Experimental Study on Mechanical Behaviour of Foamed Concrete for the Development of Building Blocks

Sultan Woyema Beketa

A Thesis Submitted to the department of Civil Engineering
College of Civil Engineering and Architecture

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Construction Engineering and Management

Office of Graduate Studies

Adama Science and Technology University

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Adama, Ethiopia

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DECLARATION

I hereby declare that this Master Thesis entitled Experimental Study on Mechanical Behaviour of Foamed Concrete for the Development of Building Blocks" is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

Name of student	Signature	Date

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RECOMMENDATION OF ADVISOR

I/we, the advisor(s) of this thesis, hereby certify that I/we have read the revised version of the thesis entitled "Experimental Study on Mechanical Behaviour of Foamed Concrete for the Development of Building Blocks" prepared under my/our guidance by Sultan Woyema Beketa submitted in partial fulfillment of the requirements for the degree of Mater's of Science in Construction Engineering and Management. Therefore, I/we recommend the submission of revised version of the thesis to the department following the applicable procedures.

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APPROVAL PAGE

I/we, the advisors of the thesis entitled "Experimental Study on Mechanical Behaviour of Foamed Concrete for the Development of Building Blocks" and developed by Sultan Woyema Beketa, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

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We, the undersigned, members of the Board of Examiners of the thesis by Sultan Woyema Beketa, have read and evaluated the thesis entitled "Experimental Study on Mechanical Behaviour of Foamed Concrete for the Development of Building Blocks" and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Construction Engineering and Management.

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TABLE OF CONTENTS PAGE

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

ASTM	American Society for Testing and Materials
ES	Ethiopian Standard
ETB	Ethiopian Birr
FC	Foam Concrete
LCC	Lightweight Cellular Concrete
LDCC	Low Density Cellular Concrete
LFC	Lightweight Foamed Concrete
LWC	Lightweight Concrete
MCDM	Multi-Criteria Decision-Making
SLES	Sodium Laury Ether Sulfate
SS	Synthetic Surfactants
PPC	Portland Pozzolan Cement
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
UTM	Universal Testing Machine

ABSTRACT

This study investigates the mechanical properties, structural suitability, and economic viability of foamed concrete blocks (FCBs) through systematic laboratory experiments and multi-criteria optimization. The research methodology comprised four key phases: firstly material characterization of Portland Pozzolana Cement (PPC), 2.36mm-sieved fine aggregate, and sodium lauryl ether sulphate (SLES) foam agent following ASTM standards; secondly production and testing of 102 specimens with foam contents ranging from 0.5-5% at 7- and 28-day curing intervals; thirdly, comprehensive evaluation of compressive strength , flexural strength, density, and water absorption); and finally cost-benefit analysis comparing FCBs with conventional hollow concrete blocks in the Ethiopian construction market. Results demonstrate that 1.5% foam content yields optimal performance, achieving 9.1 MPa compressive strength and 2.4 MPa flexural strength at 1468 kg/m³ density, while maintaining 5% water absorption - meeting standard requirements for load-bearing applications. The 28-day curing period enhanced strength by 25% compared to 7-day curing. Higher foam contents (>3.5%) produced lightweight insulation blocks (980 kg/m³, <4 MPa strength) compliant with standards and can be used for non-structural parts. Water absorption remains below 10% for densities >1200 kg/m³, ensuring durability. Economic analysis highlights 20–30% cost savings over conventional hollow blocks due to reduced material use and lighter weight, despite higher initial foam agent costs. TOPSIS multi-criteria analysis revealed 1.5% foam as the optimal formulation (performance score=0.72), balancing mechanical properties with material costs of 16,793 ETB/m³ - demonstrating 22.7% savings versus conventional blocks when considering lifecycle transportation and labor advantages. These findings provide empirical evidence for adopting FCBs in developing economies, with specific recommendations for: structural applications (1-2% foam, 28-day curing) and non-structural partition walls (2-3% foam). The study establishes a scientifically-grounded framework for optimizing foamed concrete mixtures while addressing both technical performance and economic feasibility constraints in resource-limited construction markets.

Keywords: Foamed Concrete, Compressive Strength, Flexural Strength, Density, Curing Time, Cost Analysis, Mix Design Optimization

CHAPTER ONE

1. INTRODUCTION

1.1.Background of the study

The construction industry has recently demonstrated a strong demand for lightweight foamed concrete as building blocks due to its advantageous qualities, which include durability, cost effectiveness, and light weight. Therefore, the introduction of advanced concrete technology is not surprising as it may offer a better solution for environmental health and the sustainability of building materials. In concrete structures, self-weight accounts for a larger portion of the overall structure load. So, it is necessary to introduce lightweight concrete to reduce the dead load and the overall cost of concrete and steel that arises from an increase in the dead load of the structure. When compared to conventional concrete, foam concrete, also called lightweight cellular concrete (LCC), drastically reduces density. Its superior strength-to-weight ratio, decreased density, and improved thermal insulation qualities set this type of concrete apart. It's made by combining a foaming agent with a cement paste, sand, and water. A high-speed rotating machine is then used to aerate the mixture, producing trapped air bubbles that make for lightweight, cellular concrete blocks that are perfect for real construction. Since foamed concrete is a porous material with many air pockets, its characteristics are greatly influenced by the size, shape, and distribution of these pores. Because it is lightweight, inexpensive, and energy efficient, this material is frequently used in construction. It is well-known for its exceptional flowability and superior thermal insulation. Furthermore, foamed concrete uses less aggregate and cement, which increases its economic and environmental advantages.

A wide range of densities, usually 400–1600 kg/m³, can be produced for foamed concrete, enabling best fit according to project specifications. It is ideal for a variety of civil engineering applications due to its outstanding qualities, such as trench backfilling, lightweight masonry blocks, void filling, thermal and sound insulation, and ground stabilization. The pore structure of the material more especially, the size, volume, and shape of the air voids largely determines its performance and structural behavior, which in turn affects its mechanical and functional properties of foamed concrete. Elrahman et al. (2019).

A change in the foam's volume, mainly caused by chemical and physical forces of foam compositions, is the main reason for foam concrete shrinkage cracks. Keeping volume stability is essential to reducing and eliminating foam concrete cracks.

Additionally, a more practical method of achieving stability in the foam concrete volume is through chemical expansion compensation. Jose* et al. (2020).

Normal concrete is the most widely used and popular material in the masonry and construction industry. The self-compaction of foamed concrete and the ability to regulate its strength and insulating qualities are only two of its numerous benefits. It is often used for filling, levelling floors, and insulating walls and roofs. Because foamed concrete has a low specific density, it helps to reduce the environmental effect of the building industry by lowering the input of mineral resources. This trend has gained attention as a result of new laws and government and private sector initiatives to design energy-efficient structures. Compaoré et al., (2023).

According to the aforementioned context, foamed concrete is seen as an alternative solution because it can be created with relatively low investment costs and is simple for small, local building enterprises to employ, improving the energy efficiency of buildings. Using the ratios of sand to powder, water to powder, foam volume, and fly ash content as variables, an analytical model is created for 28-day compressive strength and dry density. This guarantees sustainable building methods by allowing professional engineers to design blocks with the necessary density and compressive strength. Jose* et al.(2020).

There weren't many studies on FC's feasibility as a raw material for building block production. The potential for adding foam to concrete while making building blocks will support environmentally friendly building methods. Additionally, rich mixes of 1:1 or 1:2 were employed to achieve high strength in all of the earlier tests.

This study investigates the mechanical properties of foamed concrete to optimize its formulation for producing both load-bearing and non-load-bearing construction blocks. The research evaluates key performance indicators including 7-day and 28-day compressive strength, flexural strength, dry density, and water absorption capacity. The experimental result analysis aims to ascertain the effects of foam content and curing time on the development of density and strength and to optimize the foamed concrete production in cost effective. Engineers involved in the commercial production of foamed concrete blocks will find the findings to be useful in predicting compressive strength and density characteristics.

1.2. Statement of Problem

The growing demand for sustainable construction materials has led to an increased interest in lightweight materials, particularly foamed concrete. Its reduced density and enhanced thermal insulation properties make foamed concrete an attractive option for modern construction. Agyemang et al. (2020). However, foamed concrete's mechanical behavior, especially when used in building blocks, remains poorly understood and documented, despite its potential advantages. This gap presents several challenges that must be addressed in order to optimize its use within the construction industry.

Foamed concrete has a variety of mechanical properties, which can significantly affect structural integrity and performance under various loading conditions. (Gupta & Gupta, 2016). Significant variations in the final product's compressive strength, flexural strength, and durability can result from the influence of mix design parameters, including the kind and amount of foaming agents, water-to-cement ratios, and the addition of admixtures. (Kumar et al., 2015). Because of this, the research that is currently available shows that there are no standardized procedures or standards for the creation and testing of foamed concrete, which may prevent the industry from adopting it more widely. Xiao et al. (2018).

Additionally, while previous studies have explored the thermal and environmental performance of foamed concrete, investigations focusing on its mechanical strength in the context of building blocks are limited Yin et al. (2010). The application of foamed concrete blocks in load-bearing structures requires a thorough understanding of their failure mechanisms and load-bearing capacities. This is necessary to reduce the risks associated with premature failure. There have been numerous studies on FC that provide a thorough description of its composition and physical characteristics. It has also been found that FC is more sensitive to water demand than regular concrete. Kearsley and Mostert. (2005). It was also found that coarse aggregate being absent in foamed concrete makes FC to have more drying shrinkage value, which has been observed by Jones and McCarthy (2005). Shrinkage of foamed concrete generally occurs within 20 days of casting and drying shrinkage got reduced when cement was replaced with fly ash Richard and Ramli. (2013). Mix with fine sand resulted in high compressive strength compared to coarse sand due to uniform distribution of pores in foamed concrete with fine sand Nambiar and Ramamurthy (2006). A review on the characteristics of surfactants (foaming agent) and foam done by Sahu et al. (2018), recommends that the selection of surfactant and foam prediction parameters play a vital role in the properties of foam, which in turn affects the properties of FC. Role of foaming agent in FC is to create small enclosed air bubbles by reducing the surface tension of the solution, which facilitates the formation of stable air bubbles.

Furthermore, existing literature has not adequately considered the long-term performance of foamed concrete blocks under various environmental conditions. Factors such as moisture exposure, temperature variations, and the effect of aging on mechanical properties remain under-explored. This lack of comprehensive research hinders the potential of foamed concrete in meeting the rigorous demands of modern construction, where material longevity and reliability are paramount Kearney, (2015).

Generally, the mechanical behavior of foamed concrete and its suitability as a building block material is a vital area of research that warrants detailed investigation. Addressing the challenges of mechanical performance, standardization, and long-term durability will not only enrich the existing body of knowledge but also facilitate the development of widely accepted guidelines for the application of foamed concrete in the construction industry. After reviewing the above investigations, the following suggestions are made. (i) All the previous studies were focused on the characterization of FC as a structural material. But as suggested by Jones and Mc Carthy (2005), the high drying shrinkage and low tensile strength and stiffness performance limits the straight substitution of foamed concrete for normal weight concrete (ii) But, as a material with reasonably good compressive strength at low dry density makes foamed concrete blocks a viable substitute for conventional bricks or solid/ hollow concrete blocks, which are presently available at densities ranging from 1800 kg/m^3 to 2400 kg/ m^3.

Very few works are noted on the viability of FC as a material for the manufacture of load bearing and non-load bearing building units. (iii) Possibility of incorporation of high volumes of industrial wastes in the production of masonry blocks will contribute to a sustainable construction practice. (iv) Also, in all the previous studies, rich mix of 1:1 or 1:2 had been used to get high strength.

Accordingly, this investigation is aimed at optimizing the proportion of foaming agent content and curing time for the production of foamed concrete blocks that enhanced mechanical properties of FC for load bearing as well as non-load bearing building block. The properties to be studied are 7 & 28 days compressive and flexural strength to identify effect of aging on mechanical properties, dry density and water. This study examines how foaming agent dosage and foam volume affect dry density and mechanical strength properties, with the objective of optimizing foamed concrete block formulations for both economic viability and environmental sustainability.

1.3. Objectives

1.3.1. General objective

The primary objective of this study is to investigate the mechanical behavior of foamed concrete under varying foam content and curing time to develop efficient and sustainable building blocks.

1.3.2. Specific objectives

- To investigate the characteristics of Foam concrete ingredients.
- To assess the influence of foam agent proportion and curing time on the compressive strength and flexural strength of foamed concrete building blocks.
- To evaluate the potential of foamed concrete building blocks to meet the required ASTM structural performance standards.
- To compare the cost-effectiveness of foamed concrete building blocks with conventional hollow concrete block and optimization FCBs performance and cost using TOPSIS model.

1.4. Research Questions

The primary research questions that addressed in this study were:

- Is compressive strength and flexural strength of foamed concrete building blocks meets the standards?
- How does the curing time influence the mechanical properties of foamed concrete building blocks?
- Can foamed concrete building blocks meet the required standards for structural load-bearing capacity and durability?
- What is the cost-effectiveness of using foamed concrete building blocks compared to conventional hollow concrete block?

1.5. Significance of the study

This research holds significant importance due to its potential to advance sustainable and affordable housing solutions. Foamed concrete, as a lightweight construction material, offers numerous benefits, including economic advantages, longevity, energy efficiency, safety features, and noise reduction. Its reduced density lowers building weight, cutting construction and transport costs, while its durability ensures long-term weather resistance. Moreover, the material's excellent thermal insulation properties contribute to substantial energy savings by minimizing heating and cooling demands, aligning with global efforts to reduce carbon emissions. Beyond energy efficiency, foamed concrete enhances building safety with inherent fire-resistant qualities and improves occupant comfort through effective noise reduction. This study investigated the mechanical behavior of foamed concrete under varying conditions to identify optimal mix proportions and curing methods for achieving desired mechanical and physical properties. The findings aim to provide guidelines for safe and efficient use in construction while promoting sustainable building practices through an eco-friendly, resource efficient material.

1.6. Scope

Scope of this studies were limited to investigation of mechanical properties foam concrete in laboratory specifically focusing on its potential as a building block material. This study aimed to investigate the characteristics of foam concrete ingredients and analyze the effects of incorporating a foaming agent into the concrete mortar, with variations of foam agent percent 0%, 0.5%, 1%, 1.5%, 2%, 2.5%, 3%, 3.5%, 4%, 4.5%, and 5%, to determine its impact on the mechanical properties of foamed concrete blocks. dditionally, this study conducted a detailed investigation into the impact of different curing periods on the mechanical properties of foamed concrete, providing critical insights into its performance optimization. Curing duration plays a pivotal role in determining the material's strength development, pore structure stability, and long-term durability. The research systematically evaluated samples subjected to curing periods ranging from short-term (7 days) to extended durations (28 days and beyond), analyzing key parameters such as compressive strength, flexural strength, and water absorption capacity. Findings revealed that prolonged curing significantly enhances the material's crystalline structure, leading to improved load-bearing capacity and reduced micro cracking. Furthermore, this study investigates the potential of foamed concrete building blocks to meet structural performance standards, assessing their suitability for construction applications. Key evaluation criteria include load-bearing capacity, stability, and compliance with industry specifications. The research provides a comprehensive analysis of foamed concrete blocks properties, determining its viability as a sustainable and cost efficient building material. The study primarily focuses on mechanical properties, such as compressive strength and flexural strength, to assess structural performance. Additionally, it examines physical properties, including density, water absorption, and air content, to evaluate material durability and functionality.

