ASSESSING THE USE OF BAMBOO AS A BUILDING MATERIAL FOR ROOF COVERING IN DEVELOPING AREAS IN UGANDA

PRISCA ENABU ATIM

M22B32/013

A DISSERTATION SUBMITTED TO THE FACULTY OF ENGINEERING, DESIGN AND TECHNOLOGY IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF BACHELOR OF CIVIL AND ENVIRONMENTAL ENGINEERING OF UGANDA CHRISTIAN UNIVERSITY

February, 2026

UGANDA CHRISTIAN UNIVERSITY
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ABSTRACT

Bamboo is commonly used in roofing in the less developed areas of Uganda since it is a relatively cheap material. Its use on a larger scale is however hindered by rapid decay which affects primarily the untreated bamboo, the use of traditional methods such as smoking and water soaking, which does not effectively remove the danger of termites, fungi, borers and the effect of decay caused by moisture. This paper discusses the application of epoxy resin, a thermoset polymer, as a modern day treatment on bamboo roofing and therefore, increases its life and service life in humid tropical regions such as Kabaale and Busega. The research adopted an experimental comparative method in which sets of bamboo samples were prepared in untreated, the traditional treatment and the epoxy resin treated. Laboratory and field tests were conducted to evaluate the performance of the bamboo and the findings clearly discussed for bamboo roof covering. A practical design of interlock roof was put forward where the treated bamboo culms were mixed with a base layer, ventilated and with bamboo battens, structural calculations indicated that the system of the roof is capable of supporting the environmental loads and a service life of 15-20 years.

DECLARATION

I, ATIM PRISCA ENABU declare to the best of my knowledge that this final year research and design project report is my original work and has never been submitted for any academic award to any institution of higher learning. I have acknowledged and referenced the authors whose information I have used in this report.

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ATIM PRISCA ENABU   DATE

M22B32/013

APPROVAL

I certify that this final year research and design project report of ATIM PRISCA ENABU has been submitted to the Faculty of Engineering, Design and Technology of Uganda Christian University as a partial fulfilment of the requirements for an award of a Bachelor of Science in Civil and Environmental Engineering with my approval as the academic supervisor

Signature…………………………… Date…………………………………

MR. TOM MORE MWANJE

Academic Supervisor

DEDICATION

I dedicate this work to my parents, friends and relatives who have supported me in all aspects of life throughout my academic journey, may God bless them and keep them.

ACKNOWLEDGEMENT

I thank the Almighty God for enabling me to carry out this research project and design and seeing me through this entire period. I would also like to thank my parents my siblings for their continued support financially and emotionally and for their unwavering support which allowed me to focus. I would like to extend my gratitude to Mr. Tom More Mwanje, my research supervisor for the guidance, assistance, advice and time that he dedicated to this research project.

Appreciation goes out to all my classmates for being collaborative and active throughout this research process.

Finally, I would like to thank the faculty of engineering design and technology at Uganda Christian University for supporting us and allowing us to do this research under their guidance and supervision.

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CFR	Central Forest Reserve
NFA	National Forestry Authority
NP	National Park
MOR	Modulus of Rupture
MOE	Modulus of Elasticity
MPa	Mega Pascals
ISO	International Standards Organisation
ASTM	American Society for Testing and Materials
CCA	Chromated Copper Arsenate
%	Percent

CHAPTER 1: INTRODUCTION

1.0 Introduction and background.

Globally, the construction industry is responsible for approximately 38% of energy related carbon dioxide emissions, leading to a growing shift toward sustainable building materials and practices (UNEP, 2022). In response, many countries have turned to renewable resources like bamboo which is widely recognized for its strength, rapid growth (up to 1 meter per day in some species), and ability to sequester carbon at rates comparable to young forests (Liese & Kohl, 2015). Countries like China, India, and Colombia have successfully integrated bamboo into mainstream construction using it for structural components, roofing, and framework due to its high tensile strength ranging from 160-300 MPa and durability when properly treated. In Uganda, the demand for affordable housing has reached critical levels, with the Uganda Bureau of Statistics (UBOS) estimating a housing deficit of over 2.1 million units as of 2022, projected to rise to 3 million by 2030 if no intervention is made (UBOS, 2022). Rising costs of conventional materials such as galvanized iron sheets and fired clay tiles further complicate access to housing for low income earners. Bamboo, which grows naturally in regions like Mt. Elgon, Rwenzori, and the southwestern highlands, is a potentially viable alternative. In Busega, kabale area, located in Uganda’s central region, indigenous bamboo species such as Arundinaria alpina are already part of the natural landscape and Dendrocalamus asper (giant bamboo) can grow to a height of 30.5 m, with a diameter of 305 mm, yet remain largely untapped for structural construction. Local communities primarily use bamboo for fencing, baskets, and traditional crafts.

However, with proper treatment methods chemically by using epoxy resin, these enhances bamboo's mechanical and durability properties, with the goal of promoting its use as a sustainable, cost effective, and long lasting roofing material in empowering developing communities in Uganda.

1.1 Problem statement

Traditional bamboo roofing in developing regions in Uganda often use untreated bamboo and bamboo treated with traditional preservation methods such as smoking and water soaking in sea salt. These methods are low cost and accessible, but offer limited protection against biodegradation agents such as termites, borers, fungi, and moisture induced rot (Liese & Kohl, 2015; Obonyo et al., 2016). Research has shown that untreated and traditionally treated bamboo can start to degrade within 6 months to 3 years, particularly in humid and tropical climates like that of kabale, Busega (Liese and Tang, 2015). This has resulted in roofs with limited lifespans, leading to frequent replacements, increased costs, and reduced reliance in the durability of bamboo as a roofing material. Therefore this research aims to overcome these limitations by using modern chemical treatment which is the use of epoxy resin, a thermosetting polymer to improve bamboo's resistance to environmental and biological degradation hence improving its durability. When applied to bamboo, epoxy resin forms a protective layer, reducing moisture absorption, inhibiting fungal growth, and improving dimensional stability and mechanical performance.

Therefore, this study proposes to assess the use of epoxy resin as an advanced treatment method for bamboo used in roofing systems with an aim of developing optimized application techniques that enhance bamboo's resistance to pests, decay, fire, and moisture, thereby making it a durable, sustainable to last 15-20years, and reliable material for low cost roofing in informal and formal settlements in developing areas in Uganda.


Figure 1: Bamboo roof structure

1.2 Objectives of the study

1.2.1 Main objective

To assess the use of epoxy resin treated bamboo as a building material for roof covering in kabaale, Busega.

1.2.2 Specific objectives

1. To assess the properties of traditionally treated bamboo used in roofing in terms of resistance to termites, moisture, and decay resistance.
2. To determine the properties of bamboo that are improved by the epoxy resin treatment.

3. To compare the performance of epoxy resin treated bamboo with traditionally treated bamboo roofing and design a bamboo roof interlock style.

