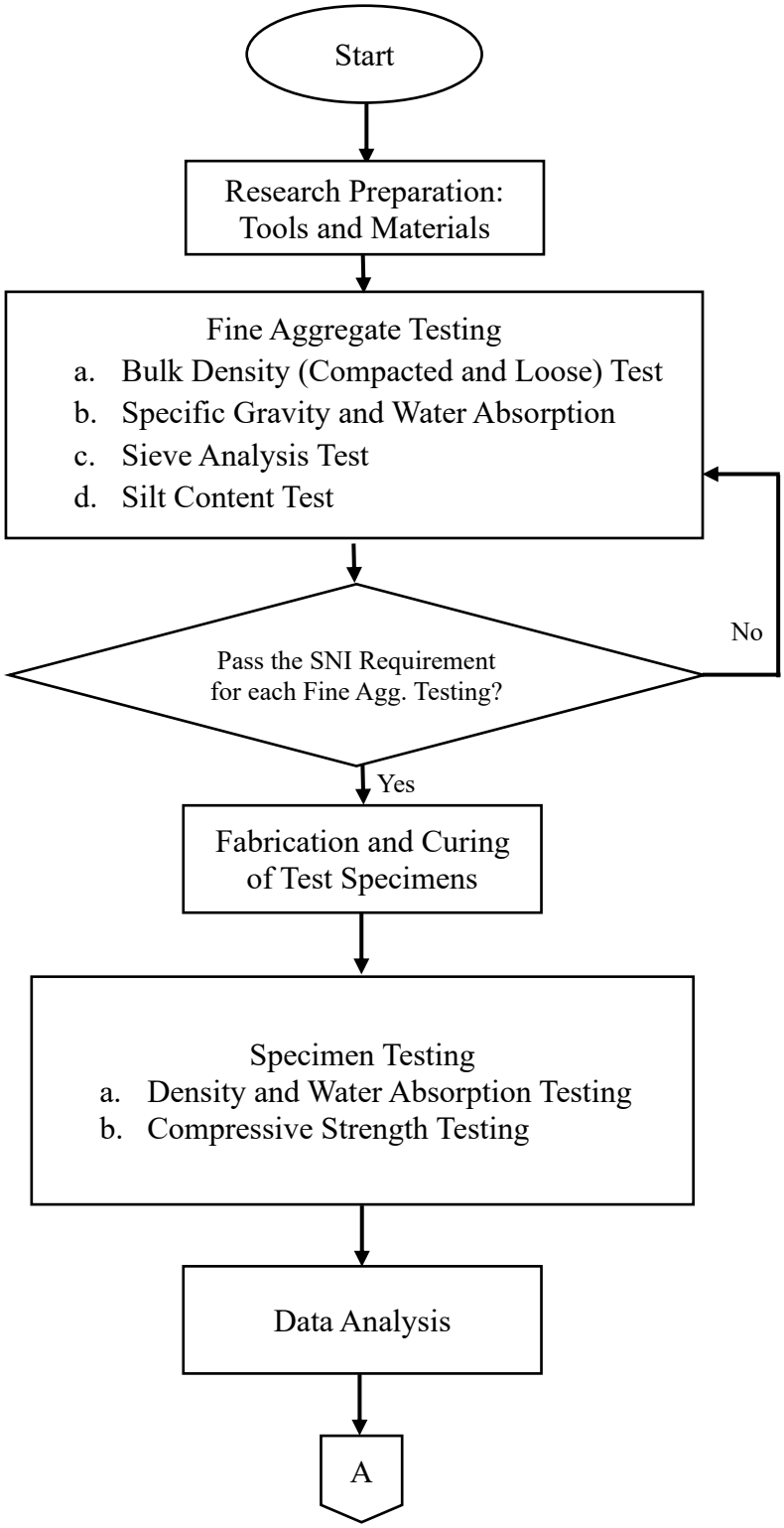
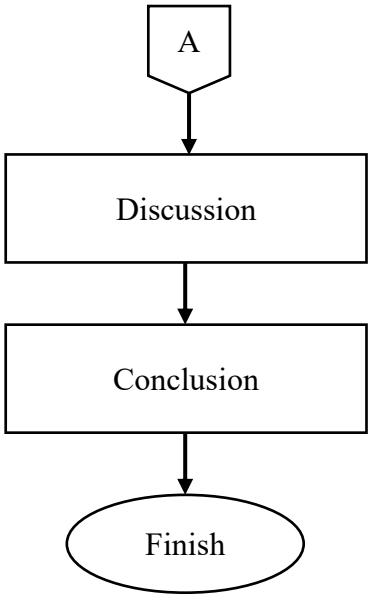


Figure 4.18 Flowchart



Continuation of Figure 4.18 Flowchart

CHAPTER V
ANALYSIS AND DISCUSSION

5.1 Overview

Before preparing the specimen tests, material testing needs to be conducted to determine the characteristics and properties of each material to be used. The testing to be carried out focuses on fine aggregate. Aggregate testing is conducted to examine and identify the physical characteristics and properties of the aggregate used as a constituent material in the mixture. In this study, the material testing is limited to fine aggregate (sand) that will be used in the production of CLC lightweight bricks. This testing is necessary because aggregate materials have specific criteria or requirements that must be met before developing the mix design, so that the resulting mixture can achieve the targeted quality.

5.2 Material Testing

The tests to be conducted on fine aggregates (sand) in this research are Bulk Density (Compacted and Loose) Tests, Specific Gravity and Water Absorption Tests, Sieve Analysis Tests, and Silt Content Tests. Based on the tests conducted on Sample 1, the following were obtained.

1. Bulk Density

   The results of this test can be calculated as follows.

   a. Compacted Volume Weight

   Aggregate Weight (W_3) $= W_2 - W_1$

   $= 7986 - 5241$

   $= 2745$ grams

   Cylinder Volume (V) $= \frac{1}{4} \times d^2 \times t$

   $= \frac{1}{4} \times 10{,}5^2 \times 19{,}8$

   $= 1714{,}48\ cm^3$

   Compacted Volume Weight $= \frac{W_3}{V}$

$= \frac{2745}{1714,48}$

$= 1,601 \text{ gram/cm}^3$

b. Loose Volume Weight

Aggregate Weight (W3) $= W_2 - W_1$

$= 7758 - 5167$

$= 2591$ grams

Cylinder Volume (V) $= \frac{1}{4} \times d^2 \times t$

$= \frac{1}{4} \times 10,3^2 \times 20$

$= 1666,46 \text{ cm}^3$

Loose Volume Weight $= \frac{W_3}{V}$

$= \frac{2591}{1666,46}$

$= 1,555 \text{ gram/cm}^3$

For sample 2, the tests were also conducted on the bulk density (compacted and loose) tests of fine aggregates, as in sample 1. The following is a recapitulation of the test results in Table 5.1 and Table 5.2 as follows.

Table 5.1 Recapitulation of Compacted Fine Aggregate Volume Test

Description	Sample 1	Sample 2	Aver.
Cylinder Diameter (cm)	10,5	10,300	10,4
Cylinder Height (cm)	19,8	20,000	19,9
Cylinder Weight (W1), gram	5241	5167	5204
Cylinder Weight + Dry Aggregate (W2), gram	7986	7758	7872
Aggregate Weight (W3), gram	2745	2591	2668
Cylinder Volume (V), cm^3	1714,485	1666,458	1690,471
Compacted Volume Weight, $gram/cm^3$	1,601	1,555	1,578

Table 5.2 Recapitulation of the Loose Fine Aggregate Volume Test

Description	Sample 1	Sample 2	Aver.
Cylinder Diameter (cm)	10,5	10,300	10,4
Cylinder Height (cm)	19,8	20,000	19,9
Cylinder Weight (W1), gram	5241	5167	5204
Cylinder Weight + Dry Aggregate (W2), gram	7309	7104	7206,5
Aggregate Weight (W3), gram	2068	1937	2002,5
Cylinder Volume (V), cm^3	1714,485	1666,458	1690,471
Compacted Volume Weight, $gram/cm^3$	1,206	1,162	1,184

Several calculations were based on the tests of the Bulk Density (Compacted and Loose) Test. The average compacted volume was 1,578 grams/cm³. Meanwhile, the average loose volume was 1,184 grams/cm³. From these results, a comparison was made because in the bulk density test, each $\frac{1}{3}$ part was compacted and tapped 25 times on the cylinder to reduce air gaps in the aggregate, whereas in the loose density test, no compaction was performed.

2. Specific Gravity and Water Absorption Test

Based on specific gravity and water absorption testing, the weight can be calculated as follows.

a. Bulk Specific Gravity $= \frac{B_k}{(B + 500 - B_t)}$

$= \frac{491}{(686 + 500 - 1006)}$

$= 2{,}728$

b. Saturated Surface-Dry (SSD) $= \frac{500}{(B + 500 - B_t)}$

$= \frac{500}{(686 + 500 - 1006)}$

$= 2{,}778$

c. Apparent Specific Gravity $= \frac{B_k}{(B + B_k - B_t)}$

$= \frac{491}{(686 + 491 - 1006)}$

$= 2{,}871$

d. Water Absorption $= \frac{(500 - B_k)}{B_k} \times 100\%$

$= \frac{(500 - 491)}{491} \times 100\%$

$= 1{,}83\%$

For sample 2, the calculations were performed in the same manner to obtain the specific gravity and water absorption values, which were then averaged. The summary table of the specific gravity and water absorption test results for fine aggregates in samples 1 and 2 is shown in Table 5.3 below.

Table 5.3 Recapitulation of Specific Gravity and Water Absorption Fine Aggregate Testing

Description	Observation Results		Aver.
	Sample 1	Sample 2	
Absolute dry mass of sand, grams (Bk)	491	492	491,50
Saturated surface-dry (SSD) mass of sand, grams	500	500	500
Mass of pycnometer filled with sand and water, grams (Bt)	1006	1004	1005
Mass of pycnometer filled with water, grams (B)	686	685	685,5
Bulk specific gravity	2,728	2,718	2,72
Saturated surface-dry (SSD) specific gravity	2,778	2,762	2,77
Apparent specific gravity	2,871	2,8439	2,86
Water Absorption	1,83%	1,63%	1,73%

Based on the test results in Table 5.3, the average saturated surface-dry (SSD) specific gravity was 2,77. The process of this test is shown in Figure 5.1 below.



Figure 5.1 Bulk Density Test Process

3. Sieve Analysis Test

The fine aggregate sieve analysis test was conducted based on SNI 03-1968-1990. This test was conducted to obtain the classification of fine aggregate (sand) based on its grains (MHB) with a test weight of 2000 grams that passed No. 4 (4,75 mm). The calculation of the aggregate sieve analysis test is as follows.

a. Percentage Retained Weight $= \frac{Retained\ Weight}{\sum Retained\ Weight} \times 100\%$

Sieve 4,80 mm (No. 4) $= \frac{1}{2000} \times 100\%$

$= 0{,}05\%$

Sieve 2,40 mm (No. 8) $= \frac{44}{2000} \times 100\%$

$= 2{,}20\%$

Sieve 1,20 mm (No. 16) $= \frac{307}{2000} \times 100\%$

$= 15{,}35\%$

Sieve 0,60 mm (No. 30) $= \frac{705}{2000} \times 100\%$

$= 32{,}25\%$

Sieve 0,30 mm (No. 50) $= \frac{427}{2000} \times 100\%$

$= 21{,}35\%$

Sieve 0,15 mm (No. 100) $= \frac{340}{2000} \times 100\%$

$= 17{,}00\%$

Pan (Retained) $= \frac{176}{2000} \times 100\%$

$= 8{,}80\%$

b. Percentage of Cumulative Retained Weight

Sieve 4,80 mm (No. 4) $= 0{,}05\%$

Sieve 2,40 mm (No. 8) $= 0{,}05\% + 2{,}20\%$

$= 2{,}25\%$

Sieve 1,20 mm (No. 16) $= 2{,}25\% + 15{,}35\%$

$= 17{,}60\%$

Sieve 0,60 mm (No. 30) $= 17{,}60\% + 32{,}25\%$

$= 52{,}85\%$

Sieve 0,30 mm (No. 50) $= 52{,}85\% + 21{,}35\%$

$= 74{,}20\%$

Sieve 0,15 mm (No. 100) $= 74{,}20\% + 17{,}00\%$

$= 91{,}20\%$

Pan (Retained) $= 91{,}20\% + 8{,}80\%$

$= 100\%$

c. Cumulative Percentage Passing

Sieve 4,80 mm (No. 4) = 100% – 0,05%
= 99,95%

Sieve 2,40 mm (No. 8) = 100% – 2,25%
= 97,75%

Sieve 1,20 mm (No. 16) = 100% – 17,60%
= 82,40%

Sieve 0,60 mm (No. 30) = 100% – 52,85%
= 47,15%

Sieve 0,30 mm (No. 50) = 100% – 74,20%
= 25,80%

Sieve 0,15 mm (No. 100) = 100% – 91,20%
= 8,80%

Pan (Retained) = 100% – 100%
= 0%

The following is a recapitulation of the sieve analysis test results, as shown in Table 5.4.

Table 5.4 Recapitulation of Sieve Analysis Fine Aggregate Testing

Sieve Size (mm)	Retained Weight (gr)	Retained Weight (%)	Cumulative Retained Weight (%)	Cumulative Percentage Passing (%)
40,00	0	0	0	100
20,00	0	0	0	100
10,00	0	0	0	100
4,80	1	0,05	0,05	99,95
2,40	44	2,20	2,25	97,75
1,20	307	15,35	17,60	82,40
0,60	705	35,25	52,85	47,15
0,30	427	21,35	74,20	25,80
0,15	340	17,00	91,20	8,80
Retained	176	8,80	100,00	0,00
Total	2000	100	238,15	

Based on the results of this fine aggregate sieve analysis test, the fineness modulus (FM) can be calculated as follows.

d. Fineness Modulus (FM)

$$= \frac{\sum Cumulative\ Percentage\ Weight}{100}$$

$$= \frac{238,15}{100}$$

$$= 2,382$$

According to SNI S-04-1989-F, the fine particle modulus value for fine aggregate must be between 1.5 and 3.8. The calculated Fineness Modulus (FM) was 2,382, which meets the specified requirements. A sieve analysis was conducted to determine the required gradation of fine aggregate in accordance with Table 5.5 below.

Table 5.5 Gradation of Fine Aggregate

Sieve Size (mm)	Percentage of Aggregate Particles Passing the Sieve			
	Zone I	Zone II	Zone III	Zone IV
10	100	100	100	100
4,8	90-100	90-100	90-100	90-100
2,4	60-95	75-100	85-100	95-100
1,2	30-70	55-90	75-100	90-100
0,6	15-34	35-59	60-79	80-100
0,3	5-20	8-30	12-40	15-50
0,15	0-10	0-10	0-10	0-15

Based on Table 5.4, the fine aggregate used in this study falls within the sand gradation of Region II, where it is classified as medium sand. From Table 5.4, the fine aggregate gradation curve shown in Figure 5.2 below was plotted, and Figure 5.3 is for the sieve analysis test process.

