COMPRESSIVE STRENGTH AND COST-EFFECTIVENESS OF CONFINED WASTE PLASTIC BOTTLE BRICK MASONRY WALLS

BY

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DECLARATION

I, MASABA EMMISON ERIC, solemnly declare that this submission titled "Compressive Strength and Cost-Effectiveness of Confined Waste Plastic Bottle Brick Masonry Walls" is entirely my original work. To the best of my knowledge and belief, it does not contain any material previously published or authored by another individual, nor any material submitted for or used to obtain any other academic degree, unless explicitly acknowledged and referenced within the text and bibliography.

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APPROVAL

The undersigned supervisors hereby certify that they have carefully evaluated the Research Thesis entitled " ***Compressive Strength and Cost-Effectiveness of Confined Waste Plastic Bottle Brick Masonry Walls***", and recommend its acceptance by Kyambogo University as fulfilling the requirements for the degree of Master of Science in Structural Engineering.

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DEDICATION

I dedicate this work to my parents, Masaba Michael J. and Kisolo Stella A., whose unwavering love and support have instilled in me the values of hard work and perseverance. To my siblings, Nakayenze Sharon Judith and Nakayenze Edith Sheba, whose belief in me continues to inspire resolve and personal growth.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

BCR	Benefit-Cost Ratio
CBA	Cost-benefit Analysis
CESMM4	Civil Engineering Standard Method of Measurement, Fourth Edition
CM	Cubic Meter
CML	Central Materials Laboratory
DPM	Damp Proof Membrane
GKMA	Greater Kampala Metropolitan Area
ISBM	Injection Stretch-Blow Moulding
MLHUD	Ministry of Lands, Housing & Urban Development
NIOSH	National Institute for Occupational Safety and Health
NDP	National Development Plan
NPV	Net Present Value
NWSC	National Water and Sewerage Corporation
PBB	Plastic Bottle Brick
PBBM	Plastic Bottle Brick Masonry
PET	Polyethylene Terephthalate
UBoS	Uganda Bureau of Statistics
Ugx./UGX	Ugandan Shilling
USD	United States Dollar
UV	Ultraviolet

ABSTRACT

Uganda faces persistent challenges of housing shortages, high construction costs, and environmental degradation resulting from unsustainable resource extraction and poor waste management. Large quantities of plastic bottles and saw dust waste remain underutilized, yet their potential as construction materials has not been sufficiently explored. This study investigated the compressive strength and cost-effectiveness of Plastic Bottle Brick (PBB) masonry walls as a sustainable alternative to conventional concrete block walls in Mbale City, Uganda. The research addressed the gap in empirical data on the structural performance of confined PBB walls with varying filler materials (uncompressed air, saw dust and pit sand). The pit sand PBB walls attained a compressive strength of 0.6 ± 0.02 MPa, which was comparable to that of the hollow concrete block walls (0.6 ± 0.06 MPa). The sawdust and air PBB walls, however, recorded lower mean strengths of 0.3 ± 0.05 MPa and 0.3 ± 0.03 MPa, respectively, which were well below the solid concrete block walls (0.8 ± 0.03 MPa). All PBB variants exhibited greater ductility, with failure strains of 1.8–2.0%, compared to 1.0–1.2% in concrete block walls. Although the PBB blocks did not meet the minimum compressive strength requirements of DS/EN 1996-1-1 DK NA:2019 for load-bearing masonry units, pit sand PBB blocks demonstrated adequate performance for small-scale or low-rise applications, while the air and sawdust filled variants were suitable for non-load-bearing infill walls. A cost-benefit analysis, based on materials, labour, time utilisation, and carbon emission costs, revealed that air PBB blocks were the most economical at UGX 11,694, followed by pit sand filled units, while solid concrete block walls were the least economical at UGX 28,759. The sawdust filled units were relatively more expensive (UGX 27,634) due to higher carbon emission costs. The study also developed a practical production method that enables PBB unit casting at a rate only 17% slower than that of conventional blocks, demonstrating commercial viability and compatibility with existing formwork systems.

Keywords: Plastic bottle brick, Masonry wall, Compressive strength, Cost–benefit analysis, Sustainable construction, Waste utilization.

CHAPTER 1: INTRODUCTION

1.1 Background

Globally, plastic waste has become a major environmental challenge because it persists in the environment and has low recycling rates. Plastic bottles, in particular, present a serious problem due to their extremely long decomposition period, which can exceed 1,000 years, and the release of toxic chemicals during degradation. These plastics contaminate soil and water and are often ingested by animals, creating health risks for both ecosystems and humans. Although plastic bottles are recyclable, only about 9% are actually recycled worldwide, while the rest accumulate in landfills or the natural environment (OECD, 2022).

In Uganda, plastic waste poses a similarly serious challenge. The National Environment Management Authority (NEMA) reports that the country produces about 600 tonnes of plastic waste each day, but only around 40% is properly collected and disposed of. The remaining 60% pollutes the environment, clogs drainage systems (see **Figure 1-1**), reduces soil fertility, and contributes to flooding, especially in urban areas (Buyondo, 2022; Muganga, 2022). The extensive pollution of water bodies such as Lake Victoria highlights the increasing threat that plastic waste poses to aquatic ecosystems and the livelihoods that depend on them.

Figure 1-1: Clogged drainage systems in Entebbe (Muganga, 2022) (left), Plastic bottle pollution of Lake Victoria (Buyondo, 2022) (right).

Efforts to manage plastic waste in Uganda have centred on reduction, reuse, recycling, and conversion into alternative products such as fuel, clothing, and materials for road construction. However, these strategies have achieved limited success in addressing the scale of the problem (Pandey, et al., 2023). As a result, innovative approaches to plastic waste management are attracting growing interest, especially those that incorporate waste materials into sustainable construction practices. One such approach is the development of Plastic Bottle Bricks (PBBs), which are produced by combining waste plastic with materials such as sand, aggregates, cement, stone dust, fly ash, or soil (Shrestha, et al., 2023). This innovation not only creates a practical use for plastic waste but also has the potential to lower construction costs and reduce the environmental impact associated with conventional building materials.

Uganda’s construction sector continues to experience challenges arising from increasing material costs and the depletion of natural resources. For example, sand extraction from Lwera wetland has caused flooding, community displacement, biodiversity loss, and damage to critical infrastructure like the Katonga Bridge (Taremwa, 2023). Sand prices have increased significantly, rising by about 45% over seven years and by 2% between September 2023 and September 2024, mainly due to shortages (UBoS, 2024). Likewise, stone dust mining, which plays an essential role in the production of concrete blocks and pavers, has led to air and water pollution, land degradation, and health problems such as silicosis and bronchitis among workers and nearby residents (Turyahabwe, et al., 2021; Leon-Kabamba, et al., 2020).

In addition to mineral-based construction inputs, other industrial by-products such as sawdust remain underutilized (see **Figure 1-2**). A study within Kampala City revealed that 69% of timber workshops discarded sawdust waste, while 22% burned it, 6% sold it as fuel, and only 3% converted it into useful energy (Sseremba, et al., 2011). Poor waste management and limited knowledge of potential uses contribute to environmental concerns. Yet, sawdust has proven valuable in various applications, including energy generation, construction, and water treatment (Udokpoh & Nnaji, 2023).

Figure 1-2: Stockpiles of underutilised sawdust at a Mbale City (Industrial area) workshop.

Uganda’s growing housing deficit, estimated at about 1.6 million homes as of 2016 (MLHUD, 2016), together with high poverty levels, where 30.1 percent of the population or about 12.3 million people live below the 2019/2020 poverty line of approximately UGX 87,000 (UBoS, 2021), and the rising cost of construction materials, underscores the urgent need for alternative building solutions. The use of waste plastic bottles in masonry construction, particularly through Confined Waste Plastic Bottle Brick (PBB) walls, offers a practical way to address both the plastic waste problem and the housing shortage while enhancing cost-effectiveness and environmental sustainability in Uganda’s construction industry. The research gap lies in the lack of scientific and contextual evidence on the structural performance, cost-effectiveness, and environmental benefits of Confined Waste Plastic Bottle Brick (PBB) masonry walls as a sustainable and affordable alternative to conventional masonry materials in Uganda.

1.2 Problem Statement

Plastic waste is a critical environmental challenge in Uganda, particularly in urban areas where only about 40 percent of plastic is collected and the remaining 60 percent ends up in the environment. Uncollected plastics contribute to water pollution, poor soil quality, and blocked drainage systems, often resulting in flooding. Improper disposal and burning of plastics release toxic chemicals, causing respiratory and other health problems. Efforts to regulate plastic use, including attempted bans, have largely failed due to weak enforcement and stakeholder interference.

Uganda generates approximately 600 tonnes of plastic waste per day, equivalent to about 219,000 tonnes annually, and a large share of this waste consists of poorly managed PET bottles. Although several studies have reported promising compressive strengths for blocks embedded with plastic bottles, there remains a shortage of peer-reviewed research on the structural performance of vertically oriented confined masonry walls, ductility/strain, failure patterns and comparative analysis with conventional materials has not been adequately investigated. This gap in structural performance and commercial viability data represents a key barrier to the broader adoption of PBB technology as a viable, sustainable, and affordable construction solution in Uganda.

The plastic waste problem is worsened by sand mining in Lwera wetland, which has caused flooding, displacement of communities, loss of biodiversity, reduced livelihoods, farmland degradation, and damage to infrastructure. Similarly, stone dust mining generates air and water pollution, land degradation, and respiratory health risks for workers and nearby residents. Furthermore, sawdust from timber processing is often discarded, creating ecological and waste management issues.

Confined Plastic Bottle Bricks (PBBs), present an opportunity to address the plastic waste crisis while also contributing to sustainable construction, reduced material costs, and mitigation of environmental degradation associated with conventional building materials.

1.3 Research objectives

1.3.1 Main objective

To evaluate the performance of PBB masonry walls through compressive strength testing and cost-benefit analysis.

1.3.2 Specific objectives

(i) To carry out comparative compressive strength analysis for the PBB blocks versus solid and hollow concrete blocks.

(ii) To determine the load carrying capacity of PBB masonry walls under axial load for varying filler materials.

(iii) To carry out cost-benefit analysis comparison between PBB masonry blocks and commercially available concrete blocks (solid and hollow) in Mbale City.

1.4 Research questions

(i) What is the difference in compressive strength between PBB blocks versus common concrete blocks?

(ii) What is the effect of axial load on PBB masonry walls for varying filler materials?

(iii) How do the cost-benefit outcomes of PBB blocks compare to those of solid and hollow concrete blocks in construction applications?

1.5 Justification

The United Nations 2030 Agenda for Sustainable Development, under Goal 14, Objective 14.1 requires a reduction in marine pollution from land-based activities. According to paragraph 221 (iv) of the National Development Plan (NDP) III, rampant degradation was partially attributed to limited; research, innovation and adoption of appropriate technologies. Additionally, paragraph 225 identifies water pollution due to unsafe disposal of Municipal waste as a major cause of increased water treatment costs, hence increased cost of water bills. Moreover, paragraph 236 emphasises the need to reduce pollution to preserve Natural Resources and the Environment. Also, objective 5, no.5, stated in table 9.1 prescribes that research to be undertaken in part by the Academia to improve resource use efficiency. This research aims at utilising plastic bottle waste in construction as an important resource, rather than being left unused in form of disposal.

1.6 Significance of the study

This study on the compressive strength of plastic bottle brick masonry walls could have significant benefits for the construction industry, environment, and society such as:

- Provide low- and middle-income citizens with a viable alternative to traditional building materials, reducing waste disposal costs and environmental impact, and encourage innovative sustainable construction practices.
- Offer waste management stakeholders a constructive solution for recycling plastic waste, mitigating the plastic pollution problem to foster a circular economy through a waste-to-resource approach.
- Provide Academia and Regulators with valuable data for revising building codes and standards to incorporate innovative, sustainable materials and support incorporation of innovative materials in building regulations.

1.7 Research scope

This research focused on evaluating the compressive strength of Plastic Bottle Brick (PBB) blocks and assessing their cost-effectiveness in comparison to commercially available solid and hollow concrete blocks in Mbale City. The literature review explored studies that are relevant and closely related to the subject matter.

The study was primarily experimental and involved several key investigations. These included comparing the compressive strength of PBBM blocks with bottles oriented vertically and horizontally, using different filler materials (uncompressed air, saw dust, and pit sand); assessing the compressive strength of PBB masonry walls under axial load; and conducting a comparative cost-benefit analysis between PBB blocks and concrete blocks (solid and hollow).

The mechanical behaviour of the wall specimens was evaluated through experimental testing. The results were analysed both photographically and analytically, with comparisons made across the different specimen types and against findings from relevant literature involving similar materials and methodologies.

Additionally, baseline surveys were conducted to gather data on mix ratios and workmanship practices for solid and hollow concrete blocks commonly used in Mbale City. Observations and measurements during the preparation of PBB blocks and concrete block specimens, paired with relevant literature also provided valuable data for the cost-benefit analysis.

The raw materials and sample preparations for the research were conducted in Mbale City. However, block and wall samples were prepared in Seeta, Mukono District, due to its proximity to the Kireka Central Materials Laboratory, where all final tests were performed. The entire research process was completed within a period of ten months, encompassing proposal development, fieldwork, data analysis, report writing, and submission of the final thesis.

1.8 Conceptual framework

This conceptual framework provides a foundation for investigating the Compressive Strength of Confined Waste Plastic Bottle Brick (PBB) Masonry Walls.

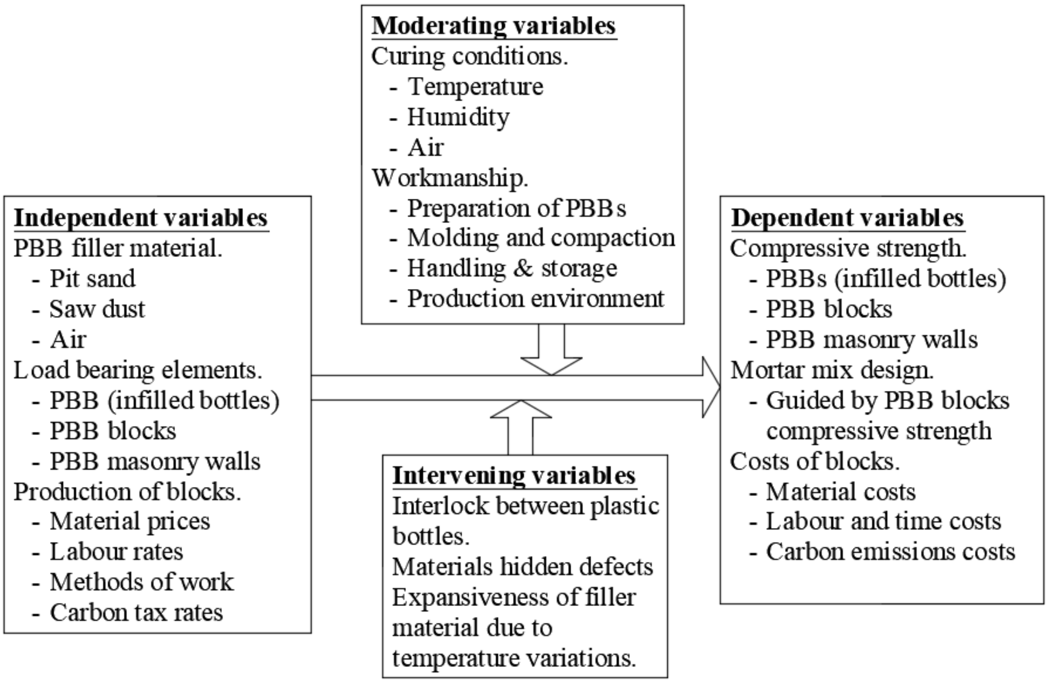


Figure 1-3: Conceptual framework for the research.

1.9 Chapter Summary

In response to Uganda's growing housing crisis marked by a 1.6-million-unit deficit and 30.1% of the population living in poverty; this study investigates a sustainable, cost-effective alternative to conventional masonry materials. Environmental degradation from sand and stone dust mining, as well as mismanaged waste streams like plastic bottles and sawdust, has worsened ecological and health issues across the country. Plastic bottles, which make up a significant portion of unmanaged urban waste, contribute to flooding and pollution, while sawdust and stone dust are poorly utilized and pose health risks. Against this backdrop, this research aims to assess the compressive strength and cost-effectiveness of Confined Waste Plastic Bottle Brick (PBB) masonry units, which incorporate plastic waste with filler materials such as uncompressed air, sawdust and pit sand. The study explores the influence of bottle orientation (vertical and horizontal), compares the mechanical performance of PBB units with commercially available concrete blocks (solid and hollow), and evaluates their economic viability. Conducted through a structured experimental approach in Mbale City, this research aligns with Uganda's National Development Plan III and the UN Sustainable Development Goals, providing a framework for sustainable construction practices and circular waste management.

CHAPTER 2: LITERATURE

2.1 Introduction

Globally, plastic waste management remains a critical environmental challenge, with plastic production exceeding 400 million tonnes annually, of which only about 9% is recycled, while the rest is either incinerated, disposed of in landfills and the environment (OECD, 2022). This accumulation of plastic waste has intensified concerns over pollution, ecosystem degradation, and greenhouse gas emissions. In sub-Saharan Africa, inadequate waste collection and limited recycling infrastructure have worsened the crisis, leading to the accumulation of non-biodegradable plastics in water bodies, soils, and urban drainage systems.

In Uganda, plastic waste generation is estimated at approximately 600 tonnes per day or about 219,000 tonnes annually, with 60% of this waste left uncollected and improperly disposed of (NEMA, 2022). Polyethylene terephthalate (PET), primarily used in beverage bottles, constitutes a significant portion of this waste stream. The ineffective management of plastic waste in Uganda contributes to severe environmental and public health challenges, including clogged drainage systems, flooding, and pollution of major water bodies such as Lake Victoria (Muganga, 2022; Buyondo, 2022).

Amid these challenges, the growing global movement toward a circular economy has promoted innovative reuse and recycling approaches that convert plastic waste into valuable products, including construction using Plastic Bottle Brick (PBB) as a sustainable strategy to reduce environmental pollution while addressing the rising housing deficit and high construction material costs in Uganda.

This chapter reviews existing literature on plastic waste management, traditional masonry materials, and the emerging application of waste plastics in construction. It further examines the mechanical performance and cost-effectiveness of Plastic Bottle Brick (PBB) masonry systems, leading to the identification of research gaps that this study seeks to address.

2.2 Housing Deficit in Uganda

The Ugandan housing situation in 2016 was characterized by inadequate housing in terms of quality and quantity, both in rural and urban areas with a housing deficit of about 1.6 million housing units. The National Housing Policy 2016 recommended that, to improve the quality of houses; continual technology and material improvements be made (MLHUD, 2016). Uganda has witnessed an increase in rural-urban migration with the 2023 urban population growth rate standing at 5.3% a year. While Uganda’s unemployment rate of 2.9%, which is one of the lowest in the region, affordability remains a key challenge. With poverty affecting 30% of the population, the dream of owning a decent home, such as a two-bedroom house priced at UGX 205 million (US$ 54,719), remains elusive for most low-income Ugandans. The country's rapid population growth of 3% and urbanization rate are exacerbating the housing shortage, resulting in a significant gap between demand and supply. As of 2023, the housing deficit stood at 2.4 million units (CAHF, 2023).

According to the Uganda National Survey Report 2019/2020, basing on the poverty line of about UGX 87,000, the share of Ugandans living in poverty stood at 30.1%, representing 12.3 million poor persons in 2019/20. Nearly 33.8% of the rural population and 19.8 % of the urban population are living in poverty (UBoS, 2021). This emphasises the need for cost effective construction materials, to partially address the housing deficit problem.

2.3 The need for change: Limitations of traditional construction methods

2.3.1 Traditional Clay bricks

The National Housing and population census of 2014 showed that burnt clay bricks are the most commonly used walling material at 36.4%. However, due to wide variations in clay brick strength ranging between 1.62 – 8.49N/mm^2, and limited information on clay brick mechanical properties, 24 structural engineering consultancy firms in Uganda surveyed had never designed clay bricks for load bearing (Stephen, 2020). Another study undertaken in Budondo Sub-county, in Jinja District revealed that the soil characteristics weren’t sufficient for brick making, with an average strength of 1.9N/mm^2 for blended bricks (Nandugwa, et al., 2021). This would suggest that some areas in Uganda don’t have suitable soil for bricks production. Additionally, traditional bricks are regarded as a durable building material; however, its production is environmentally damaging due to low product quality, inefficient manufacturing processes, and the reliance on local wood for kiln firing, which contributes to deforestation and air pollution (Hashemi, et al., 2015).

In contrast, a Plastic bottle brick (PBB) filled with sandy soil was revealed to have a mean strength of about 8.98N/mm^2 (Patel, et al., 2019). Another study on Plastic bottle bricks filled with crushed construction and demolition waste revealed a compressive strength of about 5.85N/mm^2, and a 280x160x240mm Plastic bottle brick masonry unit of compressive strength of 3.35N/mm^2 (Priya, et al., 2018). The variation in PBB strengths can be attributed to differences in bottle geometry, filler materials, and production methods. Despite these variations, plastic bottle bricks demonstrate strong potential as a viable alternative to traditional masonry.

2.3.2 Sand

Sand mining takes place in the Lwera wetland, which is near Lake Victoria, and is a key ecosystem. However, problems like flooding, fish and human displacement, road destruction, loss of biodiversity, reduced livelihood of the residents due to reduction in the long horned grasshopper population (these are caught, eaten and sold), loss of farmland, and collapse of the Katonga bridge due to flooding are all effects attributed to sand mining in the wetland (Taremwa, 2023).

According to a Uganda Bureau of Statistics (UBoS) report for September 2024, the construction input price index for sand in September 2024 was 145.24 in comparison to 100 in the base year 2017. This infers that there was a 45% rise between 2016 to 2024, and a 2% increase between September 2023 to September 2024 (UBoS, 2024). Due to such challenges, this research aims to reduce the use of sand in masonry work.

2.3.3 Stone dust

Stone dust is a by-product generated during the quarrying process, specifically when stones are crushed and sized to meet desired specifications (Silva, et al., 2023). However, the extraction and processing of stone dust release significant quantities of fine particulate matter, contributing to air and water pollution, land degradation, and the disruption of local ecosystems (Turyahabwe, et al., 2021). In addition to environmental harm, prolonged exposure to airborne stone dust poses serious health risks, including respiratory illnesses such as silicosis, chronic bronchitis, and other lung-related conditions. These risks are especially high for workers directly involved in quarrying activities and for residents living near mining sites (Leon-Kabamba, et al., 2020). In the case of Mbale City, most of the stone dust is sourced from the nearby Tororo District.

2.3.4 Concrete blocks

Although concrete is strong and durable, it is often regarded as environmentally harmful due to the high energy consumption involved in cement production. Nevertheless, compared to burned bricks, concrete may be more sustainable, as the manufacturing of burned bricks is generally inefficient and energy-intensive, leading to a greater environmental impact (Hashemi, et al., 2015). Additionally, the larger size and heavier weight of concrete blocks pose greater challenges in transportation and handling compared to clay bricks (Mushoborozi, 2023). This study aims to provide a lighter and cheaper alternative to concrete blocks.

2.4 Underutilized waste resources

2.4.1 Waste plastic bottles

Bottled water is a popular commodity with a multi-billion-dollar industry. Each plastic water bottle takes up to 1,000 years to decompose. These bottles leak harmful chemicals (believed to cause a variety of health issues, including reproductive problems and cancer) into our environment as they decompose. Plastic water production produces millions of tons of Carbon dioxide (CO_2), a major contributor to climate change (Eco friendly habits, 2021). The rise in the production of global plastics has overtaken that of almost other material in history (Dadzie, et al., 2020). In Kampala, Uganda's capital and largest city, plastic litter limits the flow of storm and waste water (Propa, 2018). Plastic bottle trash is a manageable (reuse & recycling) waste, but its disposal pollutes the environment (Furkhan, et al., 2023). Only one in six plastic bottles are properly recycled (Parab, et al., 2021).

In addition, the increased disposal of plastic materials and high durability of plastic products greatly impacts marine and coastal environments. The often-desirable characteristics of plastic such as low density and high durability become a big disadvantage once the material is in the environment (Villafañe, et al., 2018). To achieve sustainable consumption and production, as well as a circular economy, it is essential to reduce the use of raw materials and lower greenhouse gas emissions, while ensuring the continuous recycling and reuse of materials in a closed-loop system (Woldegiorgis, 2017).

Plastic bottle physical properties

Plastics are remarkably versatile materials, offering a unique combination of benefits, including affordability, low weight, high strength, durability, and resistance to corrosion, as well as excellent thermal and electrical insulation properties (Woldegiorgis, 2017). Thin-walled plastic bottles are manufactured using an injection stretch-blow moulding (ISBM) process, which creates a complex orientation pattern in the polyethylene terephthalate (PET) material. The biaxial orientation of the polymer chains varies along the axis of the bottle, leading to a non-uniform distribution of molecular orientation (Villafañe, et al., 2018). The typical properties of a PET bottle are as shown below:

Table 2-1: Typical physical properties of PET bottles (Priya, et al., 2018).

Property	**Result**
Chemical formula	$(C_{10}H_8O_4)n$
Density	$1.38 g/cm^3$ (20^oC)
Melting point	$>250^oC$, 260^oC
Boiling point	$>350^oC$ (decomposes)

Plastic Bottle Mechanical properties

Tensile tests were performed on PET bottle samples in accordance with ISO 527-3-1995, using a Lloyd LR30 K Tensile Test machine with a testing speed of 50 mm/min, and the results showed that the maximum tensile strength of the reused PET material ranged from 48.3 to 72.4 MPa. The tensile strength of the samples was affected by both the cutting method and the orientation of the samples. Notably, samples cut horizontally had their molecular chains aligned differently than the direction of the load, resulting in a shorter elongation before breaking, but exhibited a slightly higher strength (around 5%) compared to those cut vertically. Furthermore, the study found that degradation had a minimal impact on the tensile strength of the samples. Ultraviolet (UV) light exposure was found to be the most effective, followed closely by thermal degradation at elevated temperatures. (Villafañe, et al., 2018).

2.4.2 Saw dust waste

A study done on Timber workshops in Kampala City in 2011 revealed that, the commonest type of wood waste was planer shavings which were not utilised effectively. 69% of workshops discarded the sawdust waste, 22% burn it, 6% sold it as fuel, and 3% converted it into useful energy. The poor waste management was attributed to the limited knowledge of utilisation of these wastes (Sseremba, et al., 2011). Sawdust is one of the most underused wood waste portions, with masses dispersed around the region, detracting from its visual appeal, nuisance at saw mills and causing other ecological concerns. Saw dust has been used in energy generation, building construction, pollution containment, and water treatment/supply. It was recommended that sawdust waste management should be based on recovering, reusing, and recycling before considering disposal. Landfilling of sawdust is a counterproductive and retrogressive management strategy because, sawdust is a production by-product and not necessarily a waste material as it is generally perceived (Udokpoh & Nnaji, 2023).

2.5 A viable alternative: Plastic bottle brick (PBB)

2.4.1 Background of plastic bottle bricks

The strength of PBB has been often doubted by the general public, since they're made up of plastic bottles. Packing sand into plastic bottles is a technique that started around 2009 in India, South and Central America; and it was named “bottle brick” technology. It was also said that the bottle bricks are nearly 20 times stronger than common bricks (Parab, et al., 2021).

2.4.2 Preparation of plastic bottle brick

The following is a procedure for preparation of the plastic bottle bricks; (i) collection of waste PET bottles, (ii) preparation of the filler material, (iii) filling of the PET bottles with the prepared filler material, (iv) compaction of the fill material in multiple layers by tamping each layer with 25 blows and finally closing the cap (Priya, et al., 2018).

2.4.3 Mechanical properties of plastic bottle bricks

An indirect tensile strength for a cylindrical PBB according to ASTM C496/C496M, revealed a tensile strength of 16MPa (Preethi, et al., 2019). Furthermore, a compressive strength test revealed that 500ml and 600ml PBBs in the horizontal orientation had a load bearing capacity of 115kN and 230kN respectively, in comparison to a common brick having a load bearing capacity of 50kN (Priya, et al., 2018).

2.4.4 Practical application of PBBs in construction

Utilizing waste plastic bottles as a construction material is a potential solution to help address the housing shortage in developing countries, while conserving natural resources and reducing the environmental impact of traditional building materials. (Dadzie, et al., 2020). Plastic bottles are considered as urban junk, but with its sustainable characteristics it could be used as a substitute construction material (Parab, et al., 2021).

‘Plastic Bottle Village’ constructed in Panama, in which a complete two floor house was constructed from PET plastic bottles (Villafañe, et al., 2018). The Plastic Bottle Village is home to 120 sustainable homes and a few other buildings constructed with plastic, and this project used over one million plastic bottles (see **Figure 2-1**). The bottles were encased in concrete for aesthetic appeal. This makes them resemble regular homes while providing excellent insulation (Pritchard, 2023).