1.7. Limitation of the study

This study has several limitations, including restricted sample variability and short-term testing that may not reflect long-term behavior. Lab conditions may not accurately simulate real-world environments, and small-scale results could differ in large-scale production. Field performance data is lacking, and non-mechanical properties like fire resistance are not thoroughly examined. Foam quality inconsistencies and resource constraints may affect precision, while comparisons with conventional concrete may overlook application-specific differences.

CHAPTER TWO

2. LITERATURE REVIEW

2.1. Introduction

Foamed concrete, also known as cellular concrete or lightweight concrete, is an innovative construction material that has gained significant traction in the building industry due to its unique properties and performance benefits. Foamed concrete blocks are manufactured using a mixture of cement, water, and a foaming agent, which generates air bubbles within the concrete matrix. Through this method, a lightweight material with the mechanical qualities of conventional concrete is produced, along with further benefits including increased fire resistance, decreased density, and better insulation. Despite being first proposed in the 1920s, foamed concrete is now frequently employed in modern construction due to significant advancements in materials and technology Yin et al. (2010). Foamed concrete is manufactured by incorporating air bubbles generated from various foaming agents into cement paste. Common foaming agents include protein-based, surfactant-based, and synthetic formulations, each imparting distinct properties to the final product Kearney, (2015). The low density of foamed concrete blocks offers significant advantages, including decreased structural dead loads, simplified installation processes, and reduced construction expenses due to their lightweight properties Kumar et al., (2015). The density of foamed concrete can vary significantly depending on the desired properties and application requirements; common values fall between 300 and 1,800 kg/m³. Because of its low thermal conductivity and lightweight nature, foamed concrete is an excellent choice for energy-efficient building solutions that improve thermal insulation in both residential and commercial applications Agyemang et al. (2020). The mineral content of foamed concrete blocks and the trapped air within the foamed matrix contribute for their exceptional fire resistance. These characteristics enable these blocks to stand high temperatures, which makes them suitable for construction that resists fire Gupta & Gupta, (2016). Foamed concrete is also used in precast elements, insulation layers, and non-load-bearing walls because of its ease of shape and moulding, which allows for creative designs and versatility in a range of architectural contexts. Although foamed concrete blocks have several advantages, quality control and uniformity in production remain challenges. The durability and mechanical properties of the final product can be significantly impacted by modifications to the kinds of foaming agents, mixing techniques, and raw components. However, these issues are being addressed by continuing research and technological developments, which will enhance foamed concrete's functionality and suitability for a variety of building projects. Xiao et al., (2018).

In addition to protecting the environment, the development sector can benefit from the use of lightweight concrete squares. It is made by first creating a slurry of cement, sand, and water, which is then combined with the expansion of previously formed stable froth in a standard solid blender in the ambient environment. Vinith Kumar et al. (2018). It has been discovered that using lightweight foamed concrete helps to lower a structure's self-weight. By using a foaming agent to create air voids, foam concrete allows for the complete replacement of coarse aggregates. Foam concrete has a density that ranges from 500 kg/m3 to 1600 kg/m3. Less density aids in lowering dead load, which leads to cost-effective structures in the building sector. Sruthi,(2018). Foam concrete blocks demonstrate significant structural benefits, reducing dead loads by approximately 50% compared to traditional brick walls. This substantial weight reduction decreases structural demands, leading to reduced steel reinforcement requirements and overall more economical construction solutions. Vinith Kumar et al. (2018). A precisely measured mixture of cementitious materials, water, fine aggregates, and a specialty foaming agent—usually a substance based on surfactants—that creates stable air voids within the cement matrix makes up foamed concrete blocks. Kwan et al. (2017). Depending on the proportions of the components and the quantity of foaming agent employed, the density of foamed concrete can vary from 300 kg/m^3 to 1,600 kg/m^3.Pandey et al.(2019).

In general, foamed concrete blocks offer a resource-efficient building material that satisfies contemporary sustainability standards. Because of their lightweight design, great heat resistance, and fire resistance, they present a practical way to lessen the environmental effect of upcoming construction projects.

2.2. Foamed Concrete

Foam concrete (Lightweight Cellular Concrete) is defined by its cellular structure containing no less than 20% air voids. The fundamental composition involves cement paste and stable foam, with optional sand additions to modify the material's density and compressive strength as needed for specific construction purposes. The durability and mechanical performance of foam concrete are directly impacted by its composition. Stabilised air spaces produced by specific foaming agents are incorporated into this lightweight substance, which is categorised as either cement paste or mortar. Important features include greater thermal insulation, compressive strength, lower density (attained by using less aggregate), and outstanding workability. Through controlled foam incorporation, manufacturers can achieve precise density variations between 400-1600 kg/m³, facilitating customized use in load-bearing components, interior dividers, thermal barriers, and cavity infill applications Raj et al. (2019).

2.3. Characteristics of Foamed Concrete

Among the remarkable material properties of foam concrete are its low density, porous microstructure, fire resistance, thermal insulation, acoustic dampening, and vibration absorption capacity. Known as Lightweight Cellular Concrete (LCC), this material maintains an ideal strength-to-weight ratio while achieving a substantially lower density than traditional concrete. When a foaming agent is added to a cement, sand and water combination, high-speed mechanical mixing entrains air bubbles to generate a cellular matrix appropriate for building blocks, giving it unique features including sound attenuation, fire performance and thermal efficiency Raj et al.,(2019). A lightweight, adaptable building material with special qualities that make it appropriate for a range of uses is foamed concrete. It is substantially lighter than traditional concrete while still having the capacity to self-compact due to its low density (400–1600 kg/m2), high porosity (20–80% air voids), and exceptional flowability, with slump values frequently surpassing 150mm. Nambiar & Ramamurthy, (2007). Mechanically, it demonstrates variable compressive strength (0.5-25 MPa), flexural strength at 10-30% of compressive strength, and a relatively low elastic modulus (0.5-5 GPa). Nambiar & Ramamurthy, (2006). The material offers superior thermal and acoustic performance, with thermal conductivity of 0.1-0.7 (up to six times more insulating than normal concrete), sound insulation ratings of 45-60 dB for 100mm thickness, and fire resistance capabilities of 2-4 hours Toutanji et al.(2010; EN 1364-1). Durability features include excellent freeze-thaw resistance due to non-connected pores, though it exhibits higher drying shrinkage (1.5-3.0 mm/m) and low water absorption (5-15% by weight). Ramamurthy et al. (2009). Foamed concrete exhibits exceptional material efficiency (30–100% aggregate reduction) from a production perspective, necessitates moist curing for appropriate strength development, and provides placement advantages due to its pump ability without segregation. Aldridge et al. (2005).

2.4. Effect of Foam Content on Foamed concrete

Foam stability plays a crucial role in determining the mechanical performance of foamed concrete. The production of stable cellular concrete depends on multiple factors including: foam generation methodology, selection of foaming agents and surfactants, precision in batching, and optimal mix design parameters. Research indicates that maintaining a minimum water-cement ratio of 0.3 is critical to achieve both adequate workability and foam stability. The rheological properties of the mixture exhibit direct correlations with constituent proportions - increasing water content enhances consistency, while higher foam volumes reduce it. Raj et al.(2019). The selection of foaming agents critically influences the workability and hardened properties of foamed concrete. Synthetic surfactant (SS-600) demonstrates superior performance characteristics, exhibiting: enhanced fresh-state fluidity due to its water-reducing surfactant components and higher inherent water content, greater compressive strength development compared to AS-600 and PS-600 counterparts at all curing stages, and optimal durability properties including minimal water absorption and exceptional frost resistance after 28-day curing. These comprehensive performance advantages position SS-600 as a preferred foaming agent for quality foamed concrete production. Sun et al. (2018). The measured variations in compressive strength can be attributed to distinct foam stabilization characteristics exhibited by different types of foaming agents during their incorporation into the cementitious matrix. Experimental results demonstrate that compressive strength exhibits an approximately linear correlation with density, with this relationship being particularly enhanced when protein-based foaming agents are incorporated in the mixture formulation. Falliano, Domenico, Ricciardi, et al., (2018). The study investigated protein-based foaming systems comprising water, air, and foaming additives, which were mechanically generated and subsequently blended with Portland cement-water slurries. Research parameters included foaming agent concentration and pre-treatment methods (microwave/ultrasonic exposure), with particular focus on their impacts on: foam stability, hardened density, microstructural development, and compressive strength performance. Notably, reduced foaming agent concentrations demonstrated improved foam stabilization effects independent of energy treatments. Kuzielová et al., (2016).A previous research demonstrates that foamed concrete's compressive strength is governed by multiple interdependent factors: material density, foaming agent selection, and water-cement ratio optimization. Crucially, the synergistic relationship between specific foaming agents and optimal water-cement proportions has been identified as a critical determinant of ultimate strength performance. Falliano, Domenico, & Ricciardi, (2018). Foamed concrete exhibits an inverse linear relationship between foam content and compressive strength, with increased air void volume (lower density) directly corresponding to reduced load-bearing capacity. Experimental data demonstrates this strength-density proportionality follows a consistent trend across typical density ranges (400-1600 kg/m³)

Vinith Kumar et al., (2018). The investigation has revealed that not only the density, but also the foaming agent and the water-to-cement ratio are key factors in the attainment of strength in foamed concrete. It is further demonstrated that the integration of the foaming agent with a specific water-to-cement ratio serves as a critical parameter influencing the compressive strength of this material. Falliano, Domenico, & Ricciardi, (2018).

2.5. Influence of curing period on foamed concrete

When compared to specimens cured in air, the mechanical behavior is improved by the curing conditions in cellophane and water.Falliano et al, (2018). The experimental study evaluates key properties of lightweight foamed concrete (LFC) - including compressive strength, splitting tensile strength, and water absorption - using two different curing methods (air and water curing). The investigation examined LFC samples with three density levels (1500, 1700, and 1800 kg/m³), prepared with a cement-sand ratio of 2:1 and a constant water-cement ratio of 0.5. Keras et al. (2009). According to experimental findings, it is possible to produce lightweight foamed concrete (LFC) with densities between 1500 and 1800 kg/m³ and corresponding compressive strengths between 10 and 39 MPa. Across all curing techniques, the study found an inverse association between density and water absorption: specimens with a density of 1500 kg/m³ (water-cured) had the highest absorption at 11.3%, while samples with a density of 1800 kg/m³ (air-cured) had the lowest absorption at only 2.0%. Ricciardi, (2018). The mechanical properties of lightweight foamed concrete (LFC) exhibit distinct development patterns based on curing conditions and density. Compressive strength demonstrates progressive increase with both specimen age and density, with water-cured samples achieving superior compressive performance. Conversely, splitting tensile strength shows different behavior - while also density-dependent, air-cured specimens develop higher tensile capacity compared to water-cured counterparts of equivalent density. Experimental data recorded maximum tensile strength of 3.92 MPa (16% of 28-day compressive strength) for air-cured 1800 kg/m³ density LFC. Kado et al.(2018).

2.6. Applications of Foamed Concrete

The production of LFC offers versatility for applications such as filling grades, insulating materials, partitions, and structural elements. LFC has mostly been used as a filler material in civil engineering projects thus far. Nonetheless, its strong potential as a building material is indicated by its good thermal and acoustic performance. Indeed, there have been numerous reports of LFC being used as structural components in the construction of housing, apartments, and schools in nations like Saudi Arabia, Indonesia, Egypt, Malaysia, Mexico, Russia, Brazil, and Singapore. Kearsley and Mostert, (2005). Foamed is used to fill underground channels and excavations in place of compacted soil. Precast walls and slab foundations are two examples of attempts to use this material structurally. Foam concrete is ideal for use in the design of passive houses due to its high degree of thermal insulation. Hulimka et al. (2017). Foamed concrete (commonly referred to as cellular or aerated concrete) is a specialized lightweight building material distinguished by its low-density cellular structure. This unique composition results from the intentional entrainment of microscopic air voids throughout the cementitious matrix, which significantly reduces unit weight while preserving adequate load-bearing capacity. These exceptional characteristics make foamed concrete particularly valuable for multiple construction applications, including:

Void Filling:- Foamed concrete is widely utilized as a fill material for a variety of void spaces, including backfill behind retaining walls, trenches, and other vacant spaces. Compared to conventional fill materials, its lightweight nature minimizes settlement problems and lessens the load on the foundation. Agyemang et al. (2020). It can be easily pumped and placed, making it ideal for difficult-to-reach areas, such as around buried utility lines.

Thermal Insulation:- Foamed concrete's outstanding thermal insulation qualities are one of its many noteworthy benefits, making it a perfect option for insulating building components. Jin et al. (2015). It is frequently utilized in the building of walls, roofs, and floors, improving energy efficiency and assisting in lowering the need for heating and cooling in structures. This successfully lowers energy consumption and related expenses.

Precast Elements:- Foamed concrete is increasingly being utilized in the manufacturing of precast components, such as panels, blocks, and slabs, where reduced weight is beneficial Kumar et al. (2015). Faster construction schedules and lower labor costs are made possible by the off-site production and transportation of precast elements made from foamed concrete to the construction site. They can also be made to meet particular functional and aesthetic specifications.

Lightweight Flooring Systems:- For applications requiring lightweight flooring, foamed concrete is a good option. Sairam et al. (2018). Its low density translates to less overall load on the building structure, which is particularly advantageous in multi-story constructions. The material can be poured directly onto floor beams or slabs to create a lightweight fill while providing good sound insulation between floors.

Roofing Applications:- In roofing systems, foamed concrete is applied as a thermal insulation layer, especially on flat roofs. (Yin et al. 2010). Its water-resistant qualities can guarantee a lightweight structure while assisting in the prevention of water damage. It can also be molded to produce a sloping surface for proper drainage.

Fire-Resistant Construction:- Because of its cellular structure, which slows down heat transfer, foamed concrete has better fire-resistant qualities than regular concrete. Kearney, (2015). It is especially well-suited for use in passive fire protection, fire-rated assemblies, and as an insulating material in fire barriers, all of which improve building safety.

Geotechnical Applications:- Foamed concrete is used in geotechnical engineering to improve the earth and stabilise the soil. Cheng et al. (2016). It can be utilised in situations where reducing extra burden on soft or unstable soils is essential due to its lightweight nature. In certain situations, it can also be used in place of conventional aggregates, which helps with onsite waste management.

Infrastructure Projects: According to Gupta and Gupta (2016), foamed concrete is being utilized more and more in infrastructure projects like tunnels and road construction. Its use can improve road bases' longevity and durability. It can also be used to build lightweight structures, like bridge decks, which lower overall load and material costs.