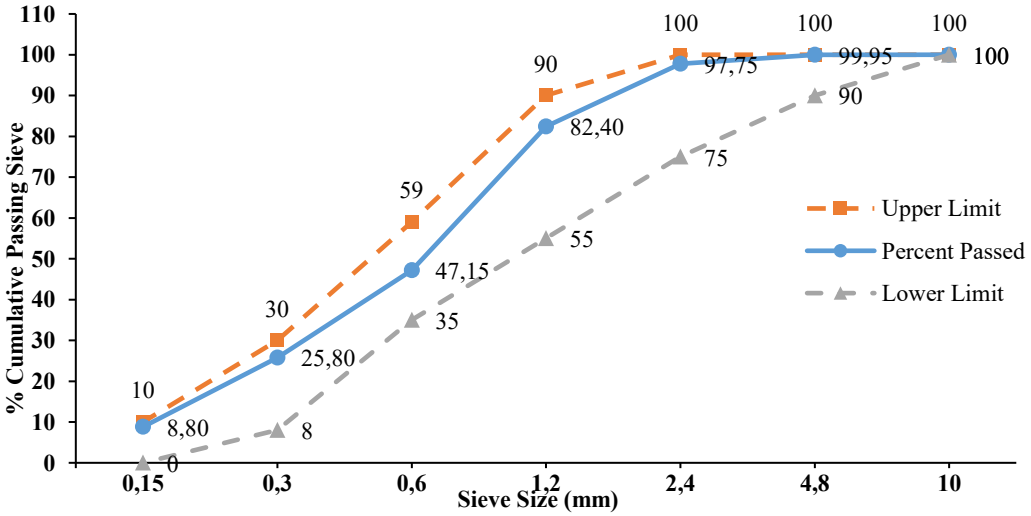


Figure 5.2 Gradation Curve for Fine Aggregates in Region II



Figure 5.3 Sieve Analysis Test Process

4. Silt Content Test (No. 200 Sieve Test) for Fine Aggregate

The No. 200 sieve test is designed to determine the percentage of silt content in the sand. The sand used was 500 grams of oven-dried sand that passed through a No. 4 sieve (4.75 mm), using a method based on SNI 4142-1996. The calculation of the silt content percentage in the sand for Sample 1 is as follows.

Oven-dried aggregate weight (W_1) = 500 gram

Oven-dry weight after washing (W_2) = 475 gram

Silt content in sand $= \frac{W_1 - W_2}{W_1} \times 100\%$

$= \frac{500 - 475}{500} \times 100\%$

$= 5\%$

For Sample 2, the same calculation method and procedure were followed, resulting in a silt content percentage of 5.00%. The following is a summary of the silt content test results for the sand, as shown in Table 5.6 below.

Table 5.6 Results of Silt Content Test (No. 200 Sieve Test)

Description	Analysis Results		
	Sample 1	Sample 2	Aver.
Oven-Dried Agg. Weight (W_1), grams	500	500	500
Dry oven-dried aggregate weight after washing (W_2), grams	475	477	476
Weight Passing Through Sieve No. 200, $[(W_1 - W_2)/W_1] \times 100$	5,00%	4,60%	4,80%

5.3 Mix Design Calculation

The density of the lightweight brick mixture is determined to be 800–1,000 kg/m³. The materials used in this study are cement, sand, water, fly ash (used as a partial cement substitute), and a foaming agent, which are mixed. The calculation for the lightweight brick mixture is as follows.

5.3.1 Calculation of the Mix Proportions for Lightweight Bricks

The mix proportion for each 1 m³ of lightweight brick is as follows.

Cement = 360 kg

Sand = 540 kg

Water = 180 liters

FAS = 1:0,5

FAF = 1:0,4

1. The next step is to calculate the volume of a single lightweight brick to determine the material requirements for each test specimen.

   Volume of Lightweight Brick $= p \times l \times t$

   $= 0{,}6 \times 0{,}1 \times 0{,}2$

   $= 0{,}012\ m^3$

   Volume of Each Variation = amount of the test specimen × volume of one lightweight brick

   $= 10 \times 0{,}012\ m^3$

   $= 0{,}12\ m^3$

2. The foam agent used in the production of CLC lightweight blocks in this study was 17 ml per specimen with a volume of 0,012 m³. This dosage was determined through a trial-and-error procedure during the preliminary stage of fabrication, in order to obtain the most suitable mixture composition. Based on the experimental trials, the use of 17 mL of foam agent and a water-to-foam ratio of 0,40 was found to be appropriate. This ratio indicates that the selected foam dosage was capable of producing sufficiently stable foam and facilitating the formation of a uniform air-void structure within the CLC lightweight block mixture.

3. Below is the calculation of material requirements for each variation.

   a. Calculation of FA0

      In the first-variation calculation, the lightweight brick mixture contains no substitute materials. The calculation is as follows.

      Fly Ash = 0 %

      Cement = (10 bricks × total cement for 1 brick) – Fly Ash
      = (10 × 4,32) – 0
      = 43,2 kg

      Sand = 10 bricks × total sand for 1 brick
      = 10 × 6,48
      = 64,8 kg

      Water= 10 bricks × The amount of water for 1 brick
      = 10 × 2,16 Liter
      = 21,6 Liter

      Foam = 17 ml

   b. Calculation of FA10

      In the second variation calculation, the lightweight brick mixture uses a substitute material, namely 10% fly ash. The calculation is as follows.

      Fly Ash = total cement for 10 bricks × the percentage of substitution
      = 43,2 kg × 10%
      = 4,32 kg

      Cement = (10 bricks × total cement for 10 bricks) – Fly Ash
      = (10 × 4,32) – 4,32
      = 38,88 kg

      Sand = 10 bricks × total sand for 1 brick
      = 10 × 6,48 kg
      = 64,8 kg

      Water = 10 bricks × The amount of water for 1 brick
      = 10 × 2,16 Liter
      = 21,6 Liter

      Foam = 17 ml

c. Calculation of FA20

In the third variation calculation, the lightweight brick mixture uses a substitute material, namely 20% fly ash. The calculation is as follows.

Fly Ash = total cement for 10 bricks × the percentage of substitution
= 43,2 kg × 20%
= 8,64 kg

Cement = (10 bricks × total cement for 1 brick) – Fly Ash
= (10 × 4,32) – 8,64
= 34,56 kg

Sand = 10 bricks × total sand for 1 brick
= 10 × 6,48
= 64,8 kg

Water = 10 bricks × The amount of water for 1 brick
= 10 × 2,16 Liter
= 21,6 Liter

Foam = 17 ml

d. Calculation of FA30

In the fourth variation calculation, the lightweight brick mixture uses a substitute material, namely 30% fly ash. The calculation is as follows.

Fly Ash = total cement for 10 bricks × the percentage of substitution
= 43,2 kg × 30%
= 12,96 kg

Cement = (10 bricks × total cement for 1 brick) – Fly Ash
= (10 × 4,32) – 12,96
= 30,24 kg

Sand = 10 bricks × total sand for 1 brick
= 10 × 6,48
= 64,8 kg

Water = 10 bricks × The amount of water for 1 brick
= 10 × 2,16 Liter
= 21,6 Liter

Foam = 17 ml

e. Calculation of FA40

In the fifth variation calculation, the lightweight brick mixture uses a substitute material, namely 40% fly ash. The calculation is as follows.

Fly Ash = total cement for 10 bricks × the percentage of substitution
= 43,2 kg × 40%
= 17,28 kg

Cement = (10 bricks × total cement for 1 brick) – Fly Ash
= (10 × 4,32) – 17,28
= 25,92 kg

Sand = 10 bricks × total sand for 1 brick
= 10 × 6,48
= 64,8 kg

Water = 10 bricks × The amount of water for 1 brick
= 10 × 2,16
= 21,6 Liter

Foam = 17 ml

The following is a summary of the material requirements for each variant, as shown in Table 5.7 below.

Table 5.7 Recapitulation of Used Materials

No	Specimen Code	Variation of Fly Ash	Volume	Cement	Fly Ash	Sand	Water	Foam Agent
		%	m³	kg	kg	kg	Liter	mL
1	FA0	0	0,012	43,2	0	64,8	21,6	17
2	FA10	10	0,012	38,88	4,32	64,8	21,6	17
3	FA20	20	0,012	34,56	8,64	64,8	21,6	17
4	FA30	30	0,012	30,24	12,96	64,8	21,6	17
5	FA40	40	0,012	25,92	17,28	64,8	21,6	17

Table 5.7 shows that the binder in variation 1 consists purely of cement with no admixtures. In variations 2 through 5, the cement content was gradually reduced and replaced with an admixture, specifically fly ash, with the proportion increased from 10% to 40%.

5.4 Specimen Preparation Process

The specimen preparation process consisted of four main stages: Material Preparation, Mixing, Casting and Molding, and Curing. Each stage was carried out systematically to ensure that the resulting specimens possessed the quality and characteristics specified in the mix design presented in Section 5.3.

5.4.1 Material Preparation

The materials prepared consisted of cement, sand, water, foam agent, and coal fly ash, with varying fly ash contents corresponding to each experimental variation. In this study, coal fly ash was used as a partial replacement for cement to assess its effects on the physical and mechanical properties of the resulting lightweight concrete. Each material was weighed using a digital balance to ensure accurate batching and compliance with the predetermined mix design.

5.4.2 Mixing Process

The mixing process was carried out using a mechanical mixer through a sequential procedure to ensure a homogeneous mortar mixture. First, sand was placed into the mixer, followed by cement. Subsequently, fly ash was added to the dry mixture according to the specified replacement level for each variation. Once the dry materials were thoroughly blended, water was gradually introduced until the required amount was fully incorporated. The final stage of mixing involved the addition of the foam agent to the mortar mixture. Mixing was then continued for approximately 5 minutes until a homogeneous mortar was obtained, allowing the foam bubbles to be evenly distributed throughout the mixture. The mixing process is shown in Figure 5.4.



Figure 5.4 Mixing Process

5.4.3 Casting and Molding

Before casting, the inner surfaces of the molds were coated with a thin layer of oil to act as a release agent, preventing the mortar from adhering to the mold surfaces and facilitating demolding after hardening. Once the mortar mixture had achieved a uniform consistency, it was carefully poured into the molds to avoid material segregation and the loss of entrained foam bubbles. After casting was completed, the specimens were allowed to harden for 24 to 48 hours, with the exact duration depending on the weather conditions during the casting process. Figure 5.5 shows the casting and molding process.



Figure 5.5 Casting and Molding Process

5.4.4 Curing

After the specimens were removed from the molds, the curing process was initiated and continued for 28 days. During this period, the specimens were stored in a protected area, shielded from direct sunlight and rainfall to minimize environmental influences on the hydration and hardening processes. Upon completion of the 28-day curing period, the specimens were considered ready for testing in accordance with the established testing procedures. Figure 5.6 records the curing process.



Figure 5.6 Curing Process

5.4.5 Specimen Cutting

After completing the 28-day curing period, the specimens were cut using a cutting wheel to obtain the dimensions required for each testing method. For the dry density and water absorption tests, the specimens were cut to dimensions of 200 × 200 × 100 mm; however, for the compressive strength test, the specimens were cut to dimensions of 100 × 100 × 100 mm. The cutting process was carried out carefully to ensure smooth cutting surfaces and accurate specimen dimensions in accordance with the testing requirements, thereby ensuring that the test results accurately represented the physical and mechanical characteristics of the Cellular Lightweight Concrete (CLC). As seen in Figure 5.7, the specimen was cut into several pieces.



Figure 5.7 Specimen Cutting

5.5 Specimen Testing

Two types of tests were conducted on the lightweight bricks, which were density and water absorption testing, and compressive strength testing. The tests were performed after the test specimens had cured for 28 days, using different testing procedures in accordance with SNI 8640:2018.

5.5.1 Density and Water Absorption Testing

The density and water absorption tests are classified as examinations of the physical properties of CLC lightweight bricks, since both describe the internal structure and condition of the material, namely its mass per unit volume and its porosity or ability to absorb water. The test was conducted on lightweight bricks that had undergone a 28-day curing period, with the test specimens immersed in water for 24 hours ± 30 minutes. The test involved measuring the dimensions and weighing the specimens before and after immersion to determine each specimen's volume and weight.

1. Density Test

The density test was conducted to determine the mass per unit volume of the lightweight brick specimens. This test referred to SNI 8640:2018 and was carried out after the specimens had undergone a 28-day curing period. Before testing, the specimens were immersed in water for 24 hours ± 30 minutes. Their dimensions (length, width, and thickness) were then measured, and their weights were

determined under the initial, oven-dry, and saturated surface-dry conditions. Table 5.8 shows the density test results.

Table 5.8 Test Results of the Density Test

Specimen Code	Sample	Nominal Density, kg/m³	Oven-Dry Density, kg/m³	Saturated Density, kg/m³
FA0	1	863,96	814,21	1054,06
	2	876,33	825,56	1069,06
	3	870,69	828,08	1061,76
	4	848,46	802,46	1035,19
	5	836,70	790,15	1021,18
	6	827,61	780,81	1009,46
Average		**853,96**	**806,88**	**1041,78**
FA10	1	862,80	813,30	1027,73
	2	891,05	837,95	1062,01
	3	831,14	792,12	990,39
	4	892,94	831,31	1063,60
	5	831,13	792,30	989,59
	6	862,15	823,14	1027,43
Average		**861,87**	**815,02**	**1026,79**
FA20	1	882,92	831,14	1008,69
	2	872,15	821,40	996,03
	3	862,83	812,31	985,81
	4	892,83	840,78	1019,87
	5	876,50	825,25	1001,25
	6	866,92	816,42	990,05
Average		**875,69**	**824,55**	**1000,28**
FA30	1	808,71	762,26	1031,07
	2	803,25	757,00	1023,75
	3	816,02	769,35	1040,42
	4	800,54	754,52	1019,95
	5	790,25	745,21	1008,21
	6	808,33	762,12	1031,73
Average		**804,52**	**758,41**	**1025,86**
FA40	1	804,86	758,14	1062,71
	2	785,65	740,37	1037,91
	3	802,30	755,57	1059,10
	4	806,53	759,85	1065,43
	5	774,71	730,12	1023,75
	6	815,00	767,81	1076,83
Average		**798,17**	**751,98**	**1054,29**

Based on Table 5.8, the oven-dry density exhibits a non-monotonic pattern as replacement increases. Over the 0%–20% replacement range, the oven-dry density tends to increase, from 806,88 kg/m³ at 0% to a maximum of 824,55 kg/m³ at 20% replacement. However, at 30% and 40% replacement, the oven-dry density

decreases substantially, reaching a minimum of 751,98 kg/m³ at 40% replacement. Figure 5.8 shows the box plot of oven-dry density, and Figure 5.9 shows the process of the test.

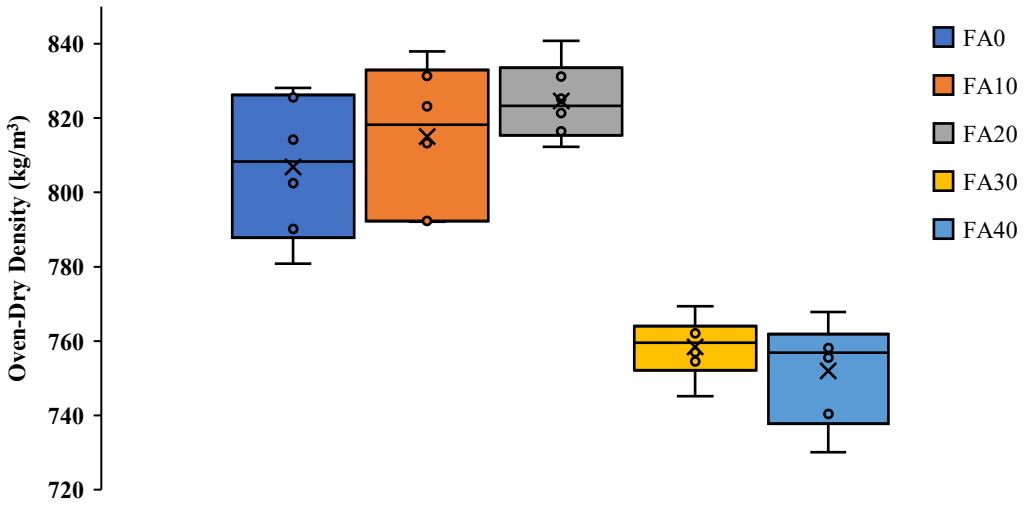


Figure 5.8 Specimen Oven-Dry Density Box Plot



Figure 5.9 Density Test

2. Water Absorption Test

The water absorption test was conducted to determine the ability of the lightweight brick specimens to absorb water. This test was carried out concurrently with the density test by immersing the specimens for 24 hours ± 30 minutes. The water absorption value was calculated as the difference between the saturated weight and the oven-dry weight, divided by the oven-dry weight and multiplied by

100% to express it as a percentage. The water absorption test process is shown in Figure 5.10, and the results of the water absorption test are presented in Table 5.9.



