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CIV 4200: CIVIL ENGINEERING PROJECT II

ASSESSMENT OF THE EFFECT OF PARTIAL REPLACEMENT OF CEMENT WITH WASTE GLASS POWDER ON THE PERFORMANCE OF WATER HYACINTH PETIOLE – CEMENT INSULATION BOARDS.

BY

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Submitted in Partial Fulfillment of the Requirements for the Award of a Degree of Bachelor of Science in Civil Engineering

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DECLARATION

We, Musana Ibrahim and Ndungutse Edmond, hereby affirm that this report has been compiled, written, and submitted in partial fulfillment of the requirements for the "Bachelor of Science in Civil Engineering' at Makerere University by us, and that it has not been submitted elsewhere.

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APPROVAL

This research is ready to be submitted with our approval as academic supervisors.

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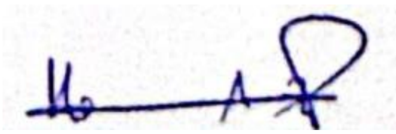

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Table of Contents

List of Acronyms

WH	Water hyacinth
WHP	Water hyacinth petiole
WGP	Waste glass powder
SDG	Sustainable Development Goals
OPC	Ordinary Portland cement
WA	Water Absorption
NDP	National Development Plan

List of Tables

List of Figures

ABSTRACT

The growing demand for sustainable construction materials has heightened interest in developing environmentally friendly insulation products from waste resources. This study investigated the production and performance of insulation boards made from water hyacinth petioles (WHP) and waste glass powder (WGP) as a partial replacement for cement. Water hyacinth served as the fibrous component, while waste glass powder was incorporated to reduce cement consumption and promote waste recycling. Although water hyacinth petioles and waste glass powder have each been investigated separately as partial cement replacements, their combined use in a single insulation board, evaluated in both pulp and staple particle forms, has not previously been studied.

WHP samples were collected from Port Bell, prepared, dried, and separated into pulp and staple particles. Waste glass collected at Makerere University was cleaned, crushed, and sieved to a fine powder. Composite boards were produced using a 60:40 WHP-to-binder ratio, with WGP replacing cement at 0%, 10%, 20%, 30%, 40%, and 50% by weight. The samples were cast, compacted, cured under laboratory conditions, and tested for bulk density, water absorption, thickness swelling, flexural strength, and thermal conductivity.

Results showed that increasing WGP content affected the boards' physical, mechanical, and thermal properties. Thermal conductivity ranged from 0.105–0.046 W/mK for P-panels and 0.098–0.033 W/mK for S-panels, indicating improved thermal insulation performance at higher WGP replacement levels. Water absorption and thickness swelling generally decreased at moderate WGP contents, while flexural strength improved due to better particle packing and matrix densification.

The cost-effectiveness analysis showed that production costs increased with partial replacement of cement by WGP, rising from UGX 30,511 to 53,881 per square meter due to reduced cement consumption. Moderate WGP replacement levels (10%–20%) provided the best balance between cost and performance, making the boards economically viable compared with conventional materials such as MDF, cement boards, and gypsum boards.

The study concluded that WHP–cement–WGP composite boards have strong potential as lightweight, low-cost, and sustainable thermal insulation materials. The findings have practical implications for sustainable construction by promoting the use of invasive water hyacinth in value-added products, reducing reliance on cement, and supporting domestic waste management by recycling waste glass into useful construction materials.

1 INTRODUCTION

1.1 Background of the Study

Globally, water hyacinth (Eichhornia crassipes) is widely recognized as the most problematic aquatic weed due to its invasive nature, severe ecological impacts, and high control costs (Midhun et al., 2023). Native to the Amazon Basin in South America, it is a perennial, herbaceous, free-floating aquatic plant (Hill & Coetzee, 2008). Water hyacinth poses significant environmental challenges to waterways. Its dense mats obstruct navigation and fishing activities and reduce the capacity of the water flow. By blocking sunlight, the mats inhibit photosynthesis, which in turn lowers dissolved oxygen levels in water bodies. This oxygen depletion has a detrimental effect on aquatic biodiversity, leading to declines in fish populations and other aquatic organisms (Nwaigwe et al., 2017).

In Africa, water hyacinth was first introduced to Egypt in 1880 and is now the dominant aquatic weed in East Africa. It has extensively invaded Lake Tana in Ethiopia, the country's largest freshwater body, which covers 3,074 km^2, causing significant negative impacts on the aquatic ecosystem (Karouach et al., 2022). A study (Dersseh et al., 2019) projected that by 2020 the infestation could reach a maximum of 30,728 ha, accounting for about 10% of the lake's total surface area.

In Uganda, water hyacinth is believed to have invaded Lake Kyoga by 1988. However, it was likely present earlier and subsequently spread to the Upper and Lower Victoria Nile and Lake Albert (Twongo et al., 1991). Lake Victoria, the world's largest tropical lake and a hotspot for ecological diversity, was invaded by water hyacinth in the late 1980s. By 1994, water hyacinth had covered nearly all the shorelines of the Upper and Lower Victoria Nile, and more than 60% of Lake Kyoga's shoreline was already infested (Taylor, 1993). By 1995, 80% of Lake Victoria's shoreline was infested (Twongo, 1998). During the first half of 1998, the primary hotspots for water hyacinth infestation were Lwera, Bunjako, Murchison, Fielding, MacDonald, and Berkeley, as well as Napoleon Gulf and the bays around the Ssesse Islands. Water hyacinth continued to invade other aquatic systems, particularly riverine ecosystems such as the Rwizi in western Uganda and streams connected to the River Manafwa in the eastern part of the country (Wanda et al., 2015).

Over the past several decades, numerous management programs have been implemented to address this environmental and economic challenge (Güereña et al., 2015). These efforts have primarily focused on eradicating water hyacinth through chemical, physical, or biological methods, but have achieved only limited, lasting success (Williams et al., 2005; Wilson et al., 2007). Current methods for controlling water hyacinth growth remain limited because of the high costs of physical techniques, the adverse environmental impacts of chemical approaches, and the slow, time-intensive nature of biological controls (Dechassa, 2020; Kulabako et al., 2025; Sharma et al., 2015). These factors have necessitated exploring more sustainable approaches to managing this weed. Water hyacinth has shown potential for diverse applications, including phytoremediation, briquette production, animal feed, biogas generation, and use as a sustainable building material. In the construction sector, researchers have explored its use in brick manufacturing as a partial replacement for cement, as a fine aggregate, as a bio-admixture in concrete, and in the production of thermal insulation materials for buildings (Philip & Rakendu, 2020).

According to (Chindaprasirt et al., 2022a), the global generation of solid waste amounts to 200 million tons annually, with glass accounting for 7% of this total. Most waste auto-glass, due to its low recycling rate, is landfilled. However, increasing landfill scarcity and the non-biodegradability of glass highlight the urgent need for sustainable use of glass. In addition, using supplementary binder materials such as waste glass powder to offset a portion of the cement used is a promising method for reducing the industry's environmental impact (Islam et al., 2017).

Amidst global climate change and rising temperatures, the demand for enhanced thermal insulation in buildings is escalating. While water hyacinth combined with cement has shown potential as a sustainable insulation material, limited research exists on the effect of adding waste glass powder as a partial cement replacement in water hyacinth-cement composites on the performance of these insulation boards. Addressing this gap could not only provide an environmentally friendly insulation solution but also offer a sustainable strategy for managing weed and waste glass.

1.2 Problem Statement

Globally, water hyacinth *(Eichhornia crassipes*) is a highly invasive aquatic weed that causes severe ecological and economic problems by forming dense mats that obstruct water navigation, reduce water flow, block sunlight, and deplete dissolved oxygen, severely affecting aquatic biodiversity (Midhun et al., 2023; Nwaigwe et al., 2017). Control efforts using chemical, physical, and biological methods have been largely limited by high costs, environmental risks, and slow effectiveness (Dechassa, 2020; Kulabako et al., 2025). However, the weed shows potential for sustainable utilization in various applications, including the production of building materials such as thermal insulation boards. Water hyacinth combined with cement has demonstrated promise as a sustainable insulation material (Philip & Rakendu, 2020).

However, cement production is a major source of greenhouse gas emissions, creating a strong need to reduce the amount of cement used in construction materials. Waste glass powder, generated from low-recycling-rate glass waste, offers a promising supplementary binder to partially replace cement and mitigate environmental impact (Chindaprasirt et al., 2022; Islam et al., 2017). Although both water hyacinth and cement have been used in insulation board production, limited research has examined the effects of using waste glass powder as a partial replacement for cement in WHP-cement composites. Addressing this gap is crucial to developing environmentally friendly insulation solutions that contribute to both invasive weed management and reduced cement consumption.