Figure 2-1: Construction of the plastic bottle village, located on the island of Bocas del Toro in Panama.

Furthermore, the 9-story exhibition hall/Eco-park pavilion in Taipei, Taiwan constructed in 2010 used 1.5 million recycled bottles where the bottles were designed using interlocking grooves, requiring little sealant for attachment as shown in **Figure 2-2**. This structure was designed to resist earthquakes and fires (Pritchard, 2023).

Figure 2-2: The 9-story exhibition hall in Taipei, Taiwan made from recycled plastic water bottles (Pritchard, 2023).

A Plastic Bottle House in Nigeria was made by packing plastic bottles with sand and then stacking and binding them with mud and strings. The developers used approximately 14,000 PET plastic bottles to build the house (see **Figure 2-3**). The house is apparently 18 times stronger than traditional houses made with regular bricks. Therefore, it could withstand earthquakes and strong winds (Pritchard, 2023). This claim is supported by Priya et al. (2018) who found that plastic bottle bricks were about 20 time stronger than traditional bricks in compression.

Figure 2-3: An image from an Aljazeera English video showing the construction of a plastic bottle house in Nigeria.

Bottle Schools have been thriving in the rural areas of Guatemala due to high poverty levels. 133 bottle schools have been built in Guatemala at an average cost of $8,500 per building, by collecting plastic bottles and filling them with inorganic materials to make “eco-bricks”/plastic bottle bricks. The filler materials used include; polystyrene, plastic bags, and chip packets (see **Figure 2-4**). After filling the bottles, they are bound with mud or concrete to form strong walls (Pritchard, 2023).

Figure 2-4: Plastic bottles constructed in Guatemala, using a vertical bottle orientation.

2.4.5 Benefits of plastic bottle bricks (PBBs)

One of the significant advantages of using waste plastic bottles as a building material is that they do not require a curing time, unlike traditional bricks which need 28 days to cure. Additionally, the production of bricks is a major contributor to carbon emissions, whereas using plastic bottles as a building material generates significantly less emissions. Moreover, plastic bottles have a durability of over 300 years, surpassing that of standard bricks, and their split tensile strength is comparable to that of traditional bricks (Preethi, et al., 2019). Furthermore, PBBs have benefits of reduced weight, cost savings, and environmental friendliness in comparison to traditional burnt clay bricks (Dadzie, et al., 2020).

Cement and bricks manufacturing processes contribute to a high emission of Carbon Dioxide (CO_2) which increases global warming. A bottle filled with mud or sand is as strong as a brick and could achieve the same purpose as a brick. Red mud and fly ash based Geopolymer can act as a green alternative to cement. Much less energy consumption (Gawade, et al., 2020).

2.4.6 Paradoxes of plastic bottle bricks

The following paradoxes were identified in utilising plastic bottle bricks for construction based on Li (2022):

- Plastic bottle bricks may deform under high pressure which limits its load bearing application. However, more recent studies have shown that bottle bricks are even stronger than the traditional bricks, with some almost 20 times stronger than traditional bricks.

- Plastics are highly flammable, and risk emission of poisonous gases including; dioxins, furans, mercury, and polychlorinated biphenyls. However, most plastic bottle bricks are densely packed to a proper density to limit the volume of oxygen, hence reducing the risk of it catching fire. Another effective way of reducing the fire risk is by providing mortar covering.
- Danger of cement reaction with the plastic bottles due to the alkaline nature of Portland cement, risking damage to the structural integrity of the building. Utilization of low PH cement is one of the viable solutions recommended, with some studies recommending using earthen mortar (organic mixture of cement, clay, sand, and straw).
- Another limitation of using plastic bottles as building materials is their susceptibility to temperature fluctuations, which can cause undesirable changes in their physical, mechanical and geometrical properties. For instance, extreme heat can make the plastic bricks soft, while cold temperatures can make them brittle, potentially leading to fracture and damage of the plastic bottle. However, applying a layer of cement mortar and paint can help protect the plastic bottle bricks from UV radiation, heat, and frictional degradation, reducing the risk of leaching.

2.6 Cost-benefit analysis

2.6.1 Definition

Cost- benefit analysis is a process of identifying, measuring and comparing the benefits and costs of an investment project or program. The role of the cost-benefit analyst is to provide information to the decision maker (Campbell & Brown, 2023). A cost-benefit analysis is the process of comparing the projected or estimated costs and benefits associated with a project decision to determine whether it makes sense from a business perspective. Cost‐Benefit Analysis (CBA) is an analytical tool for judging the economic advantages or disadvantages of an investment decision by assessing its costs and benefits in order to assess the welfare change attributable to it (European Commision, 2015). CBA involves tallying up all costs of a project or decision and subtracting that amount from the total projected benefits of the project or decision (Stobierski, 2019). A CBA has done between the proposed PBBM blocks, and Concrete Blocks (hollow and solid) for this study.

2.6.2 Steps in carrying out cost-benefit analysis

The following steps were recommended by Stobierski (2019), on how to carry out a CBA;

i. Establish a Framework for Your Analysis

To ensure accuracy in your analysis, begin by clearly defining the objectives that indicate a successful outcome. This clarity helps in identifying and understanding the associated costs and benefits. Next, establish a consistent metric for measuring and comparing these factors. While this metric is often monetary, it can also represent other units, as long as both costs and benefits are evaluated using the same standard.

ii. Identify Your Costs and Benefits

The next step involves compiling two detailed lists: one outlining all projected costs and the other highlighting the expected benefits of the proposed project or action. Begin by identifying direct costs, which include expenses directly associated with the production, development, or implementation of a product, service, or decision. These may include labour, manufacturing, materials, and inventory costs. Beyond these direct costs, it is essential to account for additional cost categories:

- **Indirect costs:** Fixed expenses such as utilities, rent, and administrative overhead that support overall operations.
- **Intangible costs:** Difficult to measure impacts like reduced customer satisfaction, which may lead to lower repeat business.
- **Opportunity costs:** The potential benefits forgone when choosing one course of action over another.

After identifying all relevant costs, attention should be given to the potential benefits of the proposed decision or initiative. These benefits can be categorized as follows:

- **Direct:** Tangible gains such as increased revenue or sales from a new product.
- **Indirect:** Positive secondary effects, like greater customer engagement or brand recognition.
- **Intangible:** Non-monetary advantages, such as enhanced employee morale or improved workplace culture.
- **Competitive:** Strategic advantages, such as being the first to enter a new market or adopt an innovative approach.

By considering both the full range of costs and the various types of benefits, a more balanced and insightful cost-benefit analysis can be conducted.

iii. Assign a Value to Each Cost and Benefit

After compiling comprehensive lists of all costs and benefits, the next step is to assign appropriate monetary values to each item. This creates a common basis for comparison. Direct costs and benefits are usually easy to quantify, while indirect and intangible ones can be more difficult. Still, it’s important to include them.

iv. Tally the Total Value of Benefits and Costs and Compare

Once all costs and benefits have been assigned monetary values, the next step is to total each list and compare the results. If the overall benefits exceed the total costs, the project or decision may be justified. Conversely, if the costs outweigh the benefits, it may be necessary to reconsider or revise the proposal. If the analysis indicates that costs exceed benefits, explore whether alternative approaches have been overlooked. There may also be opportunities to reduce costs or adjust the proposal in a way that achieves the desired outcomes more efficiently and affordably.

CBA decision making process using the Kaldor- Hicks Criterion

The decision-maker can be seen as standing at a point in a decision tree (**Figure 2-5**), where X represents the benefit of a project and Y represents its opportunity cost. If $(X - Y) > 0$, it means the project is a better use of resources than the next best alternative. This idea is based on the Kaldor-Hicks Criterion, which states that a project provides a net benefit if those who gain from it could, in theory, compensate those who lose out. However, in reality, redistributing benefits through taxes or fees can distort people's behaviour and create additional costs for the economy. Because of this, the decision-maker might decide that trying to balance gains and losses isn't worth the economic burden it would create (Campbell & Brown, 2023).

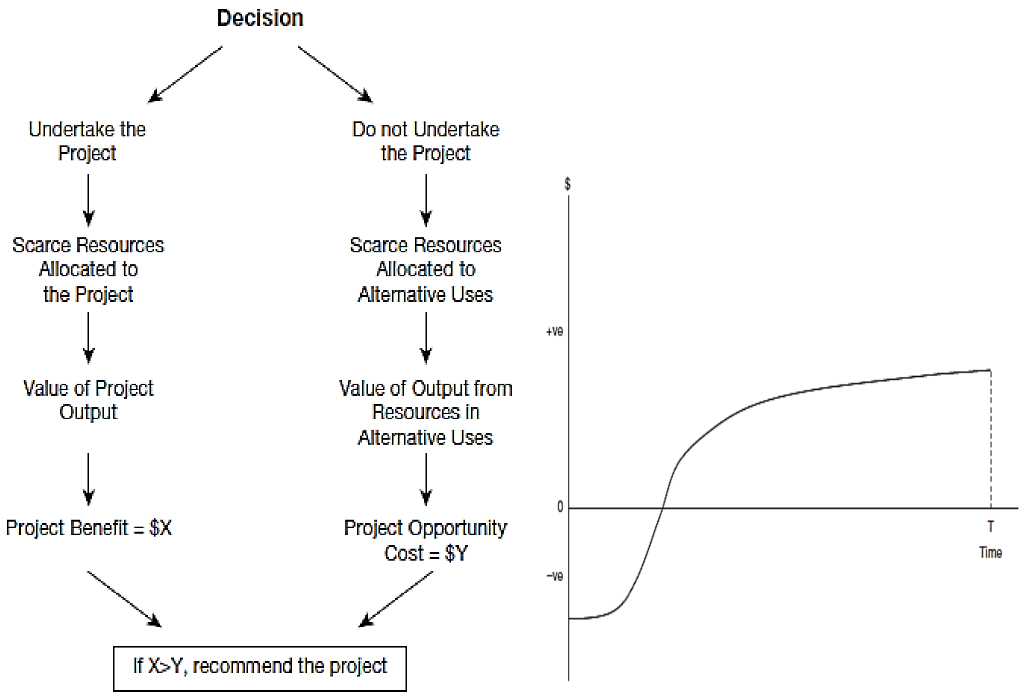


Figure 2-5: Decision making process for cost-benefit analysis (left), Typical time- stream of project net benefits (right) (Campbell & Brown, 2023).

The net present value (NPV) is the measure of the extent to which the proposed project is a better (NPV > 0) or worse (NPV < 0) use of scarce resources than the next best alternative. When computing present values for use in a cost- benefit analysis, there’s a need to decide on the appropriate discount rate. The discount rate tells us the rate at which we are willing to give up consumption in the present in exchange for additional consumption in the future (Campbell & Brown, 2023).

2.6.3 Frameworks for cost-benefit analysis

The analytical framework of CBA refers to a list of underlying concepts followed in a CBA, and is as follows (European Commision, 2015):

Opportunity cost: The opportunity cost of a good or service is defined as the potential gain from the best alternative forgone, when a choice needs to be made between several mutually exclusive alternatives.

Long‑term perspective: A long‑term outlook is adopted, ranging from a minimum of 10 years to a maximum of 30 years or more, depending on the sector of intervention. Hence the need to: set a proper time horizon; forecast future costs and benefits (looking forward); adopt appropriate discount rates to calculate the present value of future costs and benefits; take into account uncertainty by assessing the project's risks.

Calculation of economic performance indicators expressed in monetary terms: CBA is based on a set of predetermined project objectives, giving a monetary value to all the positive (benefits) and negative (costs) welfare effects of the intervention. These values are discounted and then totalled in order to calculate a net total benefit. The project overall performance is measured by indicators, namely the Economic Net Present Value (ENPV), expressed in monetary values, and the Economic Rate of Return (ERR), allowing comparability and ranking for competing projects or alternatives.

Microeconomic approach: CBA is typically a microeconomic approach enabling the assessment of the project's impact on society as a whole via the calculation of economic performance indicators, thereby providing an assessment of expected welfare changes. While direct employment or external environmental effects realised by the project are reflected in the ENPV, indirect (i.e. on secondary markets) and wider effects (i.e. on public funds, employment, regional growth, etc.) should be excluded. It is recommended, however, to provide a qualitative description of these impacts to better explain the contribution of the project to the EU regional policy goals.

Incremental approach: CBA compares a scenario with‑the‑project with a counterfactual baseline scenario without‑the‑project. The incremental approach requires that: a counterfactual scenario is defined as what would happen in the absence of the project. This takes into account all the investment, financial and economic costs and benefits resulting from the project.

2.7 Carbon embedded in materials

2.7.1 Carbon tax system

The World Bank Group carbon taxing system was adopted as an incentive to reduce carbon emissions, and this criterion was used to quantify the carbon cost for this study. However, Uganda hasn't yet implemented this carbon tax system yet, and as of 2024, South Africa was the only African country which had adopted this carbon tax system. Carbon taxes worldwide were ranging between USD 0.46 to USD 167 (World Bank Group, 2024), hence the minimum tax of USD 0.46 (about Ugx. 1,668) per ton of CO_2 emissions was used for this study. These carbon tax rates were determined based on data available on 30th May, 2025.

2.7.2 Carbon emissions for materials production

A study by the Beverage Industry Roundtable in 2012 concluded that the carbon footprint of a 500ml plastic bottle was estimated at 83g (Beverage Industry Environmental Roundtable, 2012), which is about 4.15tons of CO_2 per metric ton of plastic bottles produced. Cement production emits about 0.5071 tons of CO_2

per metric ton of cement produced (IPCC, 2006), which is about 507kg of CO_2 per kg of cement produced. Stone dust, a by-product of crushing stone into aggregates, has an estimated carbon emission factor of approximately 8.1 kg CO_2 per ton (Meddah, 2017). According to Henderson et al. (2024), the most carbon-intensive method of sand extraction has been reported to emit up to 11.73 kg CO_2 per ton. On the other hand, sisal rope produces about 0.72kg of CO_2 per kg of sisal rope produced (CarbonCloud, 2024). Furthermore, 1.567 tonne of CO_2 is emitted per ton of timber processed (Arup, 2023).

The selected carbon emissions figures were deemed appropriate for this analysis because they correspond to the materials used in this study, through comparable industrial processes. These processes typically involve similar energy inputs, raw material extraction methods, and manufacturing technologies, which collectively result in similar levels of greenhouse gas emissions. As such, using these figures ensures consistency and reliability in estimating the carbon emissions for different materials used in the production of the masonry units to be compared.

2.8 Previous studies on plastic bottle brick (PBB) masonry in construction

A ‘composite eco-brick’ consisting of three plastic bottle bricks embedded into cement mortar to form blocks of 230×100×70mm in size; was then tested under a Compression Testing machine, in comparison to a common brick. It was found that the composite eco-brick gave a 12-17% higher compressive strength in comparison to the common brick selected, and about 7% higher compressive strength when arranged into a prism (Priya, et al., 2018). A Plastic bottle block of dimensions 300×300×300mm mould, consisted of eight PBBs per block, and the voids filled with cement mortar. The blocks containing unsaturated sand filled PBB underwent compressive tests that revealed a compressive strength of 0.623MPa (Mansour, et al., 2015).

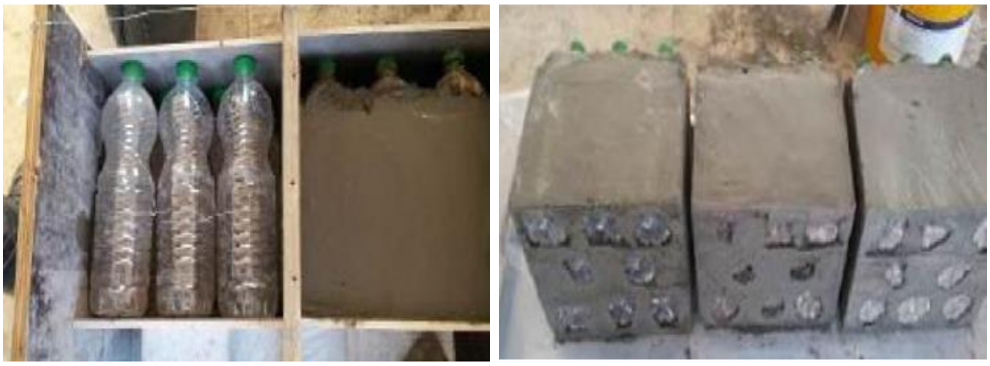


Figure 2-6: Preparation procedure for PBBM blocks (Mansour, et al., 2015).

Figure 2-7: PBB/Eco-brick, Composite eco-brick, and Eco-brick prism (Priya, et al., 2018).

Table 2-2: Literature summary on Plastic bottle brick technologies.

Citation	**Journal**	**Title**	**Finding**
(Mansour, et al., 2015)	Energy for Sustainable Development	Reusing waste plastic bottles as an alternative building material.	• Blocks with air filled bottles had higher strength of 0.69N/mm^2 than sand of 0.62N/mm^2, better thermal insulation than traditional masonry, and can be used for multi-storey building.
(Parab, et al., 2021)	International Research Journal of Engineering and Technology	Use of waste plastic bottle as a conventional construction material.	• The density of the filler material increases the compressive strength of the PBB. • 35% cost saving compared to brick construction for 1m^3 masonry.
(Priya, et al., 2018)	International Research Journal of Engineering and Technology	Replacement of bricks with plastic bottles in construction.	• 500 & 600ml PBBs a load bearing capacity of (115 & 230kN respectively) is higher than conventional bricks (50kN) • Blocks made from PBB had a higher compressive strength of 6.54 - 6.85 N/mm^2 compared to conventional brick of 5.85 N/mm^2.
(Patel, et al., 2019)	International Research Journal of Engineering and Technology	Recycling Plastic Bottle Structure	• PBB wall is 56% cheaper than traditional brick masonry. • Weight and compressive strength of a PBB (8.99 N/mm^2) is almost the same as a standard brick (10 N/mm^2).
(Raut, et al., 2015)	Journal of Advance Research in Mechanical and Civil Engineering	Investigating the Application of Waste Plastic Bottle as a Construction Material- A Review	• PBB structures have a better response to seismic activity and accidental/shock loads than bricks and blocks. • Non-brittle nature of PBB reduces construction waste. • It's environmentally friendly and energy efficient to make PBBs.
(Preethi, et al., 2019)	International Research Journal of Engineering and Technology	Reuse of Plastic Bottles in Construction of Buildings	• No curing time required for preparation of PBBs. • PBBs have a split tensile test value of 16 N/mm^2. • PBB construction is commercially feasible.

A review of previous studies (**Table 2-2**) reveals that significant progress has been made in demonstrating the feasibility of using waste plastic bottles in masonry construction. Research by Masour et al. (2015), Priya et al. (2018), and Parab et al. (2018) confirmed that PBBs can achieve compressive strengths comparable to or greater than conventional clay bricks, with cost savings of up to 35%. These studies also highlighted the environmental benefits of plastic reuse, such as reduced landfill accumulation and lower carbon emissions compared to traditional brick production. Furthermore, Patel et al. (2019) found that PBB masonry walls could be up to 56% cheaper than traditional brick masonry, reinforcing the economic potential of this technology for low-cost housing.

However, despite these promising findings, the reviewed studies exhibit several methodological and conceptual limitations. Most of the investigations focused on infilled bottle and masonry unit scale compressive tests rather than full-scale wall behaviour, offering limited insight into structural performance under realistic compression loading conditions. The majority of experiments examined horizontally oriented bottles, neglecting vertical configurations that could influence load transfer, ductility, and confinement effects. Moreover, few studies reported standardized testing protocols, making it difficult to compare results across experiments or to establish reliable performance benchmarks.

In terms of materials and construction methods, significant variability exists in bottle sizes, filler materials (sand, soil, or demolition waste), and binding agents used, resulting in inconsistent performance data. While some studies achieved high compressive strengths, the dependence on high grade cement mortar or concrete infill compromises the low-cost and eco-friendly intent of PBB technology. Additionally, very few studies have conducted comprehensive cost-benefit analyses to quantify the true economic and ecological advantages of PBB masonry compared to conventional systems.

Overall, the existing body of knowledge demonstrates that PBBs have strong potential as a sustainable construction alternative, but the lack of standardized methodologies, limited data on vertically confined wall systems, and insufficient evaluation of structural and economic performance at scale constitute major knowledge gaps. Addressing these gaps is crucial to establish PBBs as a viable, structurally sound, and cost-effective building technology for sustainable housing in Uganda and similar contexts.

2.9 Chapter summary

This chapter reviewed literature on conventional masonry materials and the development of Plastic Bottle Brick (PBB) masonry as a sustainable construction alternative. Uganda continues to face a severe housing deficit, high poverty levels, and increasing material costs, highlighting the need for affordable and environmentally friendly building solutions. Although previous studies have demonstrated that PBBs can achieve satisfactory strength and cost advantages, most research has been limited to small-scale or horizontally oriented specimens. There is little information on the structural behaviour of vertically confined PBB walls, their compressive strength, ductility, and overall performance under load. In addition, past studies provide limited cost-benefit analysis to support large-scale application. These gaps form the basis of this study, which aims to evaluate the structural performance, and cost-effectiveness, of vertically confined PBB masonry walls as a viable alternative for low-cost housing in Uganda.

CHAPTER 3: METHODOLOGY

3.1 Introduction

This chapter provides an overview of the research approach and methods used to conduct this study. A mixed-methods research design was employed, incorporating both qualitative and quantitative approaches, as well as experimental methods. The research involved survey of the concrete block makers, laboratory staff, collection of plastic bottles, mobilisation of materials (cement, sand, sisal rope, and stone dust) from local suppliers, making and testing of mortar cubes, Plastic Bottle Brick (PBB) masonry units, and PBB masonry walling units.

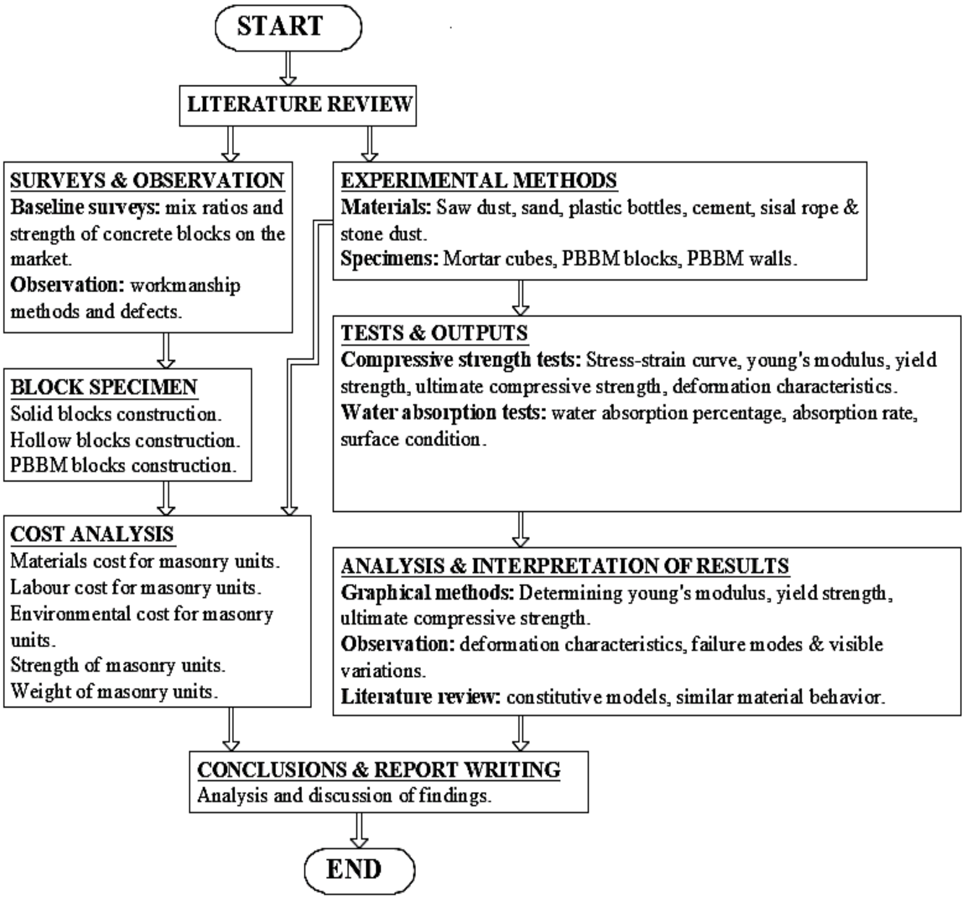


Figure 3-1: Methodology flowchart.

3.2 Data Collection

3.2.1 Data from concrete block makers

The concrete block makers' population selected and waste plastic bottles were from Mbale City. Due to an unknown population, a sample was selected to represent the perspective of all concrete block makers. The sample size was derived from an unknown population size, for a 95% confidence level and a 1% error margin; giving about 96 respondents as the minimum sample size using the formula:

$n = \frac{Z^2.p.(1-p)}{E}$ where;

n - is the sample size

Z - is the z-score (For a confidence level of 95%, the z-score is 1.96)

p - is the estimated proportion of the population which has the attribute in question (since the population is unknown, we will use 0.5 to maximize sample size)

E - is the margin of error (for example, if you can tolerate a 1% error, E would be 0.01)

3.2.2 Data from materials laboratories

The properties of concrete blocks sampled at various concrete block laboratories provided information on the compressive strength, mix ratios and dimensions of concrete blocks used in the field. This formed a baseline for custom concrete blocks which were scaled to match the volume of the PBBM blocks. Furthermore, mortar mix ratios were established using data from the Mbale Works materials laboratory.

3.2.3 Ethical Statement

Interviews were conducted to document concrete block-making practices in Mbale City, Uganda. Participation was voluntary, and respondents were assured anonymity. All respondents were aged 18 years or older, and informed consent for participation in the interviews was obtained verbally. Verbal consent was chosen to respect the respondents' convenience, as majority were engaged in block making activities at the time of data collection.

3.2.4 Sample sizes for plastic bottles

The selection of plastic bottles for this study was based on a random sample of 100 bottles obtained from a stockpile of waste plastic bottles. Analysis of the sample revealed that 67% were Elgon Water bottles, which were therefore adopted as the representative bottle type for the experimental work. Due to financial constraints, a minimum of three specimens was prepared and tested for each experimental category, namely the infilled plastic bottles (PBBs), PBB blocks, and PBB masonry walls.

3.3 Materials and Methods

3.3.1 Materials

a) Plastic bottles with bottle caps

A sample of 200 waste plastic bottles collected from various restaurants, social gatherings, and dumping points in Mbale City revealed that; 230mm high "Elgon" bottled water (500ml) had the highest population of 65% waste plastic bottles, followed by 18% consisting of 200mm high "Mirinda" soda bottles (330ml). Plastic bottles used for study were based on the highest population of plastic bottles, from the same manufacturer/company, to ensure uniformity. The bottles selected for testing had an approximately cylindrical geometry to allow for a more consistent construction as shown in **Figure 3-2**.

Figure 3-2: Stockpile having over 5000 bottles from which plastic bottles were collected (left), Plastic bottles used for making PBBs (right).

b) Saw dust

Saw dust waste as a bi-product of timber processing, was obtained from a timber processing workshops within Mbale City. Three major categories of timber waste were found as shown in Figure 3-3. Type (a), derived from sanding works, was the finest in particle size and rarest, hence most expensive at a cost of Ugx. 12,000 per sack. Type (c), derived from the timber lining process, was the largest in particle size and commonest, hence cheapest at a cost of Ugx. 2,000 per sack. Type (b), derived from the cutting process, comprised of the medium size and had relatively good availability, hence moderate a cost of Ugx. 5,000 per sack.

Type (b) was selected for its relatively workable particle size, sufficient availability and relatively low cost.

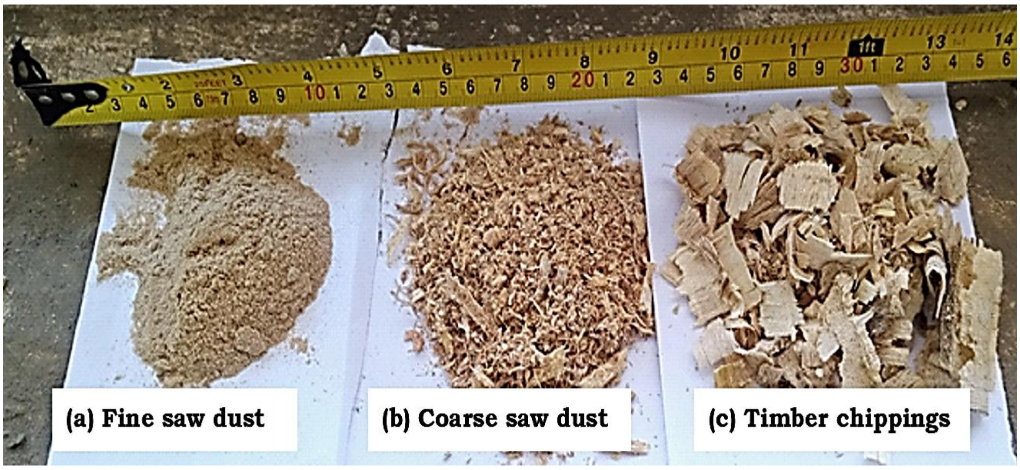


Figure 3-3: Categories of timber waste found at the timber workshops.