Figure 5.10 Water Absorption Test Process

Table 5.9 Results of the Water Absorption Test

Specimen Code	Sample	Test Results
FA0	1	23,66%
	2	22,96%
	3	23,06%
	4	22,77%
Average		**23,11%**
FA10	1	21,99%
	2	21,50%
	3	22,13%
	4	21,20%
Average		**21,71%**
FA20	1	17,32%
	2	17,05%
	3	16,83%
	4	17,07%
Average		**17,07%**
FA30	1	27,33%
	2	27,05%
	3	26,46%
	4	26,79%
Average		**26,91%**
FA40	1	30,43%
	2	29,86%
	3	29,81%
	4	29,88%
Average		**30,00%**

Based on Table 5.9, the water absorption test results show that the water absorption value varies for each mix variation. The FA0 specimen produced an average water absorption of 23,11%. Adding fly ash decreased the water absorption to 21,71% at FA10 and further to 17,07% at FA20, which was the lowest value recorded among all variations. However, at higher fly ash content, the water absorption increased again, reaching 26,91% at FA30 and 30,00% at FA40, the highest value obtained in this test. These results indicate that the water absorption of the specimens does not change linearly with the increase in fly ash content, that are the FA20 variation exhibited the best (lowest) water absorption performance, while the FA40 variation exhibited the highest water absorption. The box plot of these test results can be seen in Figure 5.11.

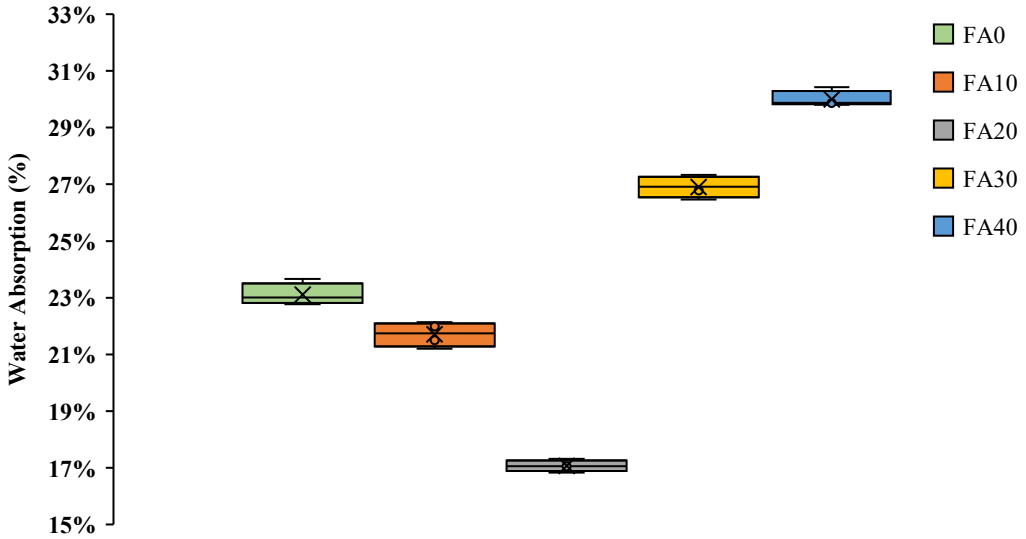


Figure 5.11 Specimen Water Absorption Box Plot

The recapitulation of the density and water absorption test results is presented in Table 5.10, while the chart of the oven-dry density test is shown in Figure 5.12.

Table 5.10 Recapitulation of Density and Water Absorption Test

Specimen Code	Nominal Density, kg/m³	Oven-Dry Density, kg/m³	Saturated Density, kg/m³	Water Absorption
FA0	853,96	806,88	1041,78	23,11%
FA10	861,87	815,02	1026,79	21,71%
FA20	875,69	824,55	1000,28	17,07%
FA30	804,52	758,41	1025,86	26,91%
FA40	798,17	751,98	1054,29	30,00%

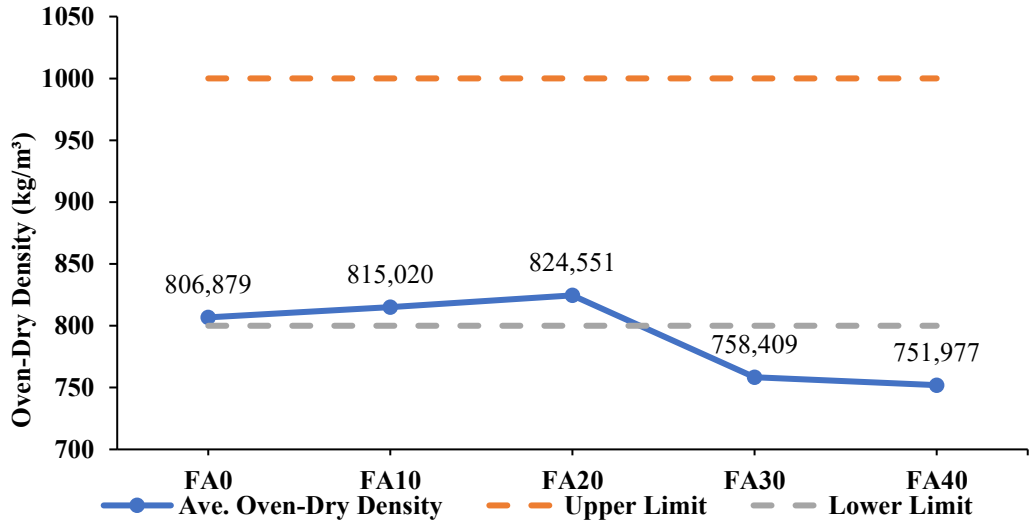


Figure 5.12 Chart of Oven-Dried Density Test

Figure 5.12 presents the average oven-dry density obtained for each specimen variation, namely FA0, FA10, FA20, FA30, and FA40, with two reference lines representing the upper limit of 1000 kg/m³ and the lower limit of 800 kg/m³ of the acceptable density range according to SNI 8640:2018. The chart shows that the FA0 specimen recorded an average oven-dry density of 806,88 kg/m³. This value increased to 815,02 kg/m³ at FA10, and reached its peak of 824,55 kg/m³ at FA20, which is the highest density among all variations. Beyond this point, the density declined to 758,41 kg/m³ at FA30 and further to 751,98 kg/m³ at FA40, the lowest value recorded in the test.

This pattern shows that the oven-dry density does not increase continuously with the addition of fly ash, but rather follows an increasing-then-decreasing trend that peaks at the FA20 variation. Up to a replacement level of about 20%, the fly

ash particles are still able to effectively fill the voids within the mixture, producing a denser and more compact specimen structure. Beyond this level, at FA30 and FA40, the excess fly ash content no longer contributes to matrix compaction, but instead, it tends to create additional air voids or disrupt the binding process of the mixture, causing the oven-dry density to drop. It is also worth noting that the FA30 and FA40 values fall below the lower limit of 800 kg/m³, meaning these two variations no longer satisfy the minimum density requirement, whereas FA0, FA10, and FA20 remain within the acceptable range of 800–1000 kg/m³. Based on this figure, FA20 can be considered the optimum fly ash replacement level in terms of oven-dry density performance. The chart of the water absorption test can be seen in Figure 5.13

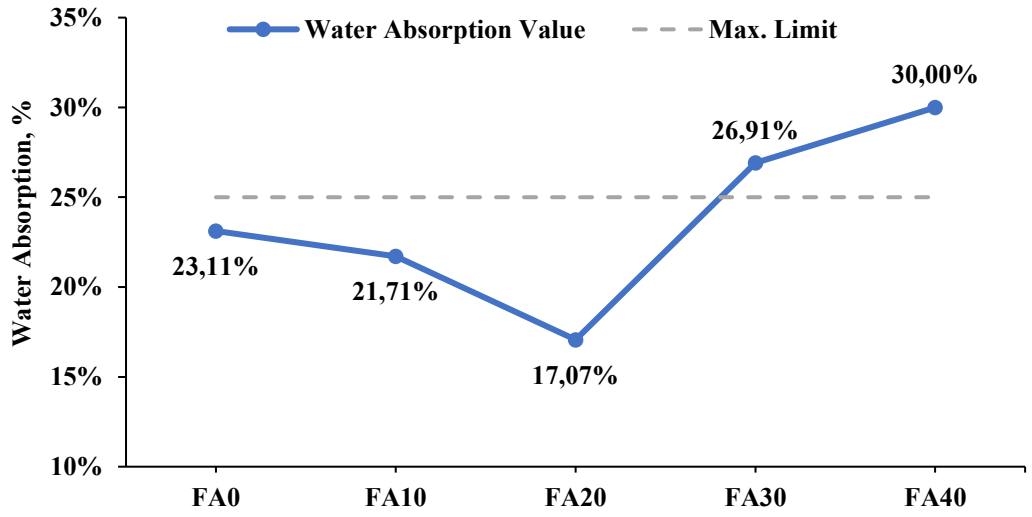


Figure 5.13 Chart of Water Absorption Test

On the other hand, the sharp rise in water absorption at 30% and 40% confirms the suspected formation of additional pore voids due to excess replacement material, as discussed in the density section. Compared with SNI 8640:2018, which limits maximum water absorption to 25% for a certain quality class, the 0%, 10%, and 20% replacements comply with that limit, while the 30% and 40% replacements exceed it. This condition is important to note because high water absorption can adversely affect the durability and long-term performance of

lightweight blocks, particularly regarding weather resistance and potential degradation from wet–dry cycles.

5.5.2 Compressive Strength Test

The compressive strength test is classified as an examination of the mechanical property of CLC lightweight bricks, as it measures the ability of the brick to withstand loads and serves as the primary indicator of its structural capacity. Based on the standard used, namely SNI 8640:2018, the compressive strength test used five whole lightweight concrete specimens, each specimen was cut into a cube measuring 100 x 100 x 100 mm. After that, the test specimens were fully submerged for 24 hours ± 30 minutes. The testing was performed using a Universal Testing Machine (UTM) in the Construction Materials Laboratory of the Civil Engineering Program at the Faculty of Civil Engineering and Planning, Universitas Islam Indonesia. Before testing, a flat surface was identified on the test specimen, and the top and bottom were then covered with steel plates to achieve optimal compressive strength. The results of the compressive strength test on lightweight bricks are shown in Table 5.11 as follows.

Table 5.11 Results of Compressive Strength Test

Specimen Code	Sample	Test Results, MPa
FA0	1	0,5783
	2	0,5725
	3	0,5978
	4	0,5587
	5	0,5666
Average		**0,5748**
FA10	1	0,5875
	2	0,576
	3	0,5909
	4	0,5941
	5	0,6064
Average		**0,5910**
FA20	1	0,6045
	2	0,6056
	3	0,6054
	4	0,6049
	5	0,6021

Specimen Code	Sample	Test Results, MPa
Average		**0,6045**
FA30	1	0,5174
	2	0,5174
	3	0,5061
	4	0,5065
	5	0,5159
Average		**0,5127**
FA40	1	0,4639
	2	0,4621
	3	0,4536
	4	0,4707
	5	0,4528
Average		**0,4606**

Based on the Table 5.11, the compressive strength test results vary for each mix variation. The highest compressive strength value, 0,6045 MPa, was obtained for the 20% variation, while the lowest compressive strength value, 0,4606 MPa, was obtained for the 40% variation. The 0%, 10%, and 30% variations produced compressive strength values of 0,5748 MPa, 0,5910 MPa, and 0,5127 MPa, respectively. The box plot of the compressive strength test results can be seen in Figure 5.14.

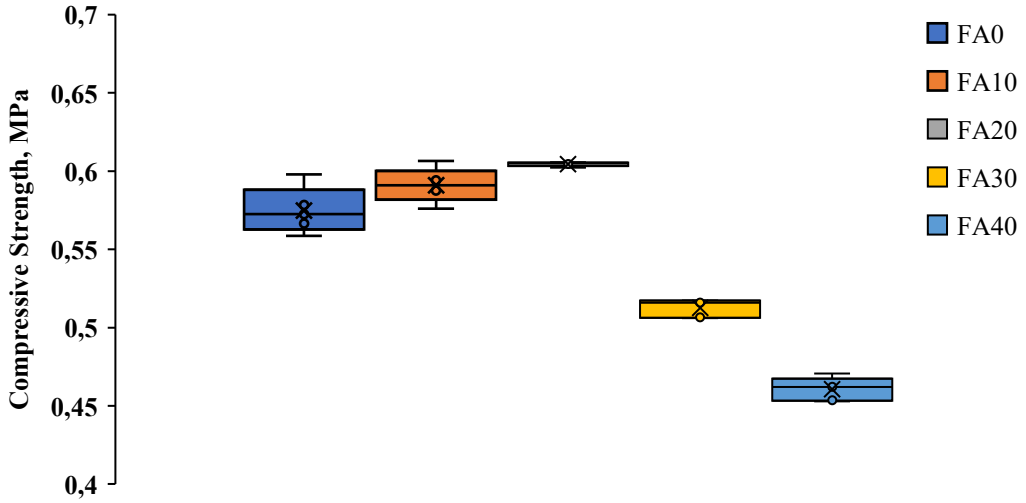


Figure 5.14 Specimen Compressive Strength Box Plot

Based on Figure 5.14, no data point in any of the variations (FA0, FA10, FA20, FA30, and FA40) lies beyond its whiskers, so no outlier is found in the compressive strength measurements. Each specimen results falls within the 1.5×IQR range of variation, indicating that there are no anomalous readings and that all specimens are valid for analysis. The absence of outliers shows that the compressive strength measurements are consistent within each variation and supports the reliability of the reported average values. The recapitulation of the compressive strength test results is presented in Table 5.12.

Table 5.12 Recapitulation of Compressive Strength Test

Specimen Code	Compressive Strength, MPa
FA0	0,5748
FA10	0,5910
FA20	0,6045
FA30	0,5127
FA40	0,4606

Compared with SNI 8640:2018, which requires a minimum average compressive strength of 2 MPa for lightweight blocks in the non-structural category, all variations in this study fall short of that minimum. Therefore, the material produced in this research cannot currently be recommended for structural or non-structural applications in accordance with the standard. It does, however, have potential for further development, for example, by optimizing the water–cement ratio, adding supplementary binders, or improving curing methods, to increase compressive strength while retaining the material's lightweight properties. Figure 5.15 shows the chart of the compressive strength test.

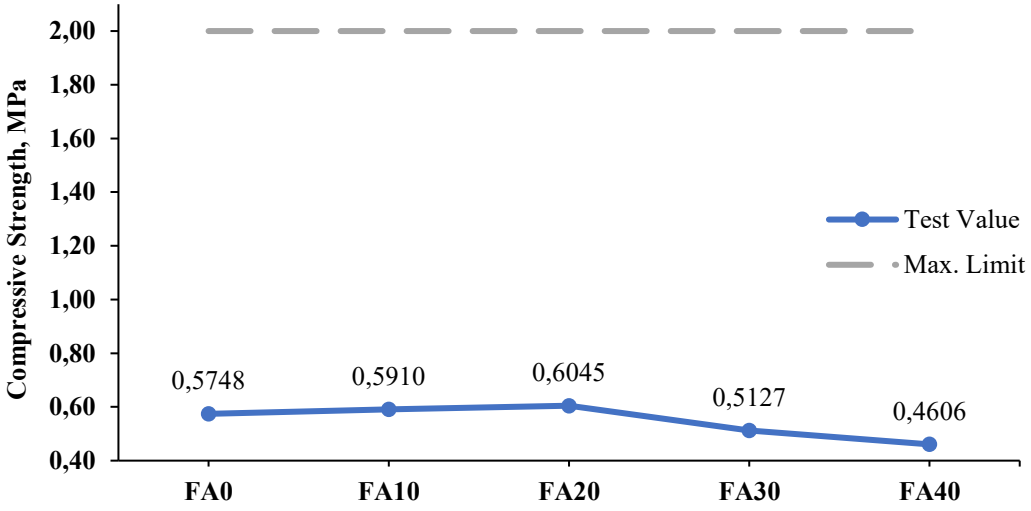


Figure 5.15 Chart of Compressive Strength Test

The reduction in compressive strength at 30% and 40% aligns with the mechanics of lightweight concrete, which is that higher porosity and lower density reduce a material's capacity to carry compressive loads. This occurs because increased pore volume reduces the contact area between particles that can effectively transfer stress. Figure 5.16 shows the compressive strength test process.