1.3 Research questions

1. What are the physical properties of the traditionally treated bamboo currently used for roofing in Kabaale, Busega particularly its resistance to termites, moisture, and long-term structural decay?
2. How does epoxy resin treatment change the mechanical strength, durability, and environmental resistance of bamboo compared to its untreated or traditionally treated form?
3. When applied in actual roofing conditions, how does the performance of epoxy resin treated bamboo compare with that of traditionally treated bamboo?
4. What bamboo roof interlocking design can best enhance stability, load distribution, and weather resistance when using epoxy resin treated bamboo?
5. What practical considerations influence whether epoxy resin treated bamboo can be adopted as a roofing material in local construction practices?

1.4 Justification

Bamboo's use in our day-to-day purposes is of a wide range for both woody materials and also as food. It has been the backbone of much of the world's rural life and will remain as the population increases. Bamboo plays an important part in the development and the transformation of rural environments, in all regions of the developing world where it grows.

Documentation of the various traditional bamboo preservation methods will be a basis for training bamboo artisans on how to successfully execute the preservation methods to ensure durability of bamboo products. (Mwanja et al., 2023)

Bamboo is a renewable, low cost, and locally available material for roofing in Uganda, where it's increasingly promoted due to its versatility, ability to regrow year round, and use in products such as roofing shingles and engineered roofing sheets (NFA, 2021). However, without adequate treatment, its performance remains inconsistent and unreliable. Epoxy resin treated bamboo has demonstrated enhanced resistance to moisture, pests, and decay, leading to improved structural integrity and extended service life (Sukumar et al., 2022). Using epoxy resin treatment can create a protective barrier that seals the bamboo surface by blocking water uptake, fills pores and micro cracks reducing sites for fungal growth, forms a tough and smooth surface discouraging termite penetration, maintains and improves mechanical strength over time and acts as a glue for the bamboo to stick together.

This study therefore aims to improve the durability and performance of bamboo roofs through using epoxy resin to treat it.

1.4.1 Scope of study

This study focuses on evaluating whether epoxy resin treated bamboo can work as a durable roofing material in Kabaale, Busega. It examines the performance of traditionally treated bamboo, the changes introduced by epoxy resin treatment, and how both materials compare when used specifically for roofing. The study is limited to selected bamboo samples and does not cover long term field performance or all possible treatment methods.

The study will be conducted in Busega, kabaale, with the coordinates "N 0°18'40.12344"E".

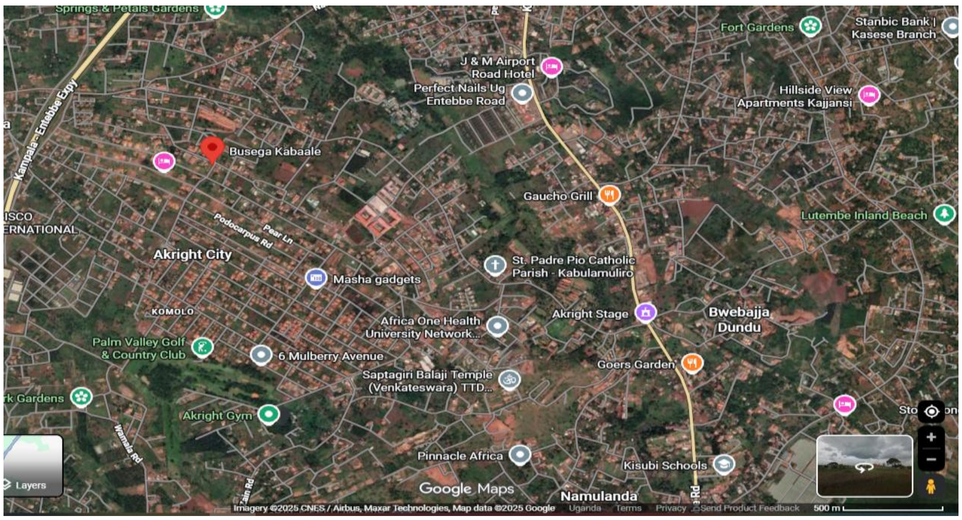


Figure 2: Location of the scope

CHAPTER 2: LITERATURE REVIEW

2.1 Roofing in construction

Roofing is a critical component of housing, shielding structures and their occupants from environmental elements like rain, heat, and wind. In Uganda and many other developing countries, roofing costs account for a significant portion of a building's total cost, limiting housing affordability for low income populations. Conventional materials such as galvanized iron sheets, clay tiles and concrete roofs are widely used, but they are becoming increasingly expensive due to inflation, transportation costs and import dependence and as a result, there is a growing interest in alternative roofing materials that are readily available, reasonably priced, and environmentally friendly.

2.2 Bamboo use as a construction material

Bamboo, in particular, has resurged in popularity due to its abundance, renewable nature, and favorable mechanical properties of tensile and flexural strengths. Bamboo is an eco-friendly roof material which has long, tubular culms divided by nodes, is a member of the grass family but behaves like wood. Recent studies have shown that there are 13 available bamboo species in Uganda with locals and artisans exploiting mainly three species. These include Oxytenanthera abyssinica, Oldenia alpine commonly known as highland bamboo and Bambusa vulgaris. Two species, O. abyssinica and O.alpina, are indigenous bamboo species, while B. vulgaris is exotic (Mwanja et al., 2023), NFA 2017.

Most of the bamboo resource in Uganda is located in the protected areas mainly forest reserves and national parks that are managed by the government on behalf of the people of Uganda. (Bamboo &., n.d.). Bamboo grows in an area of approximately

54,533ha in the protected areas of Uganda (inbar 2018). It is mainly found in Northern Uganda a (Otzi Mountain, Agoro-Agu Central Forest Reserve [CFR] and private/communal lands) for lowland bamboo (Oxytenanthera abyssinica) and Mt. Elgon, the Rwenzori Mountains, Mgahinga Gorilla National Park (NP), Bwindi NP and Echuya CFR highland bamboo (Oldeania alpina, synonym Yushania alpina) (Bamboo & Organisation, n.d.).

Certain species, such as giant bamboo (Dendrocalamus asper), Arundinaria alpina (native to Uganda), and Bambusa vulgaris (common bamboo) have qualities that make them suitable for construction, lightweight for effortless handling, rapid growth rate, yearly regeneration without replanting and capacity to sequester carbon, comparable to rapidly expanding forests (Liese & Kohl, 2015) which make it useful for roof covering.

Ugandan traditional use of bamboo as a potential material in construction is underutilized, where it is typically used for nonstructural uses like fencing, mats, and baskets. Bamboo is a naturally occurring material in places like Mount Elgon and Rwenzori, but it is rarely used for structural purposes because of durability issues, particularly when it comes to roofing such as borers and termites, attack by fungi, rot and moisture absorption, especially in humid regions like Busega.