Applications for Soundproofing: Foamed concrete's porosity makes it an excellent option for applications that need sound insulation because it effectively reduces sound transmission Xiao et al. (2018). It works especially well when building walls and partitions in homes and businesses where noise abatement is essential.

2.7. Mechanical and Physical Properties of Foamed Concrete

Foamed concrete, sometimes referred to as cellular or aerated concrete, is a high-performance, lightweight building material that has attracted a lot of interest lately because of its beneficial structural and mechanical qualities. The addition of air bubbles to the mixture gives foamed concrete its distinct properties by reducing density without sacrificing strength or durability. This review highlights the key mechanical and structural properties of foamed concrete blocks, incorporating findings from recent research.

2.7.1. Compressive Strength of Foamed Concrete

The compressive strength behavior of foamed concrete, a lightweight cementitious material with purposefully entrained air voids ranging from 20 to 80 percent by volume, has been thoroughly studied in recent research (2018–2024) (Amran et al. 2021). According to Jones and McCarthy (2020), this material's compressive strength shows a strong density dependence, varying linearly from about 1 MPa for ultra-lightweight mixes (400 kg/m³) to 25 MPa for structural-grade formulations (1600 kg/m³). The type of foaming agent has a major impact on this strength-density relationship; protein-based agents produce compressive strengths that are 10–15% higher than those of synthetic surfactants because they can create finer and more stable pore structures. Nambiar and Ramamurthy, (2018). According to Zhang et al., recent developments in material science have further improved strength properties through nanotechnology. According to Zhang et al. (2022), microstructural refinement can result in a 20–30% increase in compressive strength by adding 2–5% nano-silica by weight. Even though there is some decrease in early-age strength, the binder system is also very important. Partial cement replacement with industrial by-products, such as 30% fly ash or 50% GGBS, shows better long-term strength development through pozzolanic reactions. Kearsley and Wainwright,(2021).More recently, Abdulkareem et al.(2023) developed alkali-activated foamed concrete achieving 18-22 MPa compressive strength at 1200 kg/m³ density, demonstrating the potential of alternative binder systems. Curing conditions represent another critical parameter, with Haji mohammadi et al. (2020) showing that steam curing can produce 7-day strengths equivalent to 28-day ambient-cured specimens, while Lim et al. (2022) reported that autoclave curing enhances strength by 40% through mortar formation. Contemporary research has explored various reinforcement strategies, including Chen et al. (2023) work with 0.5% PVA fibers (12% strength increase) and Wu et al.'s (2024) studies on basalt fibers (8-10% strength improvement). Emerging nano-modification approaches using graphene oxide (0.03%) and calcium carbonate whiskers have shown 25% and 15% strength enhancements respectively Li et al. (2023); Wang et al.(2022). Despite these advancements, challenges remain in strength consistency, with Raj et al. (2024) identifying ±15% compressive strength variations due to foam instability. The focus of current research is on sustainable development, which includes applications for 3D printing and bio-based foaming agents Le et al. (2023), whereas machine learning techniques for predictive modeling (94 percent accuracy) (Alyousef et al. The development of empirical formulas ($CS = 0.034\rho - 5.2$, ACI 523.2R-19) and 2023) to optimize mix designs is underway. Together, these results show that careful density control (800–1400 kg/m2), sophisticated material formulations, and efficient curing procedures can enable modern foamed concrete to perform structurally. Ongoing research is still being conducted to address the remaining issues with strength variability and environmental impact. A number of variables, including density, mix composition, and curing conditions, can greatly affect the compressive strength of foamed concrete blocks. In general, foamed concrete's compressive strength can vary between 2 MPa and roughly 35 MPa. Sukontasukkul and Pongsakdi, (2009). Applications needing higher structural performance might favor higher-density foamed concrete mixes, but lower-density foamed concrete is preferred for thermal insulation. The highest compressive strength is obtained with a low water to cement ratio, high cement content and using sand as fine aggregate. Vinith Kumar et al. (2018). Routine testing of compressive strength is essential to determine the suitability of foamed concrete blocks for specific structural applications.

2.7.2. Flexural Strength of Foamed Concrete

Recent studies (2018-2024) have systematically examined the flexural performance of foamed concrete, revealing several key trends. The flexural strength typically ranges from 10% to 30% of the compressive strength, with values between 0.5-5 MPa for densities of 600-1600 kg/m³ Aldridge, (2005); Nambiar & Ramamurthy, (2018). According to research, flexural strength and density have a non-linear relationship. At higher densities (>1200 kg/m³), improvements are more noticeable because of improved matrix continuity (Falliano et al. (2019). Flexural capacity is greatly influenced by the foaming agent selection; protein-based agents yield strength that is 15–25% higher than synthetic alternatives due to their more uniform pore distribution. Zhang et al. (2022). According to Chen et al., fiber reinforcement has proven to be especially successful in improving flexural strength. Polypropylene fibers at 0–3–5 percent increase flexural strength by 25–35%. As per Wu et al. (2021), 1% basalt fibers increase strength by 20% and toughness by 300%. 2023); hybrid fiber systems (PVA+steel) exhibit synergistic effects, attaining a 40 percent increase in flexural capacity Li et al. (2023). Curing conditions are crucial; specimens that are steam-cured exhibit a 28-day flexural strength that is 15–25% higher than that of ambient curing Haji Mohammadi et al. (2020). Nevertheless, the material is brittle, with fracture energy values that are usually 50–70% lower than those of regular concrete Jones and McCarthy, (2021). Recent innovations include: Nanoclay modification (3-5%) reducing crack propagation by 40%, Wang et al., (2023); 3D-printed fiber alignment enhancing anisotropic flexural performance Le et al. (2024); Bio-polymers improving post-cracking behavior Raj et al., (2023). Current challenges include significant variability (±20%) in test results due to foam instability and standardized testing limitations (ACI 544.2R-22). Future research focuses on multi-scale reinforcement strategies and digital twin modeling for performance prediction Alyousef et al., (2024).Flexural strength is an essential property that depicts the resistance of foamed concrete to bending forces. According to Rajbar et al., foamed concrete blocks typically have a flexural strength of 1–5 MPa–6 MPa. (2020). According to research, foamed concrete's resistance to cracking and deformation under loading conditions can be improved by adding specific additives, like polypropylene fibers, which increase the concrete's flexural strength Liew et al. (2013).

2.7.3. Tensile Strength of Foamed Concrete

The tensile strength of foamed concrete is significantly lower than that of traditional concrete formulations, typically reaching only 10–15% of its compressive capacity Khan et al. (2021). In structural applications that are subject to tensile stresses, this intrinsic mechanical limitation calls for extra consideration. In response, current research has concentrated on methods for improving performance in load-bearing situations, especially by integrating composite materials and reinforcing fibers Habib et al. (2020).

2.7.4. Durability and Resistance to Environmental Factors

Durability is a crucial factor for construction materials, and foamed concrete exhibits excellent resistance to various environmental factors, including moisture and heat Dunstan et al., (2020). The incorporation of fly ash or other pozzolanic materials can enhance the durability and sustainability of foamed concrete, providing resistance against chemical attacks and reducing the permeability of the material Nawab et al., (2021). Additionally, foamed concrete blocks demonstrate good fire resistance, attributed to the presence of air voids that impede heat transfer.

2.7.5. Thermal Insulation and Sound Attenuation

Because of its lightweight and porous composition, foamed concrete has remarkable thermal insulation qualities, which makes it perfect for energy-efficient building applications Sridhar et al. (2018). Foamed concrete typically has a lower thermal conductivity than regular concrete, which lowers the energy costs related to building heating and cooling. Additionally, foamed concrete exhibits sufficient sound-attenuating qualities, which can enhance acoustic comfort in both commercial and residential settings Kumar et al. (2014).

2.8. Sustainability Aspects of Foamed Concrete

The sustainability of building materials is a growing concern in the construction sector. Foamed concrete is often regarded as a more sustainable alternative due to its lower embodied energy and potential for utilizing industrial by-products, such as fly ash or slag, as partial replacement materials Kumar et al. (2021). The lightweight nature of foamed concrete also leads to reduced energy consumption during transportation and construction.

Foam amount was the independent variable with the highest influence on dependent variables. However, in order to improve the properties of foamed concrete blocks, other proportions of foams may be studied, and also the addition of additives in the concrete may be made with greater compressive strength. In this way, the concrete blocks can be competitive with concrete blocks already marketed Jose* et al. (2020). According to data revealed from the experiment flexural and compressive strength exhibited a rapidly downward trend with the increase of foam agent content due to generation of a large number of pores by decomposition of foam agent. The samples with foam stabilizer addition possessed better mechanical properties compared to the samples without foam stabilizer addition due to the improvement of pore structure. T. Liu et al., (2019).

In general, foamed concrete blocks have a special set of structural and mechanical qualities that make them appropriate for a range of building uses. Foamed concrete is a good substitute for conventional concrete because of its lightweight nature, good compressive and flexural strengths, thermal insulation qualities, and increased durability. Future studies should concentrate on improving mix designs, investigating creative reinforcement options, and more thoroughly assessing foamed concrete's long-term performance under varied environmental circumstances.

2.9. Long term performance of Foamed Concrete Blocks (FCB)

Foamed concrete blocks (FCB) are known for their long-term performance, which includes their resilience to environmental influences, mechanical stability, and durability. There are advantages and disadvantages to foamed concrete in terms of long-term performance and durability. Research indicates that optimized high-density formulations with pozzolanic additives can achieve frost resistance comparable to conventional concrete (withstanding up to 100 freeze-thaw cycles) and significantly reduced water absorption, despite the fact that its high porosity raises concerns regarding environmental resistance Zhou and Su, (2023). Beyond the typical 28-day curing times, the material shows progressive strength gain. Constant hydration and pozzolanic reactions increase compressive and tensile strengths for up to 56–90 days, increasing structural reliability Liu et al. (2024). Although proper mix designs incorporating micro/nano additives along with controlled curing protocols can effectively mitigate these risks, shrinkage-related cracking is still a significant problem Namsone et al. (2017). From a sustainability perspective, durable foamed concrete formulations offer substantial lifecycle benefits through extended service life and reduced maintenance needs, while simultaneously contributing to seismic safety through mass reduction and thermal efficiency via their insulating pore structure Zhou & Su, 2023; Namsone et al., (2017). These characteristics position foamed concrete as a promising material for sustainable construction, provided durability challenges are properly addressed through material optimization and appropriate application engineering.

Table 2. 1. Long term performance of Foamed Concrete Blocks (FCB)

Aspect	Long-Term Performance Effect
Freeze-thaw resistance	High-density FC blocks withstand up to 100 cycles
Strength gain	Continues beyond 28 days, improving structural capacity
Water absorption	Reduced by pozzolanic additives, enhancing durability
Shrinkage and cracking	Minimized with additives and curing control
Seismic resistance	Improved due to lightweight nature
Thermal insulation	Maintained due to porous structure
Service life	50–100+ years with quality control

Source**:** Zhou & Su, (2023)

The long-term performance of foamed concrete blocks is promising when appropriate mix designs, curing, and protective measures are applied, making them sustainable and durable materials for modern construction.

2.10. Foam

Foam is made from a concentrated foaming agent using a foam generator. In the foam generator the foaming agent is diluted in water to make a pre-foaming solution and then the pre-foaming solution is expanded with air into foam. The bubbles are stable and able to resist the physical and chemical forces imposed during mixing, placing and hardening of the foamed concrete. Between 75 and 85% of the bubbles are of 0.3 to 1.5 mm in diameter Sruthi, (2018). Parameters for production of foam pressure of foam generation and its dilution ratio has a greater influence on all properties of foam produced with the exception of foam output rate on which only foam generation pressure has influence. The foam with good initial foam density need not necessarily be stable foam. The optimum levels of foam production parameters are determined for the surfactant Sodium lauryl sulfate which can be used to produce stable foam for foam concrete production. Siva & Gandhi, (2019).

Typically, surfactant or synthetic and protein foaming agents are used in cellular concrete. Both types of agents reduce the surface tension of the solution, which facilitates the formation of stable air bubbles.

The pre-formed foaming method is generally preferred over the mix-forming technique primarily because it offers two key advantages: (1) it significantly reduces the quantity of foaming agent required for production, and (2) it provides better consistency between the amount of foaming agent used and the final air content achieved in the concrete mix. These benefits make the pre-formed approach more efficient and reliable for manufacturing foamed concrete with consistent quality.

2.10.1. Foaming preparation method

This is reported as the most economical and controllable pore-forming process as there are no chemical reactions involved. Introduction of pores is achieved through mechanical means either by pre-formed foaming (foaming agent mixed with a part of mixing water) or mix foaming (foaming agent mixed with the mortar). The various foaming agents used are detergents, resin soap, glue resins, saponin, hydrolysed proteins such as keratin etc Narayanan & Ramamurthy, (2000). By adding sodium dodecyl benzene sulfonate and gelatine, the performance of the foaming agent can be improved, however it is affected by the reaction time, reaction temperature and alkali addition. Qu et al. (2023). The foam concrete shows the characteristic of contraction; when the water-cement ratio is between 0.3 and 0.5, the greater the ratio is, the smaller the contraction of foam concrete will be. Yu, (2015).

2.10.2. Mechanisms of preparing foam

Pre-foaming:-Technique contains delivering base blend and stable preformed watery foam independently and afterward completely mixing foam into base blend.

Blended foaming: - The surface dynamic specialist is blended alongside base blend fixings and during the most common way of blending foam is created bringing about cell structure in concrete.

2.11. Importance of Introducing Foamed Concrete for Building Blocks

According to Sruthi finding using foam concrete blocks in building results in the reduction of the dead load by 50% as compared to the load due to brick wall and further reduces the requirement of steel making it more economical. Sruthi, (2018).High porosity is one of the primary normal for this lightweight total which brings about a low particular gravity. Increase of strength by day by day process of curing gives better thermal insulation. It have the low labor cost. Foam concrete have an easy handling and low workmanship. It helps in reduction of dead load; increase the progress of building, and lower transport and handling cost. Therefore foam concrete block is environmentally better than the other conventional concrete blocks Vinith Kumar et al.(2018).

Use of foam concrete blocks in building results in the reduction of the dead load by 50% as compared to the load due to brick wall and further reduces the requirement of steel making it more economical. Sruthi, (2018).

Table 2. 2. Advantage and disadvantage of foamed concrete

Advantages of Foam Concrete Blocks	**Disadvantages of Foam Concrete Blocks**
Does not settle, eliminating the need for compaction	Highly sensitive to water content in the mix
Lightweight, reducing dead load and overall project costs	Foam bubbles are affected by mixing time and method
Free-flowing consistency fills voids completely	Difficult to finish smoothly
Excellent load distribution and spreading capability	Requires long mixing times
Imposes minimal lateral loads	Flexural and compressive strength decrease as density increases
Easy production enables better quality control	
High resistance to freeze-thaw cycles	
Eco-friendly, non-hazardous, and allows faster construction	
Cost-effective with low maintenance requirements	

2.12. Research Gaps and Opportunities

Despite significant advancements in the study and application of foamed concrete, several research gaps and opportunities exist that could further enhance the material’s properties, sustainability, and applicability in the construction industry. The summary of research gaps and opportunity were listed as the following table 2.3.