The workshops processed mostly formwork timber of type Mvule (Milicia excelsa), which is often used for making formwork boards and household furniture. The process identified to produce the highest saw dust waste volume was the cutting process for boards.

c) Cement

Pozzolanic Cement CEM IV B (P) 32.5N - PC (Tororo Cement), which is widely used in Uganda, and was acquired from hardware shops. This cement was used to make all concrete blocks and all mortar mixes used in this study.

d) Pit sand

Pit sand which is commonly available all over Uganda, and was acquired from local materials dealers from Mbale City and Seeta, Mukono District due to its proximity to the labs, however, a sieve analysis revealed high similarity in the particle distribution. This sand was used to fill the PBBs and to cast the PBBM units, due to its higher workability and adhesive properties in comparison to river/lake sand.

e) River sand

River sand, which is commonly used for most structural works in Uganda was sourced from local suppliers in Seeta, Mukono due to its proximity to the labs. This sand was used to carry out mortar works for the masonry wall samples prepared.

f) Stone dust

Stone dust is a primary material used to make most concrete blocks in Mbale City, and it often takes up the biggest composition in concrete block mix ratios. This stone dust was used in the mix design for concrete blocks produced for this study.

g) Sisal rope

The sisal ropes used were 2-3mm thick (weighing about 4.5g/m), and were acquired from hardware shops in Mbale City. Sisal rope was selected due to its relatively better bond with concrete in comparison to nylon ropes. The sisal rope was used to tie the plastic bottles together and it was cast within the block with the plastic bottle bricks.

h) Water

Potable water from NWSC supply used in mixing mortar and concrete mixes, and curing of blocks.

3.3.2 Sample preparation

a) Plastic Bottle Bricks (PBBs)

The PBBs were made from 230mm high “500ml Elgon water” plastic bottles as shown in Figure 3-4. The filler materials included Pit sand, Saw dust and Uncompressed air.

Figure 3-4: Plastic bottles used for making PBBs.

The process of plastic bottle collection can be summarised as shown in **Figure 3-5**, and was guided by Parab et al. (2021) and Priya et al. (2018).

Figure 3-5: Process for making PBBs.

i. Collection

Collection of PET waste plastic bottles used for packaging “Elgon water”, from restaurants, schools, domestic waste and festive events within Mbale City. The bottles were from the same manufacturer for uniformity, and had a cylindrical geometry. Cleaning of bottles was done by soaking empty bottles and bottle caps in detergent, rinsing, and air drying to remove moisture within the bottles.

ii. Filling of bottles

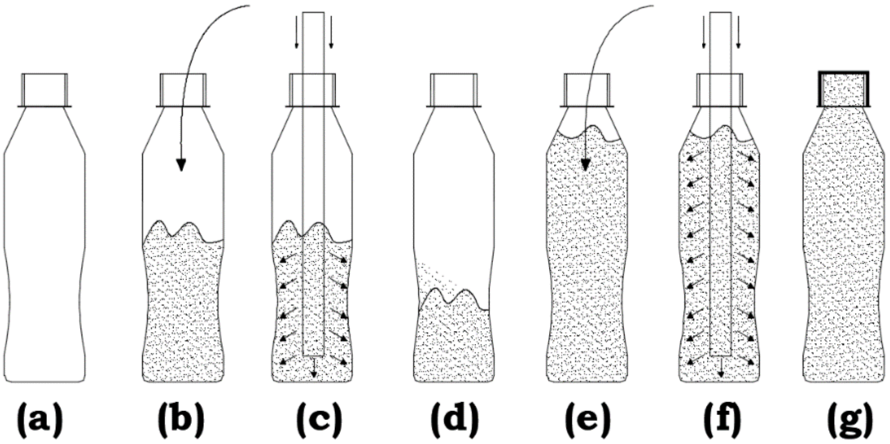


Figure 3-6: Process of filling of plastic bottles

The process for filling the plastic bottles has been summarised in **Figure 3-6** above. The plastic bottle without its cap was positioned vertically on a firm surface, (part (a)). The filler material was placed into the bottle until about halfway of the bottle, and a 10, 12 or 16mm diameter steel rod, hammered using a 0.45-0.75kg hammer head to pack the material, providing about 20 blows in 3 layers till the top is reached(parts (b), (c), (d), (e) and (f)). The filling and compaction were resumed at the top tapered section of the bottle in multiple layers until no further loose material was seen at the top (parts (f) and (g)). After an ideal compaction is reached, the plastic bottle was sealed with its bottle top and was then validated by weight.

iii. Validation

The validation of the percentage of compaction for the PBBs was done through weighing the PBBs using a portable digital weighing scale. The saw dust had a minimum weight of 180g (53% compaction) and sand had a minimum weight of 975g (80% compaction). The minimum compaction percentage was determined due to trial and error to determine the highest compaction level, without damaging the bottles. Visual inspection was done to identify defective and damaged bottles with deformations, holes and cracks. Once the desired percentage of compaction was achieved, the plastic bottle is ready for used in the PBB masonry units.

b) PBB masonry units

The PBBM units used were 400mm in length, 200mm in width and height of 250mm, based on the height of the plastic bottles in the masonry units. This is to match the solid and hollow concrete blocks on the market, which have a typical length of 400mm, width of 200mm, but the height was changed from the typical 180mm to 250mm to provide mortar cover for the 230mm bottles. The processes for preparation of PBBM units are described as summarised in **Figure 3-7** below.

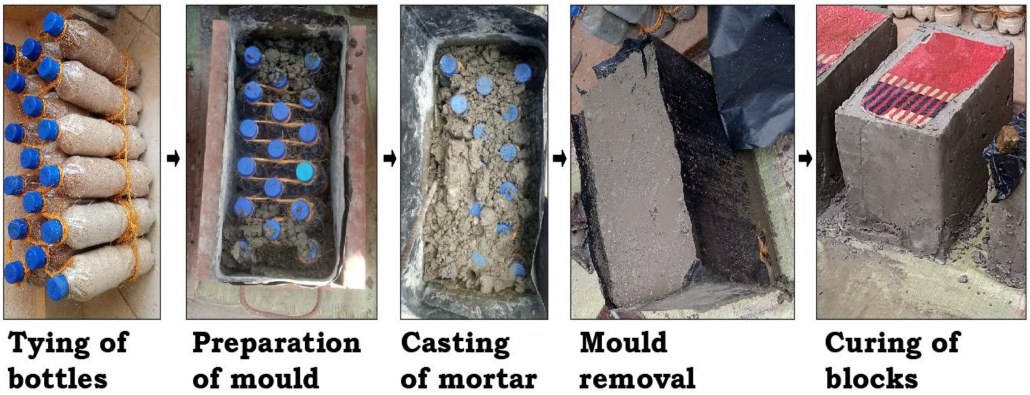

Tying of bottles → **Preparation of mould** → **Casting of mortar** → **Mould removal** → **Curing of blocks**

Figure 3-7: Process for preparing the PBBM units

The procedure for preparation of specimen PBBM units was guided by Parab et al. (2021) and Mansour et al. (2015) with relevant modifications and is summarised into the following steps; tying of plastic bottles, preparation of the mould, casting of mortar, mould removal, and curing.

i. Tying of plastic bottles

The Plastic Bottle Bricks (PBBs) are to be arranged in three interlocking courses, with the bottle caps perpendicular to the 200mm x 400mm edge and tied as shown in **Figure 3-8** on the next page.

Figure 3-8: Process of tying PBB masonry units.

The plastic bottle brick units were arranged to fit the block shape and tied using sisal rope as shown in **Figure 3-8**, and a 25mm thick timber board was used to ensure adequate clearance when placing the tied PBB structure into the steel mould.

ii. Preparation of mould

A steel mould with a height of 250mm, length 400mm, and width 200mm was placed on a spread-out polypropylene sack, placed on a firm ground/surface. Base mortar of about 15-20mm was applied at the base of the mould, and then the tied PBBs are placed into the mould. A 250mm Damp Proof Membrane (DPM) strip is placed along the internal edges of the mould to enable easy removal of the mould, give temporary support to the mortar cast in the block (about 6-12 hours), and give the block its final shape. The tied plastic bottles are then positioned so that a clearance of at least 10mm is provided from the edge of the mould, to provide acceptable mortar cover.

iii. Casting of mortar

Mortar (1:4 mix, 0.5-0.7 water : cement ratio) is then applied into the mould to fill voids using a trowel, and compaction was done by manual tamping using an H10 steel rod, ramming compaction using a 3kg rammer, and finishing using a steel float to form the top shape of the PBB block.

iv. Mould removal

The mould was removed immediately after compaction is complete, and left to harden in a sheltered area about 12-24 hours as shown **Figure 3-9** on the next page. The DPM strips were removed about 6-12 hours from casting and reused to cast other PBB masonry blocks. Curing through covering and spraying water is done starting about 24 hours after casting the mortar filling. Curing was done consistently for at least 28 days to achieve the estimated final mortar strength.

Figure 3-9: Curing of completed PBBM blocks.

c) PBBM walls

The masonry was prepared according to clauses 7.1 and 7.2 of EN 1052-1:1999, with a recommended minimum height of 1.0m, and sample masonry walls to comply with table 2 of EN 1052-1:1999, hence blocks (200mm width, 400mm length and 250mm height) are to be prepared to comply with these requirements.

Twelve blocks with four courses of blockwork (25mm mortar joints) formed a 1250mm length, 1100mm height and 200mm width typical wall samples. 25mm of mortar was placed at the bottom, and at the top of the masonry walls in compliance to EN 1052-1:1999 requirements.

Figure 3-10: PBBM wall specimens.

d) Concrete blocks

The concrete blocks used in this study consisted of solid and hollow concrete blocks, whose overall dimensions were 200mm width, 400mm height and 250mm depth. It was noted during a baseline survey that concrete blocks with 200mm width and 400mm length, often had a depth of about 180mm. However, a variation in the depth of the block was influenced by the height of the PBB masonry units for uniformity in comparison by overall volume of masonry units. The process for making the concrete blocks included; mould preparation, casting, mould removal and curing.

The mix design for the blocks was determined from a baseline survey of 117 block makers in Mbale City, through observation and interview to establish the materials, mix ratios and methods of work. A majority 53.5% of the respondents used cement, sand and stone dust to make blocks, with a mean mix ratio of about 1:[3.9]:[6.9]. However, the data had a skewness of 1.33 for the sand ratio, and 1.28 for the stone dust, which indicated a positively skewed dataset which makes the mean unreliable. Hence the mode for grouped data was considered to be more reliable which gave a ratio of 1:[2.7]:[5.6], which was rounded off to 1:3:6 to ease measurement by volume. A water:cement ratio was established to be about 0.7-0.9 from observation, and the predominant method of curing was spraying at 96.6% of the respondents.

i. Preparation of mould

A steel mould frame with a height of 250mm, length 400mm, and width 200mm was placed on a spread-out polypropylene sack, placed on a firm ground/surface. An internal mould was placed after for hollow blocks to create the voids in the block.

ii. Casting of concrete

A 1:3:6 (cement: pit sand: stone dust) concrete mix at a 0.8 water: cement ratio, was applied into the mould, and compaction was done by manual tamping using a 3kg rammer, and finishing using a steel float/trowel to form the top shape of the block.

iii. Mould removal

The mould was removed immediately after compaction is complete, and left to harden in a sheltered area about 12-24 hours as shown in **Figure 3-11** on the next page. Curing through covering and spraying water is done starting about 24 hours after casting the concrete. Curing was done consistently for at least 28 days to achieve the estimated final concrete strength.

Figure 3-11: Concrete blocks left to harden before curing.

3.3.3 Quality control considerations

To ensure the reliability, consistency, and validity of experimental results, several quality control measures were implemented throughout the study. These measures covered the selection and preparation of materials, specimen fabrication, testing procedures, and data recording.

a. Material verification

All materials used in this study were verified for quality and conformity to relevant standards before use. Cement (CEM IV B (P) 32.5N) was sourced from the same batch to maintain uniformity, while sand, stone dust, and sawdust were inspected to remove oversized particles and organic matter. The moisture content of aggregates was checked to ensure consistent water-cement ratios in mix preparation. Only clean, undamaged plastic bottles of similar geometry and capacity were selected to minimize variability in specimen dimensions and load distribution.

b. Equipment calibration

Testing equipment, including weighing scales, compression testing machines, and sieves, were were in accordance with the manufacturers' specifications and relevant standards such as EN 12390-4 for compression testing and BS EN 933-1:2012 for sieve analysis. All specimens were tested using the same compression testing machine to maintain consistency in loading conditions and minimize potential errors arising from variations between different testing equipment.

c. Specimen preparation and curing

All specimens were prepared under controlled laboratory conditions using standardized moulds and mixing procedures. Mortar and concrete mixes were batched by volume to match common practice using uniform batching boxes. During casting, samples were compacted in uniform layers using consistent energy levels to achieve comparable densities. Curing of mortar cubes, blocks, and wall units was carried out under moist conditions for at least 28 days in accordance with EN 12390-2 to ensure full strength development.

d. Testing procedures

Testing was conducted following the appropriate international standards for each material and specimen type, including EN 12390-3 for compressive strength, BS 1881-122:2011 and ASTM D570 for water absorption, and EN 1052-1:1999 for masonry wall testing. Prior to testing, all specimens were visually inspected for cracks, deformation, or surface defects, and any irregular samples were discarded. Load was applied at a controlled rate as specified in the relevant standards to prevent impact failure.

e. Data accuracy and repeatability

For each test type, a minimum of three replicate specimens was tested to establish repeatability and reduce random error. Test data were recorded digitally at each loading increment and cross-checked manually to eliminate transcription errors. Outlier results beyond ±10 % of the mean were reviewed and, where justified, excluded in accordance with standard statistical practice.

f. Documentation and traceability

Each specimen was assigned a unique identification code indicating the material type, orientation, filler type, and testing age. All data sheets, calibration records, and test results were securely stored and referenced to ensure full traceability from material collection to final analysis.

3.3 Experimental Program

Table 3-1: Summary of experimental tests and samples required at 28 days.

Sample description		**Tests performed and minimum samples**	
		Compressive strength	**Water absorption**
Mortar cubes	1:4 pit sand mortar mix	3	-
	1:4 river sand mortar mix	3	-
PBB masonry units (28 days)	Empty bottle vertical orientation	3	3
	Empty bottle horizontal orientation	3	3
	Saw dust filler vertical orientation	3	3
	Saw dust filler horizontal orientation	3	3
	Pit sand filler vertical orientation	3	3
	Pit sand filler horizontal orientation	3	3
Solid concrete blocks (28 days)	Vertical orientation	3	3
	Horizontal orientation	3	3
Hollow concrete blocks (28 days)	Vertical orientation	3	3
	Horizontal orientation	3	3
Masonry walls with masonry units in the vertical orientation at 28 days	Empty bottle masonry wall	3	-
	Saw dust filler masonry wall	3	-
	Pit sand filler masonry wall	3	-
	Solid concrete block masonry wall	3	-
	Hollow concrete block masonry wall	3	-

The vertical orientation of masonry units was selected for the wall panels due to deformation characteristics and desirable wall thickness as discussed in the Results and Discussion chapter. Furthermore, preliminary tests were carried out for the PBB masonry units, and trial concrete block samples (solid and hollow) as summarised in **Table 3-2**.

Table 3-2: Summary of experimental tests and samples required before 28 days.

Sample description		**Compressive strength tests on masonry units**		
		7 days	**14 days**	**28 days**
PBB masonry units	Empty bottle vertical orientation	3	3	-
	Empty bottle horizontal orientation	3	3	-
	Saw dust filler vertical orientation	3	3	-
	Saw dust filler horizontal orientation	3	3	-
	Pit sand filler vertical orientation	3	3	-
	Pit sand filler horizontal orientation	3	3	-
Trial solid concrete blocks	150 x 200 x 400 mm	-	-	3
	200 x 200 x 400 mm	-	-	3
Trial hollow concrete blocks	150 x 200 x 400 mm (30mm)	-	-	3
	200 x 200 x 400 mm (30mm)	-	-	3

The tests were performed to evaluate the compressive strength of commercially available concrete blocks in Mbale City and to assess the strength development of PBB masonry units over time, specifically at 7 and 14 days, with the aim of informing the discussion on their performance.

3.4 Tests conducted

The following tests were carried out to establish the properties of materials used in the construction of the load bearing walls:

- Sieve analysis test on the sand, saw dust and stone dust samples.
- Specific gravity using the pycnometer method.
- Water absorption on masonry units/blocks.
- Compressive strength of mortar cubes and masonry units/blocks.
- Compressive strength of the masonry wall structures.

3.4.1 Sieve analysis tests

The materials tested through sieve analysis included pit sand, river sand, stone dust, and sawdust. The sieve analysis followed the guidelines set out in BS EN 933-1:2012, which outlines tests for geometrical properties of aggregates.

For pit sand samples containing clay particles, washing through a fine 75µm sieve was done before dry sieving. For saw dust, river sand, saw dust and stone dust which are free from particles causing agglomeration, dry sieving was done without washing. Samples ranging between 700-1000g were taken from the sand and stone dust samples. However, a sample of about 300g was taken from the saw dust which was significantly lighter than the other samples, but had the highest sample volume.

The sieve sizes used for the analysis were of sizes 10mm, 5mm, 2.36mm, 1.18mm, 0.6mm, 0.3mm, and 0.15mm. The results were tabulated including details of mass retained and percentage mass retained for each sieve, as well as the cumulative percentage retained sequentially from the largest sieve to the smallest.

3.4.2 Specific gravity using the pycnometer method

This test was done in compliance to BS 1377-2:2022 using the pycnometer method. It was used to test saw dust, pit sand, river sand and stone dust particles, all of which have particles passing the 37.5mm test sieve.

A glass jar, whose mouth could be sealed was used as a pycnometer, using samples of about 1000g. The specific gravity (G) was determined from the formula:

$$G = \frac{(M_2 - M_1)}{\left((M_4 - M_1) - (M_3 - M_2)\right)}$$

Where: M_1 – Mass of Pycnometer in g

M_2 – Mass of Pycnometer + sample in g

M_3 – Mass of Pycnometer + sample + water in g

M_4 – Mass of Pycnometer + water in g

3.4.3 Water absorption test procedure

The water absorption test was done for all masonry unit types. This test was carried out in compliance to ASTM D570 for PBB masonry units. BS 1881-122:2011 was used for the concrete block specimens. The variations in codes was necessary since ASTM D570 handles specimens with plastics, while BS 1881-122:2011 deals with concrete samples only. The water absorption for each block was expressed in percentage, and was calculated using the formula below:

$$Water\ absorption = \frac{m_2 - m_1}{m_1} \times 100$$

Where: m_1 – mass of dry sample

m_2 – mass of wet sample

3.4.4 Compressive strength of mortar cubes and masonry units test procedure

The cube specimens tested were mortar cubes for pit sand and river sand mortar mixes. The testing procedure was based of EN 12390-3 guidelines. A Compression Testing machine complying to EN 12390-4 was used to carry out the compressive tests at a constant loading rate of 2kN/s, with about 1500kN loading capacity.

The cubes were of dimensions 150x150mm, in compliance to EN 12390-1, and were prepared and cured in compliance to EN 12390-2. The masonry units were also prepared based on the methodology described in the sample preparation section of this chapter.

The failure load, F in kN was converted to compression strength, f_c, according to clause 8 of EN 12390-3 as shown in the formula below.

$$f_c = \frac{F}{A_c}$$

Where, f_c – Compressive strength in MPa

F – maximum load at failure in N

A_c – Cross-sectional area of specimen on which compressive strength acts in mm^2

3.4.5 Compressive strength of masonry walls test procedure

Wall specimens of approximate length 1250mm, height 1100mm and 200mm wall thickness were tested for compressive strength, guided by EN 1052-1:1999, using a model 0151211001 Controls Hydraulic Power Jack, with a 750kN loading capacity. The wall specimens were hoisted from their point of construction up and placed for testing with the aid of a truck mounted crane. The wall panel is to be moved and placed into the Hydraulic Power Jack as illustrated in **Figure 3-12**.

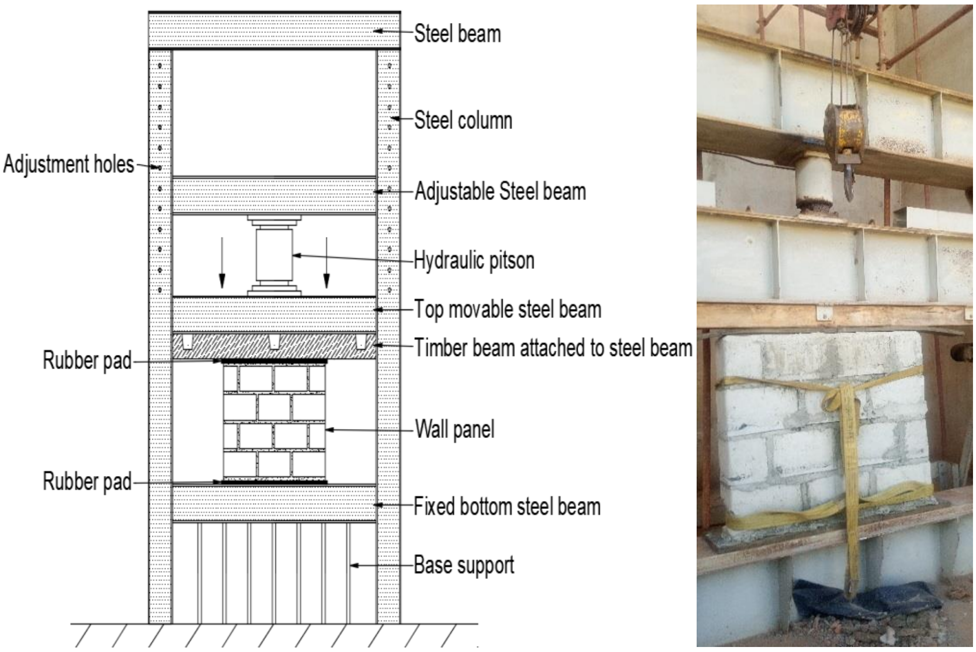


Figure 3-12: Experimental setup for testing masonry units.

The procedure for testing the wall specimens is as outlined below:

- The top movable steel beam was adjusted until sufficient space to position the wall specimens was achieved. The adjustable steel beam was then locked using steel bolts slotted into the adjustment holes.

- Rubber pads placed on top of the fixed bottom steel beam, onto which the wall was hoisted with the aid of a crane. The wall was positioned vertically with a negligible eccentricity.
- Rubber pads were placed at the top of the wall specimen so that the load is evenly applied to the wall on impact in compliance to clause 8.1 of EN 1052-1:1999.
- The load was applied using the hydraulic piston, through the top movable steel beam, until the timber beam just touches the top rubber pads. The height of the wall before loading is measured in compliance with clause 8.3 of EN 1052-1:1999.
- The wall specimen was loaded in line with clause 8.2 with the exception of the loading speed of 1mm/second due to equipment limitations.
- In line with clause 8.3 of EN 1052-1:1999, observations of cracks and load increment were monitored until maximum load was achieved and the height at maximum load was also measured.
- The loading is then removed, and the damaged wall panel was hoisted out of the setup for disposal.
- The compressive strength was then determined from Equation 1 of EN 1052-1:1999. Furthermore, the characteristic strength was determined from equation 3 and 4.

3.5 Cost benefit analysis (CBA)

3.5.1 Cost-benefit analysis framework

A cost-benefit analysis (CBA) was carried out to evaluate the commercial feasibility of plastic bottle brick masonry (PBBM) walls in comparison to conventional concrete blocks available on the market. The CBA framework adopted was based on the Kaldor-Hicks efficiency criterion, as discussed in the literature review, to assess whether the benefits outweigh the costs. The analysis focused on key economic performance indicators, specifically direct costs associated with material procurement, labour, and environmental impact quantified through the carbon emissions cost. The methodology used for the CBA is outlined in the subsequent sections.

3.5.2 Data sources for the CBA

a) Materials costs

Material prices were determined through local market surveys, with consideration given to the standard quantities in which each material is typically sold. During sample preparation, material usage was tracked by measuring the proportions used, in accordance with the guidelines outlined in the Civil Engineering Standard Method of Measurement, Fourth Edition (CESMM4). To ensure consistency, all material prices were converted to align with CESMM4-recommended units. The resulting data were organized in a tabulated format, detailing the cost of materials per masonry unit. The table included the following columns: Item Number, Item Description, Unit (standard unit of measurement), Quantity (measured proportion of material used), Rate (unit price based on market survey), and Amount (calculated as the product of Quantity and Rate).

b) Labour costs

Labour costs were assessed based on output per masonry unit, a payment approach commonly used at sites where concrete blocks are produced. This output-based method was selected over daily wage rates due to its consistency, as it reflects actual productivity rather than working hours, which can vary significantly due to differences in labour efficiency and management. Labour cost data was obtained through local surveys, although this approach is subject to some bias owing to task complexity and individual worker performance.

Labour outputs were tracked by measuring the completed work per masonry unit, with task-specific averages used in the final calculations. To account for varying wage groups, labour rates were standardized using a weighted average based on the number of workers in each rate category.

The calculated labour costs were presented in a tabulated format for each masonry unit, including the following columns: Task Number, Task Description, Unit (unit of task measurement), Quantity (number of completed outputs), Rate (unit cost of labour per task), and Amount (calculated as Quantity × Rate).

c) Time utilisation costs

Time utilisation costs were incorporated to account for the duration required to produce each masonry unit. While this approach provides valuable insights into production efficiency, it is subject to potential bias due to the complex nature of the tasks involved and variations in individual worker performance. Time costs were measured in hours per task output per labourer. Average daily labour costs, based on a 10-hour workday, were calculated for each task and then apportioned per masonry unit for use in the analysis.

The time utilisation costs were presented in a tabulated format for each masonry unit, with the table containing the following columns: Task Number, Task Description, Unit (unit of task measurement), Quantity (number of task outputs completed), Rate (labour cost per unit time), and Amount (calculated as the product of Quantity and Rate).

d) Carbon emissions cost

Carbon emissions costs were integrated into the analysis to reflect the environmental sustainability of the materials used in producing each masonry unit. Emission values for each material were sourced from literature, and carbon tax rates were aligned with global standards, particularly those recommended by the World Bank. Given that Uganda does not currently impose a carbon tax, the analysis adopted the lowest internationally recognized carbon tax rate to estimate environmental costs.

These carbon emissions costs have been organized in a tabulated format for each masonry unit. The table included the following columns: Item Number, Material Description, Unit (unit of measurement), Quantity (amount of material used), Rate (carbon cost per unit of material), and Amount (calculated as Quantity × Rate).

3.5.3 Computational framework for the CBA

The following formulas were used to establish the materials, labour, time utilisation and carbon emissions cost:

$$\text{Materials cost} = \text{Market unit price of materials} \times \text{Quantity of materials used}$$

$$\text{Labour cost} = \frac{\text{Average daily labour fee}}{\text{Average quantity of tasks achieved}} \times \text{tasks per masonry unit}$$

$$\text{Time utilisation cost} = \frac{\text{Average daily labour fee}}{\text{Average daily work hours}} \times \text{tasks duration per masonry unit}$$

$$\text{Carbon emissions cost} = \text{Quantity of materials used} \times \text{Carbon emissions per unit of material} \times \text{Carbon tax rate}$$

The total cost for the materials was calculated for each masonry unit using the formula below:

$$\text{Total masonry unit cost} = \text{Materials costs} + \text{Labour costs} + \text{Time utilisation costs} + \text{Carbon emissions costs}$$

3.5.4 Limitations and assumptions

The cost-benefit analysis (CBA) was based on a set of assumptions established for cost quantification, and it also acknowledges certain limitations that necessitated the formulation of these assumptions.

- Although the plastic bottles were obtained locally at no direct purchase cost (excluding transportation expenses), their value was estimated based on the prevailing local market rate of approximately UGX 500 per kilogram, which reflects the average price paid by waste plastic bottle collectors and buyers.
- Transportation costs for materials were not included, given their highly subjective and variable nature.
- Carbon data was literature-based due to lack of local emissions data.
- Labour rates based on prevailing market prices were averaged to ease calculations.
- Indirect benefits like pollution reduction, job creation, reduced mining demand for river/lake sand and stone dust, and contribution to SDGs, were not monetized directly since they are difficult to quantify.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results of experimental investigations into the compressive strength performance of confined waste plastic bottle brick (PBB) masonry walls, examining their potential as a sustainable and cost-effective alternative to commercially available concrete blocks in Mbale City. The central objective is to assess the feasibility of employing waste plastic bottles as the primary load-bearing component in masonry subjected to compression. The study involved a series of compressive strength tests on PBBs incorporating various filler materials (uncompressed air, saw dust and pit sand), comparative tests between PBB units and standard concrete blocks, and full-scale masonry wall tests for each unit type. Additionally, material characterization tests were performed to enhance the understanding of the composite behaviour of the PBB masonry system.