Bambusa vulgaris is selected in this study due to its widespread availability, fast growth rate, and mechanical properties suitable for roofing applications. This species exhibits high tensile strength up to 200 MPa, moderate density of 0.6-0.8 g/cm^3, and a favorable diameter to thickness ratio, making it ideal for interlocking panels (Amada et al., 1997). Moreover, its culms are relatively straight and uniform, which facilitates precise cutting and alignment in interlocking systems. Its natural silica content provides a degree of fungal resistance, and when combined with epoxy resin treatment, its durability increases substantially, meeting construction requirements in humid temperate climates such as Busega.

Conventional methods, such as smoking, soaking, and sun-drying, provide short term roofs (6 months to 3 years lifespan) protection but are ineffective for extended exposure hence epoxy resin treatment, a thermosetting polymer is used for treatment.

2.3 Traditional methods of bamboo preservation

Artisans and local bamboo growers preserve bamboo using traditional practices that have been passed down to them. (P. J. Kaur et al., 2016). Numerous previous researchers have reported that the service life of bamboo preserved using traditional methods was found to align with that of chemically preserved bamboo thereby effective. (P. J. Kaur et al., 2016), (Harivi Putri & Candra Dewi, 2020).

2.4 Properties of untreated bamboo

Studies that have been published indicate that untreated Bambusa vulgaris shows the least natural resistance to termite infestation and consequently, their exposure (both in the lab and in the field) results in shrinkage by a large degree. Sadiku et al. recorded mass loss ranging from 17.81% to 48.31% in untreated culms that were subjected to the attack of subterranean termites and powder-post beetles, and they pointed out that the degree of the decay was affected by the portion of the culm and the age (Sadiku et al. 398). Furthermore, the results of recent field trials are quite alarming: in a Ugandan research where the culms were unprotected and termite pressure was high, Mwanja et al. reported that B. vulgaris has such a high loss of weight (up to 83.4%) that it can be easily categorized among the least resistant bamboos to termites if the wood is not preserved (Mwanja et al. 293). Additionally, the comparative studies on the feeding of termites across different bamboo species have also shown that the untreated bamboo gets a 13–29% mass loss within four weeks of being exposed to Coptotermes species, and B. vulgaris is placed in the highly vulnerable class due to its high starch content (Hapukotuwa and Grace 479). In conclusion, all these pieces of evidence lead to the conclusion that untreated B. vulgaris is a material that is highly susceptible to the attack of termites, and hence it should be treated either chemically or naturally before being used in structural applications in regions prone to termites.

Moisture content (MC) is the decisive factor in determining the physical and mechanical performance of bamboo and the generally accepted MC values for untreated B. vulgaris range from 11% to 19% depending on the drying method and specimen preparation. The average working MC values during mechanical testing in PROTA, a source for species accounts, are documented to be 16–17%. In contrast, lab studies on measuring of freshly harvested or air-dried culms report MC values of 14–19% (Hartono et al.; Wakchaure and Kute). The different MCs can be attributed to the environmental conditions, age of the culm, and the drying before testing. The higher MC is related to the lower stiffness and strength which emphasizes the need for standardized conditioning prior to structural evaluation.

Untreated B. vulgaris flexural performance has been thoroughly shown, with the report of modulus of rupture (MOR) values ranging from 84 to 86 N/mm^2 at a typical laboratory moisture content of about 16-17%. PROTA species data recognize the same MOR values for both green-stem and yellow-stem cultivars, thus suggesting that the bending strength of the most common varieties is relative and consistent. The experimental works also have it that untreated culms are somewhat high in their flexural capacity when compared to many softwoods, however, the mechanical performance drops alongside the moisture content, plus the presence of nodes (Daud et al.). All these factors together made it possible to use B. vulgaris in bending as a mechanically workable material if it is well dried and protected from biological agents.

Compressive strength values for untreated B. vulgaris, which are reported in the literature, are generally within the range of 25–32 N/mm^2, when tested parallel to the grain and at moisture contents of 16–17% approx. PROTA data give these numbers as a starting point for the most common cultivars, while more extensive reviews on the bamboo mechanics not only confirm the magnitude of the results but also highlight the fact that internode position, wall thickness, and age are crucial factors influencing compressive behaviour (Sadiku). Bamboo can obtain far higher compressive strength values under special testing conditions, but these genus-level laboratory benchmarks are still suitable for structural design in the case of untreated bamboo.

The untreated Bambusa vulgaris is known for its very poor decay resistance like that of other untreated wood, and there are numerous researches confirming it through mass loss of the culm when exposed to wood-rotting fungi. In an extensive survey of the bamboo species in Indonesia, B. vulgaris lost only 2.3% of its mass when attacked by Lentinus lepideus, which was one of the mildest fungal responses but still showed some degradation (Hartono et al. 4868). Under very aggressive fungal conditions, especially Trametes versicolor (white rot), the percentage of weight loss went up significantly to

10.3%-15.4%, while Gloeophyllum trabeum (brown rot) cut 6%-7.5% of the mass of the bamboo, thus indicating that the group has no inherent biochemical defenses against lignocellulosic decay (Liu 100-101). A wider durability survey concentrating on the East African bamboo sector not only confirmed but more accurately placed B. vulgaris as the most decay-prone species when subjected to high moisture content and no preservation treatment (Mwanja et al. 289). The consensus in the literature is that untreated B. vulgaris has low natural decay resistance and thus requires preservation, seasoning, or resin-based treatments for long-term use in humid environments.

2.5 Soaking in water and water leaching

Soaking involves submerging the bamboo in the solution of the preservative for a certain period of time allowing it to pass through the bamboo's cell walls thereby protecting it from insect bio degraders (Mwanja et al., 2024). Many artisans and local people rely on soaking bamboo in both still water and running water. A study conducted by Mwanja et al., (2023) indicated that 17% of the artisans in Uganda soaked bamboo in water to preserve it. Soaking aims to reduce starch in bamboo and hence it is less likely to be attacked by bio degraders (Harivi Putri & Candra Dewi, 2020), (Liese & Tang, 2015)

A study conducted by (Harivi Putri & Candra Dewi, 2020) revealed that the traditional soaking method as an optimal preservation method, much easier to carry out and does not require a lot of costs. However, the same study cited that the method requires a long period of time to complete ranging from 7-30 days.

2.6 Treatment methods of bamboo using epoxy resin and other alternatives.

Several treatments have been explored to improve the durability of bamboo in construction, particularly in roofing applications and one promising treatment method is the use of epoxy resin known for its resistance to water, strength of adhesion, resistance to termites and fungi and enhanced stability in dimensions. Bamboo culms are protected from moisture and microbes by being covered in epoxy resin, which slows down deterioration. According to research, epoxy and related polymers can extend the lifespan of bamboo by more than 15 to 20 years, depending on usage and climate (Valerio & Ongpeng, 2023). It is now feasible for permanent structures, such as roofing systems in developing and rural areas.

2.7 Chemical methods of preservation

Modern and chemical bamboo preservation methods are relatively expensive compared to the traditional preservation methods. However they result in better surface protection and better resistance to biodegrades, termites, bacteria and fungi. The chemicals commonly used include CCA, Creosote and borax solution most of which have been scientifically verified and recommended. These chemical preservation methods include as well formulations used in treatment.