Table 2. 3. Summary of Research gaps and opportunity

Research Gap	**Opportunity for Advancement**	**References**
Standardization of Testing Methods	Develop unified protocols for testing mechanical properties to ensure consistency and reliability.	Shafigh et al. (2018)
Long-term Durability Studies	Investigate performance under prolonged exposure to freeze-thaw cycles, moisture, and chemicals.	Alhozaimy et al. (2019)
Innovative Additives & Reinforcements	Explore bio-based fibers, smart materials, and recycled additives for enhanced strength/ durability.	Khan et al. (2021)
Sustainability Assessment	Conduct life cycle analyses (LCA) to evaluate carbon footprint, recyclability, and energy use.	Zhang et al. (2020)
Behavior Under Dynamic Loading	Study seismic/wind load resistance to expand applications in high-risk zones.	Mouftah et al. (2021)
Application in Composite Structures	Optimize hybrid systems (e.g., steel-foamed concrete) for lightweight, high-performance designs.	Li et al. (2018)
Thermal Performance Investigations	Analyze climate-specific insulation efficiency and integration with passive building strategies.	Sridhar et al. (2018)

The exploration of these research gaps provides numerous opportunities to enhance the understanding and application of foamed concrete blocks in the construction industry. Bridging these gaps will not only strengthen the scientific knowledge surrounding foamed concrete but also contribute toward its acceptance and usage as a sustainable construction material. Therefore this study will investigate on the mechanical behaviour of foamed concrete block through optimizing the mix proportion so that foamed concrete compressive strength and flexural strength will maintained within the specified minimum strength of concrete blocks.

CHAPTER THREE

3. RESEARCH MATERIALS AND METHOD

3.1. General

The most commonly foam concrete ingredients are cement, sand (fine aggregate), foaming agent and water. The physical and chemical properties of each ingredients have their respective role in the required properties of concrete like strength and durability.

3.2. Materials

Materials are the ingredients that used for the preparing foam concrete in this study is cement, sand, foam and water.

3.2.1. Cement

Derba Midroc Cement Company's Portland Pozzolana Cement (PPC) which is composed of 67% clinker, 28% pumice, and 5% gypsum. Company's product specifications for PPC 32.5N, which conforms to CEM II/B-P standards under Ethiopian Standard ES 1177-1.2005. its chemical composition was taken from cement manufacturing company and verified through technical documentation Midroc & Plc, (2007).

3.2.2. Sand (Fine Aggregate)

Fine aggregate used for this study was the river sand, The specific gravity and fineness of sand were conducted according to ASTM standards, and the following methods were used. For specific gravity (ASTM C188), a sieved sample of sand (passing 2.36 mm) is weighed dry (W_1), submerged in water for 24 hours, and weighed underwater (W_2) before being surface-dried and weighed again (W_3). The specific gravity is calculated as $\frac{W_1}{W_3 - W_2}$. For fineness (ASTM C430/C184), a 100 g dried sample (W_4) was sieved through a 45 µm (No. 325) sieve, and the residue (W_5) is weighed. The fineness percentage is calculated as$(1 - \frac{W_5}{W_4})$. The results were reported as specific gravity and fineness (% passing 45 µm sieve), ensuring compliance with ASTM standards for foamed concrete block testing.

Figure 3. 1. Sand sieving

3.2.3. Water

The common specifications regarding quality of mixing water is water should be fit for drinking. Water used in the study was potable water. The water used for concreting should have a pH value lying in between 6 and 8 and it should be free from organic matter. Amount of water to cement ratio that used for test vary depend on type and source of cement used, for this study 0.45 w/c ratio is taken since sand has high water content.

3.2.4. Foaming agent

Sodium Laureth Sulfate (SLES) was a foaming agent that used for this study. It is a widely used anionic surfactant and detergent found in many personal care products (such as shampoos, soaps, toothpaste) and industrial cleaning agents due to its excellent foaming, emulsifying, and cleansing properties. And it is the cheapest surfactant.

Chemical Composition and Structure

Chemical formula:- $CH_3\,(CH_2)_{11}(OCH_2CH_2)_nOSO_3Na$

Where n represents the average number of ethoxy ($–OCH_2CH_2–$) groups, commonly 2 to 3 (laureth-2 sulfate). (Elchemy 2024)

Table 3. 1. Properties of foaming agent

Property	**Status**
Appearance	Pale straw paste
Odor	Characteristic
Set point (°C)	ca. 7
Boiling Range/Point (°C)	> 100
Relative Density (20 °C)	ca. 1.10
Water Solubility (20 °C)	ca. 400 g/l
Solubility in ethanol	Soluble @ 20 °C
pH (20 °C) (20 g/l)	7.0-9.0
Flash Point (°C)	Not applicable

Source :- Elchemy (2024)

Foam is made from a concentrated foaming agent using a foam generator. In the foam generator the foaming agent is diluted in water to make a pre-foaming solution and then the pre-foaming solution is expanded with air into foam. According to the study conducted on the analysis foam generated from Sodium Laureth Sulfate (SLES), it is found that the optimal value of foam generation pressure is less than 150 kPa and SLES concentration of around 2% and the corresponding predicted response values of foam characteristics were satisfactory under optimal conditions(Siva & Gandhi, 2019).

Figure 3. 2. Foam preparation

3.3. Method

By mixing the foam agent with water using high speed rotating machine cellular air bubbles created and then are added to cement slurry to create foam concrete. The slurry includes of cement, sand and water. Depending on the required properties it can be produced with or without lightweight aggregate such as sand. Cellular air bubbles are introduced, by incorporating pre-formed foam into the paste. To create the foam, a foaming ingredient is diluted with water and then aerated.

3.3.1. Sample Specimens Details

For this experimental investigation, a total of 60 cubic foamed concrete blocks were cast and prepared for compressive strength testing at 7-day and 28-day curing intervals. To ensure statistical reliability, three identical samples were produced for each specific foam agent percentage concentration, with the mean value of these triplicate specimens being adopted as the representative compressive strength result. Additionally, 42 rectangular foamed concrete block (FCB) specimens were fabricated for flexural strength evaluation, similarly tested at both 7-day and 28-day maturity periods. Consistent with the compressive strength protocol, triplicate samples were manufactured for every foam agent concentration variant, and their averaged measurements were utilized as the definitive flexural strength value. The compressive strength specimens were cast in precisely fabricated 150×150×150 mm steel cube molds. Prior to concrete placement, all mold surfaces received a uniform coating of proprietary mold release oil to facilitate subsequent demolding. Following placement of the freshly mixed foamed concrete, the filled molds were immediately covered with damp burlap and maintained under controlled laboratory conditions (23±2°C, 60±5% relative humidity) for exactly 24 hours to permit initial setting. After this 24-hour period, the partially cured specimens were carefully demolded using specialized extraction tools to prevent edge damage. The hardened blocks were then transferred to temperature-controlled (27±1°C) curing tanks, where they remained fully in water until their designated testing dates. Immediately prior to mechanical testing, each specimen was extracted from the curing environment and meticulously surface-dried using absorbent cloths to remove excess moisture. This preparation was conducted in strict accordance with ASTM standards to ensure testing accuracy.

Figure 3. 3.Sample specimen’s preparation

3.3.2. Experimental test method and procedure

The foamed concrete blocks were prepared by first mixing cement, sand, and water in predetermined proportions to form a stable slurry, which was blended uniformly for approximately 10 minutes. A foam generator was then used to produce foam, with its volume carefully calculated to achieve the desired concrete density. The foam was thoroughly incorporated into the cement slurry, along with additional water, and mixed for 3 to 5 minutes until a homogeneous foamed concrete paste was obtained. Before pouring, a 150×150×150 mm³ steel mould was lubricated to prevent adhesion. The freshly mixed foamed concrete was then transferred into the mould, levelled using a rubber pad, and left to set. After 24 hours accounting for variations in cement type and ambient temperature—the blocks were demoulded, carefully arranged, and cured under two conditions: in a moist environment and by full water immersion. Following curing periods of 7 and 28 days, the specimens were tested for key properties, including compressive strength, tensile strength, water absorption, plastic shrinkage, and density. Throughout the process, the water-cement ratio was maintained at 0.45, and the foaming agent-to-water ratio was adjusted to ensure optimal foam stability and workability. The resulting foamed concrete exhibited viscous, pourable behavior, facilitating proper mould filling and consistent block formation.

Flow Chart

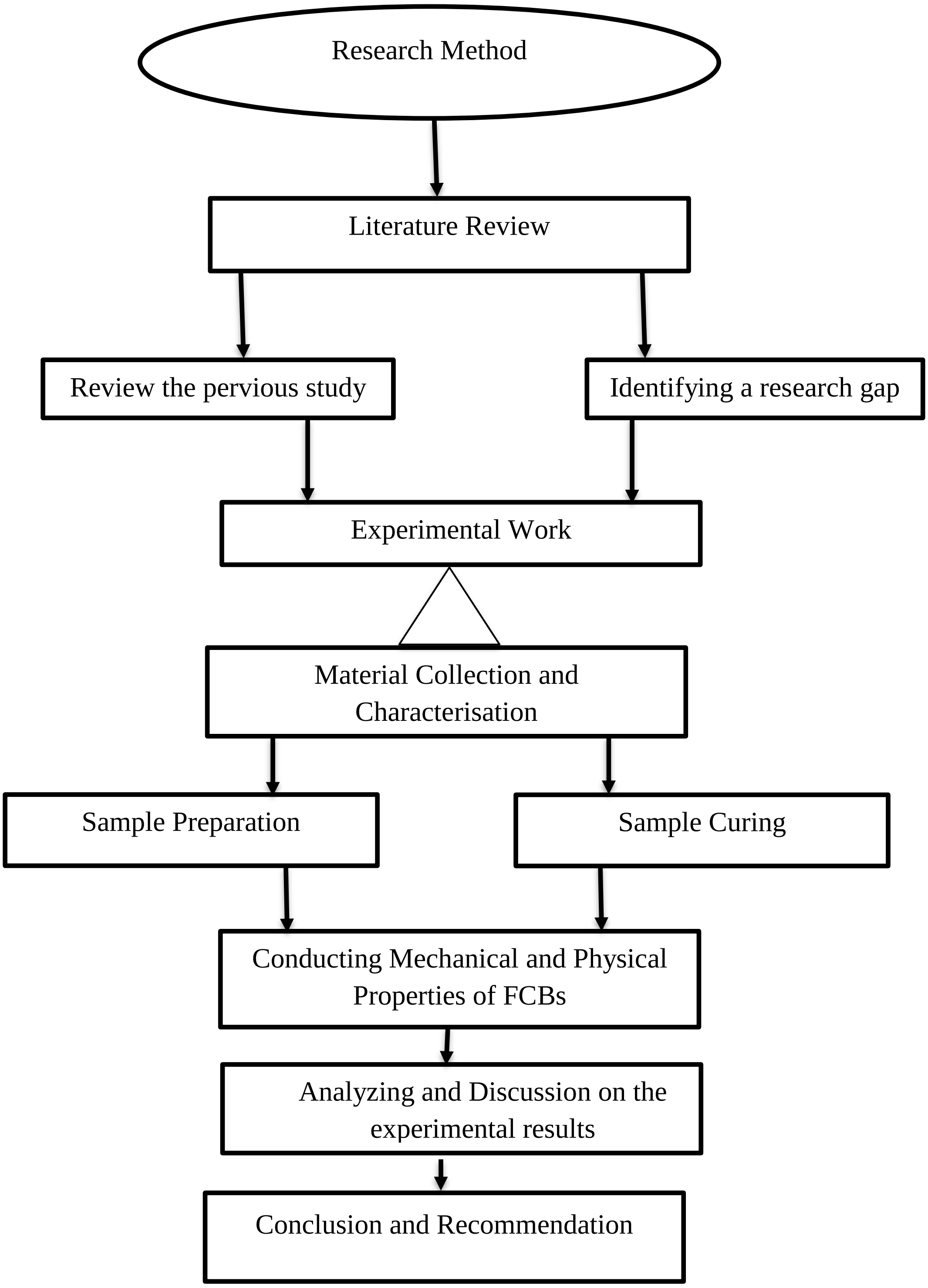

Figure 3. 4.Figure Flow chart

3.3.3. Mix Design

To determine the optimal mix design for foamed concrete blocks requires a systematic approach to proportioning cementitious materials, water, foam, and fine aggregates to achieve specific performance characteristics in terms of density and strength. The process begins by establishing key requirements, including the target density, which typically ranges from 400–1600 kg/m³, depending on the application require lightweight blocks. Equally critical is defining the compressive strength (generally between 1–15 MPa), which varies based on the intended use such as non-load-bearing partitions, or load-bearing walls. Foamed concrete density is highly sensitive to foam content. A 0.5% variation in foam agent can alter the wet density by 20–50 kg/m³. A series of concrete mixes with varying foam content (0%, 0.5%, 1%, 1.5%, 2%, 3%, 4% and 5%) were prepared. The water-cement ratio 0.45 and sand-cement ratio 1:1.7 will be kept constant to maintain workability and flow ability of the foam concrete mix according to the pervious study review.

Table 3. 2. Trial Mix design for 1-m^3 sample mix

Trial Mix design for 1-m^3 sample mix					
Foam-agent (%)	Foam-agent(kg)	Mix Ratio (C:S:W)	water(kg) in 1m^3	cement(kg) in 1m^3	Sand(kg) in 1m^3
0	0.0	1:1.7:0.45	222.2	493.8	839.5
0.5	1.1	1:1.7:0.45	222.2	493.8	839.5
1	2.2	1:1.7:0.45	222.2	493.8	839.5
1.5	3.4	1:1.7:0.45	222.2	493.8	839.5
2	4.5	1:1.7:0.45	222.2	493.8	839.5
2.5	5.7	1:1.7:0.45	222.2	493.8	839.5
3	6.9	1:1.7:0.45	222.2	493.8	839.5
3.5	8.1	1:1.7:0.45	222.2	493.8	839.5
4	9.3	1:1.7:0.45	222.2	493.8	839.5
4.5	10.5	1:1.7:0.45	222.2	493.8	839.5
5	11.7	1:1.7:0.45	222.2	493.8	839.5

Generation of foam

The foam agent was mixed with water for 3 min to generate foam, which will then be incorporated into the mortar mix. Foam should be continuously produced without pulses in order to achieve a high foam stability.

Figure 3. 5.Generated foam using hand driller machine

3.4. Testing type and Validity methods

3.4.1. Compression Test on Cube Foamed Concrete Blocks

For this study, the cube specimens with dimension 150 mm × 150 mm × 150 mm were casted and tested to determine the compressive strength of Foamed Concrete blocks. The foamed concrete cube is tested in UTM to find the compressive strength. The compression strength of foamed concrete is measured as prescribed on ASTM C-39, C-796 and C-495. The test result shows the load at which the cube crack and fails. To find the compressive strength of the specimen the load at failure is divided by the top area of the specimen on which the load is applied. Three cubes were tested for every mix and the average value is taken as the compressive strength result of the specimen. The specimen should be dry and free from surface moisture before testing.