Figure 5.16 Compressive Strength Test Process

5.5.3 Statistical Analysis

1. Regression in Correlation of Oven-dry Density and Compressive Strength

The correlation between the oven-dry density and the compressive strength, together with its linear regression line, is shown in Figure 5.17.

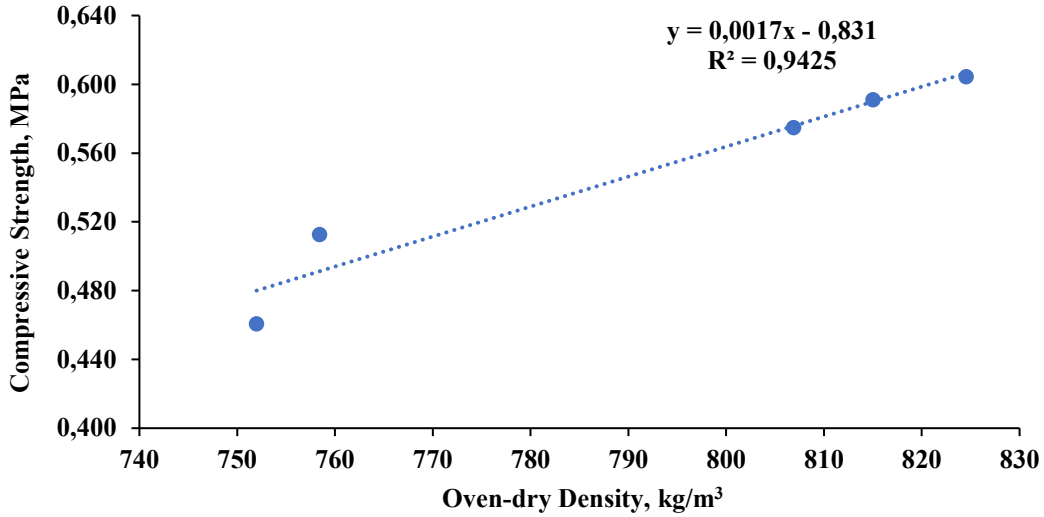


Figure 5.17 Oven-dry Density and Compressive Strength Correlation

The regression analysis in Figure 5.17 produces the linear equation y = 0,0017x – 0,831, with a coefficient of determination of R^2 = 0,9425. The positive slope of the line indicates that compressive strength increases as oven-dry density increases, so that denser specimens can withstand higher compressive loads. This is physically consistent with the behavior of cellular lightweight concrete, in which a denser and less porous matrix provides a larger effective contact area for transferring compressive stress between particles.

The coefficient of determination of 0,9425 means that about 94,25% of the variation in compressive strength can be explained by the variation in oven-dry density, while only around 5,75% is due to other factors. Because this value is close to one, the two properties have a strong positive linear relationship and the regression model fits the data well. This result directly answers the third problem formulation of this study and shows that oven-dry density can be used as a reliable predictor of the compressive strength of the CLC lightweight bricks across the fly ash variations examined.

2. Hypothesis Test

Prior to conducting the main hypothesis test, two prerequisite assumption tests were carried out on the compressive strength data, such as a normality test and a homogeneity of variance test. These two tests jointly determine whether a

parametric test (One-Way ANOVA) or a non-parametric test (Kruskal-Wallis) is the statistically appropriate method for comparing the five variation groups.

a. Normality Test

Before conducting a hypothesis test to compare the compressive strength among the five variation groups, a normality test was first performed on the compressive strength data within each group. This step is necessary to determine whether the data satisfy the assumption of a normal distribution, which subsequently determines whether a parametric test (One-Way ANOVA) or a non-parametric test (Kruskal-Wallis) is appropriate for further analysis.

The normality test was carried out using the Shapiro-Wilk test, which is appropriate for small sample sizes ($n < 50$), in this case $n = 5$ for each variation group. The hypotheses for the normality test are formulated as follows.

H_0 = The compressive strength data for each variation group are normally distributed.

H_1 = The compressive strength data for each variation group are not normally distributed.

The decision criterion applied is that if the significance value (Sig.) is greater than 0.05, the data are considered normally distributed. The opposite way, if the significance value is less than 0.05, the data are considered not normally distributed. The results of the normality test are presented in Table 5.13.

Table 5.13 The Results of Normality Test Shapiro-Wilk

Specimen Code	Statistics	df	Significant	Description
FA0	0.951	5	0.743	Normally Distributed
FA10	0.982	5	0.943	Normally Distributed
FA20	0.936	5	0.637	Normally Distributed
FA30	0.755	5	0.033	Not Normally Distributed
FA40	0.920	5	0.528	Normally Distributed

Table 5.13 shows that four of the five variation groups (FA0, FA10, FA20, and FA40) have a significance value greater than 0.05, indicating that the compressive strength data in these groups are normally distributed. However, the

FA30 group has a significance value of 0.033, which is less than 0.05, indicating that the compressive strength data in this group are not normally distributed. Because at least one group violates the normality assumption, the overall assumption of normality across all groups is considered not satisfied.

b. Homogeneity Test

The homogeneity of variance test was carried out using Levene's Test to determine whether the variance of compressive strength is equal across the five variation groups. The hypotheses for this test are formulated as follows.

H0 = The variance of compressive strength is homogeneous across all variation groups.

H1 = The variance of compressive strength is not equal across at least one variation group.

The decision criterion applied is that if the significance value (Sig.) is greater than 0.05, the variances are considered homogeneous. The results of Levene's Test, computed using four different central-tendency bases, are presented in Table 5.14.

Table 5.14 The Results of Homogeneity Test Levene's Test

Description	Levene Statistics	df-1	df-2	Sig.	Conclusion
Based on Mean	0.744	4	20	0.573	Homogeneous
Based on Median	0.532	4	20	0.714	Homogeneous
Based on Median (adjusted df)	0.532	4	14,610	0.715	Homogeneous
Based on Trimmed Mean	0.714	4	20	0.592	Homogeneous

Table 5.14 shows that all four variants of Levene's Test produce a significance value greater than 0,05 (ranging from 0,573 to 0,715). This indicates that the assumption of homogeneity of variance is satisfied across the five variation groups.

c. Summary of Assumption Tests

A parametric One-Way ANOVA requires both assumptions, namely normality and homogeneity of variance, to be satisfied simultaneously. Table 5.15 summarizes the results of both prerequisite tests.

Table 5.15 Summary of Normality and Homogeneity Test

Description	Results	Conclusion
Normality Test (Shapiro-Wilk)	FA30 is not normally distributed (Sig. = 0.033); the other four groups are normal	Not satisfied
Homogeneity Test (Levene)	All groups show equal variance (Sig. > 0.05 for all bases)	Satisfied

As shown in Table 5.15, although the homogeneity of variance conclusion is satisfied, but the normality assumption is not satisfied because the FA30 group's data are not normally distributed. Since both tests must be same for a One-Way ANOVA to be valid, besides the normality assumption fails, the One-Way ANOVA test cannot be appropriately applied in this study. Therefore, the hypothesis testing was conducted using the non-parametric Kruskal-Wallis test, which does not require the assumption of normally distributed data and is a suitable alternative to One-Way ANOVA when comparing more than two independent groups. The homogeneity test result is retained and reported as part of the complete assumption-testing procedure, and is further used in Section 4.5 as supporting information for the sensitivity analysis.

3. Kruskal-Wallis test

The Kruskal-Wallis test was conducted to determine whether there is a statistically significant difference in the distribution of compressive strength among the five fly ash variation groups. The hypotheses formulated for this test are as follows.

H0 = The distribution of compressive strength is the same across all categories of variation.

H1 = The distribution of compressive strength is not the same across at least one pair of variation categories.

The decision criterion applied is that if the Asymptotic Significance (Asymp. Sig.) value is less than the significance level ($\alpha = 0.05$), then H0 is rejected. The mean rank of compressive strength for each variation group is presented in Table 5.16.

Table 5.16 Mean Rank of Compressive Strength

Specimen Code	N	Mean Rank
FA0	5	14.00
FA10	5	17.00
FA20	5	23.00
FA30	5	8.00
FA40	5	3.00
Total	25	-

Table 5.16 shows that the FA20 group has the highest mean rank (23.00), indicating a tendency toward the highest compressive strength values among the five groups, followed by FA10 (17.00), FA0 (14.00), and FA30 (8.00). Conversely, the FA40 group has the lowest mean rank (3.00), indicating a tendency toward the lowest compressive strength values among all groups. This pattern suggests that compressive strength tends to increase as fly ash content increases from 0% to 20%, then decreases at higher replacement levels (30% and 40%).

Table 5.17 Statistics of Kruskal-Wallis Test

Parameter	Value
Total N	25
Test Statistic (H)	22.338
Degree of Freedom (df)	4
Asymp. Sig. (2-sided test)	< 0.001

Based on Table 5.17, the Kruskal-Wallis test yields a test statistic (H) of 22.338 with 4 degrees of freedom and an asymptotic significance value of < 0.001. Since this significance value is smaller than the significance level of 0.05, H0 is rejected. It can therefore be concluded that there is a statistically significant difference in the distribution of compressive strength among at least one pair of the fly ash variation groups. The results of the Bonferroni-adjusted pairwise comparisons between variations are presented in Table 5.18

Table 5.18 Pairwise Comparisons of Variation (Bonferroni-Adjusted)

Specimen Code 1 - Specimen Code 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.	Conclusion
FA40 - FA30	5.000	4.655	1.074	0.283	1.000	Not significant
FA40 - FA0	11.000	4.655	2.363	0.018	0.181	Not significant
FA40 - FA10	14.000	4.655	3.008	0.003	0.026	Significant
FA40 - FA20	20.000	4.655	4.297	< 0.001	< 0.001	Significant
FA30 - FA0	6.000	4.655	1.289	0.197	1.000	Not significant
FA30 - FA10	9.000	4.655	1.934	0.053	0.532	Not significant
FA30 - FA20	15.000	4.655	3.223	0.001	0.013	Significant
FA0 - FA10	-3.000	4.655	-0.645	0.519	1.000	Not significant
FA0 - FA20	-9.000	4.655	-1.934	0.053	0.532	Not significant
FA10 - FA20	-6.000	4.655	-1.289	0.197	1.000	Not significant

Table 5.18 shows that out of ten pairs of comparisons, three pairs exhibit a statistically significant difference after Bonferroni adjustment, namely FA40-FA10 (Adj. Sig. = 0.026), FA40-FA20 (Adj. Sig. < 0.001), and FA30-FA20 (Adj. Sig. = 0.013). The remaining seven pairs do not show a statistically significant difference. This indicates that the overall significant result obtained from the Kruskal-Wallis test is primarily driven by the distinct difference between the FA20 group (highest compressive strength) and both the FA30 and FA40 groups (which tend to exhibit lower compressive strength), as well as the difference between FA40 and FA10.

4. One-Way ANOVA

As additional supporting analysis, a One-Way ANOVA was also computed for the same data. This analysis is presented only as a sensitivity check and is not used as the primary basis for hypothesis testing, since the normality assumption required for a valid ANOVA is not satisfied by the FA30 group (see Section 4.2.1). The purpose of this section is solely to examine whether the parametric approach leads to a conclusion consistent with the non-parametric Kruskal-Wallis test. The results are presented in Table 5.19.

Table 5.19 Results of One-Way ANOVA

Source of Variation	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	0.101	4	0.025	234.806	< 0.001
Within Groups	0.002	20	0.000	-	-
Total	0.103	24	-	-	-

Table 5.19 shows an F value of 234.806 with a significance value of < 0.001, which is consistent with the Kruskal-Wallis result in indicating a statistically significant difference in compressive strength among the fly ash variation groups.

5.6 Discussion of Test Results

This section presents a discussion of the test results obtained on the lightweight blocks, including density and water absorption tests as well as compressive strength tests. The discussion compares the test outcomes with the requirements of SNI 8640:2018 to evaluate the conformity of the produced lightweight blocks' characteristics. In addition, this section provides reflections on limitations encountered during the testing process, which form the basis for recommendations for future research.

5.6.1 Test Results

1. Density Test

   a. Data Analysis

      The oven-dry density results in Table 5.10 show a non-monotonic trend across specimen codes, increasing from 806,88 kg/m³ for FA0 to 815,02 kg/m³ for FA10 and peaking at 824,55 kg/m³ for FA20, before dropping sharply to 758,41 kg/m³ for FA30 and 751,98 kg/m³ for FA40. Referring to SNI 8640:2018, which sets an acceptable oven-dry density range of approximately 800–1000 kg/m³ for this brick class, specimens FA0, FA10, and FA20 fall within this range, whereas FA30 and FA40 fall below the lower limit and therefore do not meet the standard.

      This pattern is consistent with the pozzolanic filler mechanism widely reported in fly-ash-based cellular lightweight concrete (CLC). Fly ash particles are considerably finer than cement grains, so at moderate replacement levels they fill the micro-voids between the cement paste and the foam bubbles, producing a more tightly packed, denser matrix or as the same mechanism reported for fly ash and bottom ash (FABA) lightweight bricks, where fine, void-filling FABA particles produced a denser and more compact brick as FABA content increased. A closely related study on

CLC containing high-calcium fly ash and natural zeolite similarly found that partially replacing cement with a fine pozzolan (0–30%) altered the total porosity and pore structure of the paste, with the direction and magnitude of the change depending on replacement level and pozzolan type (Jitchaiyaphum, et al., 2013).

Beyond the optimum point (in this study, above FA20), the density decline can be explained by two overlapping factors. First, once the available void space has already been filled, additional fly ash no longer contributes to packing density; instead, because fly ash reacts more slowly than cement, unreacted or only partially reacted particles increasingly act as an inert filler that leaves behind weak, less densely bonded zones. Second, a higher fly ash content raises the water demand of the mix, which can destabilize the pre-formed foam and increase the total pore volume or as the same driver identified in a response-surface-methodology (RSM) optimization study of foam-based CLC, where increasing pore volume was the dominant cause of density reduction (Rajeeth et al., 2025). A parallel trend was reported for lightweight cellular concrete filled with fly ash and waste-filler material at 10–40% replacement, where wet density decreased once replacement exceeded a certain threshold, following the same optimum-then-decline pattern observed here (Liu, Ni, Meng, Zhang, Liu, & Sun, 2020).

b. Statistical Analysis

The relationship between the Density (Oven-Dry Density) and Compressive Strength Test can also be examined quantitatively through the linear regression presented in Figure 5.17, which produced the equation $y = 0.0017x - 0.831$ with a coefficient of determination $R^2 = 0.9425$. The positive slope confirms that compressive strength increases as oven-dry density increases, while the R^2 value indicates that approximately 94.25% of the variation in compressive strength can be explained by the variation in oven-dry density, leaving only about 5.75% attributable to other factors such as pore distribution, degree of hydration,

and specimen preparation variability. This value provides quantitative support for the argument developed throughout Section 5.6.1, namely that the pore-filling mechanism is indeed the dominant factor governing all three measured properties simultaneously. A strong density-strength correlation of this kind is a characteristic feature of foam-based lightweight concrete, and comparable studies on cellular lightweight concrete have likewise reported that density is the single best predictor of compressive strength (Rajeeth et al., 2025; Liu et al., 2020).