The set-back to use of chemical methods is their harm to the health of people and the environment despite effectively increasing the durability of bamboo (Liese & Tang, 2015). Fattah et al (2014) stated that boron compounds including borax and boric acids have no adverse impacts on humans and environment as compared to other chemical preservatives. Kaur et al. (2016) concluded that boron is a less hazardous preservative and increasingly becoming critical to diminish environmental impact. This study was in line with that stated by (Kaminski et al., 2016a) that reported boron to be effective, low-cost, low mammalian toxicity and with ease of use. This makes boron and other boron based preservatives choice treatment chemicals.

With different levels of success, other treatment techniques like heat treatment, borate impregnation, and chemical preservatives have also been investigated. For instance, heat treatment increases the material's dimensional stability and resistance to decay, while borate treatment is known to improve bamboo's resistance to termites and fungi. These techniques might not, however, offer epoxy resin's degree of moisture resistance. Bamboo's feasibility as a roofing material could be greatly increased by epoxy resin's capacity to offer durable defense against environmental elements and pests, resolving many of the issues related to its use in Uganda.

2.8 Challenges of using bamboo for roofing in Uganda

While bamboo presents a promising solution for sustainable roofing in Uganda, several challenges need to be addressed. One of the major issues is the lack of awareness and technical expertise regarding bamboo treatment and construction techniques. Many local builders are unfamiliar with modern bamboo preservation methods, which limits the material's potential for widespread adoption.

Additionally, there are concerns about the long term performance of bamboo, particularly in areas with high humidity and rainfall. Despite its potential, untreated bamboo roofs require frequent maintenance and replacement, which could offset the cost benefits in the long run. Therefore, improving bamboo's durability through treatment methods such as epoxy resin is essential to making bamboo a more reliable and cost effective roofing material.

2.9 Bamboo biodegradation

Bamboo degradation is mainly due to its high nutrient content that makes it highly attractive to insect and fungal attack (Mathew & Nair, 1998). Liese & Kohl (1980) stated that bamboo has high amounts of starch and tress quantities of waxes, tannins and resins increasing its vulnerability to bio deterioration agents. Unlike the heartwood of many durable timbers, bamboo does not possess toxic extractives to impart natural durability making it more prone to bio-deterioration. The infestation makes the storage of bamboo and bamboo products very difficult decreasing their durability.

The main biological degraders of bamboo include termites, bettles (powder post), fungi mainly Schizophlyllum commune, Auricalria sp. Fungal attack on bamboo causes weathering and discolouration as well as impurities on the bamboo surface while the powder post beetles feed on the bamboo fiber (Harivi Putri & Candra Dewi, 2020).

The termites that degrade bamboo are classified as subterranean termites ; those that live in the ground and usually form mounds and dry wood termites ; that make nests in the bamboo itself (Kaminski et al., 2016b). These termites are attracted to the starch in the bamboo but also have enzymes that enable them to digest cellulose (Kaminski et al., 2016b).

Termite degradation usually occurs in the cut end portion and through the inner layer rather than in the exterior surface (Sadiku et al., 2021; Hapukotuwa & Kenneth Grace, 2011). The resistance of bamboo to multiple degradation agents has to be enhanced in order to increase its durability and for it to be considered a suitable alternative to wood (Hamid et al., 2012).

2.10 How the existing roofs are deteriorating in Uganda

Corrugated galvanized steel (CGI) are having red rust and pitting at cut edges and fasteners due to coating breakdown and chloride/sulphur pollutants, leading to perforation leaks, sheet thinning, and fastener pull through and also wind uplift damage where fixings are sparse in the long run.

Timber and bamboo roofs that are untreated and traditionally treated are exposed to termite galleries and boreholes, brown and soft rot from persistent humidity, checking and splitting from wet dry cycling, UV embrittlement on exposed fibres, and fastener decay causing sagging and leaks in a short period of time.

2.11 Treatment of Bamboo Compared to Timber

Bamboo, like timber, is susceptible to biological degradation such as fungal decay, termite attacks, and microbial activity due to its high cellulose and moisture content. However, unlike timber, bamboo has a hollow, segmented structure that makes it more prone to water absorption and cracking if untreated (Liese, 1998). Research shows that chemical treatments such as boron-based preservatives, epoxy resin impregnation, and heat treatment significantly improve bamboo durability and resistance to biological attack (Amada & Untao, 2001).

Timber treatment, on the other hand, typically involves processes such as pressure impregnation with chromated copper arsenate (CCA), creosote oil, or other fungicides. These treatments penetrate deeper into the solid wood structure due to timber's denser anatomy, whereas bamboo treatment often requires surface coating or impregnation under vacuum and pressure to reach the vascular bundles effectively. Studies comparing both materials indicate that while timber may achieve longer-term resistance due to its solid structure, treated bamboo exhibits comparable decay resistance when appropriately processed, especially with epoxy resin, which seals the fibers and reduces water uptake (Singha & Bhattacharya, 2010).

2.12 Types of Roofs Constructed Using Bamboo

Bamboo has been traditionally used in roofing across tropical and subtropical regions due to its lightweight, tensile strength, and flexibility. Common types of bamboo roofs include:

1. Thatch Bamboo Roofs which is comprising of bamboo slats with thatch or palm leaves layered above for waterproofing.
2. Bamboo Shingle Roofs which are Individual bamboo strips cut and interlocked like wooden shingles for improved durability.
3. Interlocking Bamboo Roofs which have Bamboo strips or panels that are precision-cut to fit tightly together, providing water resistance, structural stability, and ease of assembly.
4. Bamboo Panel Roofs which are prefabricated bamboo mats or panels laid over rafters.

However interlocking bamboo roofing was chosen for this study due to its superior structural performance and water-tightness compared to traditional thatch or simple bamboo slat roofs. Interlocking panels reduce gaps that can allow water ingress and enhance load distribution across the roof. Additionally, the system is modular, enabling faster construction and maintenance. Studies in Southeast Asia have demonstrated that interlocking bamboo roofs significantly reduce leakage and prolong roof lifespan when combined with protective treatments (Liang et al., 2018).

2.13 Methodological insights

For the methodology, the approach is based on international best practices for material testing and comparison and is guided by scientific standards like ASTM D3345 for termite resistance, JIS-K1571 durability tests, and ASTM D2017 for decay resistance.

These methods are widely used in testing chemically treated bamboo and other natural building materials. Studies in India, the Philippines, and China have successfully used these standards to develop practical treatment protocols for bamboo-based structures, including roof shingles, trusses, and wall panels (Valerio & Ongpeng, 2023; Minke, 2016).

By adapting these methods to the Ugandan context, especially in Kabaale, Busega, this study contributes a localized validation of epoxy resin treated bamboo in real life conditions, providing support for practice.

2.14 Bamboo's relevance globally.

This study advances a number of international goals like by encouraging long lasting, reasonably priced housing, SDG 11 which is sustainable cities and communities will be achieved, using renewable resources is one way to achieve SDG 12 which is responsible consumption and production and bamboo reduces the carbon footprint of construction and helps achieve SDG 13 which is climate action.