1.3 Justification

Water hyacinth (Eichhornia crassipes) is recognized worldwide as a highly invasive aquatic weed with severe ecological and economic consequences (Midhun et al., 2023). Its proliferation has substantially disrupted aquatic ecosystems, particularly in East Africa, where major water bodies such as Lake Victoria and Lake Kyoga have experienced extensive infestations, threatening biodiversity and local livelihoods (Wanda et al., 2015). Despite widespread efforts, conventional control methods, including chemical, physical, and biological approaches, have largely failed to provide sustainable, long-term solutions due to high costs, environmental side effects, and slow efficacy (Kulabako et al., 2025; Williams et al., 2005; Wilson et al., 2007).

Innovative applications in bioenergy, animal feed, and construction materials have shown potential to address both environmental concerns and economic incentives (Philip & Rakendu, 2020). The development of thermal insulation boards made from water hyacinth petioles and bound with cement is particularly promising because it addresses the urgent demand for eco-friendly building materials that improve energy efficiency amid climate change and rising temperatures.

This study contributes to achieving Sustainable Development Goal 6 (SDG 6) by promoting the sustainable management of water resources through the innovative use of invasive water hyacinth. It also aligns with Uganda's NDP 4, which prioritizes environmental sustainability and climate resilience by promoting resource-efficient solutions and ecosystem protection.

This study is justified in its aim to evaluate the effect of adding waste glass powder as a partial replacement for cement on the performance of water hyacinth–cement (WHP-cement) insulation boards. The findings are expected to contribute valuable knowledge toward the design and optimization of sustainable insulation products, facilitating their adoption in the construction industry. In turn, this addresses the dual goals of effective water hyacinth management and the promotion of green building solutions.

1.4 Study Objectives

1.4.1 Main objective

To assess the effect of adding waste glass powder as a partial replacement for cement on the performance of water hyacinth–cement (WHP-cement) insulation boards.

1.4.2 Specific objectives

i. To determine the physical and mechanical properties of the WHP- cement- WGP composite insulation boards.
ii. To determine the thermal insulation performance of WHP- cement- WGP insulation boards.
iii. To assess the cost-effectiveness of the application of WHP-cement-WGP insulation boards.

1.5 Scope of the Study

This study evaluated the effect of adding waste glass powder as a partial replacement for cement on the performance of WHP-cement composite thermal insulation boards. Water hyacinth was collected from Port Bell on Lake Victoria, Uganda, and waste glass was obtained from domestic waste collection points within Makerere University. The insulation boards were manufactured from WHP and cement, with waste glass powder partially replacing cement. The flexural strength of the developed boards was assessed to determine their mechanical performance. The physical performance was evaluated in terms of bulk density, water absorption, and thickness swelling. The thermal conductivity of the developed boards was measured to determine their thermal performance. The cost-effectiveness of these boards was determined by comparing the material cost of manufacturing the developed boards with that of other available boards.

2 LITERATURE REVIEW

2.1 Introduction

This chapter provides an overview of existing knowledge, identifies gaps for further exploration, informs methodologies, and facilitates the validation of new findings in the field of research. Water hyacinth poses significant environmental, health, and economic challenges due to its rapid growth and the dense mats it forms, which clog water bodies. These mats block rivers and canals, disrupting irrigation, power generation, and navigation, and may cause flooding (Sharma et al., 2015a). Globally, growing concerns about energy consumption have spurred the search for sustainable alternatives to synthetic materials, particularly in the construction sector. Adopting bio-based materials is key to reducing the energy demand involved in manufacturing and enhancing energy efficiency throughout a building's life cycle. Among these, biomass-based insulation materials have attracted interest for their lower environmental impact, non-toxicity, and biodegradability compared to inorganic or petroleum-based insulators (Salas-Ruiz et al., 2019). One promising approach is developing thermal insulation boards from WHP bound with cement. However, cement production contributes significantly to greenhouse gas emissions. To mitigate this, incorporating supplementary binder materials such as waste glass powder to partially replace cement offers a sustainable alternative that can reduce the environmental footprint of cement-based products (Islam et al., 2017).

2.2 Environmental and Socio-Economic Impacts of Water Hyacinth

Water hyacinth (Eichhornia crassipes) is one of the most invasive aquatic plants globally, causing significant ecological, economic, and social challenges. Its proliferation obstructs waterways, disrupts aquatic ecosystems, reduces biodiversity, and negatively affects fishing, transportation, and hydropower generation (Dechassa, 2020; Williams et al., 2005; Wilson et al., 2007). Despite numerous management strategies, including mechanical, chemical, and biological control, long-term effectiveness remains limited due to high costs, environmental risks, and slow response rates (Kulabako et al., 2025; Sharma et al., 2015). Despite its prolific growth, this invasive aquatic plant presents an opportunity for sustainable resource management and the development of eco-friendly building materials (García et al., 2025). The use of water hyacinth in composite materials, particularly for thermal insulation boards, not only addresses the environmental challenges posed by its rapid proliferation but also offers a sustainable alternative to conventional building materials, aligning with principles of the circular economy and waste valorization (Ojo et al., 2019).

2.3 Water Hyacinth as a Raw Material for Construction

Research on binderless WHP boards and WHP–cement composites has demonstrated thermal conductivity values comparable to conventional insulation materials (Philip & Rakendu, 2020; Salas-Ruiz et al., 2019). The invasive aquatic plant water hyacinth has been recognized as a promising sustainable raw material for producing thermal insulation boards due to its abundant availability and unique structural characteristics (Salas-Ruiz et al., 2019). Its lignocellulosic composition, particularly its high cellulose and low lignin content, makes it particularly suitable for integration into cementitious matrices, enhancing mechanical and thermal properties while offering an environmentally benign alternative to synthetic insulation materials (Philip & Rakendu, 2020; Salas-Ruiz et al., 2019).

Particle size, binder content, and processing method significantly influence board performance, with staple-based panels exhibiting superior thermal insulation due to their higher porosity (Salas-Ruiz et al., 2019). However, challenges related to mechanical strength, moisture absorption and long-term durability have been identified particularly in binderless systems (Philip & Rakendu, 2020; Salas-Ruiz et al., 2019). The incorporation of cement as a binder has been shown to improve mechanical performance and reduce water absorption, although higher cement contents may increase density and embodied environmental impacts (Salas-Ruiz et al., 2019). The environmental impacts necessitate optimization of binder content.

2.4 Characteristics of Water Hyacinth Petiole

Water hyacinth petiole (WHP) is a lightweight, porous, cellulose-rich component of WH and is widely recognized for its potential to develop sustainable, bio-based construction materials. Its internal structure consists of a large, air-filled aerenchyma cell surrounded by parenchyma and vascular bundles, giving it very low density and excellent thermal insulation, with conductivities between 0.045 and 0.060 W/mK, compared to some commercial insulation boards (Salas-Ruiz et al., 2019). The air cavities within the petiole reduce heat transfer, making it suitable for thermal insulation board production(Philip & Rakendu, 2020).

Chemically, WHP has a pH near neutral (6.5-7.0) and contains minor amounts of ash, silica, and extractives (Dechassa, 2020). WHP is a lignocellulosic biomass with a typical composition of about 25% cellulose, 23% hemicellulose, and less than 10% lignin (Kivaisi & Mtila, 1997; Salas-Ruiz et al., 2019). Its high cellulose content and low lignin make it compatible with cementitious binders, improving interfacial bonding and mechanical integrity in composites. Its organic nature makes it susceptible to degradation and moisture absorption, necessitating chemical treatments to improve compatibility with cementitious matrices (Sharma et al., 2015). WHP cellulose has also been extracted for biopolymer and hydrogel production, confirming its structural strength and chemical activity (Chaiwarit et al., 2022).

Physically, WHP exhibits low density and high water absorption, as observed in composite boards made from larger, staple-sized WHP particles, which show superior thermal insulation compared to fine pulp particles due to lower packing density and higher air retention (Salas-Ruiz et al., 2019). Its high moisture content necessitates proper drying before processing to ensure dimensional stability (Midhun et al., 2023).

Generally, WHP's combination of lightweight structure, high cellulose content, and natural insulation properties makes it an attractive material for sustainable building applications. Its effective use in cement-based composites offers a potential solution for managing this invasive species while producing low-cost, eco-friendly insulation materials (Philip & Rakendu, 2020; Sharma et al., 2015). Furthermore, the use of WHP aligns with the global drive for sustainable, low-cost, and biodegradable construction materials (Karouach et al., 2022).