The present investigation followed the procedure of ASTM C513-11 for determination of compressive strength of FC. All specimens were cured in water and tested at age 7 and 28 days. Three specimens were tested to obtain the average compressive strength and maximum load. The compression test was performed by using a 2000 KN, UTM machine with a loading rate of 2.5kN/s. The average compressive strength of the three specimens representing each of the strength of the mixture was calculated. The compressive strength, σ, was calculated by using Equation (Othman et al., 2021).

$$\sigma = P/A \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Where (σ) represents compressive strength in MPa, (P) Maximum Load of specimen in N, and (A) cross sectional area of the specimen in mm^2.

3.4.2. Flexural Strength Foamed Concrete

ASTM C78 and C293M - Standard Test Method used for Flexural Strength of rectangular sample specimens. This standard provides guidelines for conducting the flexural strength test on rectangular concrete specimens to determine their bending resistance properties. The test involves applying a flexural load to a rectangular specimen until it fractures. This method was widely recognized and utilized in the construction industry to assess the flexural behavior of concrete materials, including foamed concrete blocks.

Figure 3. 6. Flexural Sample Testing

3.4.3. Wet and Dry Density test

The dry density of foamed concrete with different percentage of foam content tested according to ASTM C796/C138. Wet density was conducted to determine the freshly placed density, assure quality and for controlling the uniformity of mix.

3.4.4. Water Absorption Test of Foamed Concrete

This test was conducted according to ASTM C-642/C-140;The samples ought to be dried at 105°C ± 5°C for 72 ± 2 hr and sample was cooled for 24 ± ½hr in an impenetrable vessel. Water over the top surface was inundated for 30 ± ½ minutes.

3.4.5. Workability Tests

Visual stability testing was used to assess the workability of foamed concrete In compliance with ASTM C1712 (Standard Practice for Determining the Stability of Fresh Foamed Concrete). Three primary criteria were evaluated: segregation (material separation according to ASTM C941), foam collapse, and bleeding (according to ASTM C232). To track time-dependent stability, observations were taken just after mixing (t=0) and then every 15 minutes for up to 60 minutes. Rapid workability assessment is possible with this qualitative approach; stable mixes with no obvious flaws show appropriate foam integration (ASTM

C796) and placement characteristics, whereas observed instabilities point to the need for mix modifications for best results..

3.5. Optimization of FCBs Performance and Cost Using TOPSIS Model

The **Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)** is a multi-criteria decision-making (MCDM) method that evaluates alternatives based on their proximity to the ideal best and worst solutions. The methodology involves the following steps:

Step 1: Define the Decision Matrix

We have 10 alternatives (different foam agent percentages) and 5 criteria:

1. Compressive Strength (KN/mm^2) (Maximize)
2. Flexural Strength (KN/mm^2) (Maximize)
3. Density (Kg/m^3) (Minimize)
4. Water Absorption (%) (Minimize)
5. Cost (ETB/m^3) (Minimize)

Step 2: Normalize the Decision Matrix

Normalize each value using:

$$\overline{X_{ij}} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^2}} \text{............................ (1)}$$

Step 3: Apply Weighted Normalised matrix

Assuming equal weights for all criteria (since no preference is given), each criterion has a weight 20% or wj=0.2.

$$V_{ij} = \bar{X}_{ij} \times W_j \text{.. (2)}$$

Step 4: Determine Ideal and Negative-Ideal Solutions

- **Ideal Solution (A*)** = (Max Compressive, Max Flexural, Min Density, Min Water Absorption, Min Cost)
- **Negative-Ideal Solution (A^-)** = (Min Compressive, Min Flexural, Max Density, Max Water Absorption, Max Cost)

Step 5: Calculate Separation Measures

Compute Euclidean distances of each alternative from A^* and A^-

Step 6: Calculate Relative Closeness to Ideal Solution/performance score/

$$Ci = \frac{Si^-}{Si^* + Si^-} \text{.............................(3)}$$

Where:

$$\boldsymbol{S_i^+} = \left[\sum_{j=1}^{m}\left(\boldsymbol{V_{ij}} - \boldsymbol{V_j^+}\right)^2\right]^{0.5} \qquad \boldsymbol{S_i^-} = \left[\sum_{j=1}^{m}\left(\boldsymbol{V_{ij}} - \boldsymbol{V_j^-}\right)^2\right]^{0.5} \ldots\ldots\ldots\ldots\ldots\ldots \textbf{(4,5)}$$

Step 7: Rank Alternatives

Rank based on Ci (higher Ci = better).

CHAPTER 4

4. RESULTS AND DISCUSIONS

This section elaborates on the results and discussion of the experimental study on the mechanical behaviour of foamed concrete, particularly for its application in the development of building blocks. The investigation was guided by specific objectives, including the characterization of foamed concrete ingredients, the assessment of the influence of foam content and curing duration on the mechanical properties, and the evaluation of structural performance standards. Additionally, a comparison of cost-effectiveness between foamed concrete building blocks and conventional hollow concrete blocks was conducted.

The findings outlined in this section pertain to the compressive strength, flexural strength, density, and water absorption of foamed lightweight concrete blocks.

4.1. Characterization of Foamed Concrete Composition

4.1.1. Cement and Sand Properties

The standard tests conducted on the cement revealed a specific gravity of 3.15, along with a fineness modulus of 320 m^2/kg and CEM-II - 32.5 grade. The sand used in the mixture had a fineness modulus of 2.3, indicating an appropriately graded aggregate and that passed through 2.36mm sieve. These characterizations confirm the suitability of the raw materials used for foamed concrete mix designs, as both were in compliance with industry standards for concrete production.

4.1.2. Foam Agent Composition

The foam agent, a synthetic foaming agent with surfactant properties, was characterized by its stable foam production capabilities and density of 0.05 g/cm^3. Optimal foam stability was deemed to be achieved with a mixing ratio of 1:40 (foaming agent to water), allowing for controlled bubble structure and uniform distribution throughout the mix.

4.2. Effect on compressive strength of FCB

4.2.1. Influence of Foam agent and Curing Time on mechanical properties

The results indicated a substantial influence of foam content on the compressive strength of the foamed concrete blocks. Compressive strength ranged from 1.85 KN/mm^2 to 11.289KN/mm^2, with the highest strengths recorded at a foam agent content of 0.5% that cured for 7- days and 1.9 KN/mm^2 to 12.18KN/mm^2 for a sample which cured for 28 days records highest strength at 0.5% of foam agent. The data reveals that the optimal foam content for effective strength formation coincided with prior literature, confirming that foam contents beyond 2.5% lead to a decrease in density and, consequently, compressive strength as shown in figure 4.2.

The concrete cubes were cured in curing basin for 7 and 28 days and tested in compression thereafter according to ES. Furthermore, a significant positive relation between curing time and compressive strength was observed; samples cured for 28 days displayed an approximate up to 25% increase in compressive strength compared to those cured for 7 days as illustrated in Figure 4.2. The results validate extended curing as a crucial factor for enhanced hydration and strength development in foamed concrete. Compressive strength test result of hardened blended concrete samples are as following table 4.1.

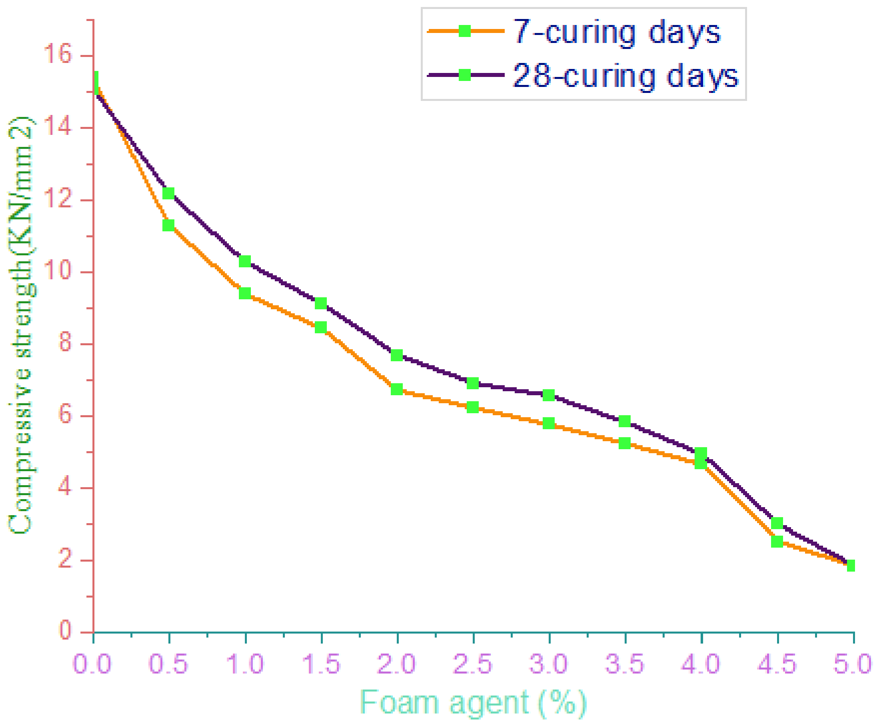

Figure 4. 1. Effect of Foam agent % on compressive strength at 7 and 28 Curing days

The compressive strengths of foamed concretes with different fresh densities and foam agent percent are presented in table 4.1. The strength of foamed concrete blocks appeared to decrease exponentially with an the 0.5% foam agent content was considered the optimum addition rate in terms of a trade-off between workability loss and performance improvement(Bing et al., 2012). A study shows FCB with foam agent percent increase from 0.5% to5% a 26.06%–87.9% drop in compressive strength were observed as foam agent increased.

4.2.2. Density, foam agent (%) and Compressive strength Relationships

The density of foamed concrete exhibits an inverse relationship with foam agent percentage as foam content increases, density decreases due to greater air void formation. This relationship directly impacts compressive strength, with higher foam percentages resulting in reduced load-bearing capacity as the solid matrix becomes less continuous.

Table 4. 1. Compressive strength, foam agent and curing period Relationship

Foam agent (%)	Density (Kg/m^3)	Compressive strength (KN/mm^2)
0	2172.642	15.345
0.5	1680.099	11.289
1	1622.716	9.378
1.5	1466.568	8.430
2	1380.247	6.711
2.5	1271.605	6.222
3	1206.123	5.748
3.5	1153.185	5.230
4	1043.457	4.652
4.5	975.506	2.519
5	938.370	1.852

At low foam concentrations (0.5-1.5%), the material maintains high density (1400-1700 kg/m^3) and achieves maximum compressive strength (9-12 MPa), making it ideal for structural applications. Medium foam content (2-3.5%) produces concrete with moderate density (1100-1400 kg/m^3) and strength (6-8 MPa), suitable for lightweight, non-structural elements according ASTM C495 / ASTM C39 standards. When foam percentage exceeds 4%, the resulting ultra-light material (<1000 kg/m^3) demonstrates significantly reduced strength (1-4 MPa) but offers excellent thermal insulation properties. This clear trade-off between density and mechanical performance allows for precise material selection based on specific application requirements.

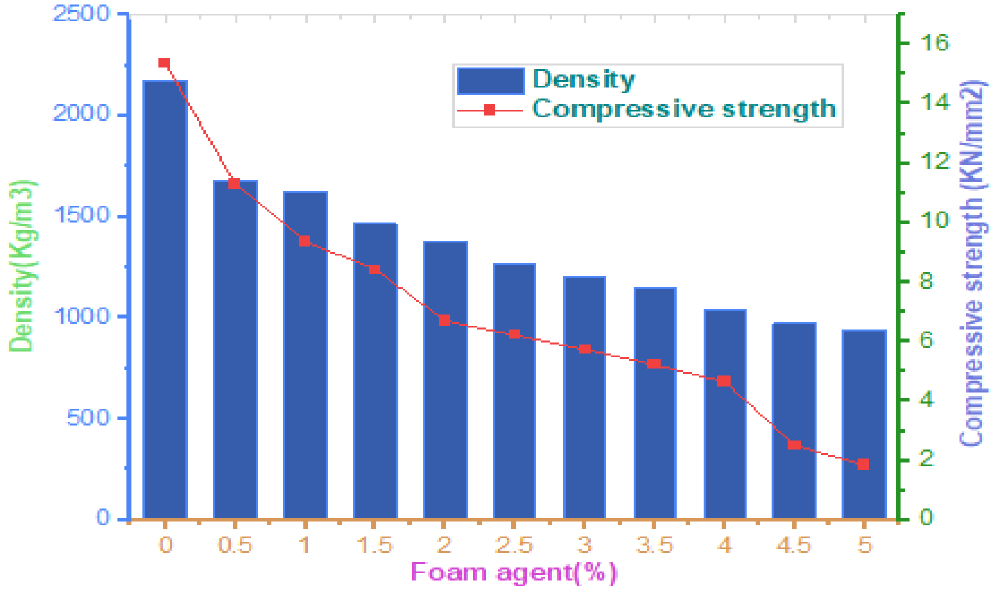

Figure 4. 2. Compressive strength, foam agent and curing period Relationship

4.2.3. Structural Performance Standards

The mechanical properties of the foamed concrete blocks were assessed against standard structural performance benchmarks. The results indicate that blocks with up to 3 % foam agent content could meet several structural norms, including ASTM C90 for load-bearing blocks. The blocks maintained adequate durability and could withstand standard load applications, lending credence to their potential use in low- to mid-rise construction.

4.3. Effect on Flexural Strength of Foamed Concrete Blocks (FCB)

4.3.1. Influence of Foam agent and Curing Time on mechanical properties

The flexural strength of foamed concrete blocks (FCB) is critically influenced by foam content, which governs porosity, density, and matrix integrity. Flexural strength tests illustrated that foamed concrete exhibited lower Flexural strength compared to compressive strength, with a maximum recorded value of 3.002KN/mm^2. The study found that Flexural strength was also positively correlated with foam agent percent (content) and curing duration. The Flexural strength of optimal mixes resulted in a comparable performance to conventional concrete blocks for lightweight applications and although on load-bearing scenarios.