In Uganda's housing industry, bamboo offers an underutilized opportunity. It can be transformed into a long lasting, environmentally friendly, and reasonably priced roofing solution with the right chemical treatment, such as the application of epoxy resin. This study offers useful implications for housing interventions in low-income Ugandan communities in addition to expanding on existing global knowledge. In order to inform future adoption, policy, and design choices in green construction, it seeks to create evidence-based treatment protocols and performance comparisons.

CHAPTER 3: MATERIALS AND METHODOLOGY

3.0 Introduction.

This chapter explains the methods and procedures used to achieve the objectives of the study. It describes the research design, materials, sampling methods, experimental procedures, data collection methods, and data analysis.

3.1 Materials of study.

i. Bamboo

The material of study for this research is Bambusa vulgaris, a fast growing tropical bamboo species widely available in Uganda with a high strength to weight ratio and offers an abundant alternative to wood and metal. The study focuses on its suitability for roof covering and its durability after epoxy resin treatment. Samples were randomly selected from a 5 year plantation using Simple Random sampling method harvested locally to ensure optimum mechanical strength.

The selection techniques are straight, uniform culms without visible cracks or insect damage and wall thickness sufficient to allow interlocking cuts and epoxy penetration.

ii. Epoxy Resin

Epoxy resin which is of high strength, waterproof thermosetting resin like bisphenol-A epoxy. The treatment material used in this study was a two part epoxy resin consisting of resin and hardener mixed in a ratio of 2:1 by volume. This resin was applied to bamboo strips by coating with a brush. The epoxy resin was selected because of its low viscosity, strong adhesion to cellulose fibers, and high water resistance, which together improve the durability of bamboo in humid climates.

iii. Preservation and testing chemicals

Fungal culture media for ASTM D2017 fungal decay test, termite test colony for ASTM D3345 termite resistance test and Soil substrate for termite and fungal resistance testing (sterilized for control).

iv. Tools and equipment

Measuring and cutting tools like saws, knives, calipers, and rulers, weighing scale for measuring resin uptake and mass loss in tests, mixing containers and stirrers for epoxy and hardener blending, brushes for applying epoxy to bamboo surfaces, culms for making composite roofing sheets and ovens for controlled curing of treated bamboo.

v. Testing Apparatus (per ASTM standards)

Moisture content tester for ASTM D4442 and Universal Testing Machine (UTM) for bending and tensile strength tests.

vi. Safety and Handling Materials

Gloves which are chemical resistant to epoxy handling, safety goggles for protection from resin splashes and bamboo splinters, protective clothing like lab coat or coveralls.

3.2 Methods of study.

3.2.1 Assessing the properties of traditionally treated bamboo used in roofing in terms of resistance to termites, moisture, and structural decay.

Activities

Conducted site surveys in Busega (Kabaale area) to observe bamboo roofed structures for signs of pest damage, decay, and rot, prioritizing a range of ages of new, medium aged, and old roots in the area. Using visual inspection to check for visible signs of pest damage (termite trails, boreholes), fungal decay (discoloration), moisture-induced wear (splitting and swelling) and general roof integrity and lifespan.

3.2.1.1 Sample preparation

Fifteen samples were sized to 6m with outer diameters ranging from 28mm to 40mm and were stacked to dry for 30 days under shade to prevent splitting and dry before soaking in water.

Figure 3: Preparation of Bamboo through culm cutting

3.2.1.2 Soaking in water

Fifteen bamboo samples labelled S1 to S15 were soaked in water for thirty days in a large drum tank to remove leached sugars, prevent microbial growth, and prepare the bamboo for other treatments. Water was changed weekly to prevent bacteria and fungi attack on the bamboo.

After soaking the bamboo, assess treatment efficiency.

Figure 4: Bamboo soaking in water

3.2.1.3 Moisture content.

The test was carried out in reference to ASTM D4442. The purpose for this test was to evaluate the readiness of bamboo for construction, ensuring that the material is stable, and suitable for long term use in roofing applications.

Requirements

An analytical balance, drying oven, desiccator, cutting tools, and sample containers.

Procedure

Three bamboo samples (25 mm × 25 mm × 200 mm) from different culms from the top, middle and bottom were cut, initial mass (wet mass, M_1) was obtained using the analytical balance and recorded. Samples were placed in a preheated oven at 103 ± 2 °C for 24 hours, removed from the oven and immediately placed in a desiccator to cool for 30 minutes. The oven-dry mass (M_2) is recorded and moisture content (MC) was calculated using the formula below

$$\text{Moisture content, MC (\%)} = \frac{M_1}{M_2} - M_2\, X100$$

The process was repeated for all samples and ensure that moisture content was gotten.

3.2.1.4 Termite Resistance.

The test was carried out in reference to ASTM D3345-22. The purpose of this test was to evaluate the ability of bamboo to withstand termite attack, ensuring that bamboo used for roofing is fit for long term structural use.

Requirements. Subterranean termites (Reticulitermes species), soil and containers analytical balance and oven at 103 ± 2 °C

Procedure

Bamboo culms were cut to (25 mm × 25 mm × 50 mm) samples, weighed and using an analytical balance and initial mass of each piece (W_1) was recorded. Sample pieces were placed in containers with moist soil, introducing a standardized termite population like 200 termites per container. Environmental conditions which were temperature 25 ± 2 °C and soil moisture 15-20% were maintained. Termite were exposed for 12 weeks, and inspection was done periodically. After exposure, bamboo pieces were removed, cleaned off soil and termites, and oven-dry at 103 ± 2 °C for 24 hours. The final mass (W_2) was recorded and weight loss **(%)** due to termite attack calculated from

$$\text{Weight Loss (\%)} = \frac{W_1 - W_2}{W_1} X100$$

Table 1: The table depicts the visual and weight loss assessment rating that was used for rating termite attack on the bamboo samples.

rating	Sample description
10	Sound, surface nibbles permitted
9	Light attack
7	Moderate attack, penetration
4	Heavy
0	Failure

3.2.2.1 Decay resistance test

The test was carried out in reference to ASTM D2017. The purpose of the decay resistance test was to determine how well bamboo can withstand fungal attack when exposed to conditions that promote decay. The test provided a controlled way to measure how bamboo loses mass after being exposed to decay causing fungi over a set period.

Requirements. Uniform bamboo samples, an oven and desiccator, a digital balance, the fungal exposure setup which is a decay fungus culture, a nutrient agar medium, and sterile containers such as jars or petri dishes, an incubator.