The results are presented and analysed to offer meaningful insights into the structural behaviour of PBB masonry, focusing on identifying trends, correlations, and notable differences among the various sample types. Analytical tools such as Sigma Plot, Microsoft Excel, and AutoCAD were employed to support data interpretation and visualization. Additionally, a review of relevant literature was used to validate the findings, highlight discrepancies, and provide possible explanations for the observed behaviour of PBB masonry.

The findings of this study hold considerable potential for influencing waste plastic bottle management, not only in Mbale City but across Uganda.

Incorporating plastic bottles into construction offers a dual benefit: it mitigates environmental pollution associated with plastic and saw dust waste while presenting a cost-effective alternative to commercially available concrete blocks in the region. Moreover, this research highlights promising and practical avenues for further investigation that have often been underexplored in existing literature.

This chapter is organized into several key sections, beginning with baseline survey findings on concrete block production practices in Mbale City, followed by material characterization to determine relevant physical and mechanical properties. The subsequent sections present the results of compressive strength tests conducted on plastic bottle bricks (PBBs), masonry units, and full masonry wall assemblies, accompanied by a comprehensive analysis of the findings.

4.2 Baseline survey findings

4.2.1 General findings

A semi-structured interview of 117 concrete block makers in Mbale City, and the results were expressed in percentage of the total respondents as detailed below.

a) Common types of concrete blocks

A survey of concrete block makers in Mbale City revealed that the majority (76.1%) manufactured both hollow and solid blocks, while 10.2% focused on hollow blocks and 13.7% on solid blocks. According to the findings, 150mm thick hollow concrete blocks were in high demand for non-structural applications like infill walls and low-load ground-level load-bearing walls. However, most respondents deemed them unsuitable for use load-bearing walls in major structural projects, such as multi-story buildings. In contrast, 200mm thick hollow blocks were considered more suitable for load-bearing walls in small structures like residential buildings. Solid blocks, while more reliable for structural works, were less frequently purchased due to their higher cost compared to hollow blocks of similar overall dimensions. The dimensions of common commercially available 150mm and 200mm hollow blocks are shown in **Appendix A.3: Pictures**.

b) Materials used for making concrete blocks

The majority (74.7%) of concrete block makers used a standard mix of cement, sand, and stone dust, while others used variations, including cement with fine-grained stone dust (17.2%), stone aggregates (4.1%), or coarse-grained river sand (4%). Admixtures and chippings were rarely used, with only 4% of respondents incorporating them into their mix design.

Many respondents preferred pit sand for its finer particles, which improved workability and stability of wet concrete blocks when combined with stone dust. In contrast, river sand's coarser particles made it less desirable, often requiring more water to achieve the right consistency and cohesion for stable wet concrete blocks.

c) Methods of production

Concrete block production was predominantly manual, with 89.7% of block makers producing blocks by hand, often on construction sites. Only 10.3% employed heavy-duty machinery in their production process. While manually produced blocks made on-site were often more cost-effective for residential projects, they typically had significantly lower compressive strength compared to machine-produced blocks.

Material measurement methods varied among concrete block makers, with over half (51.7%) using bags and wheelbarrows, 44.9% using batching boxes, and a small proportion (3.4%) using weight-based measurements. Wheelbarrow volumes were often disproportionately large compared to cement bags (more than twice).

Curing durations for concrete blocks varied widely among respondents. While 44.8% of respondents cured blocks for 2 weeks, over a quarter (27.6%) cured for just 7 days. About a quarter (24.1%) cured blocks for 21 days, and only 3.4% cured for the recommended 28 days or longer.

The average mix ratio for concrete blocks among respondents was 1: (3.9): (6.9) (cement: sand: stone dust). However, an interview with staff from the Mbale Works Materials Lab, blocks with a mix ratio of 1: (2.5): (4.5) were more likely to meet the common strength requirement of 4.0 MPa, suggesting a discrepancy between common practice and optimal mix design.

4.2.2 Data analysis

The survey found that 63.25% of respondents (74 individuals) used a cement:sand:stone dust mix for concrete block production. Although the mean mix ratio was 1: [3.9]: [6.9], the data's skewness (1.33 for sand ratio and 1.28 for stone dust) indicated a positively skewed distribution, making the mode a more reliable indicator of central tendency. The mode yielded a ratio of 1: [2.7]: [5.6], which was rounded to 1:3:6 for practical measurement purposes. The water:cement ratio was observed to be between 0.7 and 0.9, and nearly all respondents (96.6%) used spraying and covering for curing. The **Table A-1** and **Table A-2** show the grouped data for sand and stone dust mix ratios, respectively.

4.3 Characterisation of materials used

a) Saw dust

Sieve analysis was carried out on the saw dust to establish the distribution of its particle size as shown in **Figure 4-1**.

Figure 4-1: Sieve analysis for the saw dust filler material used.

The density of the saw dust was established by specific gravity experiment using the pycnometer method. It was established that the saw dust density was about 638.2kg/m^3.

b) Pit sand

The pit sand used had a higher concentration of silts as shown in **Figure 4-2** below.

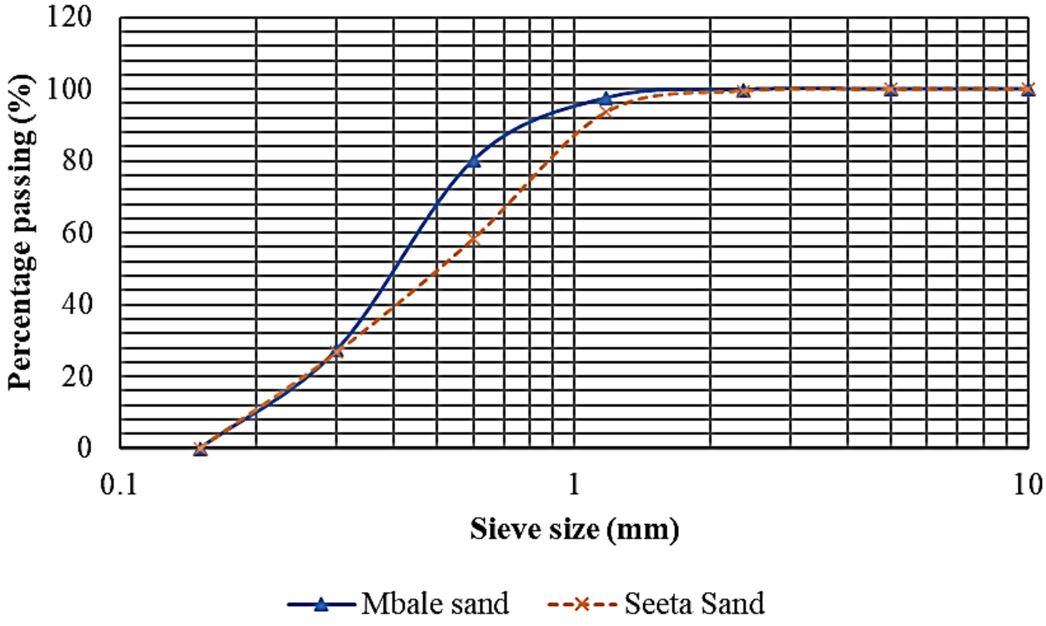


Figure 4-2: Pit sand used in the study.

The high concentration of silts was responsible for the relatively better adhesion to the plastic bottles in comparison to river sand. The density of the pit sand was established by specific gravity experiment using the pycnometer method. It was established that the pit sand density was about 2273.9kg/m^3. The masonry units were prepared in Seeta due to its proximity to the Kireka Central Materials Laboratory, which was the only facility equipped to conduct all the required tests for this study. However, sieve analysis indicated that the particle size distribution of the materials used was similar to the sand from Mbale as shown in **Figure 4-2**.

c) River sand

A sieve analysis on the sand revealed its properties as shown in **Figure 4-3**.

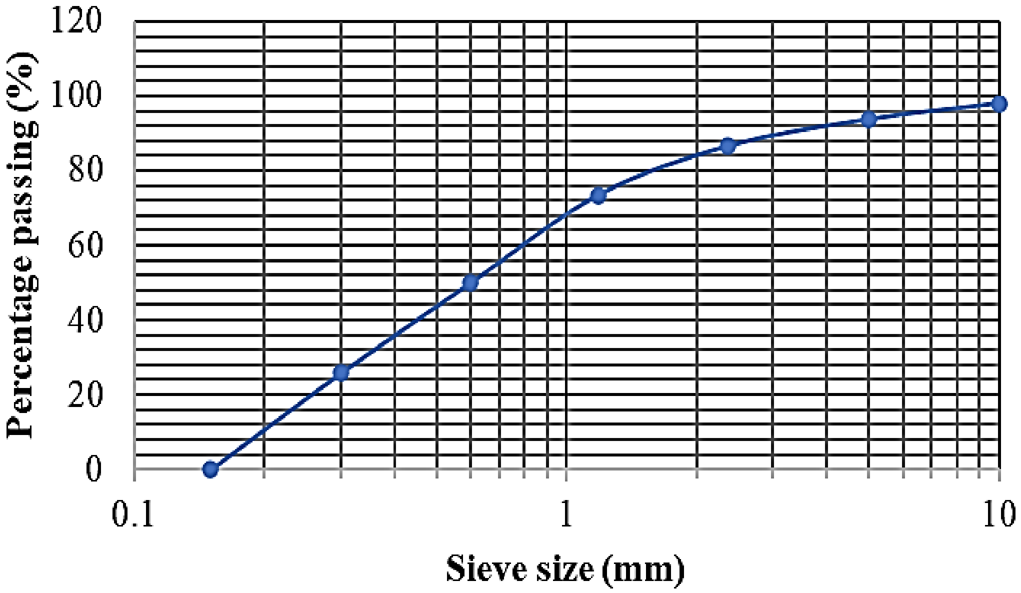


Figure 4-3: Sieve analysis for the river sand used.

The density of the sand was further established using the pycnometer method for determining specific gravity. It was established that the river sand density was about 2629.3kg/m^3.

d) Stone dust

A sieve analysis was conducted on the stone dust used for the study and its composition is represented in **Figure 4-4**.

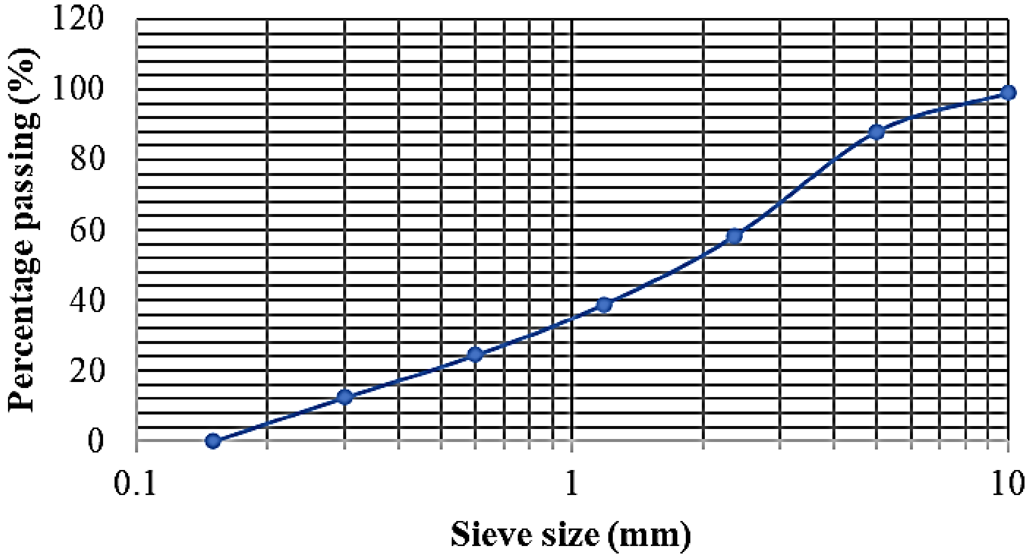


Figure 4-4: Stone dust composition by sieve analysis.

e) Sisal rope

Tensile tests were carried out on two sisal rope samples of length 500mm, 2-3mm thick, and weighing about 4.5g/m, using a Tensile testing machine, which gave an average tensile strength of 222.8MPa.

4.4 Physical properties of masonry units

a) Geometry, weight and density of masonry units

The plastic bottles, when dry and empty, weighed between 10-15g, including the bottle tops, and had an internal volume of around 535ml (0.535 x $10^{-6}m^3$). The bottles used had modal height of 225mm and major diameter of 60mm. Table 4-1 shows the weight and density of the PBBs, along with their filler materials, whose density was determined using the specific gravity test.

Table 4-1: Weight and density of PBBs used.

Sample Description	**Minimum mass (g)**	**Filler material density (kg/m^3)**	**Minimum compaction (%)**	**Minimum density of PBBs (kg/m^3)**
Empty bottle with cap	10	0	0	0
Saw dust filled bottle with cap	180	638.171	53	338.231
Pit sand filled bottle with cap	970	2273.930	80	1819.144

The minimum compaction percentage for the pit sand and saw dust was determined through trial and error to ensure maximum compaction possible through manual methods, without damaging the plastic bottle. The Mbale pit sand had the highest compaction because the fine particle content enhances the density and cohesion (Das, 2010). Sawdust is a loose, fibrous material with a high volume-to-weight ratio, coupled with high elasticity causing them to spring back, making it difficult to achieve or maintain compaction.

b) Geometry of masonry units

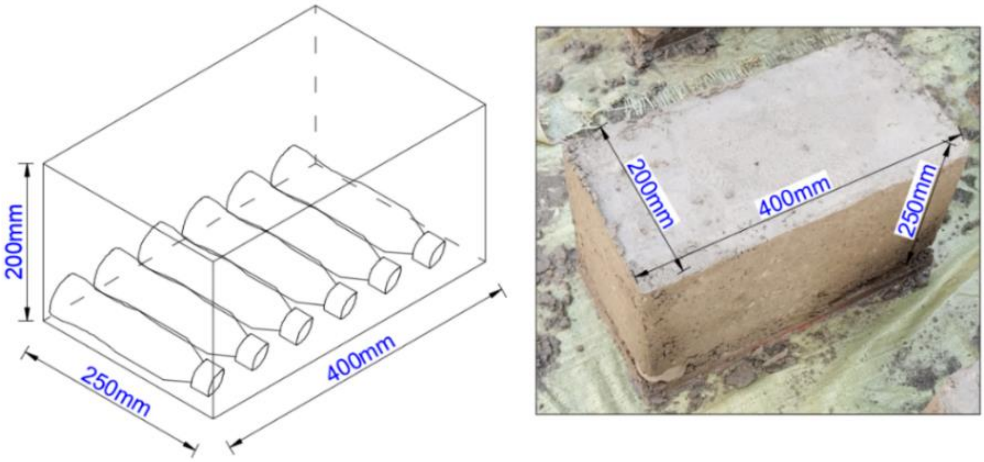
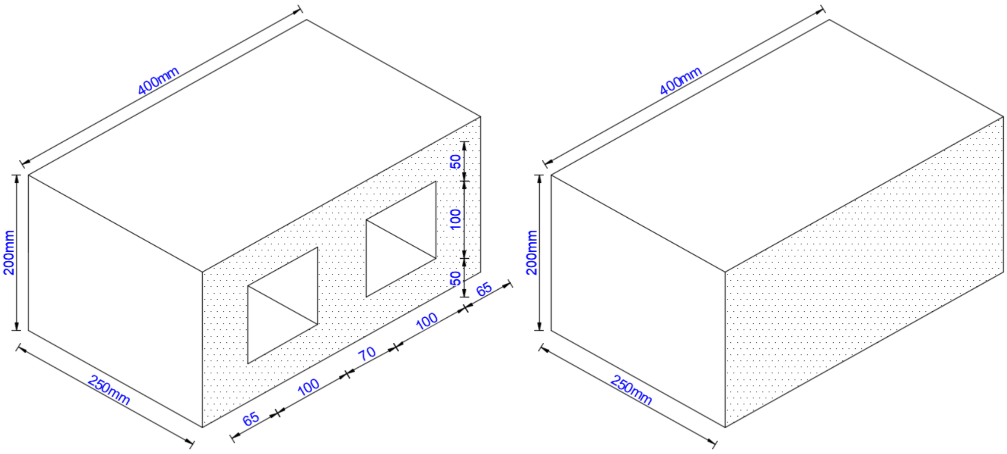


Figure 4-5: Typical Geometry of PBB masonry units.

The Plastic Bottle Brick (PBB) masonry units measured 400mm in length, 200mm in width, and 250mm in height (see **Figure 4-5**). Each unit consisted of 17 tied Elgon 500ml waste plastic bottles, arranged perpendicularly to the 200x400mm face, with varying fill materials (sawdust, pit sand, or empty). A 10mm mortar cover was applied to both the top and bottom of the unit for enhanced fire and damage resistance. The bottle cores were stacked in courses and secured together with sisal rope.



Hollow blocks **Solid blocks**

Figure 4-6: Typical Geometry of concrete blocks used.

The concrete blocks (hollow and solid) had overall measurements of 400mm in length, 200mm in width, and 250mm in height (see **Figure 4-6**). Each unit consisted of a 1:3:6 cement, sand and stone dust mix.

c) Weight and Density of masonry units

Table 4-2 on the next page presents the average mass and standard deviation for PBB and concrete masonry units, which typically ranged from 21.826kg to 41.517kg.

Table 4-2: Mass of various masonry units.

Sample ID	**Sample Description**	**Average mass (kg)**	**Standard deviation (kg)**	**Volume (m^3)**	**Density (kg/m^3)**
EB	Empty plastic bottle block	21.683	0.839	0.02	1,084.15
SD	Saw dust filled PBB block	23.186	0.460	0.02	1,159.30
PS	Pit sand filled PBB block	37.214	0.677	0.02	1,860.70
HB	Hollow concrete block	33.600	0.982	0.02	1,680.00
SB	Solid concrete block	41.517	1.123	0.02	2,075.85

The recommended maximum weight to be lifted using two hands for a substantial period of time (about 8 hours or more in a day) is 51 pounds (23.133 kg) according to (NIOSH, 2007) revised lifting equation. Based on this guideline, only the EB and narrowly SD masonry units are ergonomic for construction, and could be considered lightweight masonry units in this scenario. PS, HB and SB masonry units are 61%, 45% and 79% respectively above the minimum recommended threshold for ergonomic construction by masons on site.

d) Water absorption for masonry units

The water absorption test results for the various materials are presented in **Table 4-3** on the next page. The results show that the water absorption values ranged from 3-15% for the different blocks.

Table 4-3: Water absorption results for various masonry units

ID	**Sample Description**	**Dry mass, m_1 (kg)**	**Dry density (kg/m^3)**	**Wet mass, m_2 (kg)**	**Water absorption (%)**
EB	Empty plastic bottle block	22.38	1,119	25.00	12
SD	Saw dust filled PBB block	23.0	1,150	26.45	15
PS	Pit sand filled PBB block	34.90	1,745	36.30	4
HB	Hollow concrete block	32.10	1,605	33.48	4
SB	Solid concrete block	41.31	2,065.5	42.67	3

The significant variation between water absorption of 3-4% and that between 12-13% could be attributed to voids in-between bottles which may trap significant amounts of water when soaked. Regardless of this, the higher water absorption in the lightweight masonry units ensures a certain level or comfort in use even when wet blocks are used for construction. Table 3 of ASTM C90-22 classifies EB, SD and HB as lightweight masonry units, PS as medium-weight and SB as normal weight masonry units.

Most conventional masonry standards, including BS EN 771-1:2011 and BS EN 771-3:2011, do not explicitly prescribe fixed water absorption limits for masonry units. Instead, manufacturers are required to declare the measured values in accordance with the relevant test methods. Nevertheless, guidance from earlier standards such as BS 6073-1:1981 and international codes including ASTM C90-22 and IS 2185 (Part 1):2005, as well as prevailing industry practice, recommend acceptable water absorption ranges between 10 and 18 percent by mass for concrete masonry units. These limits are generally adopted to ensure adequate durability, reduced moisture ingress, and improved long-term performance of masonry structures. Based on these standards, the PBB blocks lie within acceptable ranges of water absorption.

4.5 Compressive strength results

4.5.1 Plastic bottle bricks (PBBs)/ Infilled plastic bottles

Compressive tests were carried out on the PBBs using a Compression Testing machine for pit sand filled bottles, saw dust filled bottles and empty bottles. The bottles were tested in the vertical and horizontal orientations with a minimum of three samples each, and the results have been summarised in **Table 4-4**.

Table 4-4: Failure load of PBBs/Infilled plastic bottles in compression.

ID	**Sample description**	**Average failure load (kN)**	**Standard deviation (kN)**	**Strain (%)**
EbV	Empty bottle in the vertical orientation	1.1	0.071	8.8
EbH	Empty bottle in the horizontal orientation	1.8	0.071	24.2
SdV	Saw dust PBB in the vertical orientation	1.3	0.000	8.8
SdH	Saw dust PBB in the horizontal orientation	5.4	0.501	42.2
PsV	Pit sand PBB in the vertical orientation	5.7	0.071	14.5
PsH	Pit sand PBB in the horizontal orientation	28.9	1.556	30.8

The failure load, rather than the compressive strength, was used for the infilled bottles/PBBs due to the non-uniformity of the bottles at the loading points. Each bottle, with varying filler materials, was tested in triplicate, and the mean failure load along with the standard deviation was calculated to evaluate result consistency. The coefficient of variation ranged from 0 to 9%, which falls within the generally acceptable limit of 10% for most statistical analyses. This forms a baseline on understanding how density of the filler material affects the load carrying capacity of the plastic bottle block cores.

a) Effect of plastic bottle orientation

From Table 4-4 it was observed that the horizontal orientation gave higher failure load in comparison to the vertical orientation. This is because, in the vertical orientation, a thin shelled cylindrical element with a lower contact area concentrates the load at contact points and promotes buckling (Young & Budynas, 2002), which was seen at the bottle neck and base in experiments. Furthermore, the plastic bottle in the vertical orientation acts as a thin walled cylindrical shell under axial compression, whose second moment of area is very small mostly due to no resistance about the central axis to bending (Young & Budynas, 2002) for empty bottles, and very little resistance to bending when filled with pit sand or saw dust, which explains the higher values between the empty bottles and those which are filled. Furthermore, thin walled cylindrical shells in axial loading a susceptible to buckling due to imperfections at the neck and base.

On the other hand, plastic bottles in the horizontal direction are compressed along their cylindrical wall, which has a greater contact area and hence less local stress concentrations. The cylindrical bottles have a higher second moment of area, which causes it to behave more like a thin walled cylinder under radial compression which causes flattening (Young & Budynas, 2002), which is better resisted by the filler material since the load is effectively transferred to the filler material better in the horizontal orientation, in comparison to the vertical orientation.

Figure 4-7: Buckling an empty plastic bottle in the vertical orientation (left), flattening of an empty plastic bottle in the horizontal orientation (right).

Furthermore, the bottles tested in the horizontal direction where characterised by larger strain values (24.2-42.2%) and excessive disfigurement in comparison to the vertical orientation which had lesser strains (8.8-14.5%) and showed more stability in spite of its lower compressive strength.

b) Effect of filler material density on the orientation of the bottle

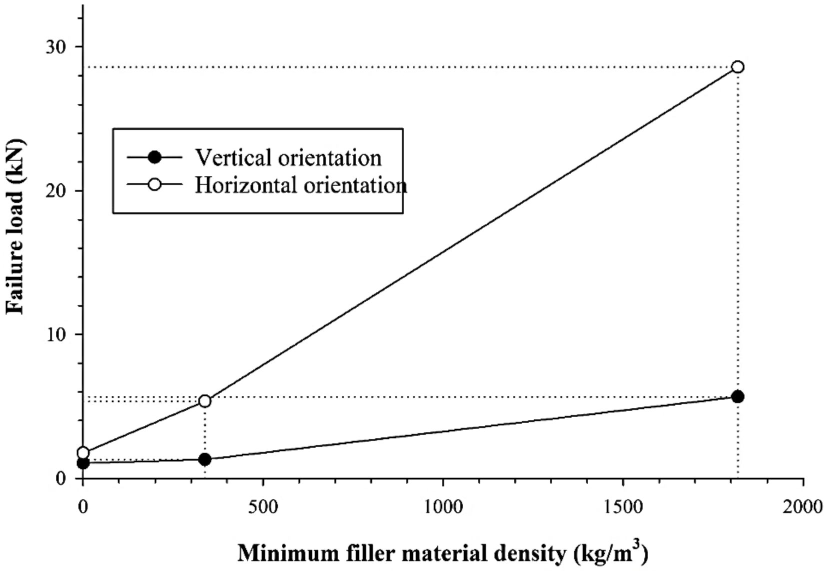


Figure 4-8: Relationship between PBB failure load and filler material density.

There was a very strong positive linear relationship between density and failure load in both the vertical and horizontal values, having Pearson correlation coefficients of 0.991 and 0.999 respectively, in support of Parab et al. (2021). This implies that the density of the filler material is to a large extent directly proportional to the load bearing capacity. Furthermore, the coefficient of determination between failure load and density was 0.995 and 0.999 respectively, which represents that the filler material density has a strong predictability relationship. However, due to limited data points, this graph may not reliably define the relationship between failure load and density of the filler material within the plastic bottles.

c) Summary of PBB compressive strength

The study revealed that plastic bottle bricks (PBBs), or infilled plastic bottles, demonstrate higher compressive strength when oriented horizontally compared to the vertical orientation, irrespective of the filler material used. This increase in strength is primarily due to a more effective load distribution over a larger surface area. However, this benefit is offset by significant drawbacks: horizontally oriented PBBs exhibit excessive deflection caused by the flattening and deformation of the bottles under compressive loads. This deformation compromises their structural rigidity, leading to potential cracking, reduced durability, and undesirable aesthetic outcomes. Consequently, despite their higher strength, horizontally oriented PBBs are less suitable for load-bearing applications where dimensional stability and integrity are paramount.

Conversely, vertically oriented PBBs, while possessing lower compressive strength, show lower strains (8.8-14.5%) and a slower rate of buckling under load. This behaviour enhances their structural performance and makes them a more practical choice for load-bearing masonry. Furthermore, vertical orientation allows for the construction of thinner, more slender walls that align better with architectural requirements for wall thickness and aesthetics. In contrast, horizontally oriented bottles necessitate comparatively thick walls due to their plastic bottle height, limiting their applicability in architectural design where slim profiles are preferred.

Overall, the vertical orientation of PBBs offers a more balanced compromise between strength, stability, and architectural feasibility, making it the recommended approach for structural applications involving plastic bottle bricks.

4.5.2 PBB masonry units

Compressive tests were conducted on PBB masonry units incorporating three types of filler materials: air, sawdust, and pit sand. For each filler type, the units were tested with the embedded plastic bottles oriented both vertically and horizontally, as illustrated in **Figure 4-9**.

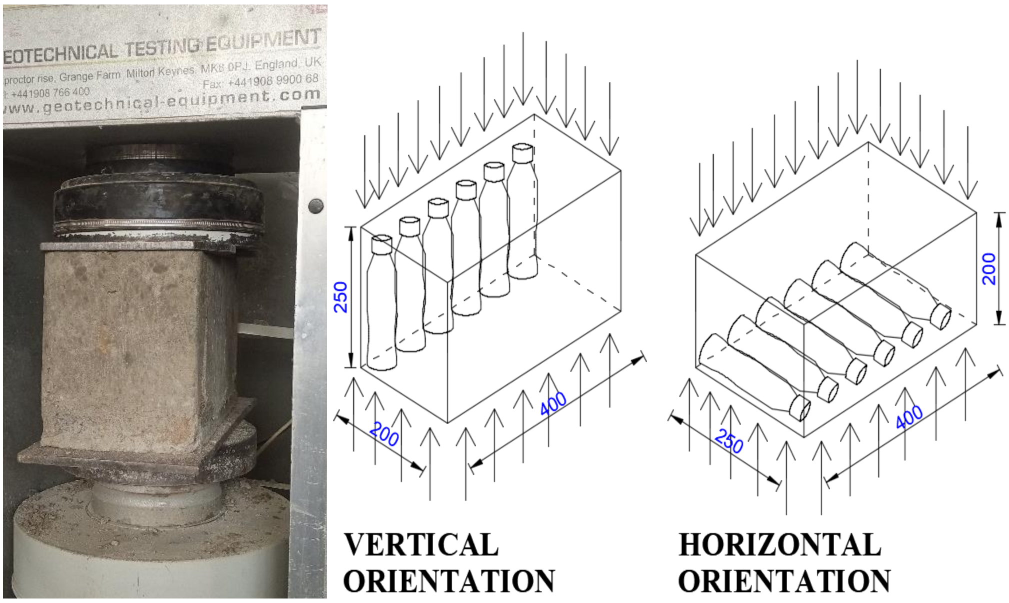


Figure 4-9: Loading of masonry unit samples using a compression-testing machine.