2.5 Water Hyacinth-Based Insulation Boards

Research on binderless WHP boards and WHP–cement composites has shown thermal conductivity comparable to that of conventional insulation materials (Philip & Rakendu, 2020; Salas-Ruiz et al., 2019). The invasive aquatic plant water hyacinth has been recognized as a promising, sustainable raw material for producing thermal insulation boards because of its abundance and unique structural characteristics (Salas-Ruiz et al., 2019). Its lignocellulosic composition, particularly its high cellulose and low lignin content, makes it well suited for integration into cementitious matrices, enhancing mechanical and thermal properties while providing an environmentally benign alternative to synthetic insulation materials (Philip & Rakendu, 2020; Salas-Ruiz et al., 2019).

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2.6 Cement Production and Supplementary Cementitious Materials

The global cement industry is a significant contributor to carbon dioxide emissions, with ordinary Portland cement production accounting for approximately 8% of anthropogenic CO2 emissions annually, driven by limestone calcination and the energy-intensive clinkering process (Yel et al., 2022, 2024). The environmental impacts of cement manufacturing have spurred extensive research into supplementary cementitious materials that can partially replace ordinary Portland cement while maintaining or improving concrete performance. This includes exploring alternative binders and incorporating industrial waste products, such as waste glass powder, into cementitious composites (Yel et al., 2022).

2.7 Waste glass powder as a supplementary cementitious material in cement-based products

The growing generation of waste glass has become a significant environmental concern due to its low recycling rates and non-biodegradability. Globally, glass constitutes a considerable fraction of municipal solid waste, with large quantities being disposed of in landfills despite its potential for reuse in construction materials (Chindaprasirt et al., 2022). In response to the environmental burden associated with both waste glass disposal and cement production, researchers have increasingly investigated the use of waste glass powder (WGP) as a supplementary cementitious material (SCM).

Supplementary cementitious materials (SCMs) such as WGP, fly ash, silica fume, and metakaolin are used to reduce the consumption of Portland cement (Zhou et al., 2025). Waste glass powder, produced by milling waste glass to microscale particle size, accelerates beneficial chemical reactions in cement-based products (Aliabdo et al., 2016). WGP affects both the workability and hydration of cementitious composites. The optimal dosage of WGP as an SCM ranges from 10 to 20 wt%, promoting the mechanical and durability properties of WGP–cement composites. WGP enhances chemical, freeze–thaw, and elevated-temperature resistance (Zhou et al., 2025). Being amorphous and silica-rich, WGP can trigger a pozzolanic reaction, with reactivity closely linked to particle size. A particle size threshold of 75 μm is generally recognized as the point of noticeable pozzolanic reactivity, and further reducing particle size significantly boosts pozzolanic activity. WGP particles sized between 0 and 25 μm show a higher strength activity index and consume more portlandite than particles sized 25–75 μm (Jiang et al., 2019).

Mixed-color waste glass offers favorable chemical composition and reactivity as an SCM, thereby enhancing the chemical stability, moisture resistance, and durability of concrete. Increasing the glass powder cement replacement level raises concrete slump; for a 33 MPa concrete mix, every 5% glass powder increases slump by approximately 10 mm. Using 10% glass powder as cement replacement improves compressive strength, tensile strength, absorption, voids ratio, and density. However, using more than 15% glass powder reduces the 28-day compressive strength of concrete. Mortar compressive strength is enhanced by up to 10% glass powder replacement (Aliabdo et al., 2016).

2.8 Performance of Water Hyacinth Petiole -based insulation boards

Using water hyacinth (WH) to develop thermal-insulation particle board demonstrates the aquatic plant's potential for use in the construction sector (Ilo et al., 2020). Valorizing WHP into sustainable building materials is a strategy to mitigate the adverse environmental impact of this weed (Philip & Rakendu, 2020).

Studies analyze two main particle-size groups: Pulp WHPs, consisting of particles that pass through a 2 mm sieve (smaller size) and are mainly composed of aerenchyma tissue; and Staple WHPs, which are particles retained on a 2 mm sieve (larger size) and are primarily composed of "fibre units" and their surrounding aerenchyma. Particle size clearly affects the physical, mechanical, and thermal properties of the resultant boards (Salas-Ruiz et al., 2019).

2.8.1 Thermal Performance of Water Hyacinth Petiole-based boards

Materials with a thermal conductivity below 0.1 W/mK are generally classified as thermal insulations. WHP-based boards demonstrate good thermal insulation performance. According to Salas-Ruiz et al. (2019), binderless Staple WHP panels exhibited a thermal conductivity of 0.047 W/(m·K). Pulp WHP panels showed a value of 0.065 W/mK. This means Staple WHP panels have 1.37 times better thermal insulation properties than pulp WHP panels.

WHP-Cement Composites: The optimal percentage for S-panels (staple/cement) was 75:25 (WHP:c), with a thermal conductivity of 0.045 W/mK. The optimal percentage for P-panels (pulp/cement) was 80:20 (WHP:c), with a thermal conductivity of 0.063 W/mK (Salas-Ruiz et al., 2019). The WH-cement composite panel board (60:40 WHP:c, particles <2.36mm sieve) exhibited a thermal conductivity lower than that of conventional woods and other conventional materials, such as MDF, particleboard, plywood, and hardboard (Philip & Rakendu, 2020).

2.8.2 Physical performance of Water Hyacinth Petiole-based boards

Bulk density decreases with increasing WHP content in cement composites. In binderless boards, staple WHP panels (251.23 kg/m3) were 1.21 times lighter than pulp WHP panels (305.25 kg/m3) (Salas-Ruiz et al., 2019a). For WHP-cement composites: S-panels range from 495.34 kg/m3 (40:60 WHP:c) to 244.65 kg/m3 (100:0 WHP:c) [information from user's text]. P-panels range from 620.35 kg/m3 (40:60 WHP:c) to 314.57 kg/m3 (100:0 WHP:c) (Salas-Ruiz & Barbero-Barrera, 2019). WHP-cement boards have a slightly lower density than wood and are less dense than commercially available materials such as MDF, particleboard, plywood, and hardboard (Philip & Rakendu, 2020).

WHP's high capacity to trap water, due to its hydrophilic cellulose and hemicellulose composition and air-filled voids, leads to high water absorption(Philip & Rakendu, 2020; Salas-Ruiz et al., 2019). Binderless boards showed very high water absorption (WA): pulp WHP boards reached 55.20%, and staple WHP boards reached 45.51%. The addition of cement significantly reduced WA; compared with the 100:0 ratio, WA was reduced by 75% for S-panels and 85% for P-panels. For WHP boards with cement added, S-panels had higher WA (111.69 wt% to 191.83 wt% for S-80) than P-panels (82.14 wt% to 113.87 wt% for P-80). The high value in S-panels is related to larger macroporous structures and the filling of internal channels in staple WHPs, while P-panels absorb water primarily through the chemical hydration of the hydrophilic component. The WA of the WH-cement composite panel board (60:40 WHP:c) was higher than that of conventional and other bio-based materials (Salas-Ruiz et al., 2019).

Thickness Swelling(TS) stability is related to particle size (Salas-Ruiz & Barbero-Barrera, 2019). Pulp WHP panels demonstrated better dimensional stability (57.68% TS) after water immersion than staple WHP panels (101.05% TS). Pulp WHP panels had 1.75 times better dimensional stability behavior than staple panels(Salas-Ruiz et al., 2019). Panels with high WHP content (P-100, S-80, S-100) exceeded the TS requirement (15%) for dimensional stability and should be discarded(Salas-Ruiz & Barbero-Barrera, 2019).

2.8.3 Mechanical Properties of Water Hyacinth Petiole Boards

All panels, whether manufactured with or without cement, were self-supporting (Salas-Ruiz & Barbero-Barrera, 2019). For binderless boards, pulp WHP panels had better mechanical properties (MOR of 0.548 MPa) and exhibited rigid behavior (Salas-Ruiz et al., 2019). Staple WHP panels had a lower MOR (0.215 MPa) but exhibited ductile behavior (able to deform significantly after the initial crack without immediate failure) (Salas-Ruiz et al., 2019). Pulp WHP panels reached an MOR 2.5 times higher than staple WHP panels(Salas-Ruiz et al., 2019). The highest MOR values were found at P-80 (0.61 MPa) for pulp panels and S-40 (0.26 MPa) for staple panels in WHP-Cement composites (Salas-Ruiz & Barbero-Barrera, 2019).

The flexural strength of the WH-cement composite panel board was lower than that of MDF and of some bio-based composites reported in the literature. However, the mechanical performance of WHP boards is generally sufficient to qualify them as structural components suitable for the construction sector (Salas-Ruiz et al., 2019).