Procedure

Bamboo culms were cut to pieces of dimensions 25 mm × 25 mm × 50 mm, samples were sterilized by autoclaving at 121 °C for 15 minutes removing pre-existing fungi. A known weight of fungal inoculum was placed in soil blocks within a container and bamboo pieces were inserted into the soil containing the fungal culture with moisture at 70-80% and temperature at 22-25 °C for 12 weeks was maintained. After the exposure period, samples were removed, soil cleaned off, and oven-dry at 103 ± 2 °C for 24 hours. Samples were weighed to determine final mass and weight loss (%) calculated as an indicator of decay resistance

$$\text{Weight Loss (\%)} = \frac{Initial\ mass - final\ mass}{Initial\ mass}\ x\ 100$$

Table 2: Rating of decay resistance on bamboo

Average weight loss, %	Average residual weight, %	Indicated class of Resistance to a specified test fungus
0 to 10	90 to 100	Highly resistant
11 to 24	76 to 89	Resistant
2 to 44	56 to 75	Moderately resistant

45 to above	55 or less	Slightly resistant or nonresistant

3.3 Determining the properties of bamboo that is improved by the epoxy resin treatment.

Activities

3.3.1 Epoxy Resin Treatment (sample preparation)

The purpose of this treatment is to produce consistently treated bamboo specimens with controlled resin uptake so it can quantify changes in physical, biological and mechanical properties.

Requirements. Bambusa vulgaris strips (200mm-250mm lengths depending on test), epoxy resin and hardener, mixing containers, brush, trays, gloves, ventilated curing area, oven, analytical balance.

Procedure

All samples were labelled using at least 5 replicates per group. Initial dimensions of length, width, diameter and initial masses before resin application for every sample were measured and recorded. Epoxy resin and hardener default mix was: 2:1 resin: hardener by volume. For concentration experiments mixes were prepared by coating in layers. Samples were prepared by lightly sanding and cleaning with water to remove wax and dust, epoxy resin was coated using a brush ensuring that the bamboo was fully covered. The coated samples were cured for 24 hours and curing conditions were recorded. After cure, final masses after resin application and dimensions were recorded and resin uptake calculated

$$\text{Resin uptake (\%)} = \frac{Mass\ after - Mass\ before}{Mass\ before}\ x100$$

Moisture content (ASTM D4442), Decay resistance (ASTM D2017) and Termite resistance (ASTM D3345) as explained in objective one after applying epoxy resin.

3.3.2 Water absorption by soaking. (ASTM D570)

The purpose for this test is to quantify how much water the treated bamboo absorbs which is indicator of dimensional stability and decay risk.

Procedure:

Samples were oven-dried to constant mass Md, cooled and measured. Samples were then immersed in distilled water at 20-25 °C for 2hours, 24 hours and 7 days. The samples were removed, surface blotted, wet mass Mw measured and water absorption calculated

$$\text{Water absorption (\%)} = \frac{Mw - Md}{Md} \text{ x } 100$$

The process is repeated for longer soak intervals if desired to observe kinetics.

3.3.3 Mechanical Tests (UTM bending and compressive strength)

The Purpose of this test is to quantify changes in mechanical properties for soaked treated bamboo and after epoxy resin treatment.

Materials and equipment: Universal Testing Machine (UTM), sample preparation tools, calipers.

Procedure

MOE, MOR and Compression were tested using the UTM at Getlab following the International Standards Organization, ASTM D198. This machine operates in such a way that it displays the values of the mechanical property being tested on the computer monitor to which it is connected. The procedure followed and the equations followed to obtain the values is described in below.

3.3.3.1 Flexural strength of bamboo (Modulus of Rupture and Modulus of Elasticity)

The mean value of the outer diameter D and the wall thickness *t* were determined. The second moment of area (used to predict behavior during the test) was calculated from the formula:

$$I_B = \pi/64 \times [D^4 - (D - 2t)^4]$$

The culm was put in its place in the bending machine, resting on two devices at the two supports, allowing the culm to find its own position. The two devices and the beam (which divides the load) were put on top of the culm, and the culm allowed to find its position.

The culm, the four devices, the load and the supports were visually aligned in one vertical plane. The loading of the culm was carried out uniformly at constant speed. The speed of testing was 0.5 mm/s. The maximum was determined accurately conforming to the standards while observing the cracks and mode of failure. After the test, the outer diameter *D* and the wall thickness *t* were measured again, as close to the points of load as possible. The average of the diameters and wall thicknesses was used to calculate the second moment of area I_B, with the formula in I above.

The Modulus of Rapture, MOR (ultimate strength) in MPa (or N/mm^2) is given by the formula:

$$MOR = F \times L \times \frac{D/2}{6} \times I_B$$

Where

F is the applied maximum load, in N (the total load applied at the two points of load)

L is the free span, in mm (or clear span);

D is the outer diameter, in mm,

*I*B is the second moment of area, in mm^4,

The modulus of elasticity, E is given by the slope of a linear part of the load-deformation diagram. The modulus of elasticity *E*, in MPa, is calculated using the formula:

$$E = 23 \times F \times L^3 \times \partial \times I_B$$

Where

F is the applied maximum load, in N (the total load applied at the two points of load);

L is the free span, in mm (or clear span);

*I*B is the second moment of area, in mm4 δ is the deflection mid-span, in mm.

Figure 5: Set up for testing flexural strength, MOE and MOR

3.3.3.2 Compressive strength

The test specimens for compression were prepared according to ISO 22157-1: 2004(E) (20200:2004, 2003). The tests parallel to the axis were made on specimens without any node and the length of the specimen were taken equal to the outer diameter.

The specimen was placed so that the centre of the movable head of the test machine is vertically above the centre of the cross-section of the specimen, and a small load of not more than 1 kN was initially applied to set the specimen. The load was applied continuously during the test to cause the movable head of the testing machine to travel at a constant rate of 0.01 mm/s. The final reading of the maximum load, at which the specimen fails, was recorded.

The maximum compressive stress, C is determined by the following formula:

$$C = \frac{FMAX}{A}$$

Where

C is the ultimate compressive stress, in MPa (or N/mm2), rounded off to the nearest 0.5 MPa,

*F*MAX is the maximum load at which the specimen fails, in N

A is the cross-sectional area in mm^2.

Figure 6: Set-up for testing compression parallel to the grain

Analyze and compare results using statistical tools such as T-tests, graphs, and percentage improvement calculations.

3.4 To compare the performance of epoxy resin treated bamboo with traditionally treated bamboo roofing and design a bamboo roof interlock style.

Activities

3.4.1 JIS Durability Test. (JIS-K 1571)

Perform durability testing under simulated real life conditions in a laboratory setting. Several bamboo preservation and treatment studies use an accelerated aging immersion cycle commonly referenced as the JIS-A accelerated aging (hot-water immersion) treatment. The literature characterizes this as immersion in hot water at 70 °C for 9 hours, then weigh and inspect this accelerated cycle has been used and cited as equivalent to roughly one year of outdoor exposure in some bamboo durability studies.

Procedure.