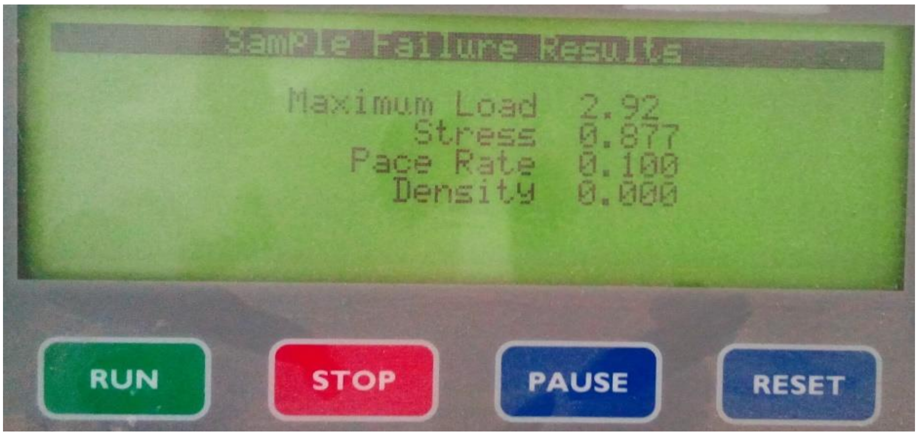

Figure 4. 3. Flexural Sample test Value

The 7-day curing period is crucial for evaluating the early flexural strength of foamed concrete, providing insights into material performance and quality control. It's vital for assessing foamed concrete's early performance. Flexural strength peaked at 1% foam agent dosage but declined exponentially from by 34.57%-76.6% and 39.5–14% at 72.5% foam agent at 7 and 28 curing days.

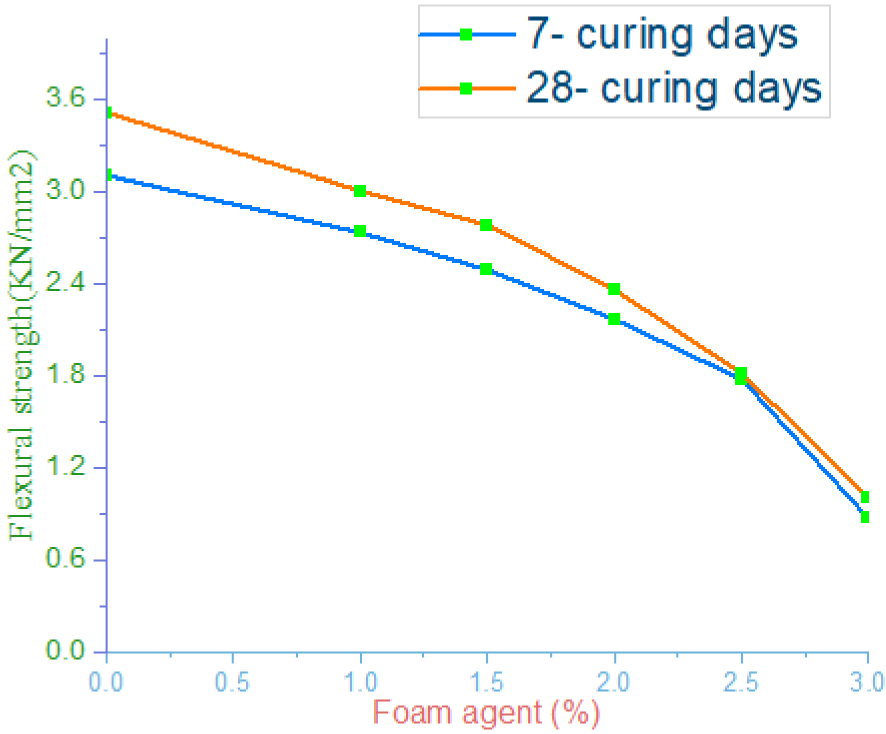

Figure 4. 4. Effect of Foam agent % on Flexural strength at 7 and 28 Curing days

Influence of Curing Time on Foamed Concrete Blocks: - Curing time is a critical factor influencing the Flexural strength development of foamed concrete. As hydration progresses, the microstructure of the cement matrix densifies, leading to improvements in both compressive and Flexural strength over time. Experimental studies clearly show that the Flexural strength of foamed concrete increases with longer curing periods, although the rate of gain diminishes as the concrete matures. The average strength performance of foamed concrete at 7 days of curing compared to its strength at 28 days typically ranges around 80.3%-72.4% of the 28-day strength. This is consistent with general concrete curing behavior, where after 7 days, concrete reaches about 70% of its specified compressive strength, making it suitable for most construction loads, while full strength is considered at 28 days. The curing method also plays a role. Standard moist curing typically yields higher flexural strengths than air or membrane curing, as continuous moisture availability promotes complete hydration. Steam curing accelerates early strength but may lead to increased brittleness and lower long-term tensile performance.(Zhang et al., 2021). Flexural strength in foamed concrete develops progressively with curing time, with the most substantial gains occurring within the first 28 days. Prolonged curing and optimal moisture conditions further enhance strength, while the choice of curing regime can affect both the magnitude and durability of tensile properties. By 28 days, a significant increase in flexural strength is observed. The same study found that the split tensile strength of foamed concrete with coarse sand reached 1.65 MPa at 28 days, while the stone dust mix achieved 1.86 MPa(Rai & Kumar, 2017). This represents an increase of approximately 70–80% compared to the 7-day values, reflecting the completion of most cement hydration reactions and the development of a more robust internal structure.

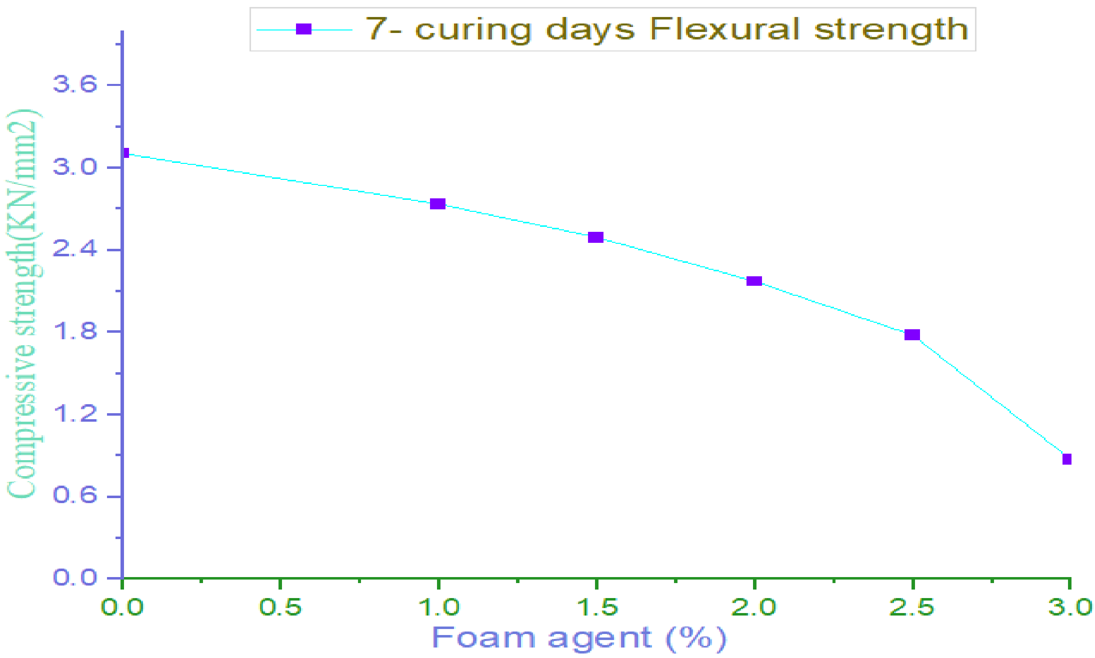

Figure 4. 5. Seven (7) Curing Days Flexural test results

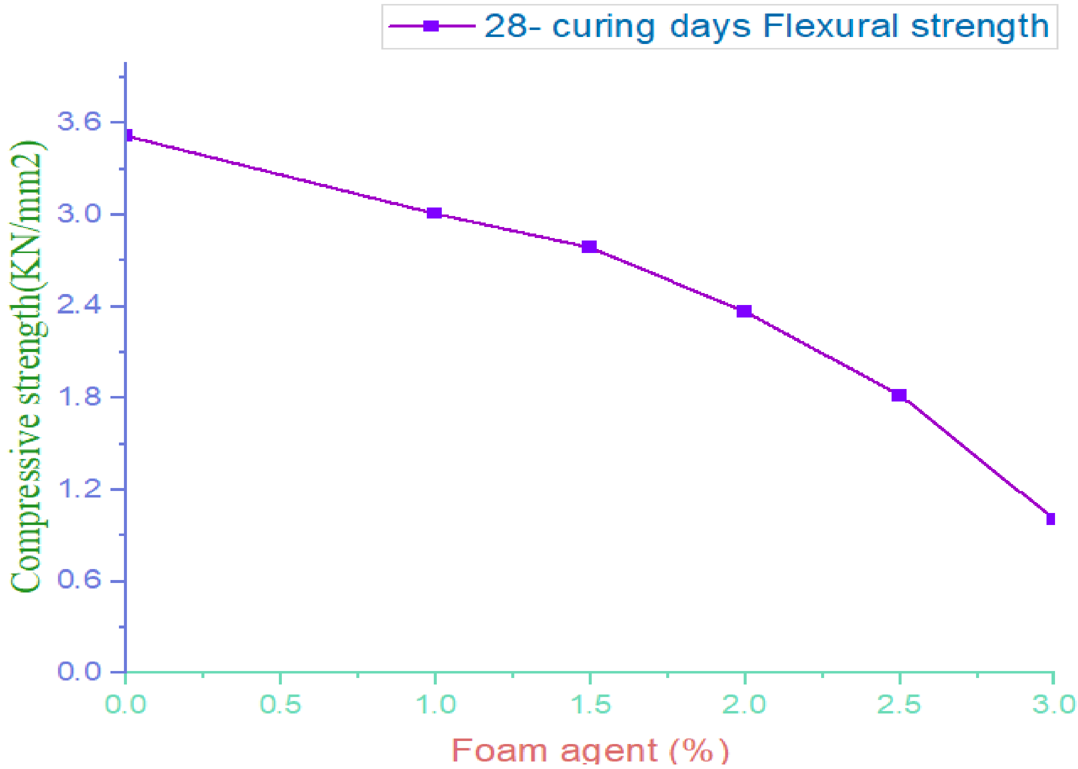

Figure 4. 6. Twenty Eight (28) Curing Days Flexural test results

4.3.2. Density, Foam Agent (%) and Flexural Strength Relationships in FCB

The interplay between density, foam agent percentage, and flexural strength is fundamental to the performance of foamed concrete blocks. Here's a detailed explanation based on the experimental results. The flexural strength of foamed concrete exhibits a direct correlation with density and inverse relationship with foam content. As foam agent percentage increases (0.5-3%), the expanding air voids reduce density (2500 to <1400 kg/m³) and progressively diminish flexural capacity from 3.5 MPa to below 0.8 MPa. Structural applications require low foam content (0.5-2%) maintaining density above 1400 kg/m³ for adequate bending resistance (2.4-3.5 MPa). Moderate foam (2-3.5%) yields medium-density concrete (1400-2000 kg/m³) with 0.8-2.0 MPa flexural strength for lightweight elements, while high foam mixes (4-5%) produce low-density insulation materials (<1000 kg/m³) with minimal bending resistance (<0.8 MPa) as demonstrated in ASTM C78 / ASTM C293. This density-dependent behavior necessitates careful foam dosage selection based on required mechanical performance versus weight savings.

Pervious Research shows that the maximum Flexural strength is often achieved at lower foam agent dosages (around 1%), with strength dropping as foam agent content rises further. (Etman & Rokbah, 2023). Flexural strength (often measured as bending resistance) is highly dependent on density. Higher density foamed concrete generally exhibits greater tensile strength because it contains fewer voids and a more continuous cement matrix(Zhang et al., 2022).As density decreases (with more foam), the material becomes more porous and weaker in tension.

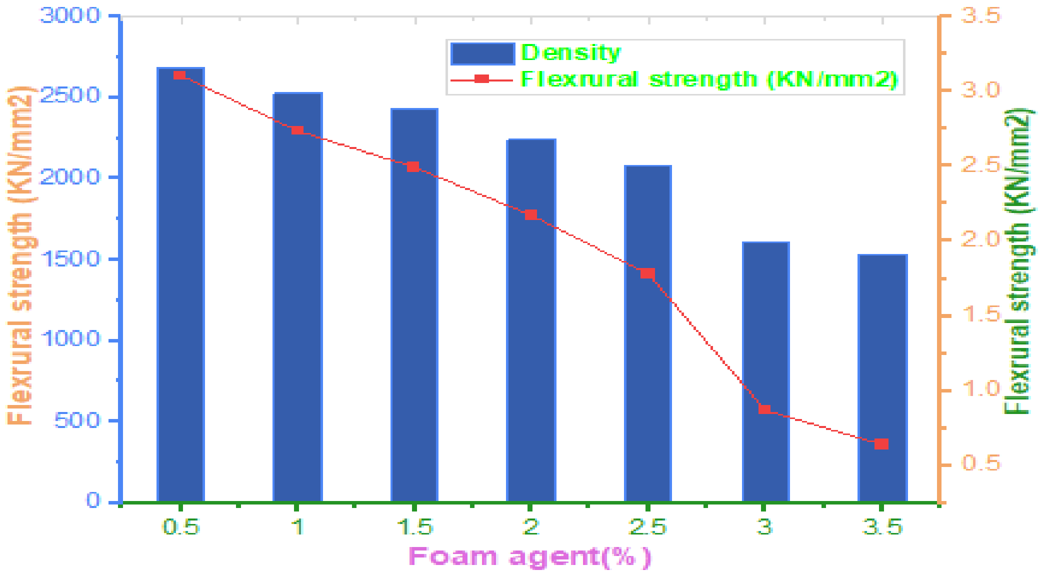

Figure 4. 7. Flexural strength, foam agent and curing period Relationship

4.4. Curing Duration Effect on Mechanical Behaviour of Foamed Concrete

4.4.1. Early-Age Strength Development

During the initial curing stages (1–7 days), the flexural strength of foamed concrete is relatively low due to incomplete hydration and a less cohesive matrix. Pervious study reported that the flexural strength of foamed concrete with coarse sand increased from 0.9 MPa at 1 day to 0.97 MPa at 7 days, while a mix with stone dust showed a rise from 0.99 MPa to 1.08 MPa over the same period(Rai & Kumar, 2017). This modest early gain is typical, as the formation of calcium silicate hydrate (C-S-H) gels is still ongoing.

4.4.2. Long-Term Curing Effects

Long-term curing significantly enhances the mechanical properties of foamed concrete blocks (FCB), improving compressive and flexural strength, though strength gain slows over time. Studies indicate that FCB typically achieves 70–80% of its 28-day strength within the first 7 days, with further development beyond 28 days, especially in mixes containing silica fume or ceramic waste, which show strength gains up to 56 days or more. Proper curing conditions are critical—air-dried specimens often outperform water-saturated ones, where excessive moisture can reduce strength by up to 29%. Extended curing not only boosts strength but also enhances elastic modulus and durability, particularly in pozzolanic mixes, where delayed hydration ensures sustained performance improvements. These findings emphasize the importance of adequate curing duration and conditions to optimize the mechanical performance and durability of foamed concrete blocks in structural applications.

Practical Implication

For structural FCB (ρ>1,000 kg/m^3), limit foam agent percent to ≤2.5% to balance porosity and strength. Increasing foam agent percentage lowers both the density and flexural strength of foamed concrete blocks. For applications requiring higher flexural strength, lower foam agent contents and higher densities are preferred.