Nevertheless, this regression result must be interpreted with care. The value of $R^2 = 0.9425$ was obtained from the average values of five variation groups, so it describes the trend between groups rather than the predictive capability of the model for an individual specimen. In addition, a high coefficient of determination indicates only the strength of the statistical association and does not by itself establish causation; density and compressive strength are both consequences of the same underlying pore structure. Accordingly, the equation should be positioned as a descriptive indicator of the relationship pattern within the tested replacement range (0-40%), and not as a general prediction formula that can be extrapolated beyond that range.

2. Water Absorption Test

The water absorption results in Table 5.9 show a trend that mirrors the density results: absorption decreases from 23,11% for FA0 to a minimum of 17,07% for FA20, then rises sharply to 26,91% for FA30 and 30,00% for FA40. SNI 8640:2018 sets a maximum water absorption limit of 25%. Accordingly, FA0, FA10, and FA20 comply with the standard, while FA30 and FA40 exceed it.

This inverse relationship between density and water absorption is expected, since both properties are governed by the same pore structure. When fly ash effectively fills the capillary voids between FA0–FA20, the matrix becomes denser, and its network of permeable, interconnected pores is reduced, so less water can be absorbed, consistent with the density-driven

durability improvement reported for fly-ash-substituted CLC bricks (Kaselle, 2020). Once replacement exceeds the optimum (FA30–FA40), the excess, less-reacted fly ash increases the proportion of capillary pores rather than closed, isolated pores. This parallels the CLC study with high-calcium fly ash and zeolite, which reported that water absorption increased as capillary porosity increased, with the effect depending on the amount of entrained air and pozzolan dosage (Jitchaiyaphum et al., 2013). A similar density–absorption relationship was reported in a study on lightweight bricks substituted with a lower-density filler material, where a decrease in specimen density was consistently accompanied by an increase in water absorption.

This condition is important to note, since bricks with water absorption above 25% are more susceptible to moisture ingress and degradation under wet–dry cycling, which can reduce long-term durability and weather resistance, particularly for elements exposed to exterior or humid environments.

3. Compressive Strength Test

The compressive strength results in Table 5.12 follow the same optimum-then-decline pattern observed in the density and water absorption results, peaking at 0,6045 MPa for FA20, after rising from 0,5748 MPa for FA0 and 0,5910 MPa for FA10, then falling to 0,5127 MPa for FA30 and 0,4606 MPa for FA40. Compared with SNI 8640:2018, which requires a minimum average compressive strength of 2 MPa for the non-structural category, none of the five specimen codes meet this requirement, so the resulting material cannot yet be classified as a standard-compliant lightweight brick.

Even so, the internal trend across variations is informative and aligns with the mechanics of foam/cellular concrete reported in the literature. The strength increase up to FA20 corresponds directly with the densification discussed in the density test above: a more tightly packed matrix, with fewer large voids and better particle-to-particle contact, can transfer compressive stress more effectively. This mirrors the finding that increasing foam or pore

content in CLC directly and significantly reduces both density and compressive strength because of the resulting increase in pore volume (Rajeeth et al., 2025), meaning that any factor which instead reduces pore volume, such as the pozzolanic filling effect of fly ash at moderate dosage, should proportionally improve strength, exactly as observed at FA20 in this study. Beyond that optimum, the sharp strength reduction at FA30–FA40 is consistent with the exponential decrease in unconfined compressive strength reported for lightweight cellular concrete as fly-ash/waste-filler replacement increased from 10% to 40%, attributed to the corresponding rise in porosity and the reduced contact area available for effective stress transfer between particles (Liu et al., 2020). National studies on fly-ash-based lightweight bricks have likewise cautioned that cement substitution must remain within a defined limit, since excessive fly ash replacement causes strength to decline once the pozzolanic reaction can no longer keep pace with the amount of unreacted material in the mix.

Given that all specimen codes remain well below the SNI 8640:2018 minimum, the material in its current formulation is best positioned as a basis for further development rather than a finished product ready for field application. Directions suggested by the literature for improving strength while retaining lightweight properties include optimizing the water-to-binder ratio, adding supplementary admixtures within the foam concrete (CLC) mix design itself (e.g., silica fume, natural zeolite, or superplasticizers), and adopting curing methods still appropriate to the CLC/foam concrete process, such as extended wet-curing duration beyond 28 days, sealed curing to preserve internal moisture, or mild elevated-temperature curing.

4. Statistical Analysis

The statistical analysis was carried out in two stages, namely assumption testing followed by hypothesis testing, so that the conclusion regarding the effect of fly ash replacement on compressive strength rests on a verified methodological basis rather than on a visual comparison of mean values alone. The Shapiro-Wilk test was selected because it is the most

appropriate normality test for small samples ($n < 50$), which applies to this study with $n = 5$ per variation group. The results in Table 5.13 show that four of the five groups (FA0, FA10, FA20, and FA40) satisfy the assumption of normality, whereas the FA30 group does not (Sig. = 0.033 < 0.05). In contrast, Levene's Test in Table 5.14 confirms that the assumption of homogeneity of variance is satisfied across all groups (Sig. = 0.573 to 0.715). Because a parametric One-Way ANOVA requires both assumptions to be met simultaneously, the failure of the normality assumption in a single group was sufficient to disqualify ANOVA as the primary basis for hypothesis testing, and the non-parametric Kruskal-Wallis test was therefore used instead. The Kruskal-Wallis test is a rank-based alternative to One-Way ANOVA that does not require the data to be normally distributed and has been applied in construction-material research to determine whether compressive strength differs significantly between treatment groups when the parametric assumptions are not met (Dębska & Lichołaj, 2017).

The Kruskal-Wallis test produced $H = 22.338$ with $df = 4$ and Asymp. Sig. < 0.001, so H0 is rejected and it is concluded that at least one variation group has a significantly different compressive strength distribution. Importantly, the mean rank pattern in Table 5.16 (FA0 = 14.00; FA10 = 17.00; FA20 = 23.00; FA30 = 8.00; FA40 = 3.00) reproduces exactly the same optimum-then-decline pattern that was observed descriptively in the density, water absorption, and compressive strength tests. This means that the peak at FA20 and the sharp decline at FA30 and FA40 are not merely descriptive tendencies or the product of specimen-to-specimen variability, but a difference that is statistically significant. The One-Way ANOVA computed as a sensitivity check ($F = 234.806$; Sig. < 0.001) yields a conclusion in the same direction, which strengthens confidence in the robustness of the result: two tests with different statistical assumptions arrive at the same conclusion. The optimum-then-decline pattern itself is also consistent with the wider fly ash literature: an experimental study on high-strength concrete containing ground fly ash reported that specimens with 10-40% fly ash replacement exhibited

higher compressive strength than the control concrete after seven days of curing, confirming that fly ash improves strength only up to a certain replacement range (Sata, Jaturapitakkul, & Kiattikomol, 2007).

The Bonferroni-adjusted pairwise comparisons in Table 5.18 identify which specific pairs of variations differ. Of the ten pairs compared, three are statistically significant, namely FA40-FA10 (Adj. Sig. = 0.026), FA40-FA20 (Adj. Sig. < 0.001), and FA30-FA20 (Adj. Sig. = 0.013). All three significant pairs involve a comparison between a high-replacement group (FA30 or FA40) and a moderate-replacement group (FA10 or FA20). This pattern indicates that the truly decisive factor is not the presence of fly ash as such, but rather the crossing of the optimum replacement threshold. The FA20-FA0 pair, for example, does not differ significantly, meaning that the strength increases from 0% to 20% is a positive tendency that could not be statistically proven at n = 5, whereas the strength reduction from FA20 to FA30 and FA40 is proven. The practical implication is that from an engineering standpoint the more critical risk is over-replacement, and thus the safe upper limit of fly ash replacement identified statistically in this study lies at 20%.

5. Adjustment of test results in accordance with SNI 8640:2018

SNI 8640:2018 classifies CLC lightweight bricks into two main groups, namely structural bricks (types IA and IB) and non-structural bricks (types IIA and IIB), with each group further distinguished by its exposure condition, that is, exposed to the environment (outdoor) or not exposed to the environment (indoor). The physical requirements for each type are presented in Table 3.1, while the classification based on oven-dry weight is presented in Table 3.2. Since the mix design in this study was directed at an oven-dry weight target of 900 kg/m³, the applicable weight category is category 900 with an acceptance range of 800 to 1.000 kg/m³, and the evaluation of conformity is accordingly carried out against the non-structural brick category. Within this category, as presented in Table 3.1, SNI 8640:2018 requires a minimum average compressive strength of 2 MPa and a minimum individual compressive strength of 1,8 MPa, together with a maximum water

absorption of 25% for type IIA (outdoor), whereas type IIB (indoor) is not subject to a water absorption limit.

Based on these criteria, the results of the three tests conducted in this study, namely oven-dry density, water absorption, and compressive strength, were compared one by one against the requirements of the standard in order to determine which classification each specimen code can be assigned to. The recapitulation of this conformity assessment is presented in Table 5.20.

Table 5.20 Recapitulation Test accordance with SNI 8640:2018

Specimen Code	Specimen Test		
	Density, kg/m³	Water Absorption, %	Compressive Strength, MPa
FA0	Pass for Classification Non-structural Bricks for Outdoor & Indoor (806,88)	Pass for Classification Non-structural Bricks for Outdoor & Indoor (23,11)	Fail at all accordance SNI 8640:2018 Requirement (0,5748)
FA10	Pass for Classification Non-structural Bricks for Outdoor & Indoor (815,02)	Pass for Classification Non-structural Bricks for Outdoor & Indoor (21,71)	Fail at all accordance SNI 8640:2018 Requirement (0,5910)
FA20	Pass for Classification Non-structural Bricks for Outdoor & Indoor (824,55)	Pass for Classification Non-structural Bricks for Outdoor & Indoor (17,07)	Fail at all accordance SNI 8640:2018 Requirement (0,6045)
FA30	Fail at all accordance SNI 8640:2018 Requirement (758,41)	Fail at all accordance SNI 8640:2018 Requirement (26,91)	Fail at all accordance SNI 8640:2018 Requirement (0,5127)
FA40	Fail at all accordance SNI 8640:2018 Requirement (751,98)	Fail at all accordance SNI 8640:2018 Requirement (30,00)	Fail at all accordance SNI 8640:2018 Requirement (0,4606)

Table 5.20 shows that the level of conformity differs from one parameter to another. In terms of oven-dry density, FA0 (806,88 kg/m³), FA10 (815,02 kg/m³), and FA20 (824,55 kg/m³) fall within the range of 800 to 1.000 kg/m³ that defines weight category 900 in Table 3.2, so these three variations are consistent with the weight class targeted in the mix design and are acceptable for the non-structural category in both outdoor (IIA) and indoor (IIB) conditions. FA30 (758,41 kg/m³) and FA40 (751,98 kg/m³), by contrast, fall below the lower limit of the targeted range and therefore do not conform to weight category 900. A comparable pattern applies to water absorption, where FA0 (23,11%), FA10 (21,71%), and FA20 (17,07%) remain below the maximum limit of 25% stipulated in Table 3.1 and thus satisfy the

requirement for both type IIA and type IIB, whereas FA30 (26,91%) and FA40 (30,00%) exceed that limit and are therefore no longer acceptable for outdoor application.

The decisive parameter, however, is compressive strength. None of the five specimen codes reaches the minimum average compressive strength of 2 MPa required for the non-structural category in Table 3.1, nor the minimum individual compressive strength of 1,8 MPa. The highest value obtained in this study, 0,6045 MPa at FA20, is only about 30% of the minimum requirement, while the lowest value, 0,4606 MPa at FA40, is approximately 23% of it. Because the compressive strength requirement applies to every class defined in SNI 8640:2018, including the least demanding one, namely type IIB for non-structural indoor use, the failure of this single parameter means that none of the variations can be assigned to any classification in the standard, even for those variations whose oven-dry density and water absorption already conform.

Accordingly, the conformity achieved by FA0, FA10, and FA20 must be read as partial conformity that is limited to the physical parameters of oven-dry density and water absorption, and not as a full classification as a lightweight brick under SNI 8640:2018. Among the five variations, FA20 remains the most favourable formulation, since it satisfies both physical parameters with the widest margin, occupies the targeted weight category 900, and records the highest compressive strength of the series. Even so, in its present formulation the lightweight brick produced in this study is not yet ready for application, and the results should be positioned as a basis for further development, particularly through improvements directed at raising the compressive strength to the level required by the standard while retaining the lightweight characteristics that have already been achieved.

5.6.2 Reflection and Evaluation of Test Results

Reflecting on the overall test results, several important observations and limitations can be drawn from the density, water absorption, and compressive strength tests conducted in this study.

1. Consistency between physical and mechanical properties. The three test results (density, water absorption, and compressive strength) show a consistent and mutually reinforcing pattern, all peaking or reaching their best value at the FA20 variation and declining beyond that point. This consistency strengthens the validity of the 20% fly ash replacement as the practical optimum point within the tested range (0–40%), and indicates that the pore-filling mechanism discussed in Section 5.6.1 is the dominant factor governing all three properties simultaneously. This consistency is further supported statistically, since the Kruskal-Wallis test ($H = 22.338$; $p < 0.001$) confirms that the differences among the variations are statistically significant, and the regression model ($R^2 = 0.9425$) confirms that density is the dominant explanatory variable behind all three properties.
2. Statistical stability and the limitation of a small sample size. The statistical analysis reinforces the descriptive findings on two levels, which are the agreement between the Kruskal-Wallis test ($H = 22.338$; $p < 0.001$) and the One-Way ANOVA sensitivity check ($F = 234.806$; $p < 0.001$) shows that the conclusion does not depend on the choice of statistical test, while the very small Sum of Squares Within Groups (0.002) relative to Between Groups (0.101) indicates that the observed differences originate from the treatment rather than from testing noise. Based on these values, the proportion of variance explained by the treatment is approximately 98%, which indicates a very large effect size and is consistent with the box plots in Figures 5.11 and 5.14, in which no outliers were detected in any variation group. Nevertheless, the sample size of $n = 5$ per variation group limits statistical power, which most likely explains why the FA20–FA0 pair did not emerge as significant after the conservative Bonferroni adjustment, and why the non-normality of FA30 may be an artefact of the small sample rather than genuine asymmetry. The conclusion that FA20 is the optimum should therefore be understood as descriptively strong and consistent across all three tests, yet statistically only partially proven at the pairwise-comparison level.

3. Incorporating silica fume as a supplementary admixture in the foam concrete (CLC) mix design itself, in combination with or as an alternative to fly ash, to improve compressive strength without sacrificing the material's low density and foam-based pore structure. This direction is directly supported by an experimental study on CLC blocks substituting cement with silica fume at 0%, 0.5%, 1%, 5%, 10%, and 15% by cement weight, which found that a 10% silica fume replacement produced the optimum compressive strength of the CLC block, an increase of 81.25% compared to the mixture without silica fume (Suryanita, et al., 2022). This finding indicates that silica fume's very fine particle size and high pozzolanic reactivity make it more effective than fly ash alone at densifying the pore walls of foam-based CLC, and that there exists an optimum dosage beyond which excess silica fume may again reduce workability and strength, a pattern consistent with the optimum-then-decline behavior already observed for fly ash in this study.
4. Evaluating alternative ambient-pressure curing regimes that remain fully consistent with the CLC/foam concrete classification, informed by a comparative experimental study on foamed concrete cured in air, sealed in a cellophane sheet, and immersed in water at 30°C (Falliano, De Domenico, Ricciardi, & Gugliandolo, 2018). That study found that air curing at room temperature and humidity produced the lowest compressive strengths across all tested mixes, attributed to insufficient hydration caused by premature moisture loss from the specimen, whereas sealing the specimens in cellophane to limit water evaporation during curing achieved the highest strengths in almost all cases, and water curing produced comparable, only slightly lower results. Adopting a sealed-curing or extended water-curing regime for the fly-ash-substituted CLC mixes in this study, rather than autoclaving, would allow the pozzolanic reaction of the unreacted fly ash (particularly at the 30% and 40% replacement levels) more time and moisture to proceed further, without altering the atmospheric-pressure curing process that defines CLC as distinct from AAC.