Compression tests were conducted in both vertical and horizontal orientations to evaluate the influence of the embedded plastic bottle's alignment on the compressive strength of the masonry units. Additionally, similar failure patterns were identified in relation to the various filler materials employed. A summary of the average compressive strength results is presented in **Table 4-5**, with detailed discussions for each filler material provided in the subsequent subheadings.

Table 4-5: Compressive strength summary for PBB masonry unit samples.

Sample ID	**Sample description**	**Average compressive strength (MPa)**		
		7 days	**14 days**	**28 days**
EBV	Empty PBB block in the vertical orientation	0.2	0.3	0.5
EBH	Empty PBB block in the horizontal orientation	0.1	0.2	0.7
SDV	Saw dust filled PBB block in the vertical orientation	0.2	0.4	0.5
SDH	Saw dust filled PBB block in the horizontal orientation	0.2	0.3	0.5
PSV	Pit sand filled PBB block in the vertical orientation	0.3	0.4	1.2
PSH	Pit sand filled PBB block in the horizontal orientation	0.8	1.1	1.2

A general increase in compressive strength was observed, primarily attributed to the ongoing mortar curing process. The results are further categorized and analysed in the subsequent subheadings, focusing on failure patterns, the relationship with density, and the influence of filler materials, with supporting literature integrated into the discussion.

a) Failure patterns

Vertical orientation

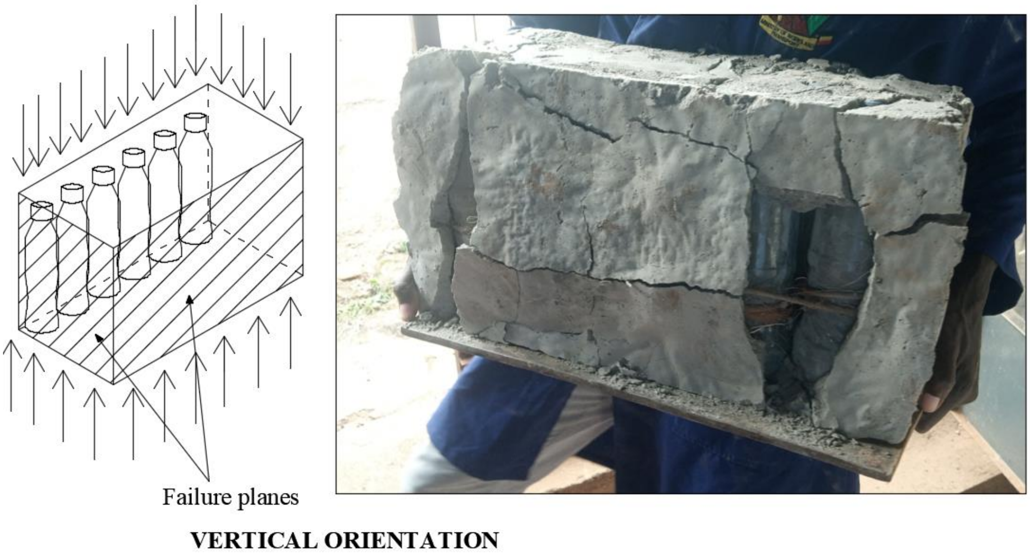


Figure 4-10: Typical failure patterns in trial samples for loading in the vertical orientation.

It was generally observed that the load was initially transmitted through the mortar and then carried by the PBBs without visible damage. Further loading led to cracking in the failure planes shown in **Figure 4-10**, with the longer edges having more damage than the shorter ends. The failure could be attributed to bucking of bottles due to a lower second moment of area and excessive deformation due to heavy loads. After significant visible deflection and cracking of mortar in the failure planes, the load was fully supported by the PBBs till visible collapse/buckling of some PBBs was observed as shown in **Figure 4-11** on the next page.

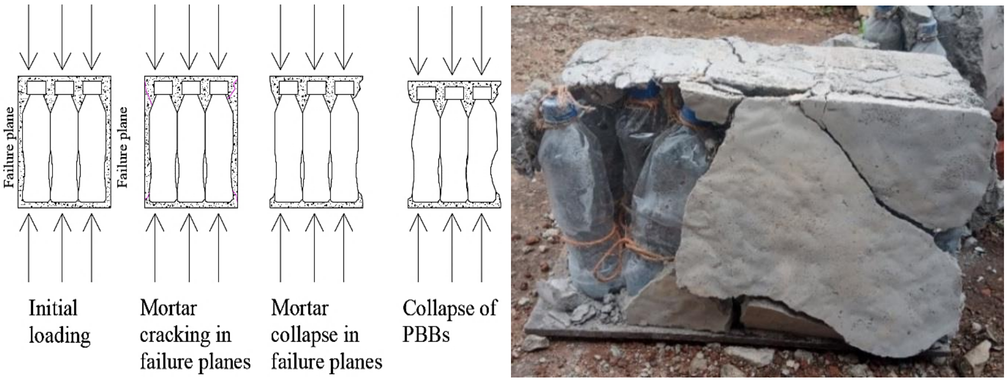


Figure 4-11: Loading of masonry units in the vertical orientation till failure/collapse.

Horizontal orientation loading

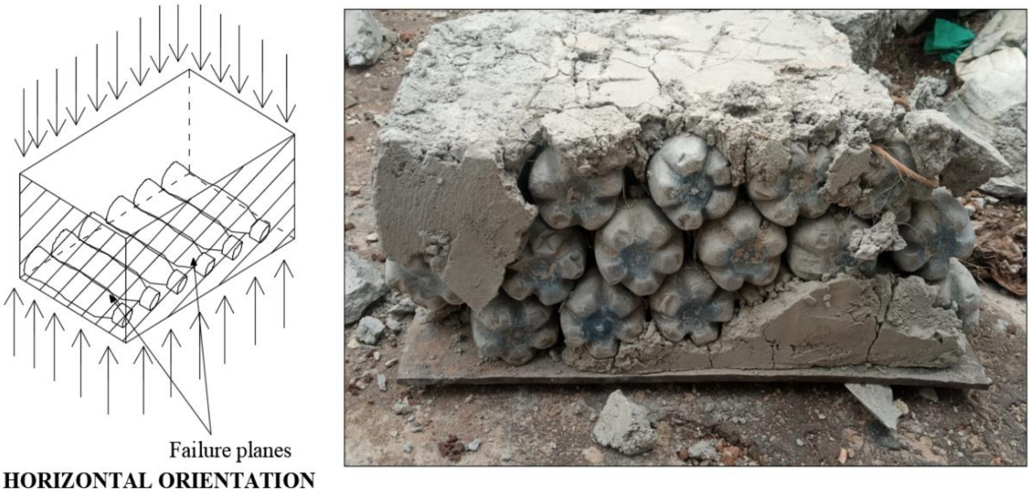


Figure 4-12: Typical failure patterns of trial samples for loading in the horizontal orientation.

It was generally observed that the load was initially transmitted through the mortar and then carried by the PBBs without visible damage. Further loading led to cracking in the failure planes shown in **Figure 4-12**, with the longer edges having more damage than the shorter ends. After significant visible deflection and cracking of mortar in the failure planes, the load was fully supported by the PBBs till collapse of some PBBs was observed as shown in **Figure 4-13**.

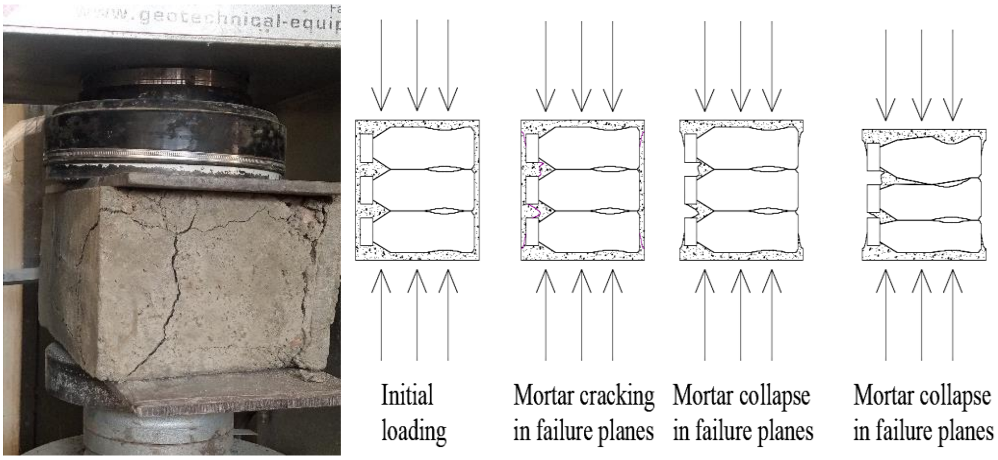


Figure 4-13: Loading of masonry units in the horizontal orientation till failure/collapse.

b) Relationship with density

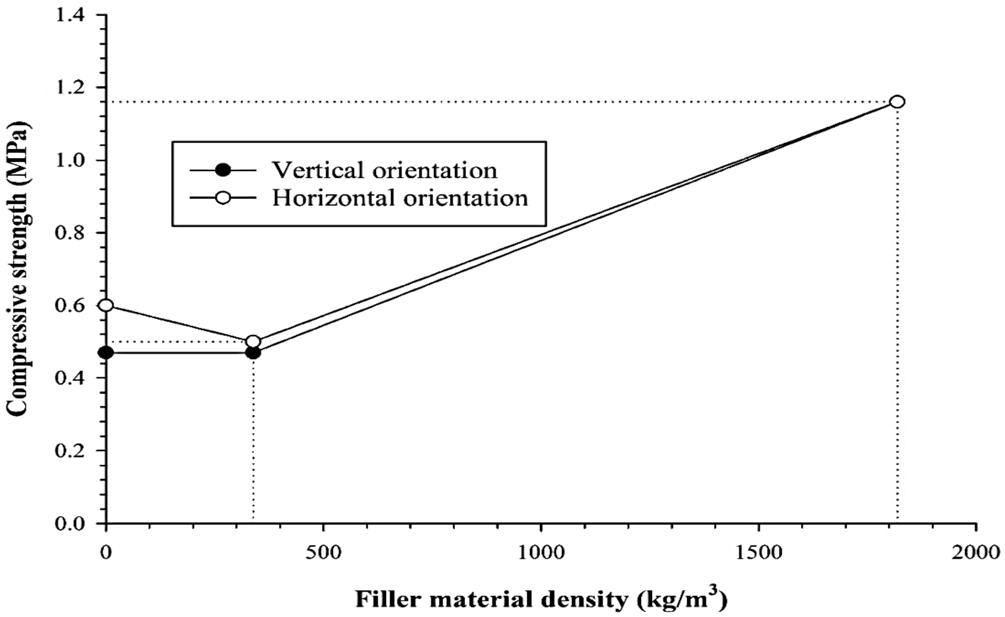


Figure 4-14: PBB masonry unit 28 days Compressive Strength vs. Filler Material Density.

The results presented in the graph indicate a clear trend in which the compressive strength at 28 days curing of the masonry units increases with the density of the filler material, consistent with findings by Parab et al. (2021). Uncompressed air, having an approximate density of 0 kg/m³, exhibited the lowest compressive strength, reflecting its limited structural contribution. Sawdust, with a minimum filler density of approximately 338.231 kg/m³ corresponding to 53% compaction, showed a marked improvement in compressive strength. The highest compressive strength was observed in specimens filled with pit sand, which had a minimum filler density of 1819.144 kg/m³ at 80% compaction. However, due to limited data points, this graph may not reliably define the relationship between failure load and density of the filler material within the plastic bottles.

c) Empty plastic bottle brick (PBB) masonry units

The compressive strength of masonry samples at 7 days, 14 days and 28 days curing duration were recorded and plotted in **Figure 4-15**, capturing the compressive strength in both the vertical and horizontal orientation for empty PBB masonry units.

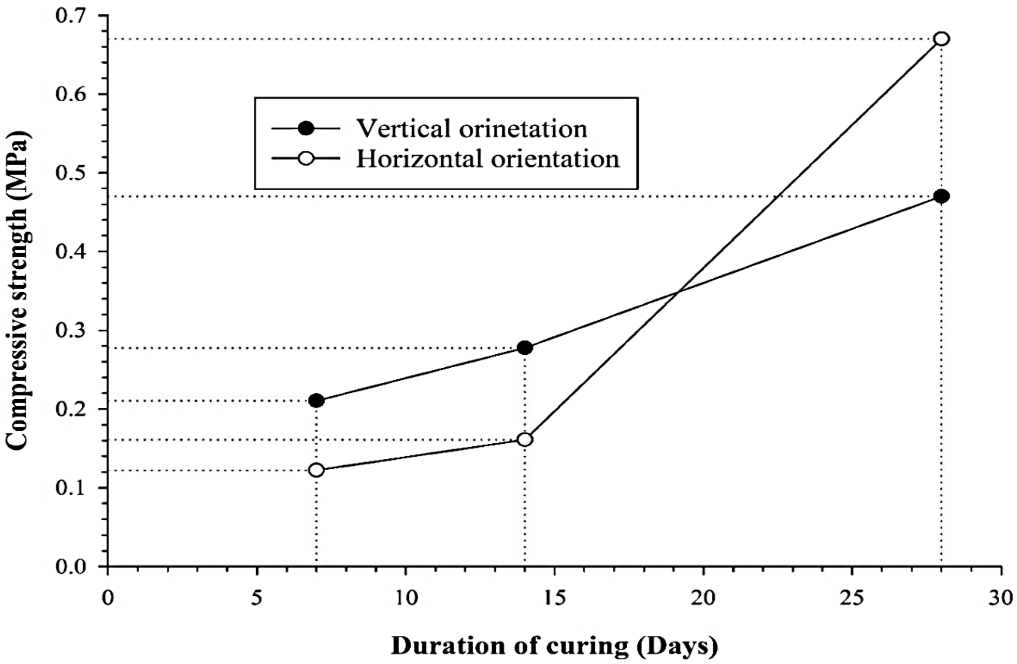


Figure 4-15: Compressive strength of empty PBB masonry units.

From the graph above, it was noted that the compressive strength at 7 days was higher in the vertical orientation compared to the horizontal orientation. However, at 28 days, the compressive strength in the horizontal orientation was higher than in the vertical orientation. The non-linear improvement from the 7 days compressive strength in the horizontal orientation (449%), in comparison to the linear strength improvement in the vertical direction (123%) could be explained by a larger strength contribution of mortar strength to the horizontal orientation, in comparison to the vertical orientation. This would imply that a reduction in the mortar strength will have a higher strength reduction effect in the horizontal orientation compared to the vertical orientation. Based on these findings, the vertical orientation was selected as the ideal orientation since its more economic because, the mortar strength could be reduced through a smaller cement content with a lesser effect on the compressive strength.

d) Saw dust filled plastic bottle brick (PBB) masonry units

The compressive strength of masonry samples at 7 days, 14 days and 28 days curing duration were recorded and plotted in **Figure 4-16**, capturing the compressive strength in both the vertical and horizontal orientation.

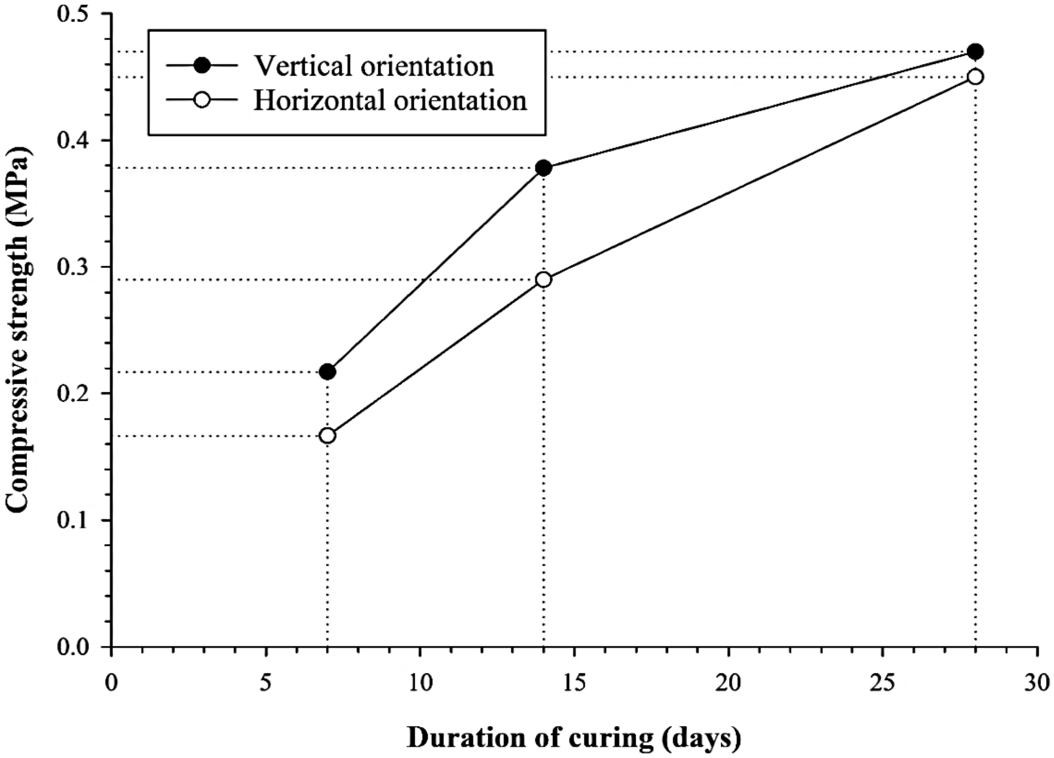


Figure 4-16: Compressive strength of saw dust filled PBB masonry units.

From the graph above, it was noted that the compressive strength was greater in the horizontal orientation than the vertical orientation at 7, 14 and 28 days. Both orientations also had a non-linear relationship, which could be attributed to the highly non-linear elasticity of saw dust and non-linear curing of mortar. The higher improvement from the 7-28 days compressive strength in the horizontal orientation (170%), in comparison to the compressive strength in the vertical orientation (116%), which could be explained by a larger strength contribution of mortar strength to the horizontal orientation, in comparison to the vertical orientation. This would imply that a reduction in the mortar strength will have a higher strength reduction effect in the horizontal orientation compared to the vertical orientation. Based on these findings, the vertical orientation was selected as the ideal orientation since its more economic because, the mortar strength could be reduced through a smaller cement content with a lesser effect on the compressive strength.

e) Pit sand filled plastic bottle brick (PBB) masonry units

The compressive strength of masonry samples at 7 days, 14 days and 28 days curing duration were recorded and plotted in **Figure 4-17**, capturing the compressive strength in both the vertical and horizontal orientation.

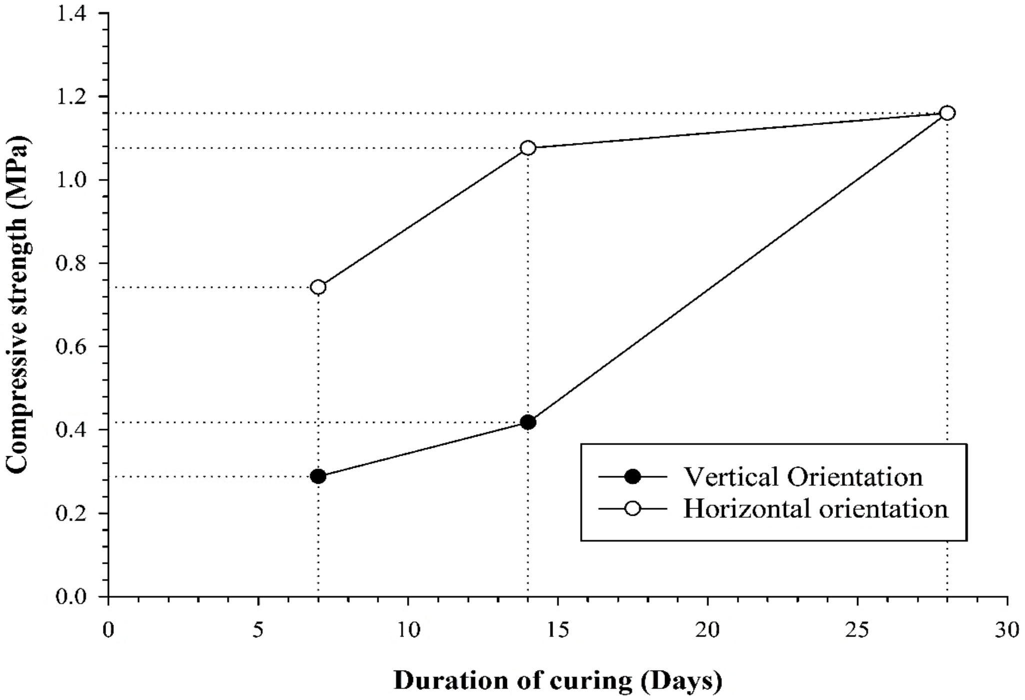


Figure 4-17: Compressive strength of pit sand filled PBB masonry units.

From the graph above, it was noted that the compressive strength was greater in the horizontal orientation than the vertical orientation at 7 and 14 days of curing, and was approximately equal in both orientations at 28 days curing. Both orientations also had a non-linear relationship, which could be attributed to the non-linear composite action of the tied PBBs in the masonry unit and non-linear curing of mortar. The higher improvement from the 7 days compressive strength in the vertical orientation (303%), in comparison to the compressive strength in the horizontal orientation (37%), could be explained by the high density of the pit sand filler material, whose strength in the horizontal direction mostly relies on the PBB strength more than the mortar strength.

However, there was significant damage and deflection in the masonry unit before the load was transmitted to the PBBs in the horizontal orientation, which could be attributed to the flattening effect of loading the PBBs in the horizontal orientation. On the other hand, the vertical orientation has a higher contribution of mortar strength in the vertical orientation due to a higher PBB resistance due to the high-density filler material. Hence, the PBBs experience lesser deflection, hence allowing for a more effective combined PBB and mortar resistance.

This would imply that a reduction in the mortar strength will have a higher strength reduction effect in the vertical orientation compared to the horizontal orientation before 28 days. Since the 28 days strength was almost identical for both orientations, the vertical orientation was selected due to its smaller thickness and larger area coverage in a stretcher bond masonry wall.

4.5.3 Concrete blocks

Concrete blocks were produced based on insights from a baseline survey to represent the typical commercially available blocks in Mbale City. The survey guided the mix design, which comprised cement, pit sand, and stone dust in a volumetric ratio of 1:3:6, with a water-to-cement ratio ranging between 0.7 and 0.9. In addition, solid concrete blocks incorporating river sand were cast to assess strength differences relative to those made with pit sand. Compressive strength tests were conducted using a Compression Testing Machine, following the guidelines of EN 12390-4, with a constant loading rate of 2kN/s. The results are presented in the subsequent section.

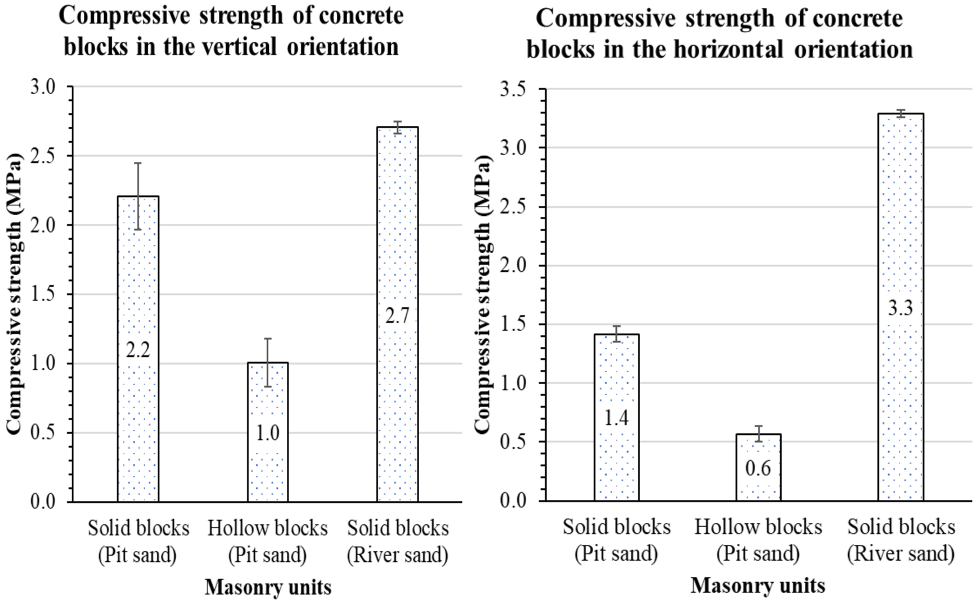


Figure 4-18: Compressive strength of concrete blocks in the vertical orientation.

In both vertical and horizontal orientations, the compressive strength of solid blocks made with pit sand was approximately 22.7% lower than that of blocks produced using river sand. This disparity is primarily attributed to differences in particle composition and grading. River sand typically consists of well-graded, coarse particles that enhance interlocking and shear resistance under compressive loads, thereby contributing to greater strength (Quayson, et al., 2018). Conversely, pit sand often contains a higher proportion of fine silt particles, which hinder proper bonding and compaction, resulting in weaker concrete.

As expected, hollow concrete blocks demonstrated lower compressive strength than solid blocks in both orientations. This reduction is mainly due to the presence of internal voids, which significantly decrease the effective load-bearing cross-sectional area (Agunwamba, et al., 2016). These voids disrupt the uniform distribution of compressive stresses, causing stress concentrations in the webs and shells that serve as the primary structural elements. Such stress concentrations increase the susceptibility to early cracking and failure under load. Moreover, the reduced mass and density of hollow blocks further diminish their resistance to crushing and buckling. In contrast, solid blocks, with their continuous and homogeneous structure, allow for uniform stress distribution, improved stiffness, and higher load-carrying capacity.

4.5.4 Comparison of PBB masonry units with concrete blocks at 28 days strength

To assess the structural performance of plastic bottle bricks (PBBs) masonry units against conventional concrete masonry units, compressive strength tests were conducted using a Compression Testing Machine in compliance with EN 12390-4, at a constant loading rate of 2kN/s to ensure consistent testing conditions across all samples. This allowed for a direct comparison of the masonry units' load-bearing capacity and failure characteristics. The results of these tests are detailed in the following chapters and provide insight into the viability of PBBs as alternative masonry units.

a) Compressive strength of masonry units in the vertical orientation

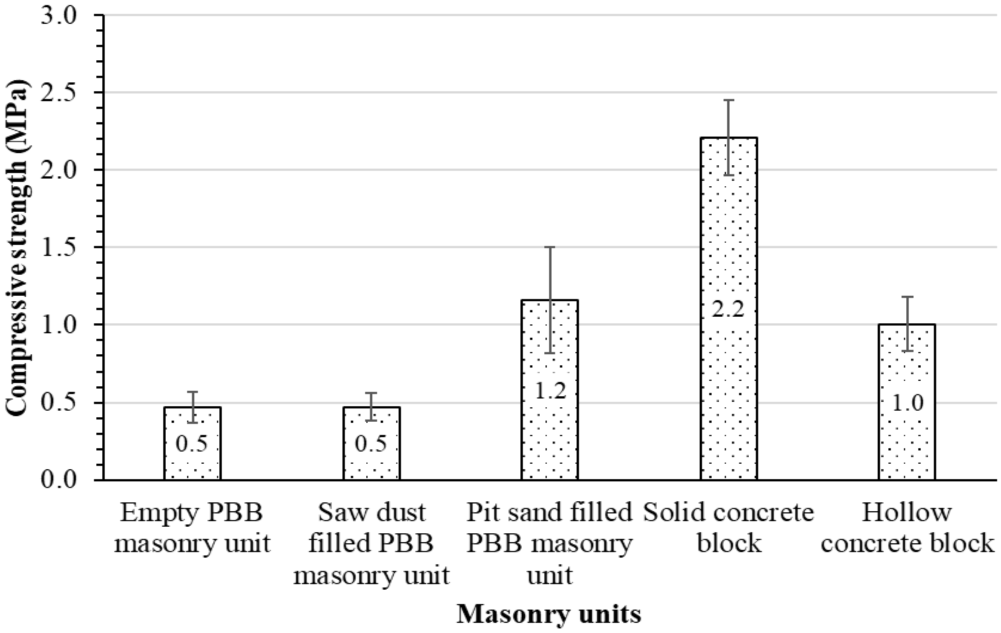


Figure 4-19: Masonry unit compressive strength in the vertical orientation.