2.9 Cost-effectiveness and Sustainability Considerations

Cost-effectiveness is critical to the adoption of alternative insulation materials. Using locally available biomass and waste materials reduces material and disposal costs (Kulabako et al., 2025). The economic viability of water hyacinth-based insulation boards is enhanced by the low cost of the raw material, given its status as an invasive species, and by the potential for reduced energy consumption in buildings. This approach not only contributes to waste valorization but also reduces the overall environmental footprint of construction by utilizing a readily available biomass resource (Philip & Rakendu, 2020). Replacing cement with WGP further lowers embodied energy and production costs while supporting circular economy principles (Islam et al., 2017).

2.10 Research Gaps

Several studies have examined water hyacinth-based insulation boards (Philip & Rakendu, 2020; Salas-Ruiz et al., 2019) and waste glass powder as a supplementary cementitious material (Aliabdo et al., 2016; Zhou et al., 2025), but these two areas have largely been explored independently. Limited studies have examined what happens when both materials are combined in a single cement-bonded insulation board. Existing studies also offer limited analysis of the cost-effectiveness of cement-bonded insulation boards. This study was therefore conducted to address these gaps by testing WHP-cement-WGP boards across a range of WGP replacement levels, comparing both particle forms, and providing a cost-effectiveness analysis based on the material prices on the Ugandan market.

3 MATERIALS AND METHODS

3.1 Introduction

This chapter outlines the methods and materials used to achieve the specific objectives of this research. The study employs quantitative methods to collect primary data through laboratory testing of Water Hyacinth Petiole-Cement-Waste Glass Powder composite boards developed for this study. The methodologies described herein are based on established scientific principles and align with recognized standards, ensuring the reproducibility and validity of the experimental findings.

3.2 Sample Collection and Preparation

3.2.1 Water Hyacinth Petiole Preparation

The water hyacinth used in this study was collected from Port Bell on Lake Victoria, Kampala, Uganda (approximate coordinates: 0°17'24.42"N, 32°39'20.70"E). The petioles were manually separated from the roots of the collected plants and thoroughly washed to remove adhering impurities and unwanted surface materials (Philip & Rakendu, 2020; Salas-Ruiz & Barbero-Barrera, 2019). The cleaned petioles were chopped into small pieces and sun-dried to constant weight (Figure 3-1), ensuring adequate moisture removal for subsequent processing (Philip & Rakendu, 2020). After drying, the WHPs were further reduced in size by manual mechanical rubbing to obtain fibrous particles suitable for board production.

Figure 3-1: Sun drying of WHP

Particle-size separation was then performed using a 2 mm sieve, yielding two distinct categories, as shown in Figure 3-2. The material that passed through the sieve was designated "pulp" WHP and used for P-panels, whereas the material retained on the sieve was designated "staple" WHP and used for S-panels (Salas-Ruiz et al., 2019; Salas-Ruiz & Barbero-Barrera, 2019). This differentiation is crucial because particle size strongly influences the thermal insulation and mechanical properties of the final composite boards.

Figure 3-2: Sieving crushed WHP

3.2.2 Cement

CEM I (42.5N) Ordinary Portland Cement, manufactured by Tororo Cement Limited (Uganda), served as the primary binder for the composite boards because of its high early strength and rapid setting.

3.2.3 Waste Glass Powder

Waste glass used in this study was collected from designated waste collection points within Makerere University. The waste glass was thoroughly washed with water to remove dirt and other impurities and then sundried before processing.

The dried glass was mechanically crushed and ground into a fine powder using a ball mill at the Department of Geology, Makerere University. The ground material was sieved through a 75 µm sieve, as shown in Figure 3-3, to obtain waste glass powder (WGP) with a uniform, fine particle size suitable for use as a partial cement replacement.

Figure 3-3: Sieving WGP

3.2.4 Health and safety during material preparation

The preparation of waste glass powder involved crushing, grinding, and sieving, which pose significant health and safety risks due to the generation of sharp fragments and fine particulate matter. To mitigate these risks, appropriate safety measures were strictly implemented throughout the experimental procedure in accordance with standard laboratory safety practices.

Personal protective equipment (PPE) was worn at all times during the handling and processing of glass materials. This included safety goggles to protect the eyes from flying particles, gloves to prevent cuts and abrasions from sharp edges, and laboratory coats to minimize skin exposure. In addition, dust masks and respirators were used to prevent inhalation of fine glass particles, which may pose respiratory hazards due to their silica content.

All crushing and grinding operations were conducted in designated laboratory facilities within the Department of Geology, where controlled environments and appropriate equipment are available for these activities. Adequate ventilation was maintained during these processes to reduce airborne dust concentrations. Careful handling procedures were followed during material transfer and sieving to minimize dust dispersion and accidental spillage.

Furthermore, strict housekeeping practices were maintained throughout the experiment. Residual glass fragments and powder were safely collected and disposed of in designated waste containers to prevent injuries and environmental contamination. Work surfaces and equipment were thoroughly cleaned after each processing stage to remove any remaining hazardous materials.

These safety precautions were essential for protecting personnel and maintaining a safe working environment during the preparation of waste glass powder, in line with established laboratory safety guidelines and occupational health standards.

3.3 Mix proportions

Waste glass powder (WGP) was blended with cement at 0%, 10%, 20%, 30%, 40%, and 50% by weight to form a binder mixture, referred to as "B." This composite binder (B) was then combined with water hyacinth petiole (WHP) at a 60:40 ratio (WHP: B).

The mix proportions were selected to evaluate the combined effects of water hyacinth petiole (WHP) and waste glass powder (WGP) as supplementary cementitious materials on the thermal, physical, and mechanical performance of composite insulation boards. The objective is to optimize board properties while enhancing material sustainability by reducing cement use and increasing waste utilization.

A 60:40 WHP-to-binder (B) ratio was adopted, based on previous studies identifying this proportion as optimal for achieving acceptable strength and thermal insulation performance in WHP-based boards (Philip & Rakendu, 2020). Waste glass powder (WGP) was incorporated as a partial cement replacement at rates of 0%, 10%, 20%, 30%, 40%, and 50% by weight of cement to assess its role as a supplementary cementitious material. The 0% WGP served as the control mixture. 10–20% were selected based on literature reporting improved mechanical and durability properties at these proportions due to the pozzolanic reactivity of finely ground glass (Aliabdo et al., 2016; Zhou et al., 2025). 20–30% WGP were described as near-optimum levels for achieving improved long-term strength and reduced porosity (Más-López et al., 2021; Mezaouri et al., 2024).

Proportions of 30–50% WGP were included to assess the effects of maximizing waste utilization and reducing cement consumption. Although these higher contents may reduce early-age strength, some research shows strength recovery or enhancement at later ages (Más-López et al., 2021), while other studies report declining strength beyond 25–30% replacement (Mezaouri et al., 2024). Investigating this broader range helps identify the optimal balance among structural performance, thermal efficiency, and sustainability benefits for WHP–cement insulation composites.

3.4 Manufacturing Process

The manufacturing process for the composite insulation boards followed several key steps:

3.4.1 Mix Design

In the design, a 60:40 WHP:Binder mix ratio was used for the samples. The water-to-WHP ratio (w:WHP) was fixed at 1.75, and the water-to-binder ratio was fixed at 0.5. Mix proportions were determined based on the WHP:Binder mix ratio. Using 500g of WHP, the corresponding binder mass was calculated as 333.3g. Water content for WHP was calculated as 875cm3 using the w:WHP. Water for binder hydration was calculated as 167cm3 using the w/c ratio. The total water content for the mix was therefore 1041.7cm3.

For 0% WGP, cement was the only binder in this proportion, with a mass of 335g and 170cm3 of water used for hydration. For 10% WGP, 10% of the binder mass was calculated as 33.3g to constitute WGP, with the remainder as cement. A mass of 35g of WGP was used and mixed with 300g of cement. 170cm3 of water was used for binder hydration.

For 20% WGP, 20% of the binder mass was calculated as 66.6g of WGP and 266.7g of cement. A mass of 67g of WGP was used and mixed with 268g of cement. 170 cm3 of water was used for binder hydration. For 30% WGP, 30% of the binder mass was calculated as 99.9g of WGP and 233.4g of cement. A mass of 101g of WGP was used and mixed with 235g of cement. 170 cm3 of water was used for binder hydration.

For 40% WGP, 40% of the binder mass was calculated as 133.2g for WGP and 200.1g for cement. A mass of 135g of WGP was used and mixed with 201g of cement. 170 cm3 of water was used for binder hydration. For 50% WGP, 50% of the binder mass was calculated as 166.5g for WGP and 166.8g for cement. A mass of 167g of WGP was used and mixed with 167g of cement. 170 cm3 of water was used for binder hydration.