5. Scope limitation of the replacement range tested. Since the tests were limited to five replacement levels (0%, 10%, 20%, 30%, and 40%) in increments of 10%, the precise location of the true optimum point cannot be determined more accurately than "somewhere between 10% and 30%, most likely near 20%." A finer increment (e.g., 5% steps) around the 15–25% range would allow a more precise identification of the optimum replacement level.
6. Recommendations for further research from a statistical standpoint. Building on the limitations identified above, several directions are recommended for subsequent studies. Increasing the number of specimens to at least 10 to 15 per variation group would raise statistical power, so that differences of small magnitude such as the FA0–FA20 pair could be tested more fairly and the normality assumption would be more likely to be satisfied in every group, allowing parametric ANOVA to be used as the primary test. Narrowing the replacement interval to 5% steps within the 15–25% range would locate the optimum point more precisely, particularly if the resulting data are fitted with a quadratic regression model to estimate the true optimum analytically rather than merely selecting the best value among the levels tested. Extending the regression analysis to a multiple-regression form that includes water absorption as a second predictor alongside oven-dry density would also help clarify the relative contribution of each property to compressive strength. In addition, reporting effect size measures such as eta-squared or epsilon-squared alongside the p-value is recommended, since a p-value only indicates whether a difference exists while the effect size indicates how large and how practically meaningful that difference is. Finally, if a subsequent study adds a second factor such as curing duration or curing method, a two-way ANOVA would be more appropriate than a one-way test because it can detect interaction between fly ash replacement level and curing treatment, an approach that has been applied in alkali-activated fly ash research, in which a two-way ANOVA with interaction followed by a Tukey post-hoc test was used to evaluate the simultaneous effects of the filler/precursor ratio and

curing humidity on compressive strength (Cerveira, Correia, Cristelo, Miranda, Castro, & Fernández-Jiménez, 2017).

CHAPTER VI
CONCLUSION

6.1 Conclusion

Based on the specimen testing presented in Chapter V, the following conclusions can be drawn.

1. The substitution of cement with fly ash affects the physical and mechanical properties of CLC lightweight bricks in a non-monotonic manner compared to the normal brick (0% fly ash, without admixture). Up to the 20% replacement level, the oven-dry density increased from 806,88 kg/m³ for FA0 to 815,02 kg/m³ for FA10 and 824,55 kg/m³ for FA20, the water absorption decreased from 23,11% for FA0 to 21,71% for FA10 and 17,07% for FA20, and the compressive strength increased from 0,5748 MPa for FA0 to 0,5910 MPa for FA10 and 0,6045 MPa for FA20. However, at the 30% and 40% replacement levels the oven-dry density dropped to 758,41 kg/m³ and 751,98 kg/m³ (both below the 800 kg/m³ lower limit of SNI 8640:2018), the water absorption rose sharply to 26,91% and 30,00% (both exceeding the 25% limit of SNI 8640:2018 as well as the normal mixture), and the compressive strength decreased to 0,5127 MPa and 0,4606 MPa, both lower than the normal brick. This indicates that a moderate amount of fly ash improves the density and strength of the CLC brick by effectively filling the voids in the mixture, whereas an excessive fly ash content instead creates additional pore voids and disrupts the binding process. The Kruskal-Wallis test ($H = 22,338$; Asymp. Sig. $< 0,001$) confirms that these differences between variations are statistically significant.
2. The 20% fly ash variation was found to be the optimal percentage among the five variations tested (0%, 10%, 20%, 30%, and 40%). This variation produced the best combination of characteristics, namely the highest oven-dry density 824,55 kg/m³, within the SNI 8640:2018 range of 800–1000 kg/m³, the lowest water absorption 17,07%, within the SNI 8640:2018 limit

of 25%, and the highest compressive strength 0,6045 MPa among all variations. Nevertheless, the compressive strength of all variations 0,4606–0,6045 MPa, including the 20% variation, remains far below the 2 MPa minimum average compressive strength required by SNI 8640:2018 for non-structural lightweight blocks, so the resulting material cannot yet be recommended for structural or non-structural building applications according to that standard. Statistically, the Bonferroni-adjusted pairwise comparisons show that the significant differences occur only between the high-replacement groups and the moderate-replacement groups, namely FA40–FA10 (Adj. Sig. = 0,026), FA40–FA20 (Adj. Sig. < 0,001), and FA30–FA20 (Adj. Sig. = 0,013), so that the safe upper limit of fly ash replacement identified in this study lies at 20%.

3. There is a positive correlation between the oven-dry density (weight of content) and the compressive strength of the CLC lightweight brick across the fly ash variations. As the oven-dry density increased from FA0 to FA20, the compressive strength increased correspondingly, and as the oven-dry density decreased at the FA30 and FA40 variations, the compressive strength also decreased, reaching its lowest value at 40% fly ash. This relationship is quantified by the linear regression $y = 0,0017x – 0,831$ with a coefficient of determination $R^2 = 0,9425$, which means that approximately 94,25% of the variation in compressive strength can be explained by the variation in oven-dry density. This is consistent with the general mechanics of lightweight concrete, in which a higher density (lower porosity) provides a larger effective contact area between particles for transferring compressive stress, while a higher porosity reduces that capacity. The relationship should, however, be read as a descriptive indicator within the tested replacement range of 0–40% rather than as a general prediction formula.

6.2 Suggestion

Based on the evaluation of the analysis and discussion results in Chapter V, the following suggestions are proposed for the improvement of this research and for future studies.

1. The density, water absorption, and compressive strength results all reached their optimum at FA20 and declined beyond it, so the 20% replacement level should be treated as the practical upper limit, with pore-filling as the dominant governing mechanism.
2. Silica fume may be added as a supplementary admixture in the CLC mix design, since a 10% silica fume replacement has been reported to increase the compressive strength of CLC blocks by 81,25% compared with a mixture without silica fume (Suryanita, et al., 2022).
3. A sealed (cellophane) or extended water-curing regime is recommended instead of plain air curing, because it yields the highest compressive strength in foamed concrete (Falliano, et al., 2018) and gives the unreacted fly ash more time and moisture to react, without departing from the atmospheric-pressure curing that defines CLC.
4. The replacement interval should be narrowed to 5% steps within the 15–25% range, since the 10% intervals used here can only locate the optimum as "somewhere between 10% and 30%, most likely near 20%".
5. From a statistical standpoint, the number of specimens should be increased to at least 10–15 per variation group so that small differences such as the FA0–FA20 pair can be tested fairly and parametric ANOVA becomes usable, the data should be fitted with a quadratic regression to estimate the optimum analytically, and effect size measures should be reported alongside the p-value; if curing duration or curing method is added as a second factor, a two-way ANOVA would be more appropriate than a one-way test.

BIBLIOGRAPHY

Agrawal, Y., Gupta, T., Sharma, R., Panwar, N. L., & Siddique, S. (2021). A Comprehensive Review on the Performance of Structural Lightweight Aggregate Concrete for Sustainable Construction. Construction Materials, 1(1), 39-62.

Anggraini, R., Nanda, R. E., Warman, H., Taufik, & Mulyani, R. (2022). Penggunaan fly ash terhadap kuat tekan dan porositas beton porous. Jurnal REKAYASA, 12(1), 11-25.

Aziz, Kurniawan. (2025). Pengaruh Subtitusi Fly Ash Terhadap Kuat Tekan dan Penyerapan Bata Beton Ringan Seluler (Cellular Lightweight Concrete). Universitas Mataram.

Benjeddou, O., Ravindran, G., & Abdelzaher, M. A. (2023). Thermal and Acoustic Features of Lightweight Concrete Based on Marble Wastes and Expanded Perlite Aggregate. Buildings, 13(4), 992.

Cerveira, A., Correia, E., Cristelo, N., Miranda, T., Castro, F., & Fernández-Jiménez, A. (2017). Statistical Analysis of the Influence of Several Factors on Compressive Strength of Alkali Activated Fly Ash. Procedia Structural Integrity, Volume 5, 601-608.

Dębska, B., & Lichołaj, L. (2017). Environmental Factors Affecting the Strength Characteristics of Modified Resin Mortars. IOP Conference Series: Earth and Environmental Science, Volume 95, Artikel 042016, 1-8.

Eniarti, M., Ngudiyono, Merdana, I. N., Sulistiyowati, T., Rawiana, S., Natasya, R. D., & Maulana, O. (2025). Durabilitas mortar dengan replacement bahan pozzolan terhadap lingkungan agresif. Spektrum Sipil, 12(1), 1-11.

Falliano, D., De Domenico, D., Ricciardi, G., & Gugliandolo, E. (2018). Experimental investigation on the compressive strength of foamed concrete: Effect of curing conditions, cement type, foaming agent and dry density. Construction and Building Materials, 165, 735–749.

Hendrawati, N., Rahmayanti, E. D., & Priapnasar, E. D. (2018). Study pembuatan durable cement dengan penambahan pozzolan silica fume. Jurnal Teknik Kimia dan Lingkungan, 2(1), 31.

Husin, A. A., & Setiadji, R. (2008). Pengaruh penambahan foam agent terhadap kualitas bata beton. Jurnal Permukiman, 3(3), 196, 199-200.

Jitchaiyaphum, K., Sinsiri, T., Jaturapitakkul, C., & Chindaprasirt, P. (2013). Cellular lightweight concrete containing high-calcium fly ash and natural zeolite. International Journal of Minerals, Metallurgy, and Materials, 20(5), 462–471.

Kaselle, Hermana. (2020). Pengaruh Substitusi Fly Ash Terhadap Kuat Tekan dan Penyerapan Bata Beton Ringan Seluler (Cellular Lightweight Concrete).

Prosiding 4th Seminar Nasional Penelitian & Pengabdian Kepada Masyarakat 2020.

Liu, X., Ni, C. W., Meng, K., Zhang, L. Y., Liu, D. X., & Sun, L. Z. (2020). Strengthening mechanism of lightweight cellular concrete filled with fly ash. Construction and Building Materials, 251, 118954.

Mariatul Kiptiah, & Giarto, R. B. (2023). Analisis perbandingan kuat tekan beton semen OPC dan semen PCC terhadap pemanfaatan Sikament-NN. Techno: Jurnal Fakultas Teknik, Universitas Muhammadiyah Purwokerto, 24(1), 27-38.

Naifah, Sabila, G. Z., Bahri, S., & Miswar, K. (2025). Pengaruh kombinasi agregat halus dan volume foam terhadap sifat mekanik beton busa. Jurnal Teknologi, 25(2), 195.

Pah, J. J. S., Hadjoh, E. K. P., & Sir, T. M. W. (2021). Hubungan antara penggunaan agregat berbeda ukuran butiran dan keringanan bata ringan CLC. Jurnal Teknik Sipil, 10(2), 113–124.

Pramesti, H. R., & Priyanto, B. (2023). Analisa produktivitas tenaga kerja dan harga satuan pekerjaan pada pekerjaan pasangan dinding bata ringan. Journal of Civil Engineering Building and Transportation, 7(1), 38–45.

Prameswari, A. R. T. W., Irianti, L., Sebayang, S., & Isneini, M. (2023). Pengaruh penggunaan Ordinary Portland Cement (OPC), semen modifikasi jenis III dan jenis IV, dan Portland Composite Cement (PCC) terhadap kuat tekan beton. Jurnal Rekayasa Sipil dan Desain (JRSDD), 11(4), 703–714.

Putra, dkk. (2024). Studi Eksperimental Sifat Mekanis Bata Ringan CLC Dengan Penambahan Fly Ash. Siklus: Jurnal Teknik Sipil. Vol. 10 No. 2.

Rahmayanti, dkk. (2023). Pemanfaatan dan Pengaruh Fly Ash Batu Bara Sebagai Subtitusi Sebagian Semen Terhadap Nilai Kuat Tekan Bata Ringan Jenis Cellular Lightweight Concrete (CLC). Siklus: Jurnal Teknik Sipil. Vol. 9 No. 2.

Rajeeth, T. J., Sharma, A., Honnalli, R., et al. (2025). Experimental investigation and optimization of cellular light weight concrete using foam content and prediction using response surface methodology. Discover Sustainability, 6, 1146.

Rodgers, Lucy. (2018). Perubahan Iklim: Inilah Penghasil Emisi CO2 Terbesar Yang Mungkin Tak Anda Sadari. BBC News Indonesia.

Thomas, Michael. (2007). Optimizing the Use of Fly Ash in Concrete. Portland Cement Association (PCA, Report IS548). 15.

Salain, I. M. A. K. (2021). Kekuatan dan permeabilitas beton abu terbang volume tinggi. Jurnal Teknik Sipil ITB, 28(2), 133-142.

Sata, V., Jaturapitakkul, C., & Kiattikomol, K. (2007). Influence of pozzolan from various by-product materials on mechanical properties of high-strength concrete. Construction and Building Materials, Volume 21, Nomor 7, 1589-1598.

SNI 8640:2018. Spesifikasi Bata Ringan Untuk Pasangan Dinding.

SNI 03-0349-1989. Bata Beton Untuk Pasangan Dinding.
SNI 2049:2020. Semen Portland Bagian 1: Spesifikasi.
SNI 03-6820-2002. Spesifikasi Agregat Halus Untuk Pekerjaan Adukan dan Plesteran Dengan Bahan Dasar Semen.
SNI 03-2847-2002. Tata Cara Perhitungan Struktur Beton Untuk Bangunan Gedung.
SNI 03-4804-1998. Metode Pengujian Bobot Isi dan Rongga Udara Dalam Agregat.
SNI 1970-1990. Metode Pengujian Berat Jenis dan Penyerapan Air Agregat Halus.
SNI 1968-1990. Metode Pengujian Tentang Analisis Saringan Agregat Halus dan Kasar.
SNI 4142-1996. Metode Pengujian Jumlah Bahan Dalam Agregat yang Lolos Saringan No. 200 (0,075 mm).
Suryanita, R., Maizir, H., Zulapriansyah, R., Subagiono, Y., & Mohd Fadzil Arshad, M. (2022). The effect of silica fume admixture on the compressive strength of the cellular lightweight concrete. Results in Engineering, 14.
Syapawi, A., Kosim, Ravsyan, R., Effendi, A., & Apriani, F. (2022). Pengaruh penambahan bahan foam agent dengan variasi komposisi batu kapur terhadap kuat tekan bata ringan. PILAR: Jurnal Teknik Sipil Politeknik Negeri Sriwijaya, 17(2), 37.

APPENDIXES

Appendix 1 – Compressive Strength Test Report for Cellular Lightweight Concrete (CLC) Bricks

UNIVERSITAS ISLAM INDONESIA

FAKULTAS TEKNIK SIPIL & PERENCANAAN

Gedung KH. Moh. Natsir
Kampus Terpadu Universitas Islam Indonesia
Jl. Kaliurang km 14,5 Yogyakarta 55584
T. (0274) 898444 ext 3200, 3201
F. (0274) 895330
E. dekanat.ftsp@uii.ac.id
W. ftsp.uii.ac.id

LAPORAN HASIL PENGUJIAN KUAT TEKAN BATA RINGAN
CELLULAR LIGHTWEIGHT CONCRETE (CLC)

Peneliti : Yunda Aliefia Bianita
Judul Penelitian : The Effect of Partial Substitution of Cement with Coal Fly Ash on the Physical and Mechanical Properties of Cellular Lightweight Concrete (CLC)
Dosen Pembimbing : Jafar, S.T., M.T., MURP.