As anticipated, the solid concrete blocks exhibited superior performance compared to the empty bottle, sawdust-filled, and pit sand-filled plastic bottle masonry (PBB) units, primarily due to their continuous and homogeneous load-bearing cross-sectional area, as noted by Agunwamba et al. (2016). In contrast, PBB units have a composite structure with confined plastic bottles at the core, which are inherently weaker in load-bearing capacity than concrete. However, the pit sand-filled PBB units outperformed the hollow concrete blocks, largely due to the enhanced structural contribution of the sand-filled bottle core. The compacted sand achieved a density of approximately 1,860.7 kg/m³, which closely approaches that of solid concrete blocks (2,075.86 kg/m³), thus contributing significantly to their compressive strength and overall load resistance.

The failure of the concrete blocks predominantly occurred along diagonal shear planes on the sides, a typical failure mode under uniaxial compressive loading due to the development of maximum shear stresses at approximately 45° to the loading axis (Celano, et al., 2021). In the case of the hollow concrete blocks, failure was primarily observed along the flanges and webs zones characterized by reduced cross-sectional area and elevated stress concentrations (Lü´, et al., 2012). These structural elements serve as the main load transfer paths; hence, under increasing compressive loads, they experienced localized cracking and eventual brittle fracture.

For the plastic bottle masonry (PBB) units, failure initiated at the interface between the mortar and the plastic bottles due to poor adhesion and material incompatibility. This debonding was followed by progressive failure through buckling of the vertically oriented plastic bottles, which acted as the primary axial load-carrying members (Wonderlich, 2014). Since plastic exhibits nonlinear, ductile deformation characteristics under compressive stress, the failure was less abrupt but marked by visible deformation and instability of the embedded bottle cores.

b) Compressive strength of masonry units in the horizontal orientation

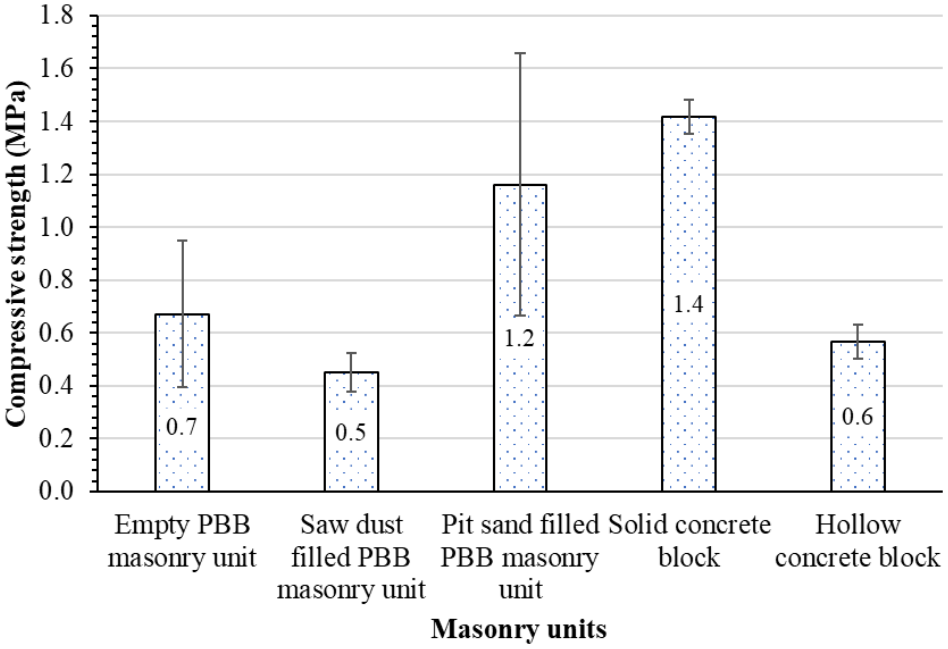


Figure 4-20: Masonry unit compressive strength in the horizontal orientation.

Consistent with the results observed in the vertical orientation, the solid concrete blocks demonstrated the highest average compressive strength in the horizontal orientation. However, the pit sand-filled plastic bottle masonry (PBB) units exhibited error bars in their standard deviation that overlapped with those of the concrete blocks. This suggests that, despite having a lower mean strength, the strength distribution of pit sand-filled PBB units lies within a comparable range.

The observed reduction in compressive strength for the concrete blocks in the horizontal orientation can be attributed to the change in loading direction, which effectively reduced the load-bearing depth from 250 mm to 200 mm. This decrease in cross-sectional depth diminished the moment of inertia and shear resistance of the units under axial compression. As a result, the overall structural stiffness and load-carrying capacity of the blocks are reduced when loaded in the horizontal orientation.

In contrast, the hollow concrete blocks exhibited standard deviation error bars that overlapped with those of both the empty bottle and sawdust-filled plastic bottle masonry units, indicating that their compressive strengths are statistically comparable. The reduced strength of the hollow blocks can be attributed partly to the decreased effective block depth from 250mm to 200mm in the horizontal orientation and partly to the inherently smaller load-bearing area. This reduced cross-sectional area leads to elevated stress concentrations, particularly along the webs and flanges, where tensile and shear stresses tend to localize during compression (Liu, et al., 2018; Agunwamba, et al., 2016). These areas are more prone to cracking and premature failure.

Interestingly, the empty bottle masonry units demonstrated slightly higher mean compressive strength than the sawdust-filled units. This could be due to the greater rigidity provided by the hollow plastic bottle structure under confinement. However, the overlapping standard deviation bars between these two types suggest that the difference in strength is not statistically significant, and their performance under compressive loading can be considered equivalent within the experimental margin of error.

c) Conclusion on concrete block strength

Blocks produced using river sand exhibited a notable improvement in compressive strength compared to those made with pit sand, specifically, by approximately 22.5% in the vertical orientation and a substantial 132.1% in the horizontal orientation. This enhancement is attributed to river sand’s better gradation and lower silt content, which promote superior particle interlock and cement hydration, resulting in stronger and more durable concrete. Despite this, pit sand is more commonly used in practice due to its availability and lower cost. As such, concrete blocks made with pit sand were selected as a more realistic benchmark for this study.

Interestingly, pit sand blocks performed better in the vertical orientation, while river sand blocks exhibited slightly higher strength in the horizontal orientation. Given this high correlation and practical considerations, the vertical orientation was deemed more representative and was prioritized for comparative analysis.

Among the PBB masonry units, those filled with compacted pit sand significantly outperformed both the empty bottle and sawdust-filled variants, with an average compressive strength increase exceeding 70% in both orientations. When compared to solid concrete blocks, pit sand-filled PBB units exhibited 47% lower strength in the vertical orientation and 18% lower strength in the horizontal orientation. Nonetheless, they surpassed the performance of hollow concrete blocks in both directions, highlighting their potential as a structurally viable and more sustainable alternative to conventional hollow masonry units.

4.5.5 Masonry wall tests

Compressive strength is a fundamental mechanical property that significantly affects the load-bearing capacity and overall structural performance of masonry wall panels. It determines how well a wall can resist vertical loads without experiencing failure, making it a key criterion in the assessment of materials for structural applications.

This section presents the results and analysis of compressive strength tests performed on five types of masonry wall panels. These included panels made from plastic bottle bricks (PBBs) with vertically oriented bottles filled with different materials (air, sawdust and pit sand), as well as panels made from conventional concrete masonry units, both solid and hollow blocks. The main goal of this investigation is to evaluate and compare how well each wall type resists axial (vertical) loads, and to determine their potential suitability for use in load-bearing masonry construction.

a) Compressive strength of masonry wall panels

The compressive strength tests were conducted using a hydraulic power jack, which applied a gradually an axial load at a loading speed of 1mm/second until failure occurred. The setup ensured uniform load distribution across the wall panels. **Figure 4-21** on the next page illustrates the compressive strength results for all tested specimens which shows that; the average compressive strength values ranged from 0.3 MPa to 0.8 MPa, with a standard deviation of less than 0.06 MPa, indicating relatively consistent behaviour within each group of wall panels.

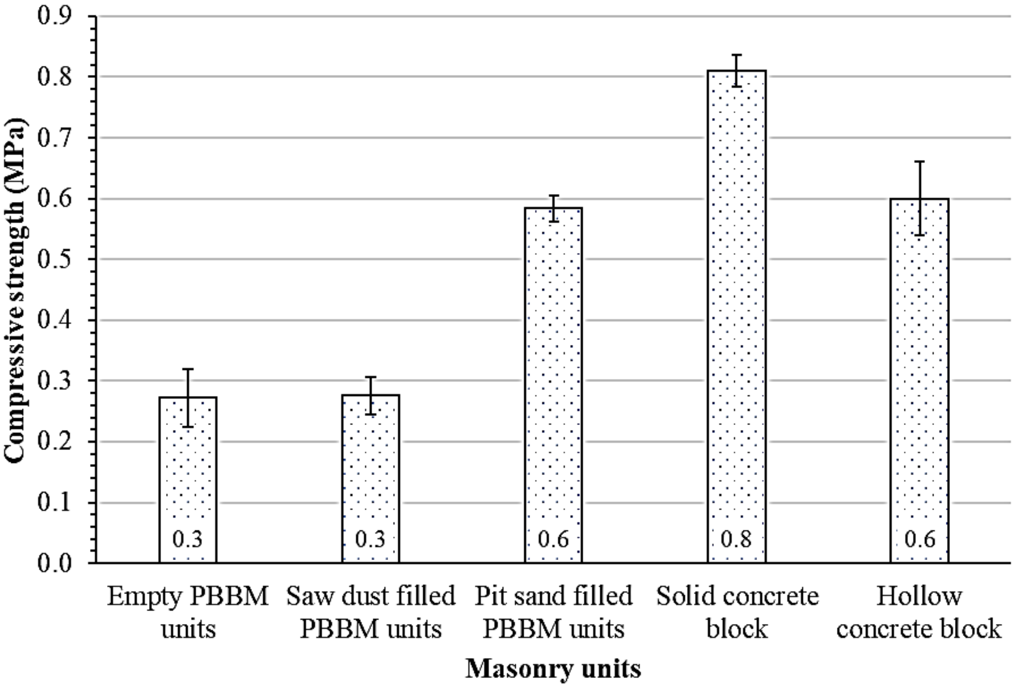


Figure 4-21: Compressive strength of masonry wall panel samples.

The compressive strength results showed that solid concrete blocks outperformed all plastic bottle brick (PBB) masonry wall panels by more than 30%, as well as surpassing hollow concrete blocks, confirming their superior load-bearing capacity among the tested specimens. Hollow concrete blocks displayed compressive strength values similar to those of PBB panels filled with pit sand, indicating that pit sand provided a significant improvement in the structural performance of the PBB units. In contrast, both unfilled (air-filled) PBB walls and those filled with sawdust exhibited comparable compressive strength values, suggesting that sawdust contributed little to no structural advantage over empty bottles.

Despite their generally lower compressive strength, the PBB masonry walls exhibited a distinct advantage in terms of failure behaviour. While the concrete masonry walls particularly those made with solid and hollow blocks failed suddenly and catastrophically once their ultimate load was reached (Rafi & Khan, 2024), the PBB panels underwent a more gradual and ductile failure, evident by higher strain values as discussed in the subsequent subheadings. This ductility is advantageous in structural applications where energy absorption and warning before failure are critical. The PBB walls' ability to deform without immediate collapse suggests potential for use in structures where resilience and post-peak load performance are valued, particularly in low-load or non-load-bearing applications.

b) Deformation values for masonry wall panels

In addition to compressive strength, deformation behaviour is a critical parameter in assessing the structural performance of masonry wall panels. It provides insight into the material’s ductility, energy absorption capacity, and post-peak performance, all of which are essential for ensuring stability under load, especially in seismic or dynamic conditions.

The masonry panels tested were about 1100mm in height and 200mm thick, which gives a slenderness ratio of 5.5, which implied that these are short walls and are unlikely to buckle due to geometry, based on Eurocode 6 (EN 1996-1-1) guidelines. Based on this guideline, measurements of strain were based on vertical deflection, since buckling was highly unlikely.

The deformation was measured on both the left and right side of each masonry wall panel, and the results for strain have been summarised in **Table 4-6** below.

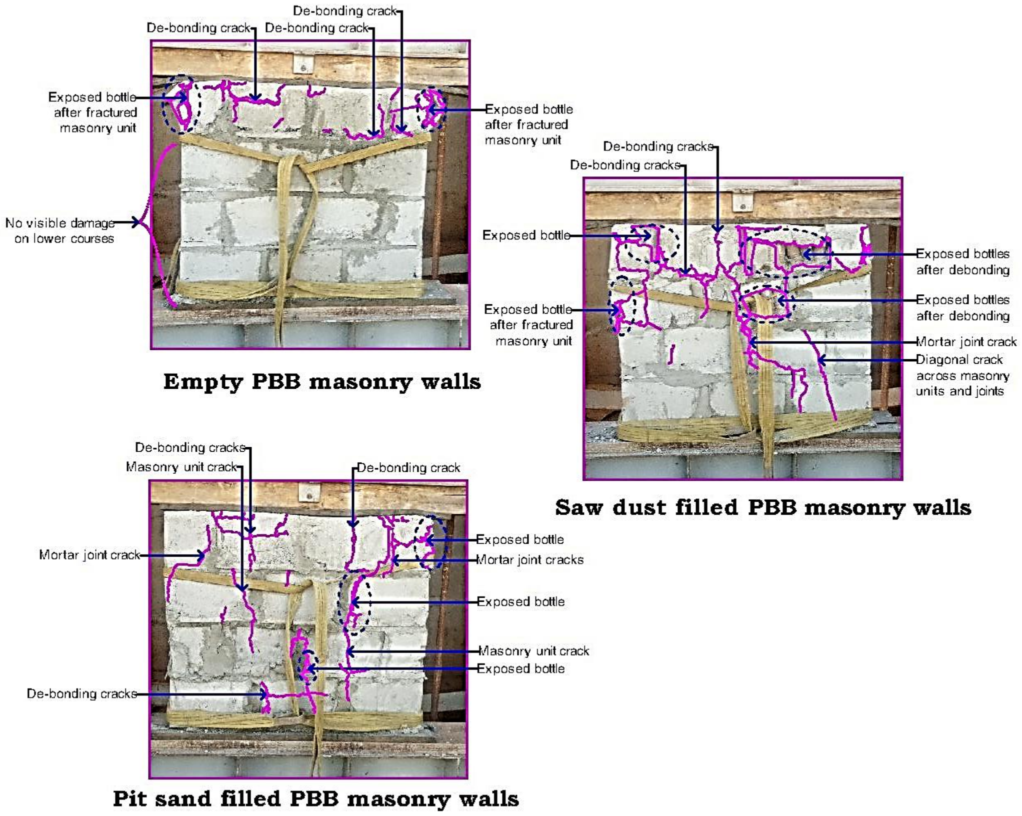
Table 4-6: Deflection and strain results for masonry walls at peak load.

Sample ID	**Wall description**	**Average strain (%)**	**Standard deviation (%)**
EBW	Empty Plastic bottle walls	1.8152	0.047
SDW	Saw dust filled bottle walls	1.8792	0.031
PSW	Pit sand filled bottle walls	2.0022	0.022
SBW	Solid concrete block walls	1.1583	0.026
HBW	Hollow concrete block walls	0.9631	0.060

Plastic bottle brick (PBB) masonry walls demonstrated significantly higher strain values (1.815–2.002%) compared to the concrete blocks (0.963 – 1.158%), indicating at least 57% greater ductility than solid concrete block walls (SBW). The PBB masonry walls exhibited more gradual and progressive cracking patterns, whereas concrete block walls tended to experience sudden cracking followed by catastrophic failure. This enhanced ductility is attributed to the confinement effect provided by the sisal-wrapped plastic bottles within the masonry units. As a result, PBB walls show a greater capacity for energy absorption, delayed crack propagation, and potentially improved performance under dynamic or impact loading conditions. Although these units may not meet standard strength requirements, their superior ductility makes them well-suited for use in low-risk or secondary structural applications, such as infill walls, where enhanced deformation capacity is advantageous.

c) Failure patterns

The failure patterns for PBB masonry wall samples were observed for each masonry walls specimen, and the failure patterns at collapse have been traced as seen in **Figure 4-22**.



Empty PBB masonry walls

Saw dust filled PBB masonry walls

Pit sand filled PBB masonry walls

Figure 4-22: Crack propagation for PBB masonry walls at peak load.

The crack propagation for the empty bottle PBB masonry wall specimens was typically only occurring in the first course of the wall panel. This could be explained by buckling of the empty bottles without sufficiently transferring loads to the lower courses. However, for saw dust, even though the peak load was almost the same as for the empty bottle wall, the loads were distributed throughout the wall specimen due to the contribution of the saw dust in resisting bottle buckling.

The failure patterns for concrete block wall samples were observed for each masonry walls specimen, and the failure patterns at collapse have been traced as seen in **Figure 4-23**.

Solid concrete block wall specimen **Hollow concrete block wall specimen**

Figure 4-23: Crack propagation for concrete block walls at peak load.

d) Comparison with masonry units

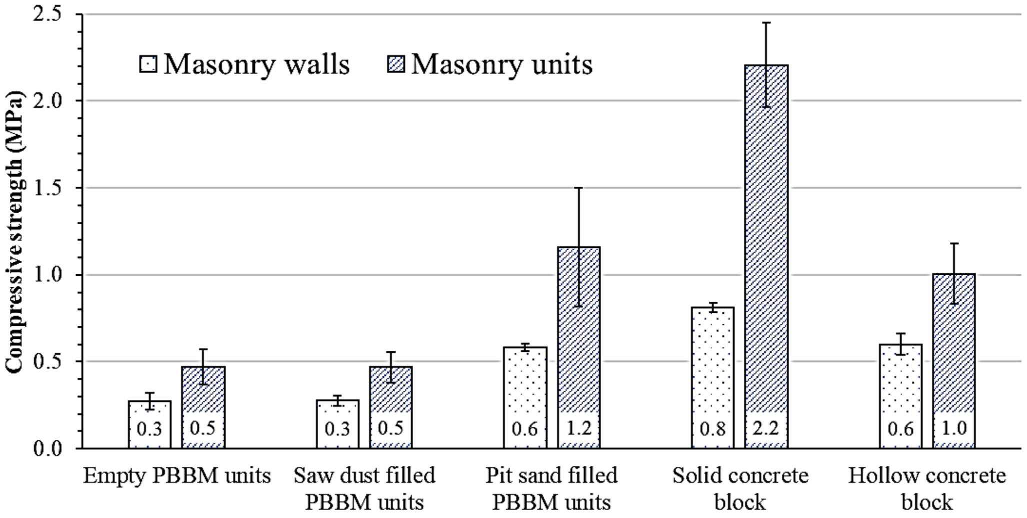


Figure 4-24: Comparison of compressive strength between masonry walls and units.

The observed reduction in compressive strength from individual masonry units to full wall panels reflects the structural behaviour of masonry under axial load. Wall panels exhibited lower strength than the constituent units due to the influence of mortar joints, minor misalignments, and other inherent discontinuities, consistent with the mechanisms described in BS 5628-1:2005, Clause 3.3, and Eurocode 6 (BS EN 1996-1-1:2005, Clause 5.2.2). For the PBB masonry walls, the reduction ranged from 40–50%, while concrete block walls exhibited reductions of 40–64%, highlighting the combined effects of joint behaviour, unit heterogeneity, and wall geometry on overall performance. The comparable reductions between PBB and conventional concrete block masonry, and agreement with the findings of Tokpomehoun et al. (2022), who reported wall-to-unit ratios of 44–52%, indicate a predictable correlation between unit-level and panel-level behaviour. These results underscore the importance of considering wall-level structural effects in design and analysis, rather than relying solely on unit compressive strengths, particularly for non-uniform or alternative masonry units such as infilled bottles or PBBs.

e) Stress-strain at collapse

The results in for strain in **Table 4-6** reveal that solid concrete blocks achieved the highest compressive strength, approximately 0.82 MPa, at a relatively low strain of around 1%. This behaviour reflects a stiff, brittle material response with limited deformation before failure, characteristic of high-strength conventional masonry. However, this is higher than the recommended strain in Eurocode 6 (BS EN 1996-1-1:2005), which recommends 0.2-0.3% strain as a way of safeguarding concrete structures from serviceability failure due to visible cracking. However, it falls short in terms of compressive strength recommended for most conventional codes for load bearing walls which is about 5MPa.

Hollow concrete blocks exhibited moderate performance, reaching compressive strengths near 0.6 MPa at strains also close to 1%, but slightly less than that of the solid blocks. They are less ductile since failure occurs due to stress concentrations at flange-web connections. Among the PBBM specimens, the pit sand-filled units showed the highest ductility (2%), with compressive strength values also around 0.6 MPa. This indicates enhanced ductility and energy absorption capacity, making these units more resilient under axial loads. However, it also falls short in terms of compressive strength recommended for most conventional codes, but could compensate in cases where ductility is a major requirement.

In contrast, the sawdust-filled bottle and empty bottle walls exhibited the lowest compressive strength, both reaching only about 0.3 MPa, despite experiencing large strains approaching 2%. The similarity in performance between these two types suggests that sawdust contributed minimally to load-bearing capacity compared to the empty bottle configuration. However, their ability to undergo significant deformation before failure points to a highly ductile but structurally weak behaviour.

Solid concrete blocks offer superior strength with minimal deformation, making them ideal for high-load structural applications. On the other hand, pit sand-filled PBBM units, while not as strong, demonstrate considerable ductility and deformation tolerance, suggesting potential for use in low-load or non-load-bearing walls where energy absorption and sustainability are prioritized. Sawdust and empty PBBM units, given their poor strength characteristics, are best suited for non-structural applications such as thermal insulation or partitioning, rather than load-bearing walls.

4.6 Cost-benefit analysis

4.6.1 Materials costs

a) PBB masonry units' materials costs

Based on the market prices established in **Table A-9** in Appendices, the material rates were established using the formula below:

$$Materials\ rate\ (Ugx.) = \frac{Material\ market\ price}{Standardised\ material\ quantity}$$

The quantity of materials was measured using units complying to the CESMM4 recommended material units to standardise the calculations. 17 plastic bottles, around 11.05m of sisal rope, and approximately 0.01275 cubic meters of a 1:4 dry mortar mix by volume were used to produce each PBB masonry unit, and have been summarised into **Table 4-7**. A detailed costing of materials is appended in

Appendix A.6: Cost-benefit analysis raw data.

Table 4-7: Material cost summary per PBB masonry unit produced.

No.	Material Description	Amount (Ugx.)
1.	Empty plastic bottle brick masonry units	3,473
2.	Saw dust filled plastic bottle brick masonry units	3,561
3.	Pit sand filled plastic bottle brick masonry units	3,746

b) Concrete blocks materials costs

Approximately 0.026842 cubic meters of a 1:3:6 dry concrete mix was used to produce the solid blocks, and 0.02147368 cubic meters of a 1:3:6 dry concrete mix used to produce the hollow blocks, and have been summarised into the **Table 4-8**. A detailed costing of materials is appended in

Appendix A.6: Cost-benefit analysis raw data.

Table 4-8: Material costs per concrete masonry unit produced.

No.	Material Description	Amount (Ugx.)
1.	Solid concrete blocks	3,861
2.	Hollow concrete blocks	6,949

4.6.2 Labour costs

a) PBB masonry units labour costs

The labour rates were quantified based on outputs using the formula below.

$$\text{Labour rate} = \frac{\text{Daily labour rate for a task}}{\text{Quantity of task outputs}}$$

Based on the above inputs, the labour costs for each PBB masonry unit were quantified in **Table 4-9** below. A detailed costing of labour is appended in

Appendix A.6: Cost-benefit analysis raw data.

Table 4-9: Labour costs per masonry unit produced for PBB masonry units.

No.	Task Description	Amount (Ugx.)
1.	Empty plastic bottle brick masonry units	1,574
2.	Saw dust filled plastic bottle brick masonry units	4,124
3.	Pit sand filled plastic bottle brick masonry units	3,274

b) Concrete block labour costs

The labour costs for each concrete block have been quantified in **Table 4-10**. A detailed costing of labour is appended in

Appendix A.6: Cost-benefit analysis raw data.

Table 4-10: Labour costs per masonry unit produced for concrete blocks.

No.	**Process Description**	**Amount (Ugx.)**
1.	Solid blocks	1,574
2.	Hollow blocks	1,574

4.6.3 Time utilisation cost

The time costs were based on observations of how long it took labour to accomplish specific tasks, which was recorded in hours. The duration per output was based on an approximated 10-hour work day, and hence the time taken to achieve each task was quantified using the formula below.

$$\text{Duration per output (hours/output)} = \frac{\text{Quantity of task outputs achieved daily}}{10}$$

Considering a weighted average labour cost of about Ugx. 15,000 was recorded, for a 10-hour working day, which gives an hourly rate of about Ugx. 1,500 per hour. The quantification of time in monetary terms has been calculated in **Table 4-11** on the next page. A detailed costing of time utilisation cost is appended in

Appendix A.6: Cost-benefit analysis raw data.

Table 4-11: Time utilisation cost in Ugandan Shillings (Ugx.).

Masonry unit ID	**Description of masonry unit**	**Time utilisation cost (Ugx)**
EBB	Empty bottle block	911
SDB	Saw dust filled block	6,215
PSB	Pit sand filled block	6,215
SCB	Solid concrete block	455
HCB	Hollow concrete block	455

4.6.4 Carbon emissions cost

Based on a literature review on carbon emissions used to process the materials used in this study, these figures were used to quantify carbon emissions for all materials. The estimated minimum carbon tax worldwide (as of 30th May, 2025), was adopted for this quantification, which equals to about Ugx. 1,668. The formula below was used to quantify the carbon emissions cost.

$$\begin{aligned}&\text{Carbon emissions cost for a material}\\&\qquad= \text{Quantity of materials used}\\&\qquad\times \text{Carbon emissions per unit of material} \times \text{Carbon tax rate}\end{aligned}$$

Based on the above inputs, the calculations were tabulated in **Table 4-12** on the next page for each masonry unit type. A detailed costing of carbon emissions cost is appended in

Appendix A.6: Cost-benefit analysis raw data.

Table 4-12: Embodied carbon emissions in each masonry unit.

No.	**Material Description**	**Amount (Ugx.)**
1	Empty bottle block	5,736
2	Saw dust filled bottle block	13,734
3	Pit sand filled bottle block	6,060
4	Solid concrete block	22,869
5	Hollow concrete block	18,264

4.7.5 Cost comparison

In accordance with the Kaldor-Hicks efficiency criterion discussed in the literature review, five different masonry units were evaluated based on four key factors: material costs (resource utilization), labour costs (human capital), time-related costs (construction time efficiency), and carbon emissions (environmental impact). The results were consolidated into a stacked column chart, as shown in **Figure 4-25** on the next page, to illustrate the cost trade-offs among the different masonry units.

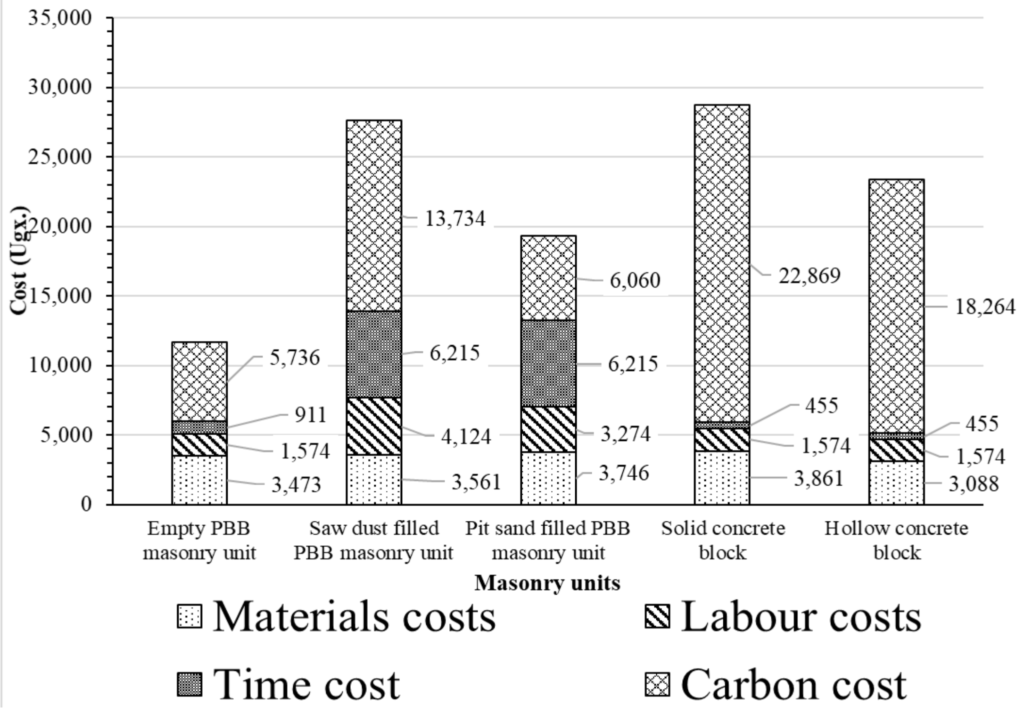


Figure 4-25: Cost-benefit assessment for masonry units.