3.4.2 Procedure

The mixing process was carried out separately to ensure proper material interaction. The required amount of water was added to the WHP and mixed to ensure proper WHP wetting. The binder was also mixed with the calculated amount of water to form a homogeneous paste. The wetted WHP was then added to the paste and mixed manually. The mixture was poured into molds measuring 150 x 150 x 25mm, wrapped in a layer of polythene to prevent moisture loss, and placed on a flat surface. The mixtures were compressed using a system of concrete blocks weighing approximately 22 kg to achieve a compaction force of 0.04 MPa for 24 h, as illustrated in Figure 3-4.

Figure 3-4: Sample under compaction using concrete blocks

The samples were kept for 7 days at laboratory temperature to promote hydration reactions. After 7 days of curing, the polythene layer was removed, and the samples were kept under laboratory conditions for up to 28 days of curing, as shown in Figure 3-5.Figure 3-5

Figure 3-5: Curing of the sample boards in the laboratory

3.5 Flexural Strength determination

The flexural strength of the composite boards was determined in accordance with ASTM D1037. Flexural strength is a key indicator of a material's resistance to bending before fracture (Philip & Rakendu, 2020). Three specimens from each WGP composition were prepared. The dimensions of each specimen, including length (L), thickness (d), and width (b), were measured and recorded. The specimens were tested under a three-point bending setup using a Lloyd Instruments LRX Plus (Figure 3-6). Each specimen was placed horizontally on two supports with a known span length, and a load was applied at the center of the specimen at a constant rate until failure. The maximum load carried by the specimen before failure, P_{max}, was recorded. The modulus of rupture, R, was then calculated.

$$R = \frac{3P_{max}L}{2bd^2}$$

Figure 3-6: Lloyd Instruments LRX Plus

3.6 Physical properties assessment

3.6.1 Bulk density determination

The bulk density of the composite boards was determined in accordance with ASTM C303, based on the direct relationship between the mass and volume of the dried specimens after 28 days of curing. Bulk density is a critical parameter for predicting thermal performance (Philip & Rakendu, 2020). An electronic balance with a precision of 0.01 g and a ruler were used. For each WGP composition, three replicate specimens were produced and tested under identical conditions. The mean of the three specimens was calculated and reported to minimize experimental error and improve accuracy.

3.6.2 Water absorption determination

The water absorption capacity of the composite boards was measured in accordance with ASTM C1763. Although this standard is specific to cellular plastic insulation, its principles for measuring water absorption by weight gain after immersion are applicable and can be adapted for bio-based composite materials. The high water absorption capacity of WHP, due to its hydrophilic cellulose and hemicellulose content, necessitates careful evaluation of this property (Philip & Rakendu, 2020; Salas-Ruiz et al., 2019). The dry mass of each specimen was measured and recorded using an electronic balance as W1. The specimens were constrained and then completely immersed in water at room temperature for 2 hours. They were then removed from the water, drained, surface water removed, and weighed immediately, with the result recorded as W2.

$$WA(\%) = \frac{W_2 - W_1}{W_1} \times 100$$

3.6.3 Thickness of Swelling Determination

Thickness swelling was assessed to evaluate the dimensional stability of the boards under moist conditions. This involved measuring the change in thickness after exposure to water for a specified period, in accordance with relevant sections of ASTM D1037. The thickness of the specimens was measured midway along each of the four sides, and the average of the four measurements was calculated and recorded as T1. After a 2-hour submersion, the specimens were drained, surface water removed, and the thickness of all four sides of each specimen was measured. The average of the four measurements was calculated as T2.

$$TS(\%) = \frac{T_2 - T_1}{T_1} \times 100$$

3.7 Thermal conductivity of the developed boards

For panels intended for thermal insulation, thermal conductivity was measured to quantify their heat-transfer characteristics (Philip & Rakendu, 2020). The aim was to ensure the boards met the classification for thermal insulators (thermal conductivity below 0.1 W/mK) (Salas-Ruiz et al., 2019). The thermal conductivity of the developed WHP–cement–WGP insulation boards was determined using a QTM-500 Quick Thermal Conductivity Meter (Figure 3-6) based on the transient heat flow (hot-wire) method. Three specimens for each waste glass powder (WGP) composition were prepared for testing. The dimensions and surfaces of the specimens were checked to ensure proper contact with the probe sensor. The probe of the thermal conductivity meter was firmly placed on the specimen surface to ensure accurate heat transfer during measurement. The thermal conductivity values obtained for the three specimens of each composition were averaged and reported in W/mK.

Figure 3-7 QTM-500 Quick Thermal Conductivity meter

3.8 Cost-Effectiveness Analysis of the Developed Boards

The cost-effectiveness of the developed WHP–cement–WGP composite boards was evaluated through a material cost analysis. The assessment considered costs incurred during the collection, processing, and production of the boards. Water hyacinth petiole (WHP) was collected from Port Bell on Lake Victoria, and waste glass was obtained from waste collection points within Makerere University. Costs for transportation, collection, crushing, and grinding were recorded.

The unit costs of cement, WHP processing, WGP processing, and mold fabrication were obtained from prevailing local market prices and actual project expenditures. The material cost for each board composition was calculated using the quantities of materials used and their corresponding unit costs. The total production cost per board and the cost per square meter were then determined. The cost per square meter was calculated by dividing the total cost for each WGP percentage by the total board area produced (0.135 m^2).

4 RESULTS AND DISCUSSION

4.1 Bulk density

As the percentage of cement replaced by waste glass powder (WGP) increased, the bulk density of the composite insulation boards decreased progressively for both P-panels and S-panels. Across WGP replacement levels of 0%, 10%, 20%, 30%, 40%, and 50%, the bulk density ranged from 462.519 kg/m³ to 391.745 kg/m³ for P-panels and from 384.012 kg/m³ to 268.751 kg/m³ for S-panels (Figure 4-1).

The reduction in bulk density with increasing WGP replacement agrees with findings reported by (Más-López et al., 2021) who observed that increasing lightweight and porous constituents within cement-bonded composites reduced overall compactness and density. Similar trends were also reported by (Mezaouri et al., 2024) where partial replacement of cement with waste glass powder produced lower-density composites due to increased internal porosity and reduced matrix continuity.

However, the density values obtained in this study were comparatively lower, possibly due to the lower compaction pressure used during sample preparation and the highly porous structure of water hyacinth petioles. The lower density of S-panels compared with P-panels is consistent with observations by Salas-Ruiz et al. (2019), who reported that staple-based water hyacinth panels exhibit higher porosity and lower compactness than pulp-based panels.

The observed densities fall within the range reported for lightweight natural-fiber-based insulation materials, indicating the potential suitability of the developed composites for non-structural thermal insulation applications. The lower densities achieved, particularly at higher WGP replacement levels, improve thermal insulation performance by increasing porosity and reducing heat transfer through the material. However, excessive reductions in density may compromise mechanical strength, underscoring the need to optimize the cement replacement level to balance lightweight characteristics, thermal efficiency, and structural integrity.

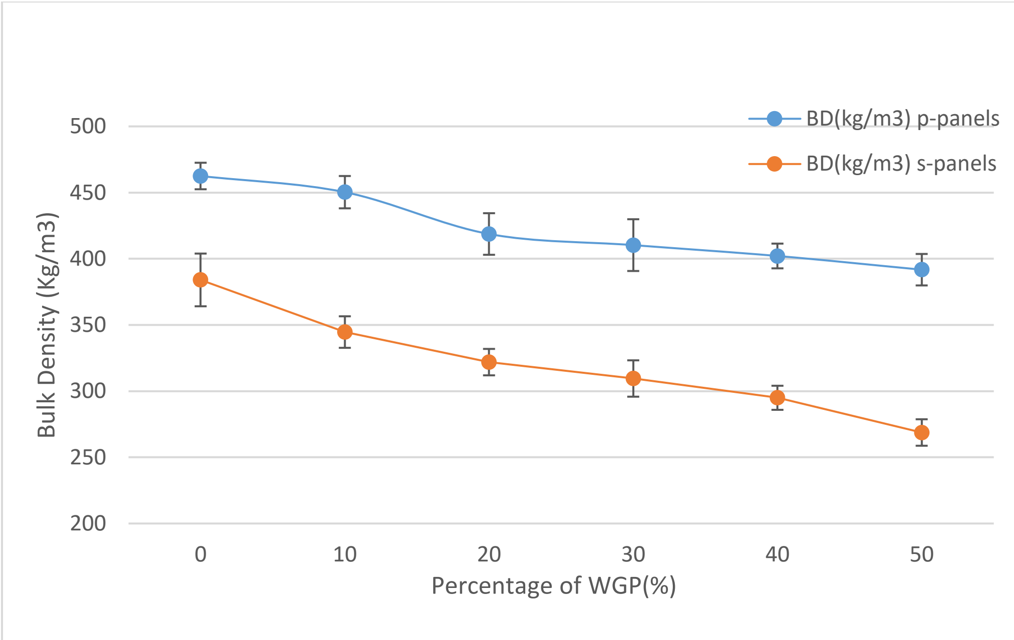

Figure 4-1: Variation of bulk density with percentage of WGP

4.2 Water absorption

4.2.1 Water Absorption (WA)

The water absorption (WA) values of both P-panels and S-panels decreased as the partial replacement of cement with waste glass powder (WGP) increased. For P-panels, WA ranged from 71.062 wt% to 21.712 wt%, while S-panels ranged from 93.567 wt% to 44.432 wt% across WGP replacement levels of 0–50% (Figure 4-2). The reduction in water absorption with increasing WGP content aligns with findings from Aliabdo et al. (2016), who reported that finely ground waste glass particles improve particle packing and reduce permeability by filling internal voids within the cement matrix. Similar observations were reported by Zhou et al. (2025), where increased WGP replacement enhanced resistance to moisture penetration due to micro-filler effects and secondary pozzolanic reactions.