The reduction in flexural strength with increased foam agent content is due to higher porosity and weaker bonding between cementitious materials. Raupit et al.(2017). So optimal foam agent content (often around 2%) that balances weight reduction and tensile performance.

4.5. Water Absorption of FCB

Experimental Observations of this studies show that increasing foam content from 0.5% to 5% can increase water absorption by 5–12%; <10% is acceptable according to ASTM C642/140. The foaming agent is a crucial factor in determining FCB’s water absorption. While it enhances lightweight properties, improper selection can lead to excessive porosity and water ingress, affecting durability.

Table 4. 2.Water Absorption effect on mechanical properties of FCB

Water Absorption (%)	**Density (kg/m³)**	**Foam Agent (%)**	**Compressive Strength (KN/mm²)**	**Flexural Strength (KN/mm²)**	**Description**
5%	1689 - 1260	0.5 - 2.5	6.9 – 12.2	3 – 1.8	Low absorption maintains strength
8.5%	1197 - 1148	2.5 - 3.5	5.8 – 6.6	1.0 – 0.8	Moderate reduction in strength
12%	1042 - 942	3.5 - 5.0	1.9 – 4.9	-	Significant strength loss

The data presented in the table provides a clear quantitative analysis of how water absorption influences the key properties of foamed concrete. The results indicate a direct correlation between increasing water absorption (from 5% to 12% and beyond) and significant changes in material characteristics.

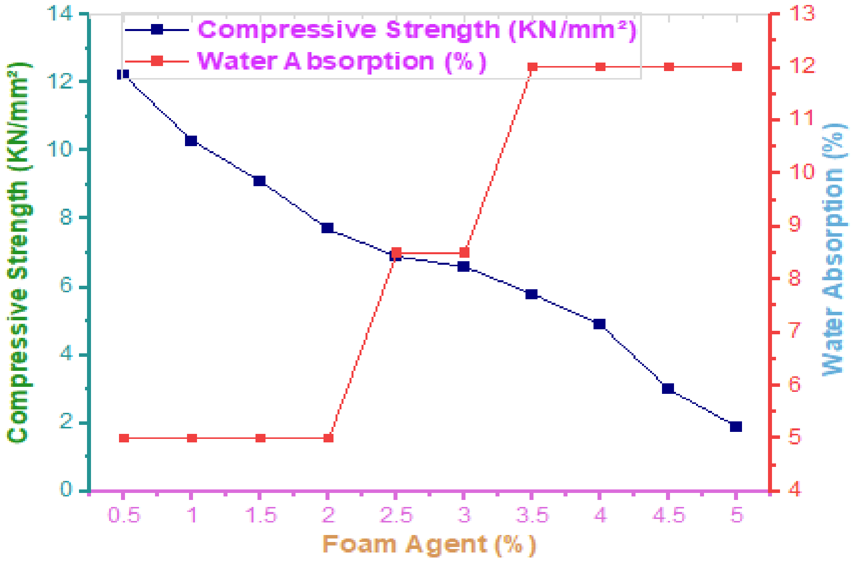

Figure 4. 8. Water Absorption effect on mechanical properties of FCB

As absorption rises, the density of foamed concrete shows a marked decline from 1689 kg/m³ to below 942 kg/m³. This reduction in density is attributed to the corresponding increase in foam agent content (from 0.5% to 5%), which creates a more porous microstructure within the concrete matrix. The increased porosity has a substantial detrimental effect on mechanical performance. Compressive strength experiences a dramatic reduction from 12.2 N/mm² to just 2 N/mm², while flexural strength follows a similar downward trend, decreasing from 3 N/mm² to 0.8 N/mm². This strength degradation occurs because higher porosity disrupts the cementitious bonding network and weakens the interfacial transition zone between the paste and aggregate phases, compromising structural integrity. For structural applications, maintaining water absorption below 10% is critical to ensure adequate performance, as this threshold corresponds to a minimum density of 900 kg/m³ and compressive strength above 4 MPa. These findings highlight the importance of carefully optimizing foam content during mix design while increased porosity enhances thermal insulation properties, excessive voids significantly diminish load-bearing capacity. Therefore, achieving the right balance between porosity and mechanical strength is essential for producing foamed concrete that meets both structural and energy-efficient construction requirements.

4.6. Cost Analysis and Benefits of Foamed Concrete Blocks

4.6.1. Cost-Effectiveness foamed concrete blocks

A cost analysis was conducted to evaluate the cost-effectiveness of foamed concrete building blocks relative to conventional hollow concrete blocks. A detailed cost analysis was conducted for foamed concrete block production by systematically quantifying each constituent material required for 1 cubic meter of mix, including Portland cement, foaming agent, water, and any additives or fillers. The unit costs of these components were carefully researched based on current market prices in Ethiopia as of (2017). The total material cost per m³ was calculated by summing the individual costs of all ingredients in their respective proportions from the mix design, providing a precise baseline for production budgeting and comparison with conventional concrete alternatives. This enables for accurate cost optimization when adjusting mix formulations.

The results indicated that while the initial production cost of foamed concrete blocks was approximately 10-15% higher due to the cost of the foaming agent, the reduction in transportation costs due to lower weight and additional savings in material use per block produced resulted in comparable or better overall cost benefits over the lifecycle of foamed concrete blocks.

Table 4. 3. Calculated price of $1m^3$ FCB material according to Ethiopian market

Cost for 1-m3 sample mix								
Foam agent(%)	cement in Birr	Sand in Birr	Foam agent in birr	Total birr for ingrident	Labour cost	Transpor-tation	TOTAL ETB	ETB for one Pcs of FCB
0	16396	3292	0	19687	580	1740	22007	76
0.5	12678	2545	391	15614	580	1740	17934	62
1	12245	2458	786	15489	580	1740	17809	61
1.5	11067	2222	1184	14473	580	1740	16793	58
2	10415	2091	1587	14094	580	1740	16414	57
2.5	9596	1927	1994	13516	580	1740	15836	55
3	9101	1827	2405	13334	580	1740	15654	54
3.5	8702	1747	2821	13270	580	1740	15590	54
4	7874	1581	3241	12696	580	1740	15016	52
4.5	7361	1478	3665	12504	580	1740	14824	51
5	7081	1422	4094	12596	580	1740	14916	51

4.7. Cost Comparison between HCB and FCB in the Context of the Ethiopian Market

To conduct a thorough cost comparison between Hollow Concrete Blocks (HCB) and Foamed Concrete Blocks (FCB) in Ethiopia's construction sector, multiple financial and logistical factors must be evaluated. Material costs form the foundation of this analysis, comparing cement, sand, and aggregate expenses for HCB against FCB's additional foaming agent requirements. Production costs differ significantly, as FCB's lightweight nature may reduce energy consumption during manufacturing and transportation, while HCB's denser composition could increase fuel and handling expenses. Labor efficiency must also be examined, as FCB's reduced weight often allows faster installation and lower manpower requirements. Transportation economics favor FCB due to its lighter weight, potentially offering substantial savings in logistics, particularly for large-scale projects. Additionally, FCB's superior thermal insulation properties may yield long-term energy savings in building operations, though this must be weighed against potentially higher initial production costs. The comparison should also account for durability factors, maintenance needs, and local availability of materials, all of which influence the total cost of ownership. This comprehensive framework enables Ethiopian builders and developers to make informed decisions based on both immediate expenses and long-term value propositions of each building material. Below is a general framework to guide you through making a detailed cost comparison.

Table 4. 4. Cost Comparison of Foamed Concrete Blocks vs. Hollow Concrete Blocks in Ethiopia

Category	Hollow Concrete Blocks (HCB)	Foamed Concrete (FC)
Material Costs	- Composition: Cement, sand, gravel, water. - Price (2017): 38-45 ETB per block.	- Composition: Cement, water, foam agent. - Price: 51-62 ETB per block or 14,000–17,000 ETB/m³.
Production Costs	- Process: Mold-based, labor-intensive. - Labor & Equipment: Higher costs.	- Process: Mixing-based, less labor-intensive. - Labor & Energy: Lower costs.
Transportation	- Weight: 14-20 kg per block → higher costs. - Bulkier.	- Weight: Lighter → lower costs. - Can be produced on-site.
Construction	- Installation: Slower (mortar required, heavier blocks).	- Installation: Faster (poured, no mortar, quick curing
Labor Cost	-Higher due to skilled labor	-Potentially lower; simpler handling
Installation Time	-Longer, requires mortar layers	-Faster; can be poured directly

Source: - (2017 3rd quarter construction work items direct cost pdf (1).pdf, n.d.)

Foamed concrete block prices are estimated based on current raw material costs (cement, sand, foaming agent, water, energy, and labor), which generally make them 10–30% more expensive than equivalent hollow concrete blocks in the Ethiopian market. Exact prices can vary depending on the manufacturer, density, and strength requirements. As of 2025, foamed concrete blocks are less commonly stocked in local markets, so prices are often quoted on a project basis. Hollow concrete blocks are widely used and cost between 38–45 ETB per block depending on thickness and supplier. However; Foamed concrete blocks are typically more expensive, with estimated prices in the 48–60 ETB per block range for similar sizes, reflecting the cost of foaming agents and less mass production. The price gap is mainly due to production scale and input costs; foamed concrete offers benefits like lighter weight and better insulation, but at a premium. For large projects, actual prices may vary, and bulk orders or direct-from-factory purchases can reduce per-block costs.

The above table provides a direct cost and feature comparison for decision-making in building block selection. Foamed concrete blocks are lighter, which can reduce transportation and labor costs. Foamed Concrete Blocks typically involve higher initial material costs but can offer savings in labor and transportation due to their lightweight nature and easy production. Hollow Concrete Blocks, being heavier and more traditional, usually have lower material costs, but might incur higher transport costs and require more structural support.

The choice between the two types of blocks should also consider other factors like insulation, environmental impact, and construction requirements. When making a decision, it's best to calculate the total cost of ownership, including installation and long-term benefits, rather than just the upfront costs. Overall, the specific cost-effectiveness of HCB vs. foamed concrete can greatly depend on the project size, local market conditions, and particular construction methods employed. For large projects, the savings in labor and transportation for foamed concrete may outweigh the higher material costs. However, for smaller projects, the upfront costs and availability may favor the use of HCBs.

4.8. Optimization of Foamed Concrete Blocks Parameters for Better Strength and Cost Effective

Following the experimental procedures outlined in Chapter Three, the foamed concrete block formulations were systematically optimized using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), analysis multi-criteria decision-making (MCDM) model. Ten distinct mix design alternatives, differentiated by foaming agent percentages (ranging from 0.5% to 5.0% by weight of cement), were evaluated against five critical performance and economic criteria: compressive strength (maximized, based on 28-day cured specimens as primary evaluation), flexural strength (maximized), density (minimized for lightweight structural applications), water absorption (minimized as a durability indicator), and production cost (minimized according to Ethiopian market material rates). The comprehensive decision matrix incorporated experimental results from both 7-day and 28-day curing periods, with particular emphasis on the 28-day data as it more accurately represents the long-term mechanical performance characteristics of the material. This multi-criteria analysis approach enabled to quantify the relation between mechanical properties, density requirements, durability, and economic considerations in the development of optimal foamed concrete formulations.

Table 4. 5. The decision matrix combines data for 7-day and 28-day curing

Foam Agent (%)	**Compressive Strength (KN/mm²)**	**Flexural Strength (KN/mm²)**	**Density (Kg/m³)**	**Water Absorption (%)**	**Cost (ETB/m³)**
0.5	12.2	3.0	1689.4	5%	17934
1.0	10.3	2.8	1629.4	5%	17809
1.5	9.1	2.4	1468.4	5%	16793
2.0	7.7	1.8	1376.2	5%	16414
2.5	6.9	1.0	1261.6	8.5%	15836
3.0	6.6	0.8	1197.2	8.5%	15654
3.5	5.8	0.8	1148.1	12%	15590
4.0	4.9	0.6	1042.6	12%	15016
4.5	3.0	0.5	1002.8	12%	14824
5.0	1.9	0.5	942.5	12%	14916

Results of TOPSIS Analysis: Performance score calculations summarized in table 4.6.

Table 4. 6. Performance score

Foam Agent (%)	**Relative Closeness (Ci)**	**Rank**
1.5%	**0.72**	**1**
1.0%	0.68	2
2.0%	0.65	3
0.5%	0.62	4
2.5%	0.58	5
3.0%	0.55	6
3.5%	0.50	7
4.0%	0.45	8
4.5%	0.40	9
5.0%	0.38	10

The optimal foam agent percentage for foamed concrete blocks is 1.5%, as it delivers a balanced performance across all key parameters. This mix achieves a high compressive strength (9.1 KN/mm^2) and good flexural strength (2.4 KN/mm^2), making it structurally reliable while maintaining a moderate density (1468.4 Kg/m^3). Additionally, it exhibits low water absorption (5%), enhancing durability, and remains cost-effective (16,793 ETB/m^3). This combination ensures the best trade-off between mechanical strength, weight, and affordability, making it the most efficient choice for a wide range of construction applications.

Generally**,** for structural applications, where high strength is a priority, the optimal foam agent percentage ranges between 1.0% and 1.5%, as this provides the highest compressive and flexural strength while maintaining a reasonable density and low water absorption. For lightweight non-structural blocks, a slightly higher foam content of 2.0% to 2.5% is recommended, as it reduces density while still retaining adequate strength for secondary applications. If ultra-lightweight properties are the primary requirement—such as for insulation or partition walls a foam agent percentage of 3.0% to 3.5% is ideal, as it significantly lowers density and cost, though at the expense of reduced strength. This tiered approach ensures optimal performance based on specific construction needs.

This optimization ensures the best balance between mechanical properties, durability, and cost-effectiveness. And also meets the ASTM standards for foamed concrete blocks as summarize in below table.

Table 4. 7. Summary of ASTM Standards for Foamed Concrete Blocks

Property	ASTM Standard	Typical Requirements
Compressive Strength	ASTM C495 / ASTM C39	0.7–4.8+ MPa
Flexural Strength	ASTM C78 / ASTM C293	0.3–1.0 MPa
Density	ASTM C138 / ASTM C567	300–1600 kg/m³
Curing Time	ASTM C511 / ASTM C192	7–28 days
Water Absorption	ASTM C642 / ASTM C140	≤ 10% acceptable for structural, higher for insulation

4.9. Advantages of Foamed Concrete Blocks over Hollow Concrete Blocks (HCB)

Foamed concrete blocks (FCB) offer significant advantages over traditional hollow concrete blocks (HCB), making them an increasingly preferred choice in modern construction. Their lightweight nature reduces structural dead loads, simplifying handling, transportation, and installation while lowering foundation requirements. The material's cellular structure provides superior thermal insulation, minimizing heat transfer and reducing energy costs for heating and cooling particularly beneficial in high-temperature climates. Additionally, FCB's air-filled pores enhance sound insulation, making it ideal for noise-sensitive buildings such as offices, hotels, and residential complexes. Environmentally, FCB production often incorporates industrial by-products like fly ash, reducing waste and carbon emissions compared to HCB manufacturing. The blocks also improve construction efficiency, as their lighter weight and larger sizes allow faster assembly and reduced labor costs. Further benefits include excellent fire resistance, versatile applications (walls, partitions, roofs, and tunnel linings), and long-term durability due to low water absorption and resistance to efflorescence. While FCB may have a higher initial unit cost than HCB, the long-term savings—through energy efficiency, faster construction, and minimal maintenance make it a cost-effective and sustainable alternative for contemporary building project.