All the three PBB masonry units (Empty bottle, Saw dust filled and Pit sand filled) consistently show lower material costs compared to their Solid Concrete Block (SCB) counterparts owing to the use of low-cost or waste materials like discarded plastic bottles, while the Hollow Concrete Blocks (HCB) had the lowest material costs due to voids which reduced the majority costs of cement and stone dust required hence driving down the cost.

However, the labour cost for the concrete masonry units (SCB and HCB) was generally lower than the PBB masonry units, which is attributed to mechanisation, economies of scale and simpler production methodology in comparison to PBB masonry units with a more complex methodology of production. However, this labour cost can be driven down by mechanisation of the PBB masonry unit making processes, most especially bottle filling which takes up more than 50% of the labour cost for SDB and PSB. Additionally, the time cost was significantly the highest for SDB and PSB due to time required for filling bottles which takes about 85% of the time to make each masonry unit. This too could be reduced through mechanisation of the bottle filling process.

Where the plastic bottle bricks truly excel is in carbon cost. EBB and PSB show substantially lower carbon costs, reflecting the environmental benefit of repurposing plastic waste and minimizing the need for energy-intensive materials like cement. In contrast, the conventional SCB and HCB demonstrate the highest carbon costs by a wide margin, primarily due to the emissions associated with cement production and aggregate mining. Notably, while SDB has a higher carbon cost than EBB and PSB, it remains significantly lower than both concrete-based alternatives. This suggests that plastic bottle masonry units, despite being more labour and time intensive, offer major environmental savings, especially in carbon-sensitive or climate-conscious construction scenarios.

4.7.6 Cost-benefit comparison

The cost-benefit analysis was conducted using Net Present Value (NPV)/Net benefit and Benefit-Cost Ratio (BCR), as established in the literature. Costs considered included material and labour expenses, while benefits accounted for time utilization savings and reductions in carbon emissions to determine the NPV and BCR values as shown in the formulae below.

$$\text{Carbon reduction benefit} = 22{,}869 - \text{Carbon emissions costs}$$

A maximum carbon emissions cost of Ugx. 22,869 for solid concrete blocks was selected as a baseline for determining the carbon reduction benefit for the remaining masonry units.

$$\text{Time saving benefit} = 455 - \text{Time utilisation costs}$$

A time utilisation cost of Ugx. 455 for solid concrete blocks was selected as a baseline for determining the time saving benefit for the remaining masonry units.

$$\text{Total costs} = \text{Material costs} + \text{Labour costs}$$

$$\text{Total benefits} = \text{Time saving benefit} + \text{Carbon reduction benefit}$$

$$\text{Net benefit} = \text{Total benefits} - \text{Total costs}$$

$$\text{BCR} = \frac{\text{Total benefits}}{\text{Total costs}}$$

From the above formulae, the Net benefits and Benefit-cost ratios for each masonry unit were summarised in **Table 4-13** on the next page.

Table 4-13: Net benefits and Benefit-cost ratios for masonry units.

Masonry unit ID	**Masonry unit description**	**Total costs (Ugx.)**	**Total benefit (Ugx.)**	**Net benefit (Ugx.)**	**BCR**
EBB	Empty bottle block	5,047	16,677	11,630	3.30
SDB	Saw dust bottle block	7,685	3,375	-4,310	0.44
PSB	Pit sand bottle block	7,020	11,049	4,029	1.57
SCB	Solid concrete block	5,435	0	-5,435	0.00
HCB	Hollow concrete block	4,662	4,605	-57	0.99

In **Table 4-13**, the BCR for solid blocks is shown as zero because their carbon emissions and time utilization costs were used as the baseline for assessing carbon reduction and time-saving benefits. Among the alternatives, the sawdust-filled bottle block was the least favourable, with costs exceeding benefits by 56%, primarily due to high labour and carbon emission costs, making it the least cost-effective among the PBB options. In contrast, the empty bottle blocks demonstrated the highest net benefits and BCR, establishing them as the most cost-effective solution, followed by the pit sand-filled bottle blocks. As expected, hollow blocks performed better than the baseline solid blocks in terms of BCR, though they lagged behind the empty and pit sand bottle blocks in overall benefits.

4.7 Comparisons with literature (Analysis of results)

4.7.1 Proposed method of wall construction using PET bottles

Two proposed construction methods using PET bottles (see **Figure 4-26**) include: (1) substituting conventional bricks with Plastic Bottle Bricks (PBBs) within masonry walls, and (2) remoulding PET bottles into interlocking units with customized grooves. However, the first method was found to have aesthetic limitations, while the second method, though aesthetically appealing, was not cost-effective due to the additional processing required to reshape the bottles (Pradeep, et al., 2022). In contrast, the proposed PBB masonry units offer the advantage of matching the aesthetics of conventional concrete blocks and do not require masons to acquire additional skills, unlike the previously discussed alternatives. Moreover, while these units are both visually and functionally compatible with standard construction practices, an estimation based on the PET bottles used in this study indicates that the first method of replacing bricks with PET bottles using approximately 2 cm mortar spacing, is actually less cost-effective. This is due to its higher mortar consumption, at least 4% more than the proposed PBBs, even before accounting for additional mortar wastage typically associated with this method. Interlocking bottles have been proposed as infill wall materials for shelters, particularly in humanitarian crises, due to their potential advantages in speed and cost of construction (Mansour & Mansour, 2020). However, these bottles are not currently in production or readily available, and their benefits would only be realized in the highly unlikely event of a large-scale humanitarian aid initiative utilizing them.

Figure 4-26: Method 1 (left), method 2 (right) (Pradeep, et al., 2022).

A study by Premalatha et al. (2016) utilized Method 1 described above but incorporated a steel mesh between the courses of Plastic Bottle Bricks (PBBs) to enhance strength. While this form of confinement improved compressive strength, it was not cost-effective due to the high cost of steel. In contrast, using sisal rope as a confining material proved to be a more economical alternative. The proposed method in that study was intended for use in low-rise buildings, aligning with the application recommended by the present study.

4.7.2 Method of confinement

A study by Jo (2024) utilised empty plastic bottles, primarily confined at the top and bottom and arranged vertically, to construct chairs. The bottles were secured using a weaving or tying method. Parab et al. (2021) tied bottles at the top with an intersecting weaving method. A combination of the two confinement methods were used, where the bottles were tied at the top and bottom to improve load bearing capacity of the masonry unit bottle core. This was done to reduce instability due confinement of only one side.

Figure 4-27: Tying of plastic bottles at the bottom (Jo, 2024) (left); tying of bottles at the top (Parab, et al., 2021) (central); confinement of bottles for this study (right).

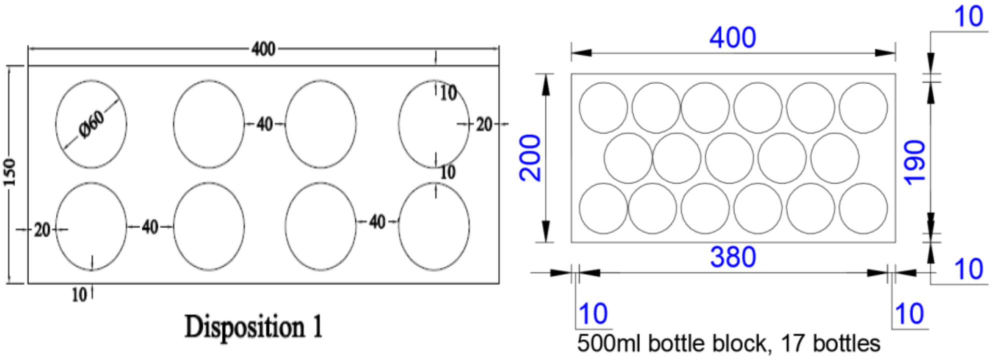
4.7.3 Plastic Bottle Brick (PBB) compressive strength

Most studies explored carried out compressive strength tests on PBBs in the horizontal orientation using compression testing machines. The tested PBBs all experienced flattening, similar to the PBBs tested during this study.

The average compressive strength of pit sand-filled plastic bottle bricks (PBBs) in the horizontal orientation was 28.9kN. In comparison, a similar study using 500 ml plastic bottles filled with sand reported a compressive strength of approximately 11.25kN (Muyen, et al., 2016). The compressive strength of a 500ml bottle filled with fly ash, whose fineness modulus was close to that of the pit sand used in this study was about 18.1kN (Premalatha, et al., 2016). Another study which tested the compressive strength of a 500ml bottle filled with This difference may be attributed to variations in bottle geometry and the properties of the sand filler.

4.7.4 PBBs embedded in mortar and concrete

Plastic Bottle Bricks (PBBs) have been embedded in concrete and mortar to produce masonry units aimed at enhancing load-bearing capacity and simplifying construction. One study embedded PBBs in self-compacting concrete to form 150×400×200mm blocks and tested their compressive strength, with eight bottles oriented vertically but positioned at varying dispositions. The results showed 28-day compressive strengths ranging from 9 to 20 MPa (Robleh, et al., 2021), significantly higher than those proposed in the present study. However, this increased strength was attributed to the use of concrete instead of pit sand-based mortar, as well as a substantially lower bottle cross-sectional area (4.7%) compared to the current study’s 60.1%.



Disposition 1

500ml bottle block, 17 bottles

Figure 4-28: Bottles embedded in concrete (Robleh, et al., 2021) (left); Bottles embedded in mortar for the current study (right).

A similar study by Wonderlich (2014) also embedded eight 500ml horizontally oriented bottles in a 400×200mm cross-section of a 1: [4.4] mix of mortar covering, similar to the current study with the major difference of unconfined bottles. The compressive strength of the various bottle brands ranged from 2.2-6.2 MPa, which is much higher than the 0.7MPa got in this study. However, the higher compressive strength is most likely attributed to the mortar strength. In addition, the higher concentration of cement use is less cost effective than the current study.

Tokpomehoun et al. (2022) embedded 500 ml bottles in a 1:3 cement mortar mix, confined with steel wire, and infilled them with Red Coffee Soil, Murram Soil, and Black Cotton Soil materials with densities comparable to pit sand. The 28-day compressive strengths ranged from 1.8 to 2.8MPa, exceeding the 1.2MPa observed for pit sand-filled PBBs in this study. This increase is attributed to the higher-grade mortar, stronger steel wire confinement, and geometric differences. Masonry walls with horizontally embedded bottles recorded compressive strengths of 0.8–1.4 MPa, compared to 0.6 MPa in this study, likely due to orientation effects and the aforementioned factors. Despite higher strengths, the study reported greater structural damage and unit failure. Additionally, the use of steel wire and higher cement content reduced cost-effectiveness and environmental sustainability due to increased carbon emissions.

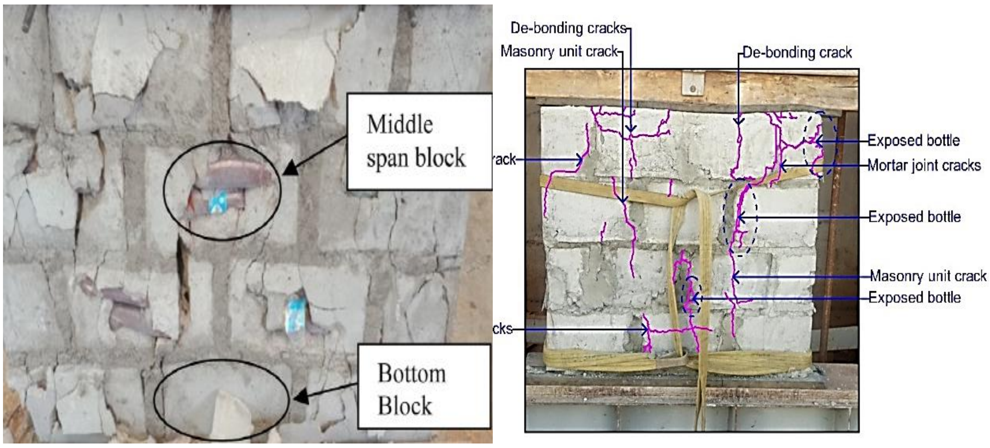


Figure 4-29: Excessive debonding (Tokpomehoun, et al., 2022) (left); Lesser debonding for the current study's walls (right).

All masonry units with plastic bottle cores reviewed had a high formwork requirement if the masonry units were to be produced on a large scale. In contrast, the methodology of this study proposed a method which used reusable Damp Proof Membrane strips as temporary support, hence allowing for a scalable masonry unit production operation in that the formwork could be removed immediately after casting. This makes the masonry units competitive with the concrete blocks which also have this similar trait of immediate formwork removal.

4.7.5 Conclusion of PBB comparisons

The plastic bottle brick (PBB) masonry units used in this study have addressed a significant number of problems which were facing the viability of using plastic bottles in the construction industry such as cost effectiveness in comparison to commercially available alternatives, speed of production, reskilling requirements and aesthetics. However, most of the masonry units proposed in the studies had a significantly higher compressive strengths, mostly due to the contribution of concrete and mortar cross-sectional area, which offsets the benefit of higher strength due to high production costs.

4.8 Data availability

4.8.1 Data repository

The datasets generated and/or analysed during this study are available in the zenodo.org repository, at https://doi.org/10.5281/zenodo.17115207.

4.8.2 Limitations and gaps in data provision

The Kireka Central Materials Laboratory (CML) did not issue certificates for the water absorption and compressive strength tests of masonry walls. However, photos and videos of the procedures have been deposited in the repository to ensure transparency of the methods used.

Details of the bottle confinement/tying process could not be fully described in the methodology due to its complexity. Supplementary photos have been provided in the repository to illustrate the procedure.

4.8.3 Commitment to provide data

The data supporting the findings of this study is available from the researcher upon reasonable request, provided that disclosure does not compromise privacy or confidentiality.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

The study explored the compressive strength of Plastic Bottle Brick (PBB) masonry walls for varying filler materials (uncompressed air, saw dust and pit sand), as a viable solution to the plastic bottle and pit sand waste problem, while providing cost-effective alternatives to commercially available concrete blocks in Mbale City. The study examined the compressive strength of masonry units with the embedded bottles in the vertical and horizontal orientation, comparison of the proposed PBB blocks with commercially available solid and hollow concrete blocks, compressive strength of masonry walls for each block type, and a comparative cost-benefit analysis between the proposed PBB blocks and commercially available concrete blocks.

5.2 Conclusion

The study revealed that among the PBB variants, the pit sand filled blocks achieved the highest mean compressive strength of 1.2 ± 0.34 MPa, closely approaching the performance of commercial hollow concrete blocks, which averaged 1.0 ± 0.17 MPa. In contrast, the sawdust filled and air filled PBB walls recorded mean compressive strengths of 0.5 ± 0.10 MPa and 0.5 ± 0.09 MPa, respectively in the vertical orientation, all of which were significantly lower than those of solid concrete blocks (2.20 ± 0.24 MPa). Overall, the PBB blocks did not meet the minimum compressive strength requirements specified in DS/EN 1996-1-1 DK NA:2019 for load bearing masonry. Therefore, they are more appropriately suited for use as non-loadbearing infill walling materials.

In addition, the pit sand filled PBB walls attained a mean compressive strength of 0.6 ± 0.02 MPa, which was comparable to that of the hollow concrete block walls (0.6 ± 0.06 MPa). The sawdust filled and air filled PBB walls, however, recorded lower mean strengths of 0.3 ± 0.05 MPa and 0.3 ± 0.03 MPa, respectively, which were well below the solid concrete block walls (0.8 ± 0.03 MPa). Despite their lower peak strength, all PBB walls exhibited superior ductility and gradual failure patterns (1.8, 1.9, and 2.0%), contrasting with the brittle collapse observed in concrete block walls (1.2 and 1.0%) respectively. These results indicate that while pit sand-filled PBBs possess adequate compressive capacity for small-scale or low-rise load-bearing applications, the air- and sawdust-filled types are more suited for lightweight, non-load-bearing infill walls.

A cost–benefit analysis was conducted for all masonry wall types, taking into account material costs, labour costs, time utilisation, and carbon emission costs. The results showed that the empty bottle masonry units were the most economical, with an average cost of UGX 11,694, while the solid concrete block walls were the least economical, costing UGX 28,759. The sawdust filled bottle masonry units, priced at UGX 27,634, were the only PBB variant whose cost exceeded that of the hollow concrete block walls (UGX 23,381), primarily due to the carbon emissions cost of saw dust. The study also established a practical production methodology through which PBB masonry units could be fabricated at a casting speed only 17% slower than that of solid and hollow concrete blocks, making the process commercially viable and compatible with existing formwork systems used in the local construction industry.

5.3 Limitations of the study

- Financial constraints limited the sample size for testing, bottle types used, number of filler materials tested, number of orientations tested, and number of orientations within the wall panels.
- The available wall testing equipment did not have a continuous strain measurement system, which limited the stress-stain graphical analysis of this study.
- The scope of the research was to comprehensive to also include durability and fire resistance tests.

5.4 Recommendations

5.4.1 Guidelines for Engineering Practices and Applications

- Empty bottle and saw dust filled bottle blocks can be used as lightweight infill walls.
- Pit sand filled bottle blocks can be used for minor load bearing applications such as low-rise structures.

5.4.2 Policy and Environmental Policy Recommendations

- Promote and fund research and development initiatives focused on innovative technologies that integrate plastic waste into sustainable construction solutions.
- Mandate waste segregation at the source in urban municipalities to promote the collection and reuse of PET bottles for further research.
- Launch public awareness campaigns on the dangers of plastic pollution and the benefits of converting waste into building resources.

5.4.3 Recommendations for further research

- Plastic bottles are susceptible to heat. However, due to the scope limitations of this study, no fire resistance tests were conducted on the plastic bottle brick masonry units, which is an essential requirement for evaluating their safety and performance.
- The study was limited to basic vertical and horizontal bottle orientations. However, exploring more complex configurations and tying methods is essential to further optimize the load bearing capacity of the PBB masonry units.
- This study was limited to the use of “500 ml Elgon water bottles”. However, alternative bottle types, such as soft drink bottles with thicker walls may offer geometric and structural advantages that could enhance the load bearing capacity of the masonry units. Further research is needed to explore these possibilities.
- Due to equipment limitations, the stress-strain behaviour of the masonry units and wall panels could not be characterized; an essential step in developing reliable design codes. Further investigation is necessary to establish this relationship.
- To enhance production efficiency and reduce costs, the development of mechanical compaction methods is essential.

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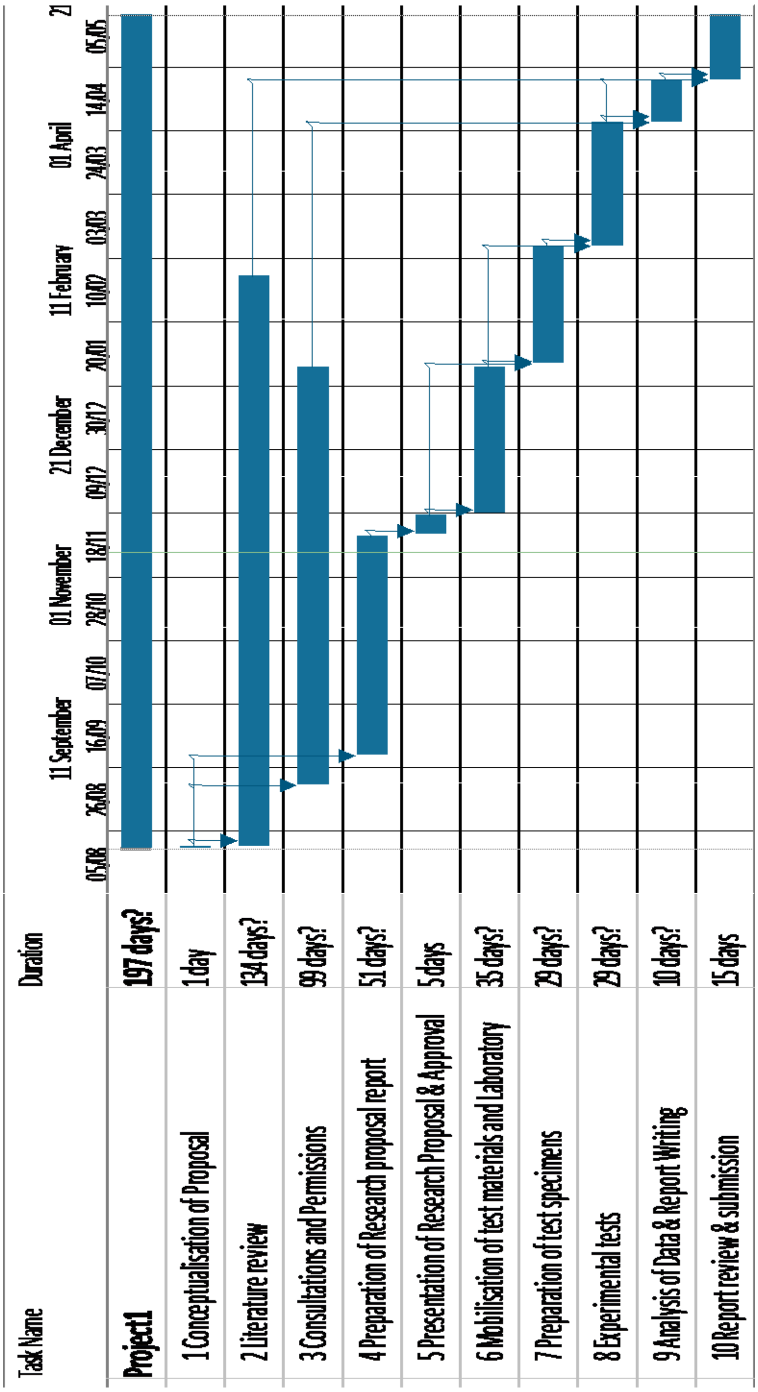
Chapter A : APPENDICES

Appendix A.1: Timeline



Appendix A.2: Budget

1	BUDGET FOR THE STUDY				
No.	**Description**	**Unit**	**Quantity**	**Rate**	**Total (UGX)**
1	Compressive tests	Sample	30	15,000	450,000
2	Fire resistance	Sample	36	20,000	720,000
3	Water absorbtion	Sample	36	5,000	180,000
4	Software Lincencing fees	Item	3	500,000	1,500,000
6	Plastic bottles with cover	Pieces	4894	100	489,400
8	Cement	Bags	21	35,000	735,000
9	Sand (Elf Truck - 2CM)	Trip	1	200,000	200,000
10	Transport & logistics	Item	1	1,200,000	1,200,000
11	Miscalleneous	Item	1	800,000	800,000
12	Consultation expenses	Item	1	800,000	800,000
SUB TOTAL					7,074,400
GRAND TOTAL (UGX)					**7,074,400**

Appendix A.3: Pictures

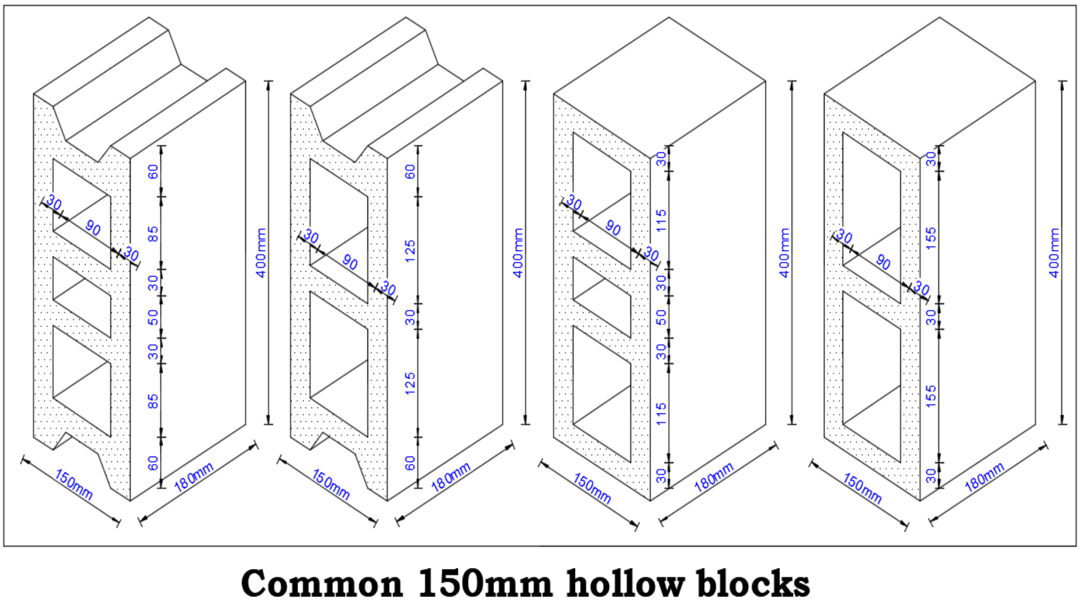


Figure A-1: Dimensions of common 150mm concrete blocks in Mbale City.

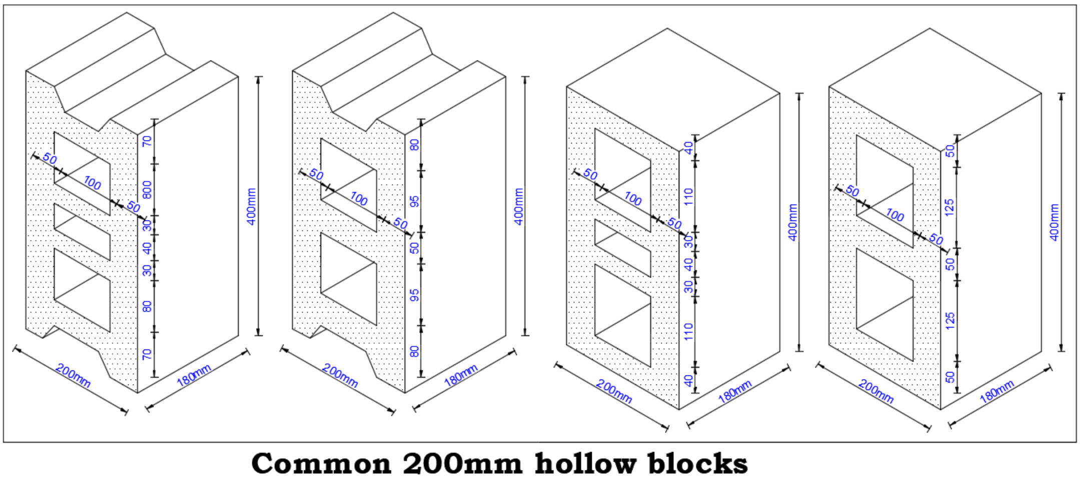


Figure A-2: Dimensions of common 200mm concrete blocks in Mbale City.

Figure A-3: Plastic Bottle Bricks (PBBs) production speed similar to concrete blocks.

Figure A-4: Filling of plastic bottles was done manually.

Appendix A.4: Tables

Table A-1: Data analysis to establish the modal sand ratio.

Class width	**Midpoint, x**	**Frequency, f**
1-2	1.5	4
2-3	2.5	28
3-4	3.5	16
4-5	4.5	14
5-6	5.5	0
6-7	6.5	0
7-8	7.5	4
8-9	8.5	0
9-10	9.5	8
Total		**74**

Table A-2: Data analysis to establish the modal stone dust ratio.

Class width	**Midpoint, x**	**Frequency, f**
1-2	1.5	4
2-3	2.5	7
3-4	3.5	4
4-5	4.5	12
5-6	5.5	15
6-7	6.5	0
7-8	7.5	11
8-9	8.5	0
9-10	9.5	5
10-11	10.5	4
11-12	11.5	0
12-13	12.5	8
13-14	13.5	0

14-15	14.5	0
15-16	15.5	0
16-17	16.5	0
17-18	17.5	0
18-19	18.5	0
19-20	19.5	4
Total		**74**

Table A-3: Failure load of PBBs in compression

ID	Sample description	Failure load (kN)	Average failure load (kN)	Standard deviation (kN)
EbV	Empty bottle in the vertical orientation	1.0	1.1	0.071
		1.1		
EbH	Empty bottle in the horizontal orientation	1.7	1.8	0.071
		1.8		
SdV	Saw dust filled bottle in the vertical orientation	1.3	1.3	0.000
		1.3		
SdH	Saw dust filled bottle in the horizontal orientation	6.2	5.4	1.202
		4.5		
PsV	Pit sand filled bottle in the vertical orientation	5.6	5.7	0.071
		5.7		
PsH	Pit sand filled bottle in the horizontal orientation	27.5	28.9	1.556
		29.7		

Table A-4: Compressive strength results for PBB masonry units at 28 days.