The reduction in water absorption may be attributed to densification and improved particle packing resulting from incorporating finely ground waste glass powder into the cementitious matrix. The finer WGP particles likely filled internal voids and pore spaces, thereby reducing the permeability and moisture uptake capacity of the composite boards. In addition, the pozzolanic reaction between WGP and calcium hydroxide generated during cement hydration may have contributed to the formation of additional cementitious products, resulting in a less porous microstructure.

Despite the observed reduction in WA values, S-panels consistently exhibited higher water absorption than P-panels. This behavior can be attributed to the coarser staple water hyacinth particles used in S-panels, which created larger macro-pores and internal channels that facilitated greater water penetration and retention. In contrast, the finer pulp particles used in P-panels enhanced compaction and reduced interconnected void spaces, thereby limiting moisture ingress.

The decrease in WA with increasing WGP replacement aligns with the observed reduction in bulk density and indicates improved dimensional stability and moisture resistance of the composite boards. Lower water absorption is desirable for insulation materials intended for building applications, as excessive moisture uptake can compromise durability, dimensional stability, and thermal performance. The results, therefore, suggest that partially replacing cement with WGP can improve the hygric performance of WHP-based insulation boards while simultaneously enhancing sustainability by reducing cement consumption and utilizing waste glass.

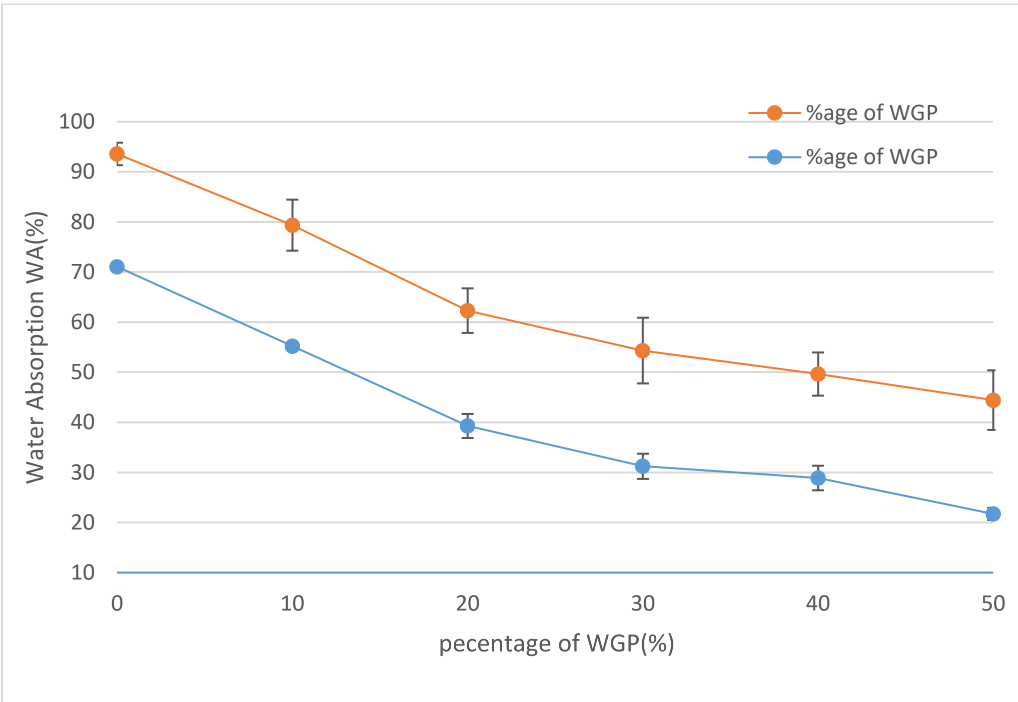

Figure 4-2: Variation of water absorption with percentage of WGP

4.3 Thickness of Swelling

Thickness swelling (TS) results showed a decrease with increasing waste glass powder (WGP) content for both pulp (P) and staple (S) panels. For the P panels, TS decreased from 32.986% to 9.649%, while for the S panels, it decreased from 51.021% to 19.916% as the WGP content increased. This indicates that incorporating WGP improved the dimensional stability of the developed boards. The reduction in TS may be attributed to the filler effect of the finely ground waste glass powder. The WGP particles filled pores and voids within the composite matrix, resulting in a denser, more compact structure that limited water penetration during immersion. Similar findings were reported by Aliabdo et al. (2016), who observed that waste glass powder reduces pore connectivity and improves dimensional stability in cement-based composites through filler and pozzolanic effects.

According to Figure 4-3, the results further showed that thickness swelling increased with bulk density. This behavior may be associated with the greater amount of solid material and reduced flexibility in denser boards. As the boards became denser, moisture absorbed during immersion generated greater internal stresses within the compact matrix, leading to more noticeable thickness expansion. This relationship aligns with observations reported by Salas-Ruiz et al. (2019), who found that thickness swelling in water hyacinth-based composites is strongly influenced by the hygroscopic nature of the fibers and the porosity of the board structure.

Despite this relationship, the overall decrease in thickness swelling with increasing WGP content suggests that the benefits of improved particle packing and reduced porosity outweighed the effect of increased density. Therefore, the findings indicate that moderate incorporation of WGP improved the dimensional stability and moisture resistance of the WHP–cement composite boards.

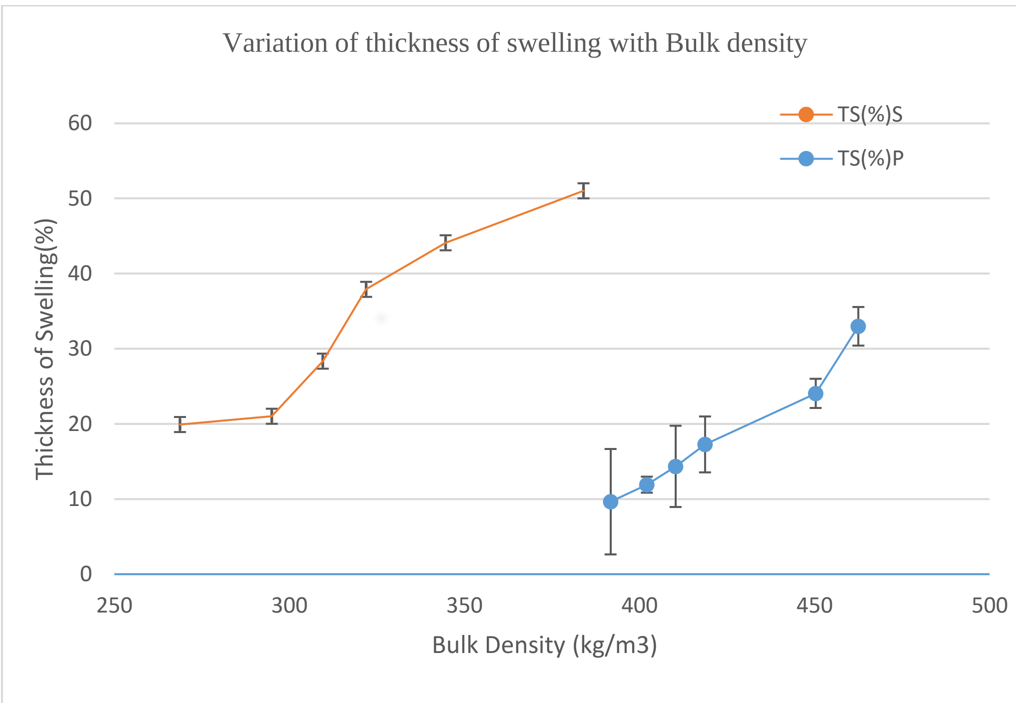

Figure 4-3: Thickness of Swelling against Bulk density

4.4 Flexural strength

The flexural strength results showed that both the waste glass powder (WGP) replacement level and the water hyacinth petiole (WHP) particle type significantly influenced the mechanical performance of the developed insulation boards. The P-panels recorded flexural strength values of 0.211, 0.197, 0.236, 0.199, 0.191, and 0.186 MPa for 0%, 10%, 20%, 30%, 40%, and 50% WGP replacement, respectively, while the S-panels recorded lower values of 0.131, 0.099, 0.145, 0.097, 0.089, and 0.081 MPa over the same replacement range, as shown in Figure 4-4. The variation in flexural strength with increasing WGP replacement is comparable to findings reported by Mezaouri et al. (2024), who observed that excessive replacement of cement with waste glass powder reduces the amount of hydration products responsible for effective bonding within cementitious composites.