1. Variasi Fly Ash 0%

No	Kode benda uji	Dimensi			Luas Bidang Tekan (A)	Berat	Nilai kgf	Beban	Kuat Tekan
		p	l	t					
		mm	mm	mm	mm²	g	Kgf	N	N/mm²
1	FA0-1A	95	98	102	9310	870	475	4659,75	0,5005
2	FA0-2A	97	90	96	8730	835	535	5248,35	0,6012
3	FA0-3A	98	94	99	9212	855	485	4757,85	0,5165
4	FA0-4A	96	90	98	8640	889	565	5542,65	0,6415
5	FA0-5A	98	96	100	9408	878	595	5836,95	0,6204
6	FA0-6A	101	95	101	9595	870	592,5	5812,425	0,6058
7	FA0-7A	95	92	102	8740	854	577,5	5665,275	0,6482
8	FA0-8A	96	99	100	9504	862	537,5	5272,875	0,5548
9	FA0-9A	100	92	95	9200	878	490	4806,9	0,5225
10	FA0-10A	91	90	100	8190	848	477,5	4684,275	0,5720
Rata - rata									**0,5783**

No	Kode benda uji	Dimensi			Luas Bidang Tekan (A)	Berat	Nilai kgf	Beban	Kuat Tekan
		p	l	t					
		mm	mm	mm	mm²	g	Kgf	n	n/mm²
1	FA0-1B	98	94	102	9212	869	592,5	5812,425	0,6310
2	FA0-2B	94	98	102	9212	843	547,5	5370,975	0,5830
3	FA0-3B	92	99	94	9108	862	542,5	5321,925	0,5843
4	FA0-4B	94	100	95	9400	875	500	4905	0,5218
5	FA0-5B	100	95	96	9500	862	492,5	4831,425	0,5086
6	FA0-6B	98	94	95	9212	898	497,5	4880,475	0,5298
7	FA0-7B	93	92	96	8556	885	477,5	4684,275	0,5475
8	FA0-8B	91	94	102	8554	893	547,5	5370,975	0,6279
9	FA0-9B	95	100	98	9500	853	540	5297,4	0,5576
10	FA0-10B	94	91	101	8554	868	552,5	5420,025	0,6336
Rata - rata									**0,5725**

UNIVERSITAS ISLAM INDONESIA

FAKULTAS
TEKNIK SIPIL
& PERENCANAAN

Gedung KH. Moh. Natsir
Kampus Terpadu Universitas Islam Indonesia
Jl. Kaliurang km 14,5 Yogyakarta 55584
T. (0274) 898444 ext 3200, 3201
F. (0274) 895330
E. dekanat.ftsp@uii.ac.id
W. ftsp.uii.ac.id

No	Kode benda uji	Dimensi			Luas Bidang Tekan (A)	Berat	Nilai kgf	Beban	Kuat Tekan
		p	l	t					
		mm	mm	mm	mm²	g	Kgf	n	n/mm²
1	FA0-1C	98	97	100	9506	876	595	5836,95	0,6140
2	FA0-2C	99	90	98	8910	897	565	5542,65	0,6221
3	FA0-3C	99	100	94	9900	837	500	4905	0,4955
4	FA0-4C	97	90	95	8730	849	567,5	5567,175	0,6377
5	FA0-5C	94	100	100	9400	881	595	5836,95	0,6210
6	FA0-6C	99	91	102	9009	874	565	5542,65	0,6152
7	FA0-7C	97	98	100	9506	865	590	5787,9	0,6089
8	FA0-8C	95	93	100	8835	842	527,5	5174,775	0,5857
9	FA0-9C	98	100	98	9800	865	585	5738,85	0,5856
10	FA0-10C	91	100	102	9100	845	550	5395,5	0,5929
Rata - rata									0,5979

No	Kode benda uji	Dimensi			Luas Bidang Tekan (A)	Berat	Nilai kgf	Beban	Kuat Tekan
		p	l	t					
		mm	mm	mm	mm²	g	Kgf	n	n/mm²
1	FA0-1D	95	100	99	9500	890	495	4855,95	0,5112
2	FA0-2D	91	91	95	8281	880	510	5003,1	0,6042
3	FA0-3D	91	94	97	8554	889	500	4905	0,5734
4	FA0-4D	97	100	100	9700	887	522,5	5125,725	0,5284
5	FA0-5D	96	91	98	8736	894	490	4806,9	0,5502
6	FA0-6D	99	99	95	9801	841	567,5	5567,175	0,5680
7	FA0-7D	97	90	98	8730	847	475	4659,75	0,5338
8	FA0-8D	96	100	102	9600	842	517,5	5076,675	0,5288
9	FA0-9D	93	98	94	9114	886	595	5836,95	0,6404
10	FA0-10D	97	100	101	9700	878	542,5	5321,925	0,5487
Rata – rata									0,5587

UNIVERSITAS ISLAM INDONESIA

FAKULTAS
TEKNIK SIPIL
& PERENCANAAN

Gedung KH. Moh. Natsir
Kampus Terpadu Universitas Islam Indonesia
Jl. Kaliurang km 14,5 Yogyakarta 55584
T. (0274) 898444 ext 3200, 3201
F. (0274) 895330
E. dekanat.ftsp@uii.ac.id
W. ftsp.uii.ac.id

No	Kode benda uji	Dimensi			Luas Bidang Tekan (A)	Berat	Nilai kgf	Beban	Kuat Tekan
		p	l	t					
		mm	mm	mm	mm²	g	Kgf	n	n/mm²
1	FA0-1E	91	93	101	8463	865	530	5199,3	0,6144
2	FA0-2E	96	98	97	9408	886	542,5	5321,925	0,5657
3	FA0-3E	95	97	102	9215	850	592,5	5812,425	0,6308
4	FA0-4E	95	91	95	8645	866	490	4806,9	0,5560
5	FA0-5E	97	95	98	9215	840	475	4659,75	0,5057
6	FA0-6E	100	99	97	9900	845	477,5	4684,275	0,4732
7	FA0-7E	101	96	97	9696	888	500	4905	0,5059
8	FA0-8E	92	91	94	8372	901	490	4806,9	0,5742
9	FA0-9E	94	91	101	8554	875	537,5	5272,875	0,6164
10	FA0-10E	94	92	96	8648	868	550	5395,5	0,6239
Rata – rata									0,5666

2. Variasi Fly Ash 10%

No	Kode benda uji	Dimensi			Luas Bidang Tekan (A)	Berat	Nilai kgf	Beban	Kuat Tekan
		p	l	t					
		mm	mm	mm	mm²	g	Kgf	N	N/mm²
1	FA10-1A	98	92	94	9016	860	575	5640,75	0,6256
2	FA10-2A	97	97	95	9409	833	597,5	5861,475	0,6230
3	FA10-3A	99	99	102	9801	852	495	4855,95	0,4955
4	FA10-4A	93	93	102	8649	835	527,5	5174,775	0,5983
5	FA10-5A	98	94	98	9212	871	595	5836,95	0,6336
6	FA10-6A	101	99	98	9999	858	597,5	5861,475	0,5862
7	FA10-7A	95	93	96	8835	881	525	5150,25	0,5829
8	FA10-8A	100	91	99	9100	869	497,5	4880,475	0,5363
9	FA10-9A	91	97	101	8827	843	545	5346,45	0,6057
10	FA10-10A	93	100	95	9300	870	557,5	5469,075	0,5881
Rata - rata									0,5875

UNIVERSITAS ISLAM INDONESIA

FAKULTAS
TEKNIK SIPIL
& PERENCANAAN

Gedung KH. Moh. Natsir
Kampus Terpadu Universitas Islam Indonesia
Jl. Kaliurang km 14,5 Yogyakarta 55584
T. (0274) 898444 ext 3200, 3201
F. (0274) 895330
E. dekanat.ftsp@uii.ac.id
W. ftsp.uii.ac.id

No	Kode benda uji	Dimensi			Luas Bidang Tekan (A)	Berat	Nilai kgf	Beban	Kuat Tekan
		p	l	t					
		mm	mm	mm	mm²	g	Kgf	N	N/mm²
1	FA10-1B	100	93	101	9300	890	562,5	5518,125	0,5933
2	FA10-2B	98	94	94	9212	855	487,5	4782,375	0,5191
3	FA10-3B	95	95	101	9025	893	557,5	5469,075	0,6060
4	FA10-4B	96	96	99	9216	824	565	5542,65	0,6014
5	FA10-5B	96	97	98	9312	837	537,5	5272,875	0,5662
6	FA10-6B	101	93	101	9393	891	590	5787,9	0,6162
7	FA10-7B	99	95	100	9405	857	512,5	5027,625	0,5346
8	FA10-8B	100	98	96	9800	866	517,5	5076,675	0,5180
9	FA10-9B	100	98	102	9800	837	572,5	5616,225	0,5731
10	FA10-10B	97	94	94	9118	860	587,5	5763,375	0,6321
Rata - rata									0,5760

No	Kode benda uji	Dimensi			Luas Bidang Tekan (A)	Berat	Nilai kgf	Beban	Kuat Tekan
		p	l	t					
		mm	mm	mm	mm²	g	Kgf	N	N/mm²
1	FA10-1C	99	90	101	8910	889	490	4806,9	0,5395
2	FA10-2C	95	91	99	8645	880	482,5	4733,325	0,5475
3	FA10-3C	96	99	102	9504	838	495	4855,95	0,5109
4	FA10-4C	91	96	100	8736	854	525	5150,25	0,5895
5	FA10-5C	97	96	96	9312	851	572,5	5616,225	0,6031
6	FA10-6C	97	90	100	8730	831	522,5	5125,725	0,5871
7	FA10-7C	91	91	102	8281	866	595	5836,95	0,7049
8	FA10-8C	94	94	101	8836	825	527,5	5174,775	0,5856
9	FA10-9C	98	99	95	9702	893	575	5640,75	0,5814
10	FA10-10C	91	96	97	8736	852	587,5	5763,375	0,6597
Rata - rata									0,5909

UNIVERSITAS ISLAM INDONESIA

FAKULTAS
TEKNIK SIPIL
& PERENCANAAN

Gedung KH. Moh. Natsir
Kampus Terpadu Universitas Islam Indonesia
Jl. Kaliurang km 14,5 Yogyakarta 55584
T. (0274) 898444 ext 3200, 3201
F. (0274) 895330
E. dekanat.ftsp@uii.ac.id
W. ftsp.uii.ac.id

No	Kode benda uji	Dimensi			Luas Bidang Tekan (A)	Berat	Nilai kgf	Beban	Kuat Tekan
		p	l	t					
		mm	mm	mm	mm²	g	Kgf	N	N/mm²
1	FA10-1D	95	92	102	8740	830	577,5	5665,275	0,6482
2	FA10-2D	100	95	98	9500	844	487,5	4782,375	0,5034
3	FA10-3D	96	94	97	9024	871	497,5	4880,475	0,5408
4	FA10-4D	98	94	102	9212	823	575	5640,75	0,6123
5	FA10-5D	98	90	95	8820	872	497,5	4880,475	0,5533
6	FA10-6D	96	93	100	8928	856	597,5	5861,475	0,6565
7	FA10-7D	91	99	95	9009	881	572,5	5616,225	0,6234
8	FA10-8D	92	96	101	8832	859	597,5	5861,475	0,6637
9	FA10-9D	101	100	98	10100	877	595	5836,95	0,5779
10	FA10-10D	95	97	100	9215	894	527,5	5174,775	0,5616
Rata - rata									0,5941

No	Kode benda uji	Dimensi			Luas Bidang Tekan (A)	Berat	Nilai kgf	Beban	Kuat Tekan
		p	l	t					
		mm	mm	mm	mm²	g	Kgf	N	N/mm²
1	FA10-1E	91	93	98	8463	892	587,5	5763,375	0,6810
2	FA10-2E	99	97	98	9603	861	487,5	4782,375	0,4980
3	FA10-3E	96	92	100	8832	890	542,5	5321,925	0,6026
4	FA10-4E	96	91	101	8736	824	592,5	5812,425	0,6653
5	FA10-5E	99	92	95	9108	893	590	5787,9	0,6355
6	FA10-6E	95	98	95	9310	861	597,5	5861,475	0,6296
7	FA10-7E	91	95	102	8645	836	595	5836,95	0,6752
8	FA10-8E	101	93	98	9393	840	495	4855,95	0,5170
9	FA10-9E	94	90	94	8460	856	485	4757,85	0,5624
10	FA10-10E	100	96	100	9600	837	585	5738,85	0,5978
Rata - rata									0,6064

UNIVERSITAS ISLAM INDONESIA

FAKULTAS
TEKNIK SIPIL
& PERENCANAAN

Gedung KH. Moh. Natsir
Kampus Terpadu Universitas Islam Indonesia
Jl. Kaliurang km 14,5 Yogyakarta 55584
T. (0274) 898444 ext 3200, 3201
F. (0274) 895330
E. dekanat.ftsp@uii.ac.id
W. ftsp.uii.ac.id

3. Variasi Fly Ash 20%

No	Kode benda uji	Dimensi			Luas Bidang Tekan (A)	Berat	Nilai kgf	Beban	Kuat Tekan
		p	l	t					
		mm	mm	mm	mm²	g	Kgf	N	N/mm²
1	FA20-1A	97	100	101	9700	847	597,5	5861,475	0,6043
2	FA20-2A	96	99	97	9504	856	595	5836,95	0,6142
3	FA20-3A	97	100	101	9700	840	595	5836,95	0,6017
4	FA20-4A	97	100	102	9700	845	595	5836,95	0,6017
5	FA20-5A	99	98	98	9702	839	592,5	5812,425	0,5991
6	FA20-6A	101	97	94	9797	829	597,5	5861,475	0,5983
7	FA20-7A	97	98	101	9506	852	587,5	5763,375	0,6063
8	FA20-8A	101	95	94	9595	875	602,5	5910,525	0,6160
9	FA20-9A	99	98	100	9702	886	600	5886	0,6067
10	FA20-10A	100	99	101	9900	845	602,5	5910,525	0,5970
Rata - rata									0,6045

No	Kode benda uji	Dimensi			Luas Bidang Tekan (A)	Berat	Nilai kgf	Beban	Kuat Tekan
		p	l	t					
		mm	mm	mm	mm²	g	Kgf	N	N/mm²
1	FA20-1B	97	101	101	9797	833	600	5886	0,6008
2	FA20-2B	101	96	101	9696	818	602,5	5910,525	0,6096
3	FA20-3B	97	100	100	9700	816	600	5886	0,6068
4	FA20-4B	95	101	94	9595	845	592,5	5812,425	0,6058
5	FA20-5B	98	99	97	9702	826	600	5886	0,6067
6	FA20-6B	97	101	99	9797	874	597,5	5861,475	0,5983
7	FA20-7B	97	100	101	9700	829	602,5	5910,525	0,6093
8	FA20-8B	101	96	102	9696	864	592,5	5812,425	0,5995
9	FA20-9B	95	100	99	9500	875	585	5738,85	0,6041
10	FA20-10B	98	96	101	9408	828	590	5787,9	0,6152
Rata - rata									0,6056

UNIVERSITAS ISLAM INDONESIA

FAKULTAS TEKNIK SIPIL & PERENCANAAN

Gedung KH. Moh. Natsir
Kampus Terpadu Universitas Islam Indonesia
Jl. Kaliurang km 14,5 Yogyakarta 55584
T. (0274) 898444 ext 3200, 3201
F. (0274) 895330
E. dekanat.ftsp@uii.ac.id
W. ftsp.uii.ac.id

No	Kode benda uji	Dimensi			Luas Bidang Tekan (A)	Berat	Nilai kgf	Beban	Kuat Tekan
		p	l	t					
		mm	mm	mm	mm²	g	Kgf	N	N/mm²
1	FA20-1E	98	99	94	9702	876	592,5	5812,425	0,5991
2	FA20-2E	98	99	96	9702	846	595	5836,95	0,6016
3	FA20-3E	96	101	101	9696	829	602,5	5910,525	0,6096
4	FA20-4E	98	100	95	9800	884	597,5	5861,475	0,5981
5	FA20-5E	96	99	101	9504	876	590	5787,9	0,6090
6	FA20-6E	101	94	100	9494	872	590	5787,9	0,6096
7	FA20-7E	98	100	100	9800	864	597,5	5861,475	0,5981
8	FA20-8E	99	101	98	9999	867	602,5	5910,525	0,5911
9	FA20-9E	97	100	96	9700	874	602,5	5910,525	0,6093
10	FA20-10E	98	100	97	9800	827	595	5836,95	0,5956
Rata - rata									0,6021