Bamboo pieces that were naturally soaked in water and once treated with epoxy resin were picked and uptake recorded in % mass gain and % mass loss. JIS-A hot-water cycle (70 °C, 9 h), was applied which was an equivalent of one year. The assessment of mass gain, mass loss, and visual degradation to quantify durability effect in relation to the initial value was then done. Soaked bamboo was then compared to epoxy resin treated bamboo under mechanical strength tests, termite resistance, decay resistance, moisture content and JIS A aging test. The results were used to prove if epoxy resin treatment on bamboo can be adapted for wide scale adoption in Uganda.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.0 Introduction

This chapter explains the findings from all the tests in the laboratory carried out on both traditionally treated and epoxy resin treated bamboo. The results are organized around the study objectives, and each shows what was observed there meanings for real roofing situations. The chapter also interprets the results, compares them with existing research, and discusses their practical implications for durability.

4.1 Table 3: Summary of laboratory test results for objective 1.

Material	Parameters tested	Value obtained	Average value	Standards required
Bamboo soaked in water	Moisture content(ASTM D4442)	12.69%	12.78%	12%-15%
		12.77%		
		12.87%		
	Termite resistance(ASTM D3345)	6.60%	6.53%	Rate damage as per ASTM D3345
		5.62%		
		7.38%		
	Decay resistance(ASTM D2017)	13.40%	12.86%	Indicated class of resistance to a specified test fungus
		13.29%		
		11.86%		
		68.9 MPa		

	Compressive strength(ISO 22157-1:2004)	71.1 MPa	57.9 MPa	40MPa-60MPa
		46.8 MPa		
		45.0 MPa		
	Flexural strength(ASTM D198)	92.1 MPa	103.1 MPa	70MPa-120MPa
		110.1 MPa		
		107.2 MPa		

4.2 Table 4: Summary of laboratory test results for objective 2.

Material	Parameter tested	Value Obtained	Average values	Standards required
Bamboo treated with epoxy resin.	Moisture content(ASTM D4442)	10.91%	10.91%	12%-15%
		10.90%		
		10.92%		
	Termite resistance(ASTM D3345)	0.95%	1.0%	Rate damage as per ASTM D3345
		0.98%		
		1.14%		
	Decay resistance(ASTM D2017)	2.56%	2.30%	Indicated class of resistance to a specified test fungus
		1.84%		
		2.45%		
	Compressive strength(ISO 22157-1:2004)	87.8 MPa	88.1 MPa	60MPa- 90MPa
		88.4 MPa		
	Flexural strength(ASTM D198)	136.4 MPa	138.0 MPa	110MPa-160MPa
		132.9 MPa		
		144.6 MPa		

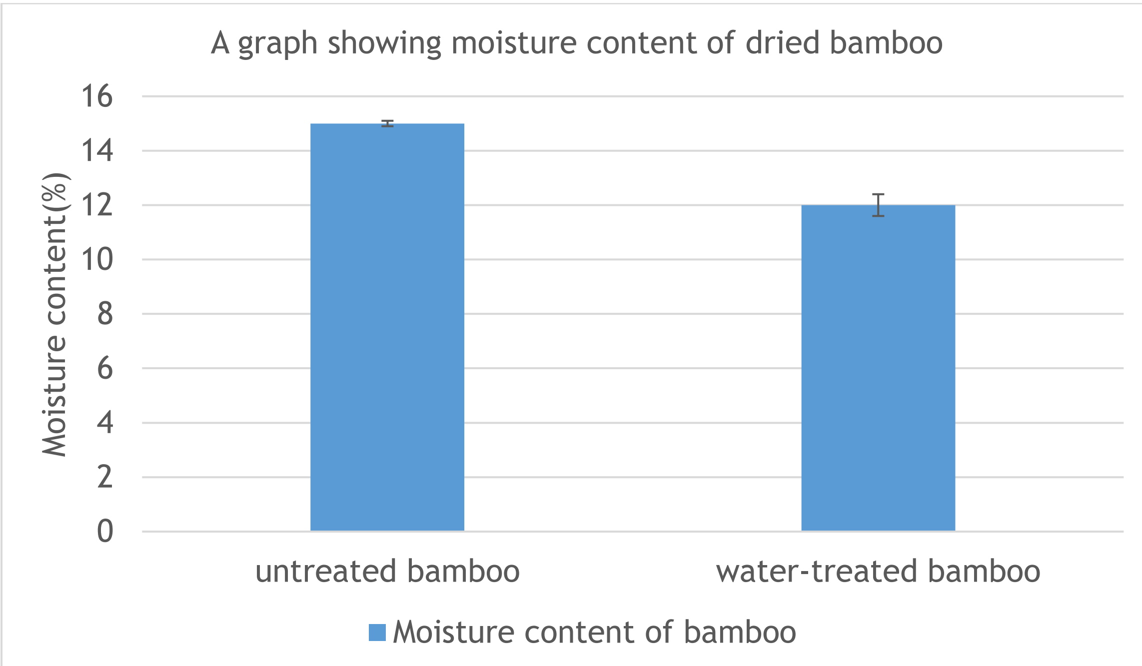
4.3 Table 5Summary of laboratory test results for objective 3

Material : Bamboo soaked in water							
Parameter tested : JIS-K 1571							
Year equivalent	Y1	Y2	Y3	Y4	Y5	Y6	Y7
Average mass difference(g)	6.5	15.4	11.3	5.7	3.3	1.1	0.20

Material : Bamboo treated with epoxy resin															
Parameter tested : JIS-K 1571															
Year equivalent	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10	Y11	Y12	Y13	Y14	Y15
Average mass difference(g)	0.7	1.2	3.8	4.3	5.7	6.5	6.1	5.4	4.9	4.3	3.5	3.1	2.7	2.2	1.6