Generally, the P-panels exhibited better flexural performance than the S-panels. This can be attributed to the finer particle structure of WHP pulp, which enhanced particle packing, reduced macro-void formation, and improved bonding between WHP particles and the cementitious matrix. Improved matrix continuity promoted better stress transfer during bending, resulting in higher flexural strength. Similar findings have been reported in previous studies on natural fiber composites, where reduced porosity and improved particle distribution enhanced mechanical performance (Salas-Ruiz & Barbero-Barrera, 2019).

The highest flexural strength for the P-panels was achieved at 20% WGP replacement (0.236 MPa). This improvement may be linked to the pozzolanic reactivity of finely ground waste glass powder. At moderate replacement levels, the silica in WGP reacts with calcium hydroxide formed during cement hydration to produce additional calcium silicate hydrate (C–S–H) gel, thereby improving bonding within the composite matrix. Similar observations were reported by Aliabdo et al. (2016), who found that moderate WGP replacement levels improved mechanical properties due to filler and secondary hydration effects.

Beyond 20% replacement, a gradual decline in flexural strength was observed in both panel types. This decline can be explained by reduced cement content, which limited the formation of sufficient cementitious products required for strong matrix continuity and effective stress transfer. Higher WGP contents may also have increased internal porosity and weakened the bonding structure, leading to premature crack initiation under load.

The S-panels consistently exhibited lower flexural strength because the larger particle size and fibrous structure of staple WHP produced a more heterogeneous composite with larger internal voids and weaker bonding zones. Although the staple structure may enhance thermal insulation by increasing air entrapment, the resulting porosity negatively affected the boards' mechanical performance. Previous studies have shown that higher porosity in lightweight composites is directly associated with lower modulus of rupture and reduced structural integrity (Asasutjarit et al., 2009).

Despite low strength values, the developed boards exhibited self-supporting behavior, indicating their suitability for non-load-bearing insulation applications. Overall, the findings suggest that 10% to 20% WGP replacement provided the optimal balance between sustainability and flexural performance, while pulp-based WHP panels were mechanically superior to staple-based panels due to improved particle packing and reduced porosity.

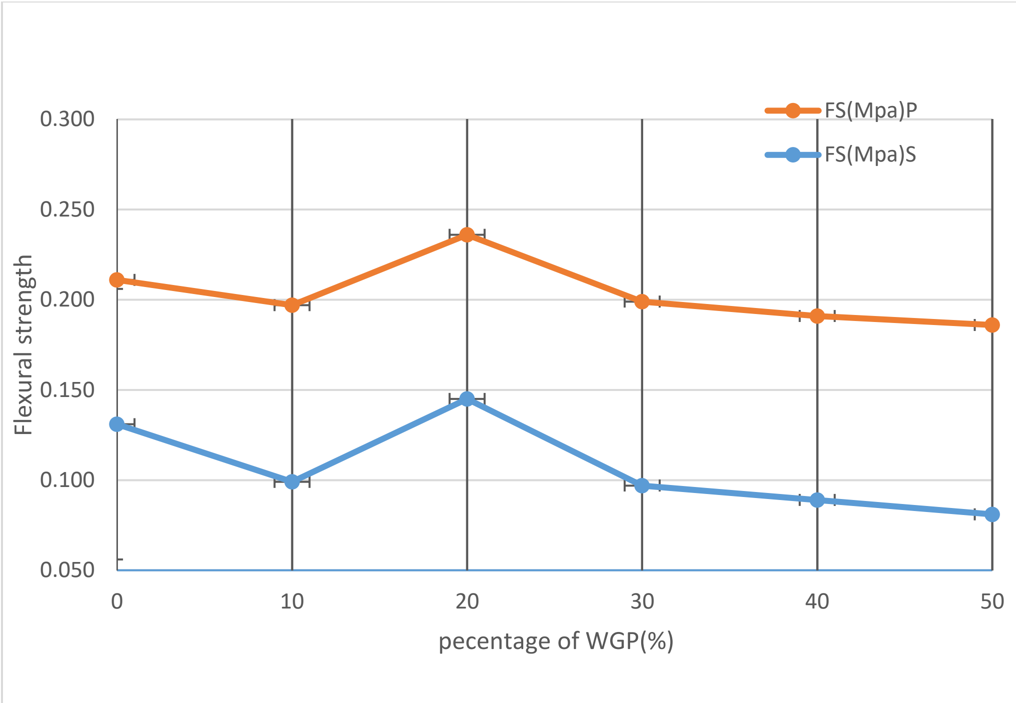

Figure 4-4: Variation of flexural strength with WGP

4.5 Thermal conductivity

The WHP–cement–WGP composite boards exhibited good thermal insulation performance, with thermal conductivity decreasing as the percentage of cement replaced by waste glass powder (WGP) increased, as shown in Figure 4-3. For P-panels, thermal conductivity ranged from 0.105 W/mK to 0.046 W/mK, corresponding to bulk densities of 462.519 kg/m³ to 391.745 kg/m³. Similarly, S-panels recorded thermal conductivity values from 0.098 W/mK to 0.033 W/mK, with corresponding bulk densities decreasing from 384.012 kg/m³ to 268.751 kg/m³.

The inverse relationship between thermal conductivity and bulk density aligns with previous studies on natural fiber insulation materials reported by Philip & Rakendu (2020) and Salas-Ruiz et al (2019), who found that lightweight, highly porous water hyacinth composites exhibit improved thermal insulation performance due to increased entrapped air volume within the matrix.

The reduction in thermal conductivity with increasing WGP replacement can be attributed to a decrease in bulk density and an increase in internal porosity within the composite boards. Lower-density materials generally contain larger volumes of entrapped air, and since air has very low thermal conductivity, overall heat transfer through the material is significantly reduced. The incorporation of waste glass powder likely produced a less compact matrix and promoted the formation of additional microvoids, thereby enhancing the boards' thermal insulation capacity. The lower thermal conductivity values achieved at higher WGP replacement levels may also be linked to the increased porosity and reduced compactness caused by partial cement replacement. Similar behavior was reported by Chindaprasirt et al. (2022), who found that incorporating glass waste improved thermal insulation properties by reducing heat transfer through the material matrix.

S-panels consistently exhibited lower thermal conductivity than P-panels. This behavior is associated with the coarser staple water hyacinth particles used in S-panels, which produced larger macro-porous structures and greater internal air spaces within the composite matrix. In contrast, the finer pulp particles used in P-panels resulted in denser packing and reduced pore volume, leading to comparatively higher thermal conductivity.

Furthermore, the results suggest that partially replacing cement with waste glass powder not only contributes to waste valorization and reduced cement consumption but also enhances the thermal efficiency of WHP-based insulation boards by improving their insulating microstructure.