Sample ID	**Sample description**	**Failure load (kN)**	**Compressive strength (N/mm^2)**	**Average compressive strength (N/mm^2)**	**Standard deviation (N/mm^2)**
EBV	Empty bottle block vertical orientation	39.05	0.488	0.47	0.101
		28.84	0.361		
		44.9	0.561		
EBH	Empty bottle block horizontal orientation	60.27	0.603	0.67	0.277
		84.56	0.846		
		56.02	0.56		
SDV	Saw dust block vertical orientation	40.91	0.511	0.47	0.088
		42.68	0.533		
		29.65	0.371		
SDH	Saw dust block horizontal orientation	44.3	0.443	0.45	0.074
		52.72	0.527		
		37.91	0.379		
PSV	Pit sand block vertical orientation	114.22	1.428	1.16	0.340
		62.24	0.778		
		102.2	1.278		
PSH	Pit sand block horizontal orientation	107.19	1.072	1.16	0.496
		169.52	1.695		
		71.51	0.715		

Table A-5: Compressive strength results for concrete blocks at 28 days.

Sample ID	**Sample description**	**Failure load (kN)**	**Compressive strength (N/mm^2)**	**Average compressive strength (N/mm^2)**	**Standard deviation (N/mm^2)**
SBV	Solid concrete block vertical orientation (Pit sand)	157.45	1.9681	2.2073	0.243
		176.03	2.2004		
		196.28	2.4535		
SBH	Solid concrete block horizontal orientation (Pit sand)	149.08	1.4908	1.4173	0.065
		136.69	1.3669		
		139.43	1.3943		
HBV	Hollow concrete block vertical orientation (Pit sand)	89.82	1.1228	1.0063	0.174
		64.53	0.8066		
		87.16	1.0895		
HBH	Hollow concrete block horizontal orientation (Pit sand)	63.96	0.6396	0.5681	0.064
		51.45	0.5145		
		55.03	0.5503		
RSV	Solid concrete	213.85	2.6731	2.7042	0.044
		218.82	2.7353		

	block vertical orientation (River sand)				
RSH	Solid concrete block horizontal orientation (River sand)	331.16	3.3116	3.2915	0.028
		327.14	3.2714		

Table A-6: Compressive test results for masonry walls with masonry units at 28 days.

Sample ID	**Sample description**	**Failure load (kN)**	**Compressive strength (N/mm^2)**	**Average compressive strength (N/mm^2)**	**Standard deviation (N/mm^2)**
EBW	Walls constructed using empty bottle masonry units	81	0.324	0.27	0.047
		65	0.26		
		58	0.232		
SDW	Walls constructed using saw	76	0.304	0.28	0.031
		61	0.244		
		70	0.28		

	dust filled bottle masonry units				
PSW	Walls constructed using pit sand filled bottle masonry units	140	0.56	0.58	0.022
		150	0.6		
		148	0.592		
SBW	Walls constructed using solid concrete blocks	196	0.784	0.81	0.026
		203	0.812		
		209	0.836		
HBW	Walls constructed using hollow concrete blocks	135	0.54	0.60	0.060
		165	0.66		
		750	0.6		

Table A-7: Deflection and strain results for masonry walls at peak load.

Sample ID	**Side measured**	**Initial height (mm)**	**Final height (mm)**	**Extension (mm)**	**Strain (%)**	**Average strain (%)**	**Standard deviation (%)**
EBW	EBW1 left side	1118	1100	18	1.6100	1.8152	0.047
	EBW1 right side	1140	1110	30	2.6316		
	EBW2 left side	1130	1117	13	1.1504		
	EBW2 right side	1140	1115	25	2.1930		
	EBW3 left side	1130	1113	17	1.5044		
	EBW3 right side	1110	1090	20	1.8018		
SDW	SDW1 left side	1138	1129	9	0.7909	1.8792	0.031
	SDW1 right side	1110	1101	9	0.8108		
	SDW2 left side	1147	1110	37	3.2258		
	SDW2 right side	1146	1085	41	3.5777		
	SDW3 left side	1123	1105	18	1.6028		
	SDW3 right side	1105	1091	14	1.2670		
PSW	PSW1 left side	1096	1120	20	1.8248	2.0022	0.022
	PSW1 right side	1076	1100	20	1.7857		
	PSW2 left side	1100	1086	14	1.2727		
	PSW2 right side	1144	1125	19	1.6608		
	PSW3 left side	1095	1078	17	1.5525		
	PSW3 right side	1149	1104	45	3.9164		
SBW	SBW1 left side	1085	1065	20	1.8433	1.1583	0.026
	SBW1 right side	1085	1079	6	0.5530		
	SBW2 left side	1103	1097	6	0.5440		
	SBW2 right side	1103	1097	6	0.5440		
	SBW3 left side	1094	1075	19	1.7367		
	SBW3 right side	1099	1080	19	1.7288		
HBW	HBW1 left side	1109	1098	11	0.9919	0.9631	0.060
	HBW1 right side	1091	1090	1	0.0917		

	HBW2 left side	1106	1089	17	1.5371		
	HBW2 right side	1096	1090	6	0.5474		
	HBW3 left side	1116	1102	14	1.2545		
	HBW3 right side	1106	1091	15	1.3562		

Table A-8: Summary of cost-benefit analysis costs.

Masonry unit ID	**Masonry unit description**	**Material costs (Ugx.)**	**Labour costs (Ugx.)**	**Time cost (Ugx.)**	**Carbon cost (Ugx.)**	**Total cost (Ugx.)**
EBB	Empty bottle block	3,473	1,574	911	5,736	**11,694**
SDB	Saw dust filled block	3,561	4,124	6,215	13,734	**27,634**
PSB	Pit sand filled block	3,746	3,274	6,215	6,060	**19,295**
SCB	Solid concrete block	3,861	1,574	455	22,869	**28,759**
HCB	Hollow concrete block	3,088	1,574	455	18,264	**23,381**

Appendix A.5: Test procedures

A.5.1 Sieve analysis test procedure

The materials tested through sieve analysis included pit sand, river sand, stone dust, and sawdust. The sieve analysis followed the guidelines set out in BS EN 933-1:2012, which outlines tests for geometrical properties of aggregates, as described in **Figure A-5** below.

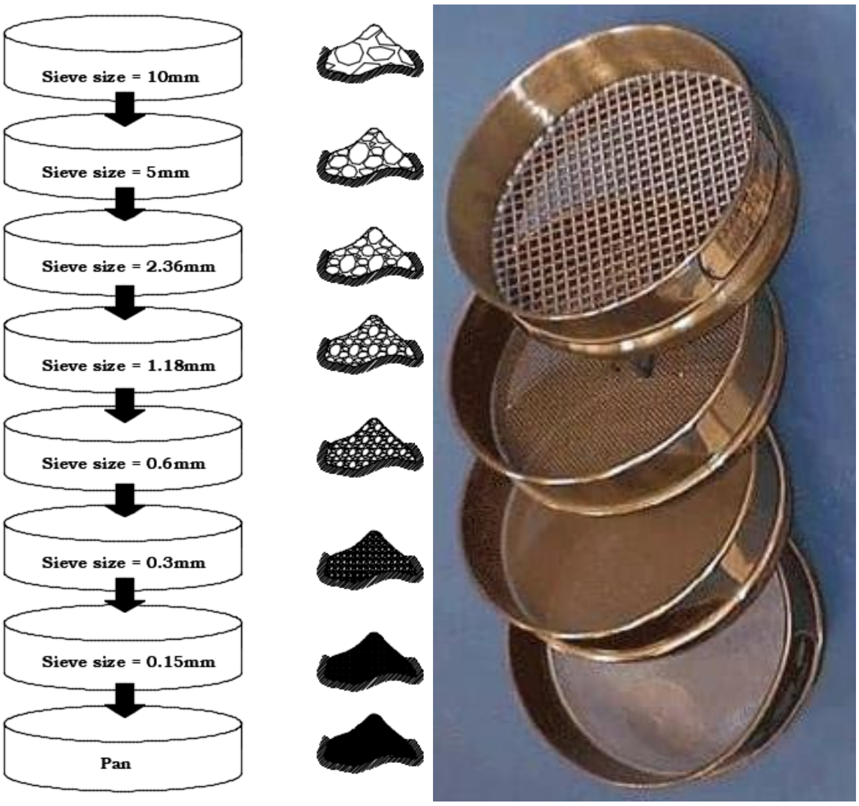


Figure A-5: Experimental setup for the sieve analysis.

- For pit sand samples containing clay particles which may cause agglomeration of particles, separation by washing through a fine 75µm sieve before determining particle size distribution by dry sieving was done. For saw dust, river sand, saw dust and stone dust which are free from particles causing agglomeration, dry sieving was done without washing.

- Samples ranging between 700-1000g were taken from the sand and stone dust samples. However, a sample of about 300g was taken from the saw dust which was significantly lighter than the other samples, but had the highest sample volume.
- A thermostatically ventilated oven was set at about 110°C, till the samples were fully dry.
- The sieve sizes used for the analysis were of sizes 10mm, 5mm, 2.36mm, 1.18mm, 0.6mm, 0.3mm, and 0.15mm. The samples were placed on the top 10mm sequentially down to the 0.15mm sieve (see **Figure A-5**), with a nesting guard sieve and cover at the top of the sieve stack.
- The shaking was done using a mechanical shaker for about 5-10 minutes, and the sample was allowed to settle for about 5 minutes.
- The sieve stack was disassembled and the mass retained on each sieve was measured using a digital weighing scale. A wire brush is used to remove particles attached onto the sieves.
- The percentage of fines (f) was calculated based on Clause 8 of BS 812-103.1:1985 using the formula below:

$$Percentage\ of\ fines, f = \frac{(M_1 - M_2) + P}{M_1} \times 100$$

Where, M_1 – is the dried mass of the test portion, in kilograms

M_2 – is the dried mass of the residue retained on the 0,063 mm sieve, in kilograms

P – is the mass of the screened material remaining in the pan, in kilograms

Furthermore, for dry sieving, $f = \frac{100P}{M_1}$

- The results were tabulated including details of mass retained and percentage mass retained for each sieve, as well as the cumulative percentage retained sequentially from the largest sieve to the smallest. A graph of percentage passing vs sieve size using a logarithmic sieve size axis scale in compliance with Figure D.1 in the BS EN 933-1:2012 Annexes.

A.5.2 Specific gravity using the pycnometer method

This test was done in compliance to BS 1377-2:2022 using the pycnometer method. It was used to test saw dust, pit sand, river sand and stone dust particles, all of which have particles passing the 37.5mm test sieve. The procedure below outlines how the test was carried out for various samples:

- A sample of about 1000g was obtained and oven dried at about 100ºC.
- A glass jar, whose mouth could be sealed was used as a pycnometer to maintain a constant volume was cleaned using potable water and left to dry in open air, and then its mass, M_1 is measured.
- The oven dried sample was then transferred into the pycnometer, and then its mass, M_2 is measured.
- The pycnometer was then filled with water, and shaken using a mechanical shaker for 20-30 to ensure that the sample is fully saturated with water. The remaining air in the was after expelled by filling the pycnometer to the brim, without spilling any of the water + sample mixture. The mass of this pycnometer + water + sample is measured as mass, M_3.

- The pycnometer was then emptied and rinsed thoroughly. It was then filled with water to the brim with no space for air, and its mass, M_4 was measured.

The specific gravity, G was then measured using the formula below.

$$G = \frac{(M_2 - M_1)}{\left((M_4 - M_1) - (M_3 - M_2)\right)}$$

Where: M_1 – Mass of Pycnometer in g

M_2 – Mass of Pycnometer + sample in g

M_3 – Mass of Pycnometer + sample + water in g

M_4 – Mass of Pycnometer + water in g

A.5.3 Water absorption test procedure

The water absorption test was done for all masonry unit types. This test was carried out in compliance to ASTM D570 for PBB masonry units. BS 1881-122:2011 was used for the concrete block specimens. The variations in codes was necessary since ASTM D570 handles specimens with plastics, while BS 1881-122:2011 deals with concrete samples only.

Figure A-6: Oven drying of samples (left), Immersion of samples (right).

The procedure for carrying out this test is as outlined below:

- The specimens were dried in a ventilated oven for about 24 hours for composite specimens in compliance to ASTM D570 at a temperature of approximately 100ºC (see **Figure A-6**).
- The specimens are then allowed to cool under room temperature in an air tight dry vessel.
- The mass, m_1 of each specimen is measured immediately after cooling.
- Completely immerse the specimen so that is about 25mm below the water surface., and leave the samples immersed for at least 30 minutes.
- The specimen was then removed from the water, shaken and wiped to get rid of free water from the surface of the sample.
- The mass, m_2 of the specimen is then recorded.
- The water absorption, expressed in percentage for each specimen was calculated using the formula below:

$$Water\ absorption = \frac{m_2 - m_1}{m_1} \times 100$$

Where: m_1 – mass of dry sample

m_2 – mass of wet sample

A.5.4 Compressive strength of mortar cubes and masonry units test procedure

The cube specimens tested were mortar cubes for pit sand and river sand mortar mixes. The testing procedure was based of EN 12390-3 guidelines. A Compression Testing machine complying to EN 12390-4 was used to carry out the compressive tests at a constant loading rate of 2kN/s, with about 1500kN loading capacity. The following procedure outlines the procedure for testing the mortar cubes, guided by **Figure A-7**.

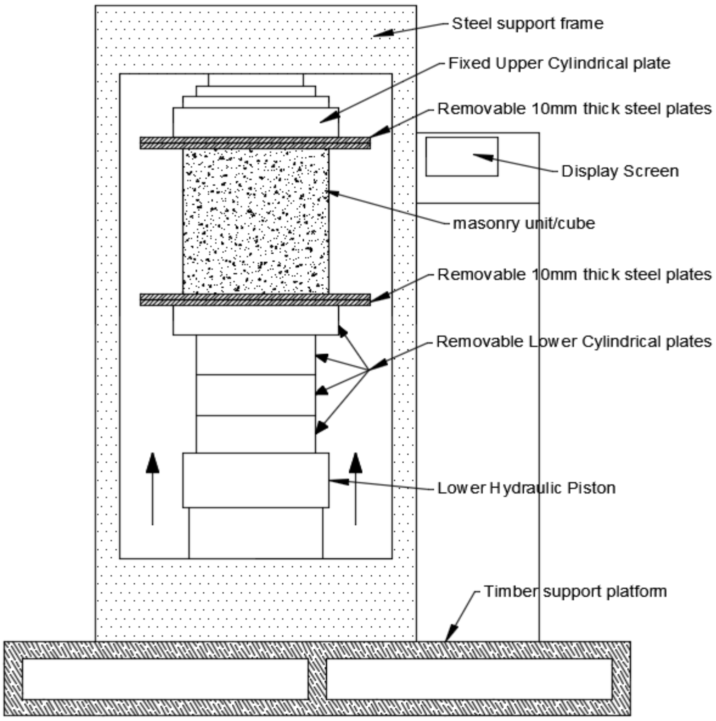


Figure A-7: Experimental setup for cube and masonry unit compressive tests.

- The cubes were of dimensions 150x150mm, in compliance to EN 12390-1, and were prepared and cured in compliance to EN 12390-2. The masonry units were also prepared based on the methodology described in the sample preparation section of this chapter.
- The removable lower cylindrical discs and 10mm thick steel were added and removed so that little clearance (less than 25 mm) is left for upward movement of the Hydraulic piston after sample placement.
- The machine loading surfaces were cleaned using a brush and rug to remove any debris, and the sample is positioned symmetrically across the loading surfaces.

- The load was then applied at a loading rate of 2kN/s, and a load vs time graph was plotted on the display screen. The specimen was observed for failure patterns, and the graph was analysed.
- The failure load, F in kN was converted to compression strength, f_c, according to clause 8 of EN 12390-3 as shown in the formula below.

$$f_c = \frac{F}{A_c}$$

Where, f_c – Compressive strength in MPa

F – maximum load at failure in N

A_c – Cross-sectional area of specimen on which compressive strength acts in mm^2

Appendix A.6: Cost-benefit analysis raw data

A.6.1 Material costs

All materials used in the study were locally sourced, and a brief market survey revealed materials rates as summarised in **Table A-9** below.

Table A-9: A summary of rates for locally purchased materials.

No.	**Material Description**	**Unit**	**Rate (Ugx.)**
1.	50kg Tororo Cement, CEM IV B (P) 32.5N – PC	Bag	31,000
2.	90m sisal rope	Rolls	5,000
3.	2 cubic meter trip of pit sand	Trip	60,000
4.	2 cubic meter trip of river sand	Trip	90,000
5.	2 cubic meter trip of stone dust	Trip	160,000
4.	Empty bottles with bottle tops	Item	20

a) PBBs material costs

The material cost calculations are summarised in **Table A-10** below.

Table A-10: Material costs per PBB masonry unit produced.

No.	**Material Description**	**Unit**	**Quantity**	**Rate (Ugx.)**	**Amount (Ugx.)**
1.0	**Empty plastic bottle brick masonry units**				
1.1	Cement	kg	3.57	620	2,213
1.2	Pit sand	CM	0.0102	30,000	306
1.3	Empty bottles with bottle tops	Item	17	20	340
1.4	Sisal rope	Rolls	11.05	55.6	614
	Sub Total				**3,473**
2.0	**Saw dust filled plastic bottle brick masonry units**				

2.1	Cement	kg	3.57	620	2,213
2.2	Pit sand	CM	0.0102	30,000	306
2.3	Empty bottles with bottle tops	Item	17	20	340
2.4	Sisal rope	m	11.05	55.6	614
2.5	Saw dust	kg	3.06	28.6	88
	Sub Total				**3,561**
3.0	**Pit sand filled plastic bottle brick masonry units**				
3.1	Cement	kg	3.57	620	2,213
3.2	Pit sand	CM	0.0193	30,000	579
3.3	Empty bottles with bottle tops	Item	17	20	340
3.4	Sisal rope	m	11.05	55.6	614
	Sub Total				**3,746**
GRAND TOTAL					**10,780**

b) Concrete block materials costs

The material cost calculations are summarised in **Table A-11** below.

Table A-11: Material costs per concrete masonry unit produced.

No.	**Material Description**	**Unit**	**Quantity**	**Rate (Ugx.)**	**Amount (Ugx.)**
1.0	**Solid concrete blocks**				
1.1	Cement	kg	3.758	620	2,330
1.2	Pit sand	CM	0.0081	30,000	243
1.3	Stone dust	CM	0.0161	80,000	1,288
	Sub Total				**3,861**
2.0	**Hollow concrete blocks**				
2.1	Cement	kg	3.006	620	1,864

2.2	Pit sand	CM	0.0064	30,000	192
2.3	Stone dust	CM	0.0129	80,000	1,032
	Sub Total				**3,088**
GRAND TOTAL					**6,949**

A.6.2 Labour costs

All labour wages were established by carrying out a brief market survey on typical wages to accomplish certain tasks. However due to the complexity of the tasks, the wage had to be negotiated using the typical wage as a baseline.

a) PBB masonry units labour costs

The implementation of various tasks in the production in PBB masonry units were monitored, and the average outputs in a day per unit of labour were summarised in Error! Reference source not found..

Table A-12: Task output per unit of labour daily for PBB masonry units.

No.	Task Description	Unit	Quantity of outputs
1.	Cleaning of plastic bottles	Bottles	687
2.	Filling of plastic bottles with sand	Bottles	78
3.	Filling of plastic bottles with sand	Bottles	46
4.	Tying of PBBs into masonry units	Blocks	38
5.	Casting of masonry units	Blocks	27
6.	Curing of all masonry units	Blocks	130

The labour rates were quantified based on outputs using the formula below.

$$\text{Labour rate} = \frac{\text{Daily labour rate for a task}}{\text{Quantity of task outputs}}$$

Based on the above inputs, the labour costs for each PBB masonry unit were quantified in Table 4-9 below.

Table A-13: Labour costs per masonry unit produced for PBB masonry units.

No.	**Task Description**	**Unit**	**Quantity**	**Rate (Ugx.)**	**Amount (Ugx.)**
1.0	**Empty plastic bottle brick masonry units**				
1.1	Cleaning of plastic bottles	Bottles	17	2.5	43
1.2	Tying of plastic bottles	Item	1	500	500
1.3	Casting of masonry unit	Item	1	714	714
1.4	Curing of blocks	Item	1	317	317
	Sub Total				**1574**
2.0	**Saw dust filled plastic bottle brick masonry units**				
2.1	Cleaning of plastic bottles	Bottles	17	2.5	43
2.2	Filling of plastic bottle bricks	Item	17	150	2,550
2.3	Tying of plastic bottle bricks	Item	1	500	500
2.4	Casting of masonry unit	Item	1	714	714
2.5	Curing of blocks	Item	1	317	317
	Sub Total				**4,124**
3.0	**Pit sand filled plastic bottle brick masonry units**				
3.1	Cleaning of plastic bottles	Bottles	17	2.5	43
3.2	Filling of plastic bottle bricks	Item	17	100	1,700
3.3	Tying of plastic bottle bricks	Item	1	500	500
3.4	Casting of masonry unit	Item	1	714	714
3.5	Curing of blocks	Item	1	317	317
	Sub Total				**3,274**

b) Concrete block labour costs

The implementation of various tasks in the production in concrete blocks were monitored, and the average outputs in a day per unit of labour were summarised in **Table A-14** below.

Table A-14: Task output per unit of labour daily for concrete blocks.

No.	**Task Description**	**Unit**	**Quantity**
1.	Casting of masonry units	Blocks	33
2.	Curing of all masonry units	Blocks	100

The labour rates were quantified based on outputs using the formula below.

$$\text{Labour rate} = \frac{\text{Daily labour rate for a task}}{\text{Quantity of task outputs}}$$

Based on the above inputs, the labour costs for each concrete block were quantified in **Table A-15** on the next page.

Table A-15: Labour costs per masonry unit produced for concrete blocks.

No.	**Process Description**	**Unit**	**Quantity**	**Rate (Ugx.)**	**Amount (Ugx.)**
1.0	**Solid blocks**				
1.1	Casting of masonry unit	Item	1	1,400	1,400
1.2	Curing of blocks	Item	1	317	317
	Sub Total				**1,574**
2.0	**Saw dust filled plastic bottle brick masonry units**				
2.1	Casting of masonry unit	Item	1	1,400	1,400

2.2	Curing of blocks	Item	1	317	317
	Sub Total				**1,574**
GRAND TOTAL					**3,148**

A.6.3 Time utilisation cost

a) PBB masonry units’ production time

The time costs were based on observations of how long it took labour to accomplish specific tasks, which was recorded in hours. The duration per output was based on an approximated 10-hour work day, and hence the time taken to achieve each task was quantified using the formula below.

$$\text{Duration per output (hours/output)} = \frac{\text{Quantity of task outputs achieved daily}}{10}$$

Based on the above inputs, the duration to produce each PBB masonry unit were quantified in **Table A-16** on the next page:

Table A-16: Average time utilisation/duration for a labour unit per masonry unit produced.

No.	Process Description	Unit	Quantity of output	Daily output (hour/output)	Duration (hours)
1.0	**Empty plastic bottle brick masonry units**				
1.2	Tying of plastic bottles	Item	1	0.25	0.25
1.3	Casting of masonry unit	Block	1	0.357	0.357
	Sub Total				**0.607**

2.0	**Saw dust filled plastic bottle brick masonry units**				
2.1	Filling of plastic bottle bricks	Bottle	17	0.208	3.536
2.2	Tying of plastic bottle bricks	Item	1	0.25	0.25
2.3	Casting of masonry unit	Block	1	0.357	0.357
	Sub Total				**4.143**
3.0	**Pit sand filled plastic bottle brick masonry units**				
3.1	Filling of plastic bottle bricks	Bottle	17	0.208	3.536
3.2	Tying of plastic bottle bricks	Item	1	0.25	0.25
3.3	Casting of masonry unit	Block	1	0.357	0.357
	Sub Total				**4.143**
GRAND TOTAL					**8.893**

b) Concrete blocks production time

The time costs were based on observations of how long it took labour to accomplish specific tasks, which was recorded in hours. The duration per output was based on an approximated 10-hour work day, and hence the time taken to achieve each task was quantified using the formula below.

$$\text{Duration per output (hours/output)} = \frac{\text{Quantity of task outputs achieved daily}}{10}$$

Based on the above inputs, the duration to produce each concrete block were quantified in **Table A-17** below:

Table A-17: Average time utilisation for a labour unit per concrete block produced.

No.	Process Description	Unit	Quantity/output	Daily output (hour/output)	Duration (hours)
1.0	**Solid block**				
1.1	Casting of masonry unit	Item	1	0.303	0.303
	Sub Total				**0.303**
2.0	**Hollow block**				
2.1	Casting of masonry unit	Item	1	0.303	0.303
	Sub Total				**0.303**
GRAND TOTAL					**0.606**

c) Time utilisation cost

Considering a weighted average labour cost of about Ugx. 15,000 was recorded, for a 10-hour working day, which gives an hourly rate of about Ugx. 1,500 per hour. The quantification of time in monetary terms has been calculated in **Table A-18**.

Table A-18: Time utilisation cost in Ugandan Shillings (Ugx.).

Masonry unit ID	Description of masonry unit	Time utilisation /duration (hours)	Rate (Ugx./hour)	Time utilisation (Ugx)
EBB	Empty bottle block	0.607	1,500	911
SDB	Saw dust filled block	4.143	1,500	6,215

PSB	Pit sand filled block	4.143	1,500	6,215
SCB	Solid concrete block	0.303	1,500	455
HCB	Hollow concrete block	0.303	1,500	455
	Total			**14,251**

A.6.4 Carbon emissions cost

Based on a literature review on carbon emissions used to process the materials used in this study, these figures were used to quantify carbon emissions for all materials as summarised in **Table A-19** on the next page.

Table A-19: Carbon emissions from literature.

No.	**Material Description**	**Carbon emissions (kg of CO$_2$ /ton)**	**Citation**
1	Cement	507.1	(IPCC, 2006)
2	Pit sand	11.73	(Henderson, et al., 2024)
3	Plastic bottles	4,150	(Beverage Industry Environmental Roundtable, 2012)
4	Sisal rope	0.00072	(CarbonCloud, 2024)
5	Saw dust	1,566.98	(Arup, 2023)
6	Stone dust	8.1	(Meddah, 2017)

The estimated minimum carbon tax worldwide was adopted for this quantification, which equals to about Ugx. 1,668. The formula below was used to quantify the carbon emissions cost.

$$\begin{aligned}&\text{Carbon emissions cost for a material}\\ &\qquad = \text{Quantity of materials used}\\ &\qquad \times \text{Carbon emissions per unit of material} \times \text{Carbon tax rate}\end{aligned}$$

Based on the above inputs, the calculations were tabulated in **Table A-20** on the next page, for each masonry unit type.

Table A-20: Embodied carbon emissions in each masonry unit.

No.	**Material Description**	**Quantity (kg)**	**Materials unit carbon emissions (kg of CO_2 /ton)**	**Carbon emissions (kg)**	**Rate (Ugx. /ton)**	**Amount (Ugx.)**
1	**EMPTY BOTTLE BLOCK MASONRY UNITS**					
1.1	Cement	3.57	507.1	1810.347	1,668	3,020
1.2	Pit sand	18.555	11.73	217.65015	1,668	363
1.3	Plastic bottles	0.34	4,150	1411	1,668	2,354
1.4	Sisal rope	0.05	0.00072	0.000036	1,668	0
	Subtotal 1					5,736
2	**SAW DUST FILLED BOTTLE BLOCK MASONRY UNITS**					
2.1	Cement	3.57	507.1	1810.347	1,668	3,020
2.2	Pit sand	18.555	11.73	217.65015	1,668	363

2.3	Plastic bottles	0.34	4,150	1411	1,668	2,354
2.4	Sisal rope	0.05	0.00072	0.000036	1,668	0
2.5	Saw dust	3.06	1,566.98	4794.95268	1,668	7,998
	Subtotal 2					13,734
3	**PIT SAND FILLED BOTTLE BLOCK MASONRY UNITS**					
3.1	Cement	3.57	507.1	1810.347	1,668	3,020
3.2	Pit sand	35.109	11.73	411.82857	1,668	687
3.3	Plastic bottles	0.34	4,150	1411	1,668	2,354
3.4	Sisal rope	0.05	0.00072	0.000036	1,668	0
	Subtotal 3					6,060
4	**SOLID CONCRETE BLOCK MASONRY UNITS**					
4.1	Cement	3.758	507.1	1905.6818	620	1,182
4.2	Pit sand	14.735	11.73	172.84155	30,000	5,185
4.3	Stone dust	33.955	8.1	275.0355	60,000	16,502
	Subtotal 4					22,869
5	**HOLLOW CONCRETE BLOCK MASONRY UNITS**					
5.1	Cement	3.006	507.1	1524.3426	620	945
5.2	Pit sand	11.642	11.73	136.56066	30,000	4,097
5.3	Stone dust	27.206	8.1	220.3686	60,000	13,222
	Subtotal 5					18,264
GRAND TOTAL						66,664

Appendix A.7: Lab tests