4. Variasi Fly Ash 30%

No	Kode benda uji	Dimensi			Luas Bidang Tekan (A)	Berat	Nilai kgf	Beban	Kuat Tekan
		p	l	t					
		mm	mm	mm	mm²	g	Kgf	N	N/mm²
1	FA30-1A	95	90	99	8550	877	505	4954,05	0,5794
2	FA30-2A	98	94	96	9212	862	430	4218,3	0,4579
3	FA30-3A	100	91	96	9100	874	400	3924	0,4312
4	FA30-4A	101	96	101	9696	815	532,5	5223,825	0,5388
5	FA30-5A	95	99	102	9405	818	495	4855,95	0,5163
6	FA30-6A	100	91	94	9100	833	425	4169,25	0,4582
7	FA30-7A	96	92	94	8832	848	485	4757,85	0,5387
8	FA30-8A	94	90	101	8460	817	457,5	4488,075	0,5305
9	FA30-9A	95	91	100	8645	818	535	5248,35	0,6071
10	FA30-10A	98	97	95	9506	879	500	4905	0,5160
Rata - rata									0,5174

UNIVERSITAS ISLAM INDONESIA

FAKULTAS
TEKNIK SIPIL
& PERENCANAAN

Gedung KH. Moh. Natsir
Kampus Terpadu Universitas Islam Indonesia
Jl. Kaliurang km 14,5 Yogyakarta 55584
T. (0274) 898444 ext 3200, 3201
F. (0274) 895330
E. dekanat.ftsp@uii.ac.id
W. ftsp.uii.ac.id

No	Kode benda uji	Dimensi			Luas Bidang Tekan (A)	Berat	Nilai kgf	Beban	Kuat Tekan
		p	l	t					
		mm	mm	mm	mm²	g	Kgf	N	N/mm²
1	FA30-1B	95	98	100	9310	866	475	4659,75	0,5005
2	FA30-2B	98	93	94	9114	859	542,5	5321,925	0,5839
3	FA30-3B	100	91	98	9100	843	420	4120,2	0,4528
4	FA30-4B	94	91	94	8554	875	440	4316,4	0,5046
5	FA30-5B	93	99	97	9207	841	512,5	5027,625	0,5461
6	FA30-6B	91	97	98	8827	842	512,5	5027,625	0,5696
7	FA30-7B	91	97	101	8827	864	422,5	4144,725	0,4696
8	FA30-8B	99	92	96	9108	830	470	4610,7	0,5062
9	FA30-9B	93	98	99	9114	808	482,5	4733,325	0,5193
10	FA30-10B	96	94	99	9024	868	480	4708,8	0,5218
Rata - rata									0,5174

No	Kode benda uji	Dimensi			Luas Bidang Tekan (A)	Berat	Nilai kgf	Beban	Kuat Tekan
		p	l	t					
		mm	mm	mm	mm²	g	Kgf	N	N/mm²
1	FA30-1C	97	96	100	9312	875	440	4316,4	0,4635
2	FA30-2C	96	99	97	9504	817	545	5346,45	0,5625
3	FA30-3C	92	91	99	8372	814	402,5	3948,525	0,4716
4	FA30-4C	94	91	100	8554	811	497,5	4880,475	0,5705
5	FA30-5C	96	100	95	9600	876	507,5	4978,575	0,5186
6	FA30-6C	101	95	100	9595	855	472,5	4635,225	0,4831
7	FA30-7C	101	94	94	9494	871	452,5	4439,025	0,4676
8	FA30-8C	96	94	98	9024	815	425	4169,25	0,4620
9	FA30-9C	96	100	94	9600	828	532,5	5223,825	0,5441
10	FA30-10C	101	92	100	9292	867	490	4806,9	0,5173
Rata - rata									0,5061

UNIVERSITAS ISLAM INDONESIA

FAKULTAS TEKNIK SIPIL & PERENCANAAN

Gedung KH. Moh. Natsir
Kampus Terpadu Universitas Islam Indonesia
Jl. Kaliurang km 14,5 Yogyakarta 55584
T. (0274) 898444 ext 3200, 3201
F. (0274) 895330
E. dekanat.ftsp@uii.ac.id
W. ftsp.uii.ac.id

No	Kode benda uji	Dimensi			Luas Bidang Tekan (A)	Berat	Nilai kgf	Beban	Kuat Tekan
		p	l	t					
		mm	mm	mm	mm²	g	Kgf	N	N/mm²
1	FA30-1D	100	96	94	9600	840	427,5	4193,775	0,4369
2	FA30-2D	100	93	100	9300	820	477,5	4684,275	0,5037
3	FA30-3D	97	94	99	9118	850	512,5	5027,625	0,5514
4	FA30-4D	99	93	97	9207	851	522,5	5125,725	0,5567
5	FA30-5D	99	91	101	9009	824	492,5	4831,425	0,5363
6	FA30-6D	101	98	97	9898	821	455	4463,55	0,4510
7	FA30-7D	93	95	102	8835	863	527,5	5174,775	0,5857
8	FA30-8D	101	94	99	9494	824	535	5248,35	0,5528
9	FA30-9D	92	91	98	8372	827	420	4120,2	0,4921
10	FA30-10D	101	95	102	9595	812	390	3825,9	0,3987
Rata - rata									0,5065

No	Kode benda uji	Dimensi			Luas Bidang Tekan (A)	Berat	Nilai kgf	Beban	Kuat Tekan
		p	l	t					
		mm	mm	mm	mm²	g	Kgf	N	N/mm²
1	FA30-1E	99	90	102	8910	860	412,5	4046,625	0,4542
2	FA30-2E	96	93	96	8928	817	497,5	4880,475	0,5466
3	FA30-3E	93	99	96	9207	832	492,5	4831,425	0,5248
4	FA30-4E	101	96	102	9696	860	437,5	4291,875	0,4426
5	FA30-5E	97	95	98	9215	835	432,5	4242,825	0,4604
6	FA30-6E	95	93	101	8835	868	542,5	5321,925	0,6024
7	FA30-7E	95	91	98	8645	837	540	5297,4	0,6128
8	FA30-8E	95	91	94	8645	845	447,5	4389,975	0,5078
9	FA30-9E	100	92	100	9200	848	510	5003,1	0,5438
10	FA30-10E	98	96	96	9408	836	445	4365,45	0,4640
Rata - rata									0,5159

UNIVERSITAS ISLAM INDONESIA

FAKULTAS
TEKNIK SIPIL
& PERENCANAAN

Gedung KH. Moh. Natsir
Kampus Terpadu Universitas Islam Indonesia
Jl. Kaliurang km 14,5 Yogyakarta 55584
T. (0274) 898444 ext 3200, 3201
F. (0274) 895330
E. dekanat.ftsp@uii.ac.id
W. ftsp.uii.ac.id

No	Kode benda uji	Dimensi			Luas Bidang Tekan (A)	Berat	Nilai kgf	Beban	Kuat Tekan
		p	l	t					
		mm	mm	mm	mm²	g	Kgf	N	N/mm²
1	FA20-1C	99	98	100	9702	830	592,5	5812,425	0,5991
2	FA20-2C	98	98	101	9604	831	590	5787,9	0,6027
3	FA20-3C	99	97	98	9603	849	590	5787,9	0,6027
4	FA20-4C	97	99	99	9603	835	602,5	5910,525	0,6155
5	FA20-5C	98	98	102	9604	858	597,5	5861,475	0,6103
6	FA20-6C	101	98	99	9898	822	600	5886	0,5947
7	FA20-7C	97	99	99	9603	881	590	5787,9	0,6027
8	FA20-8C	99	98	94	9702	863	602,5	5910,525	0,6092
9	FA20-9C	97	100	100	9700	826	602,5	5910,525	0,6093
10	FA20-10C	95	101	100	9595	853	595	5836,95	0,6083
Rata - rata									0,6055

No	Kode benda uji	Dimensi			Luas Bidang Tekan (A)	Berat	Nilai kgf	Beban	Kuat Tekan
		p	l	t					
		mm	mm	mm	mm²	g	Kgf	N	N/mm²
1	FA20-1D	97	95	102	9215	868	572,5	5616,225	0,6095
2	FA20-2D	97	99	94	9603	870	600	5886	0,6129
3	FA20-3D	100	94	94	9400	881	587,5	5763,375	0,6131
4	FA20-4D	98	100	97	9800	882	597,5	5861,475	0,5981
5	FA20-5D	96	101	99	9696	869	600	5886	0,6071
6	FA20-6D	97	99	101	9603	866	600	5886	0,6129
7	FA20-7D	98	101	102	9898	828	602,5	5910,525	0,5971
8	FA20-8D	100	98	99	9800	871	597,5	5861,475	0,5981
9	FA20-9D	99	100	100	9900	884	602,5	5910,525	0,5970
10	FA20-10D	100	98	96	9800	860	602,5	5910,525	0,6031
Rata - rata									0,6049

UNIVERSITAS ISLAM INDONESIA

FAKULTAS TEKNIK SIPIL & PERENCANAAN

Gedung KH. Moh. Natsir
Kampus Terpadu Universitas Islam Indonesia
Jl. Kaliurang km 14,5 Yogyakarta 55584
T. (0274) 898444 ext.3200, 3201
F. (0274) 895330
E. dekanat.ftsp@uii.ac.id
W. ftsp.uii.ac.id

5. Variasi Fly Ash 40%

No	Kode benda uji	Dimensi			Luas Bidang Tekan (A)	Berat	Nilai kgf	Beban	Kuat Tekan
		p	l	t					
		mm	mm	mm	mm²	g	Kgf	N	N/mm²
1	FA40-1A	99	98	98	9702	810	482,5	4733,325	0,4879
2	FA40-2A	91	97	100	8827	842	332,5	3261,825	0,3695
3	FA40-3A	100	97	95	9700	794	372,5	3654,225	0,3767
4	FA40-4A	92	93	100	8556	797	442,5	4340,925	0,5074
5	FA40-5A	96	99	100	9504	799	477,5	4684,275	0,4929
6	FA40-6A	92	91	94	8372	856	415	4071,15	0,4863
7	FA40-7A	92	92	94	8464	798	485	4757,85	0,5621
8	FA40-8A	91	99	99	9009	838	337,5	3310,875	0,3675
9	FA40-9A	95	98	102	9310	848	470	4610,7	0,4952
10	FA40-10A	91	95	99	8645	808	435	4267,35	0,4936
Rata - rata									0,4639

No	Kode benda uji	Dimensi			Luas Bidang Tekan (A)	Berat	Nilai kgf	Beban	Kuat Tekan
		p	l	t					
		mm	mm	mm	mm²	g	Kgf	N	N/mm²
1	FA40-1B	93	95	98	8835	829	465	4561,65	0,5163
2	FA40-2B	99	90	94	8910	804	417,5	4095,675	0,4597
3	FA40-3B	93	94	98	8742	860	380	3727,8	0,4264
4	FA40-4B	93	96	100	8928	834	487,5	4782,375	0,5357
5	FA40-5B	100	98	98	9800	833	420	4120,2	0,4204
6	FA40-6B	97	99	96	9603	817	392,5	3850,425	0,4010
7	FA40-7B	93	92	99	8556	828	360	3531,6	0,4128
8	FA40-8B	100	96	101	9600	840	440	4316,4	0,4496
9	FA40-9B	96	92	94	8832	854	437,5	4291,875	0,4859
10	FA40-10B	93	92	99	8556	860	447,5	4389,975	0,5131
Rata - rata									0,4621

UNIVERSITAS ISLAM INDONESIA

FAKULTAS
TEKNIK SIPIL
& PERENCANAAN

Gedung KH. Moh. Natsir
Kampus Terpadu Universitas Islam Indonesia
Jl. Kaliurang km 14,5 Yogyakarta 55584
T. (0274) 898444 ext 3200, 3201
F. (0274) 895330
E. dekanat.ftsp@uii.ac.id
W. ftsp.uii.ac.id

No	Kode benda uji	Dimensi			Luas Bidang Tekan (A)	Berat	Nilai kgf	Beban	Kuat Tekan
		p	l	t					
		mm	mm	mm	mm²	g	Kgf	N	N/mm²
1	FA40-1C	94	97	94	9118	832	472,5	4635,225	0,5084
2	FA40-2C	95	96	99	9120	835	350	3433,5	0,3765
3	FA40-3C	98	94	94	9212	836	477,5	4684,275	0,5085
4	FA40-4C	91	97	102	8827	847	367,5	3605,175	0,4084
5	FA40-5C	94	93	100	8742	817	407,5	3997,575	0,4573
6	FA40-6C	100	97	95	9700	857	485	4757,85	0,4905
7	FA40-7C	98	99	99	9702	857	432,5	4242,825	0,4373
8	FA40-8C	97	95	94	9215	838	490	4806,9	0,5216
9	FA40-9C	96	95	102	9120	820	402,5	3948,525	0,4330
10	FA40-10C	99	93	102	9207	825	370	3629,7	0,3942
Rata - rata									0,4536

No	Kode benda uji	Dimensi			Luas Bidang Tekan (A)	Berat	Nilai kgf	Beban	Kuat Tekan
		p	l	t					
		mm	mm	mm	mm²	g	Kgf	N	N/mm²
1	FA40-1D	91	92	94	8372	806	482,5	4733,325	0,5654
2	FA40-2D	92	100	100	9200	847	457,5	4488,075	0,4878
3	FA40-3D	91	96	100	8736	795	472,5	4635,225	0,5306
4	FA40-4D	101	99	97	9999	804	460	4512,6	0,4513
5	FA40-5D	93	90	96	8370	796	365	3580,65	0,4278
6	FA40-6D	92	90	96	8280	800	490	4806,9	0,5805
7	FA40-7D	95	100	101	9500	838	397,5	3899,475	0,4105
8	FA40-8D	91	93	96	8463	855	330	3237,3	0,3825
9	FA40-9D	94	95	101	8930	852	420	4120,2	0,4614
10	FA40-10D	100	91	98	9100	828	380	3727,8	0,4096
Rata - rata									0,4707

UNIVERSITAS ISLAM INDONESIA

FAKULTAS
TEKNIK SIPIL
& PERENCANAAN

Gedung KH. Moh. Natsir
Kampus Terpadu Universitas Islam Indonesia
Jl. Kaliurang km 14,5 Yogyakarta 55584
T. (0274) 898444 ext 3200, 3201
F. (0274) 895330
E. dekanat.ftsp@uii.ac.id
W. ftsp.uii.ac.id

No	Kode benda uji	Dimensi			Luas Bidang Tekan (A)	Berat	Nilai kgf	Beban	Kuat Tekan
		p	l	t					
		mm	mm	mm	mm²	g	Kgf	N	N/mm²
1	FA40-1E	101	90	102	9090	858	362,5	3556,125	0,3912
2	FA40-2E	92	96	101	8832	804	487,5	4782,375	0,5415
3	FA40-3E	101	97	98	9797	828	430	4218,3	0,4306
4	FA40-4E	91	93	95	8463	847	452,5	4439,025	0,5245
5	FA40-5E	101	91	97	9191	862	495	4855,95	0,5283
6	FA40-6E	100	97	98	9700	805	397,5	3899,475	0,4020
7	FA40-7E	97	98	99	9506	852	405	3973,05	0,4180
8	FA40-8E	94	100	99	9400	797	495	4855,95	0,5166
9	FA40-9E	98	96	95	9408	810	367,5	3605,175	0,3832
10	FA40-10E	91	97	102	8827	840	352,5	3458,025	0,3918
Rata - rata									0,4528

6. Rekapitulasi Nilai Rata-rata Semua Variasi

No	Kode Benda Uji	Nilai Rata-rata Kuat Tekan
		N/mm²
1	FA0	0,5748
2	FA10	0,5910
3	FA20	0,6045
4	FA30	0,5127
5	FA40	0,4606

Diperiksa Oleh,
Kepala Lab. BKT

Astriana Hardawati, S.T., M.Eng.

Didata Oleh,
PLP/Teknisi

Daru Salam, A.Md.