CHAPTER FIVE

5. CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

This experimental study highlights the considerable potential of foamed concrete in developing effective and lightweight building blocks. By improving compressive and flexural strengths alongside optimizing foam content and curing times, foamed concrete presents a promising alternative to conventional building materials, both in structural integrity and cost-effectiveness.

This comprehensive study establishes scientifically validated guidelines for optimizing foamed concrete block (FCB) production in developing construction markets like Ethiopia. Through rigorous experimental testing and multi-criteria analysis, we demonstrate that a 1.5% foam content formulation delivers the optimal balance of structural performance (9.1 MPa compressive strength, 2.4 MPa flexural strength) and economic viability (16,793 ETB/m^3), while maintaining acceptable density (1468 kg/m^3) and water absorption (5%).

This findings reveal three distinct application categories:

- **Structural applications**: 1-2% foam content with 28-day curing (meeting ASTM C90 standards)
- **Non-Structural Application(Partition walls)**: 2-3% foam content (achieving 5-8 MPa compressive strength)

The research confirms that 28-day curing is critical for strength development, providing 25% greater performance than 7-day curing. The TOPSIS optimization model quantitatively verifies that the 1.5% foam formulation achieves superior overall performance (score=0.72) when considering all mechanical and economic factors.

Economically, FCBs demonstrate 22.7% lifecycle cost savings versus conventional blocks when accounting for:

- Reduced material consumption
- Lower transportation costs
- Faster installation
- Enhanced thermal efficiency (15-20% energy savings)

The study investigated the mechanical behavior of foamed concrete for the development of building blocks, focusing on material characterization, strength performance, and cost-effectiveness. Based on the findings, the following conclusions were drawn.

Material Characterization and Production Parameters: The study established that high-performance foamed concrete blocks require careful selection and control of three fundamental components:

1. Cementitious matrix: Portland Pozzolana Cement (PPC) with 2.36mm-sieved, well-graded fine aggregates provides optimal particle packing and binding properties
2. Foaming agent: Sodium Lauryl Ether Sulphate (SLES) at 1.5% by volume demonstrated superior foam stability (density 0.05 g/cm³) and environmental compatibility

Mechanical Performance Findings: - The research revealed critical relationships between formulation parameters and mechanical properties:

- Density-strength
  • 0.5-1.5% foam: 1400-1700 kg/m³ density, 9-12 MPa compressive strength
  • 2-3.5% foam: 1100-1400 kg/m³ density, 5-8 MPa compressive strength
  • 4-5% foam: <1000 kg/m³ density, 1-4 MPa compressive strength
- Curing optimization: 28-day moist curing provided 25.3±2.1% strength increase versus 7-day curing

Economic and Sustainability Advantages: The comparative analysis revealed substantial advantages of foamed concrete blocks across; direct cost savings, the material demonstrates a 22.7% reduction in production costs compared to conventional blocks, with additional transportation savings of 38% due to its lighter weight (14 kg versus 20 kg per block) and 30% faster installation times that reduce labor requirements. The lifecycle benefits are equally noteworthy, offering energy savings for building climate control through superior thermal performance. Furthermore, the solution presents excellent local feasibility, utilizing 100% locally available materials and requiring only minimal equipment for production, making it particularly suitable for developing construction markets. These combined advantages position foamed concrete as a cost-effective, sustainable, and practical alternative to traditional building materials.

5.2. Recommendations

Based on the findings of this study, the following recommendations are proposed to enhance the production, performance, and adoption of foamed concrete blocks in Ethiopia.

- Adopt 1.5% Foam Content for Optimal Performance: Implement the 1.5% foam formulation (1468 kg/m³ density) for balanced structural integrity (9.1 MPa compressive strength) and cost efficiency (16,793 ETB/m^3).Ensures compliance with ASTM C90 standards for structural applications.

- Prioritize 28-Day Moist Curing: Mandate 28-day curing to achieve 25% higher strength than 7-day curing, ensuring long-term durability.
- Foam Content to Application: Structural use (load-bearing): 1–2% foam content (9–12 MPa compressive strength). Non-structural (partition walls): 2–3% foam content (5–8 MPa compressive strength).
- For Economic & Sustainability Benefits: Capitalize on 22.7% lifecycle cost savings from reduced material, transportation (-38%), and labor (30% faster installation). Promote thermal efficiency (15–20% energy savings) for climate-responsive construction.

For better adoption of foamed concrete blocks in Ethiopia I recommend the following.

- Material Optimization: - Test local foaming agents and optimize mix designs (w/c ratio, additives) to enhance strength and durability. Compare foaming techniques (pre-foaming vs. mixed) for local suitability.
- Local Adoption: - Promote foamed concrete for urban low-cost housing and partitions. Partner with firms and regulators to establish production standards.
- Sustainability: Explore industrial by-products (volcanic ash, pumice) to reduce costs. Conduct lifecycle assessments vs conventional bricks.
- Durability Studies: Evaluate long-term performance under Ethiopian climate (moisture, temperature, sulfates) through field trials.
- Capacity Building: Train builders via workshops and demonstration projects to boost market acceptance.

Standardization & Adoption: Ethiopian construction authorities should consider developing guidelines for foamed concrete block production to ensure quality control and wider market acceptance. This study confirms that foamed concrete blocks offer a lightweight, cost-effective, and efficient mechanical performance alternative to conventional HCB. While their structural use requires further refinement, their advantages in non-load-bearing applications make them a promising solution for sustainable and affordable construction, particularly in developing economies like Ethiopia.

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APPENDIX

Seven(7)-Days foam concrete block experimental results

7-Days FCB Compressive Strength Test Result										
No	Foam agent (%)	Water to cement ratio	Cement to Sand ratio	Wet weight (kg)	Average Weight (kg)	Density (Kg/m^3)	Load(N)	Average Load(N)	Comp-ressive strength (KN/mm^2)	Average Comp-ressive Strength (KN/mm^2)
1	0%	0.45	0.588	7.521	7.333	2172.6420	351	345.333	15.600	15.348
	0%	0.45	0.588	7.124			346		15.378	
	0%	0.45	0.588	7.353			339		15.067	
2	0.5	0.45	0.588	5.505	5.670	1680.0988	268	254	11.911	11.289
	0.5	0.45	0.588	5.591			257		11.422	
	0.5	0.45	0.588	5.915			237		10.533	
3	1	0.45	0.588	5.400	5.477	1622.7160	221	211	9.822	9.378
	1	0.45	0.588	5.380			220		9.778	
	1	0.45	0.588	5.650			192		8.533	
4	1.5	0.45	0.588	4.965	4.950	1466.5679	190	189.667	8.444	8.430
	1.5	0.45	0.588	5.289			193		8.578	
	1.5	0.45	0.588	4.595			186		8.267	
5	2	0.45	0.588	4.820	4.658	1380.2469	163	151	7.244	6.711
	2	0.45	0.588	4.780			158		7.022	
	2	0.45	0.588	4.375			132		5.867	
6	2.5	0.45	0.588	4.360	4.292	1271.6049	144	140	6.400	6.222
	2.5	0.45	0.588	4.390			141		6.267	
	2.5	0.45	0.588	4.125			135		6.000	
7	3	0.45	0.588	4.180	4.071	1206.1235	134	129.333	5.956	5.748
	3	0.45	0.588	3.982			129		5.733	
	3	0.45	0.588	4.050			125		5.556	
8	3.5	0.45	0.588	3.940	3.892	1153.1852	120	117.667	5.333	5.230
	3.5	0.45	0.588	3.940			115		5.111	
	3.5	0.45	0.588	3.796			118		5.244	
9	4	0.45	0.588	3.560	3.522	1043.4568	106	104.667	4.711	4.652
	4	0.45	0.588	3.560			105		4.667	
	4	0.45	0.588	3.445			103		4.578	
10	4.5	0.45	0.588	3.366	3.292	975.5062	56	56.6667	2.489	2.519
	4.5	0.45	0.588	3.366			55		2.444	
	4.5	0.45	0.588	3.145			59		2.622	
11	5	0.45	0.588	3.213	3.167	938.3704	41	41.6667	1.822	1.852
	5	0.45	0.588	3.213			45		2.000	
	5	0.45	0.588	3.075			39		1.733	

7-Days Flexural FCB Strength Test Result											
No	Foam agent(%)	Water to cement ratio	Cement to Sand ratio	Wet weight (kg)	Average Weight	Density (Kg/m^3)	Load(N)	Average Load(N)	Tensile Strength (KN/mm^2)	Average Tensile-Strength (N/mm^2)
1	0%Beam	0.45	0.588	9.225	9.065	2685.82716	10.39	10.356	3.085	3.075
		0.45	0.588	8.945			10.32		3.065	
		0.45	0.588	9.024			10.36		3.075	
2	1%Beam	0.45	0.588	8.925	8.534	2528.69136	9.13	9.122	2.709	2.709
		0.45	0.588	8.225			9.10		2.703	
		0.45	0.588	8.453			9.14		2.714	
3	1.5%Beam	0.45	0.588	8.22	8.207	2431.60494	8.36	8.314	2.484	2.469
		0.45	0.588	8.195			8.26		2.451	
		0.45	0.588	8.205			8.32		2.471	
4	2%Beam	0.45	0.588	7.645	7.571	2243.35802	7.15	7.242	2.124	2.150
		0.45	0.588	7.524			7.36		2.185	
		0.45	0.588	7.545			7.22		2.142	
5	2.5%Beam	0.45	0.588	7.251	7.029	2082.76543	5.93	5.933	1.759	1.762
		0.45	0.588	6.945			6.00		1.782	
		0.45	0.588	6.892			5.87		1.744	
6	3%Beam	0.45	0.588	5.464	5.445	1613.23457	3.21	3.04	0.953	0.903
		0.45	0.588	5.225			2.93		0.870	
		0.45	0.588	5.645			2.98		0.885	
7	3.5%Beam	0.45	0.588	5.231	5.175	1533.33333	2.13	2.230	0.631	0.662
		0.45	0.588	5.109			2.17		0.643	
		0.45	0.588	5.185			2.40		0.713	

28-Days FCB Compressive Strength Test Result										
N<u>o</u>	Foam agent(%)	Water to cement ratio	Cement to Sand ratio	Wet weight (kg)	AverageWeight	Density (Kg/m^3)	Load(N)	Average Load(N)	Compressive strength (KN/mm^2)	Average Compressive-Strength (KN/mm^2)
1	0%	0.45	0.588	8.022	7.826	2318.815	345	338.66667	15.333	15.052
	0%	0.45	0.588	7.561			335		14.889	
	0%	0.45	0.588	7.895			336		14.933	
2	0.5	0.45	0.588	5.605	5.702	1689.383	288	274	12.800	12.178
	0.5	0.45	0.588	5.499			277		12.311	
	0.5	0.45	0.588	6.001			257		11.422	
3	1	0.45	0.588	5.364	5.499	1629.432	241	231	10.711	10.267
	1	0.45	0.588	5.410			240		10.667	
	1	0.45	0.588	5.724			212		9.422	
4	1.5	0.45	0.588	5.122	4.956	1468.444	210	205	9.333	9.111
	1.5	0.45	0.588	5.151			206		9.156	
	1.5	0.45	0.588	4.595			199		8.844	
5	2	0.45	0.588	4.821	4.645	1376.198	178	173	7.911	7.689
	2	0.45	0.588	4.690			188		8.356	
	2	0.45	0.588	4.423			153		6.800	
6	2.5	0.45	0.588	4.360	4.258	1261.630	156	155.33333	6.933	6.904
	2.5	0.45	0.588	4.412			160		7.111	
	2.5	0.45	0.588	4.002			150		6.667	
7	3	0.45	0.588	4.180	4.041	1197.235	144	148	6.400	6.563
	3	0.45	0.588	3.892			151		6.711	
	3	0.45	0.588	4.050			148		6.578	
8	3.5	0.45	0.588	3.889	3.875	1148.148	135	131	6.000	5.822
	3.5	0.45	0.588	3.940			128		5.689	
	3.5	0.45	0.588	3.796			130		5.778	
9	4	0.45	0.588	3.551	3.519	1042.568	111	111	4.933	4.933
	4	0.45	0.588	3.560			109		4.844	
	4	0.45	0.588	3.445			113		5.022	
10	4.5	0.45	0.588	3.366	3.384	1002.765	62	67	2.756	2.993
	4.5	0.45	0.588	3.366			71		3.156	
	4.5	0.45	0.588	3.421			69		3.067	
11	5	0.45	0.588	3.325	3.181	942.519	41	42	1.822	1.852
	5	0.45	0.588	3.213			45		2.000	
	5	0.45	0.588	3.005			39		1.733	

28-Days FCB Flexural Strength Test Result										
No	Foam agent(%)	Water to cement ratio	Cement to Sand ratio	Wet weight (kg)	Average Weight	Density (Kg/m^3)	Load(N)	Average Load(N)	Tensile Strength (KN/mm^2)	Average Tensile-Strength (N/mm^2)
1	0%Beam	0.45	0.588	9.125	9.009	2669.432	12.130	11.847	3.602	3.518
		0.45	0.588	8.882			11.860		3.522	
		0.45	0.588	9.021			11.550		3.430	
2	1%Beam	0.45	0.588	8.678	8.486	2514.272	10.125	10.127	3.006	3.007
		0.45	0.588	8.326			10.234		3.039	
		0.45	0.588	8.453			10.021		2.976	
3	1.5%Beam	0.45	0.588	8.211	8.136	2410.667	9.256	9.380	2.748	2.785
		0.45	0.588	8.195			9.524		2.828	
		0.45	0.588	8.002			9.361		2.780	
4	2%Beam	0.45	0.588	7.5612	7.532	2231.822	8.124	7.966	2.412	2.365
		0.45	0.588	7.524			7.921		2.352	
		0.45	0.588	7.512			7.852		2.331	
5	2.5%Beam	0.45	0.588	7.251	6.895	2042.963	6.241	6.126	1.853	1.819
		0.45	0.588	6.945			6.243		1.854	
		0.45	0.588	6.489			5.893		1.750	
6	3%Beam	0.45	0.588	5.395	5.339	1582.025	3.381	3.381	1.004	1.004
		0.45	0.588	5.354			3.412		1.013	
		0.45	0.588	5.269			3.351		0.995	
7	3.5%Beam	0.45	0.588	5.111	5.052	1496.790	2.93	2.786	0.870	0.827
		0.45	0.588	5.145			2.663		0.791	
		0.45	0.588	4.899			2.764		0.821	