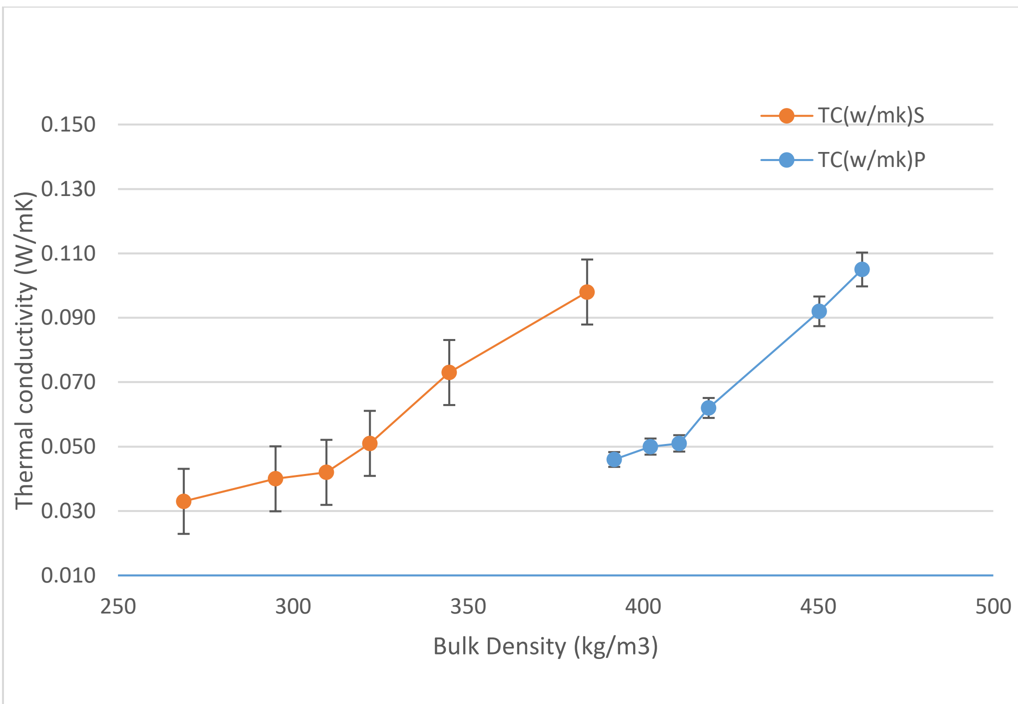

Figure 4-5: Thermal conductivity of WHP boards depending on their bulk densities.

4.6 Cost-Effectiveness Analysis of WHP-Cement-WGP Composite

The cost analysis showed that the production cost of the developed WHP–cement–WGP insulation boards increased with higher waste glass powder replacement. The estimated production cost of the developed boards ranged from UGX 30,511/m² to UGX 53,881/m², depending on the WGP replacement levels, as shown in Table 4-1. The increase in cost was mainly attributed to the crushing and grinding costs associated with producing fine waste glass powder suitable for use as a supplementary cementitious material. Although increasing WGP replacement reduced cement consumption and consequently lowered cement cost, the reduction was relatively small compared to the processing cost of WGP.

The control boards (0% WGP) had the lowest production costs because no waste glass processing was required. However, boards with moderate WGP replacement levels (10–20%) offered a more balanced performance by combining lower production costs with improved thermal and physical performance. Higher WGP replacement levels (30–50%) had higher production costs due to the larger quantities of processed glass powder required.

In comparison, gypsum boards available on the local market range from UGX 30,000 to UGX 70,000, depending on quality, while cement boards cost approximately UGX 80,000. Medium Density Fibreboards (MDF) are sold for approximately UGX 110,000, whereas block boards cost about UGX 60,000. This comparison indicates that the developed WHP–cement–WGP boards are economically competitive, particularly at lower and moderate WGP replacement levels.

The developed WHP–cement–WGP composite boards demonstrated significant potential as a cost-effective alternative to conventional insulation materials by utilizing locally available waste resources. Water hyacinth was obtained free of charge from Port Bell, reducing the cost of acquiring fibrous raw materials, while waste glass was collected from disposal sites within Makerere University, minimizing material procurement expenses and promoting waste valorization. This approach aligns with the broader case made by Güereña et al. (2015), who demonstrated that reframing water hyacinth as a resource for integrated use, rather than purely as an invasive nuisance, can generate measurable economic, social, and environmental benefits for communities around Lake Victoria.

Partially replacing cement with waste glass powder further reduces reliance on ordinary Portland cement, one of the most expensive constituents in cement-based composites. Because cement contributes significantly to the overall production cost and carbon footprint of construction materials, reducing its proportion lowers both manufacturing costs and environmental impacts. Recycling waste glass into cement-based construction products not only reduces the burden on landfills but also helps preserve resources and reduce the carbon footprint associated with cement production (Jiang et al., 2019).

Furthermore, using water hyacinth helps manage the environment by controlling the invasive weed that affects water bodies such as Lake Victoria, while incorporating waste glass powder supports sustainable domestic waste management by recycling and reducing landfill accumulation. Therefore, the developed composite boards provide both economic and environmental benefits, making them promising sustainable insulation materials for low-cost building applications.

Table 4-1: Unit Cost of Production

WGP %	Cement Used (g)	Cement Cost (UGX)	WGP Used (g)	WGP Cost (UGX)	WHP Cost (UGX)	Total Cost per board (UGX)	Cost per m² per board (UGX/m²)
0%	335	369	0	0	3,750	4,119	30,511
10%	300	330	35	700	3,750	4,780	35,407
20%	268	295	67	1,340	3,750	5,385	39,889
30%	235	259	101	2,020	3,750	6,029	44,659
40%	201	221	135	2,700	3,750	6,671	49,415
50%	167	184	167	3,340	3,750	7,274	53,881

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study investigated the feasibility of producing sustainable thermal insulation boards from water hyacinth petiole (WHP), cement, and waste glass powder (WGP). The findings demonstrated that locally available waste materials can be successfully used to produce environmentally friendly construction materials.

The physical and mechanical performance of the developed boards was influenced by the incorporation of WGP. Moderate levels of WGP improved dimensional stability and mechanical performance by reducing water absorption and thickness swelling, while enhancing the modulus of rupture through improved particle packing and matrix bonding. However, excessive replacement of cement with WGP negatively affected board performance due to reduced cementitious bonding within the composite matrix.

The developed WHP–cement composite boards also exhibited low thermal conductivity, confirming their suitability as lightweight thermal insulation materials. The lightweight, porous structure of water hyacinth significantly contributed to the boards' thermal insulation performance by reducing heat transfer.

The cost-effectiveness assessment showed that the developed boards can be produced using relatively low-cost and locally available materials. Moderate WGP replacement levels of 10%-20% provided the best balance between performance and production cost, demonstrating the economic potential of the boards for non-structural building applications.

The study further demonstrated the environmental benefits of using water hyacinth and waste glass in construction materials. Using water hyacinth helps manage the invasive weed that affects water bodies such as Lake Victoria, while incorporating waste glass powder supports sustainable domestic waste management by recycling and reducing glass waste disposal. Overall, the study confirmed that WHP–cement–WGP composite boards have strong potential as sustainable, eco-friendly, and cost-effective thermal insulation materials.

5.2 Recommendations

Based on this study's findings, moderate waste glass powder (WGP) replacement levels of 10% to 20% are recommended for producing WHP–cement composite boards because they offer the best balance among board performance, thermal insulation, and cost-effectiveness while reducing cement consumption.

Further studies should investigate methods to reduce the boards' high water absorption, such as chemical treatment of water hyacinth fibers or the use of waterproofing additives. Additional research should also be conducted on properties such as fire resistance, durability, and long-term performance under different environmental conditions to determine the boards' suitability for broader building applications.

Future studies should further optimize production parameters, including water content, compaction pressure, and curing conditions, to improve the quality and overall performance of the boards. The use of water hyacinth and waste glass powder in construction materials should also be encouraged as a sustainable approach to invasive weed management, domestic waste reduction, and environmentally friendly construction practices.

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Appendix

Figure B2 1: WHP collection

Figure B2. 1: Sun drying WHP

Figure B2. 2: rubbing between hands

Figure B2. 3: sieving of water hyacinth

Figure B2. 4: sieving WGP

Figure B2. 5: staple and pulp WHP

Appendix 2

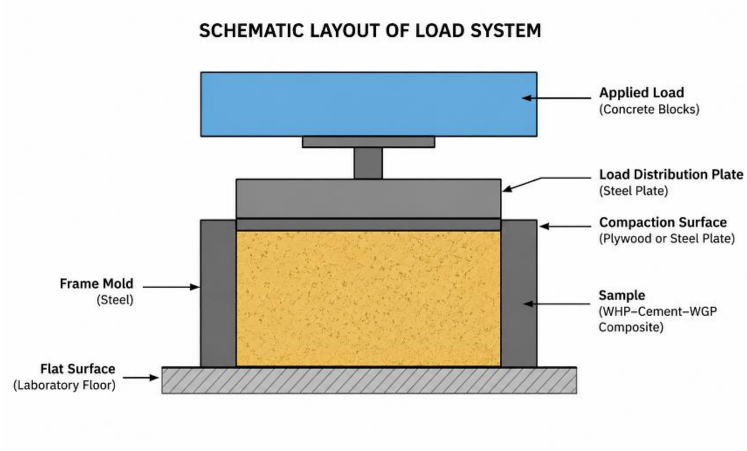

Figure A2. 1: schematic layout of the load system

Figure A2. 2: moulds

Figure A2. 3: uniform loading of samples

Figure A2. 4: Samples curing

Figure A2. 5: Water Absorption test

Figure A2. 6: thermal conductivity test

Figure A2. 7: Flexural strength testing