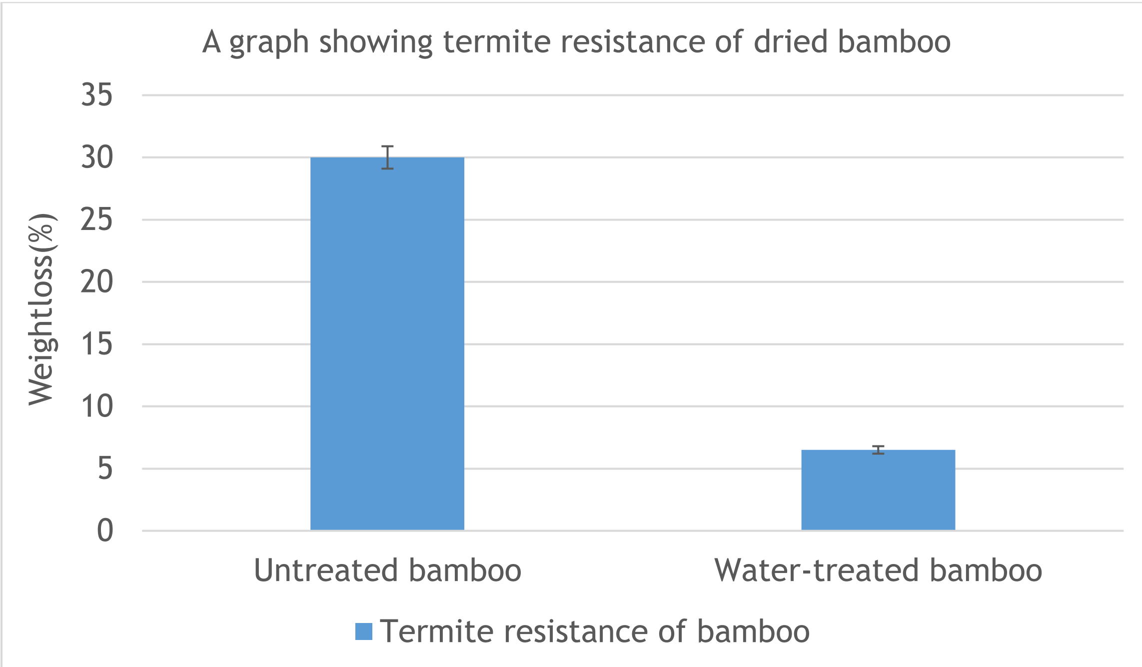
4.4 Results for the first objective

4.4.1 Moisture content



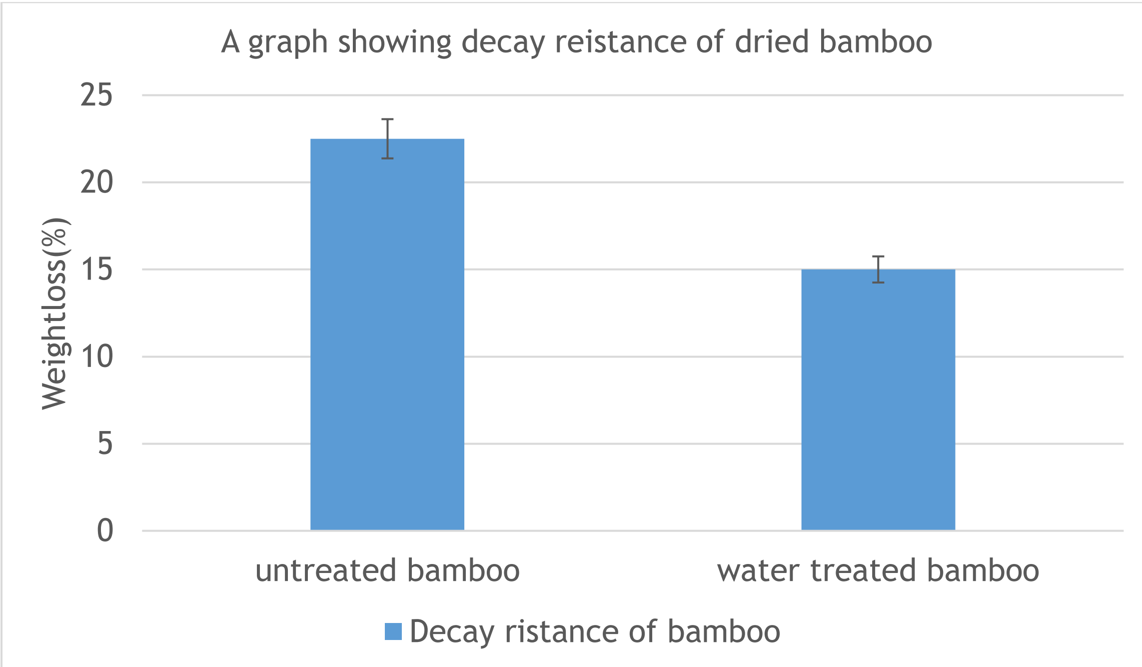
The change in moisture content, which was about 15% for untreated bamboo and reduced to 12% for water-treated specimens, was mainly due to the treatment changing the bamboo material's composition and microstructure. The water treatment is responsible for the elimination of water-soluble and hydrophilic compounds, such as amorphous polysaccharides and simple sugars. When these compounds are extracted, the number of hydroxyl groups trapped in the material's polymer matrix that are responsible for the water molecules' adsorption through hydrogen bonding, are reduced, and thus it directly contributes to the reduced hygroscopicity of the material. In addition, the water treatment causes very changes to the structure of the cell wall polymers where water is absorbed.

4.4.2 Termite resistance



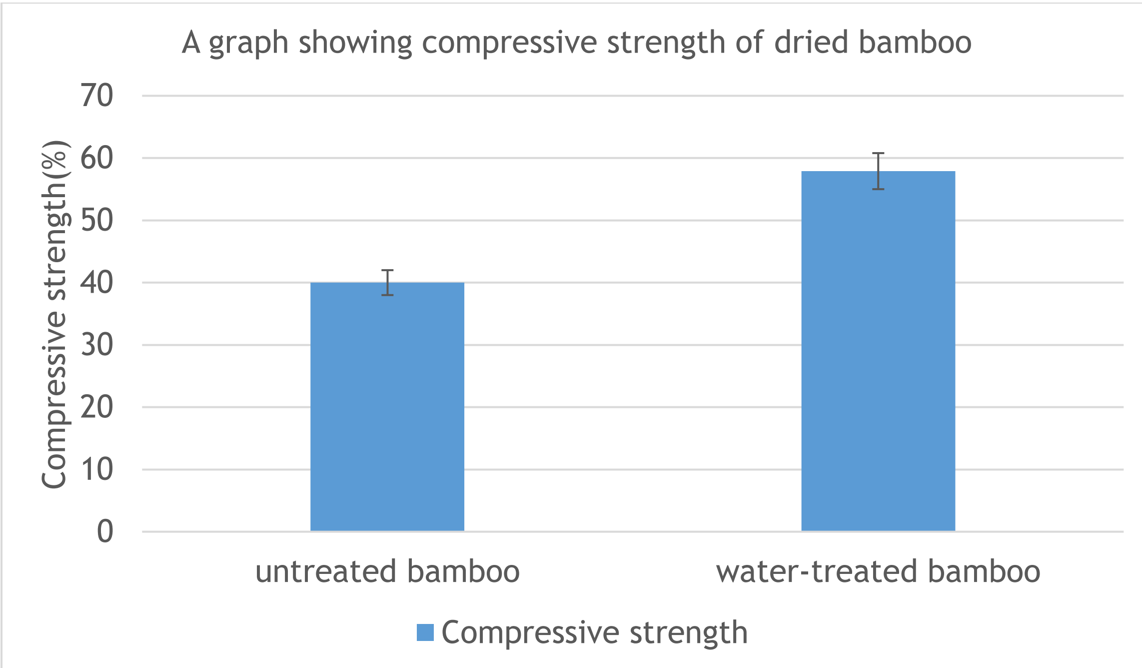
Water-treated bamboo presented a massive decline in mass loss from termite degradation with roughly 30% to only 6.5% and the main factor of this was due to the hydro treatment which leached away the hydrophilic and nutrient-rich constituents. By this process, the material's palatability and nutritive value to termites was reduced as the sugar sources are made unavailable. At the same time, the treatment caused physical and chemical changes in the lignocellulosic matrix that affects the surface and cell wall in terms of the trait and access, which altogether support the alteration in biological resistance and the sustaining of structural integrity under the termite invasion.

4.4.3 Decay resistance



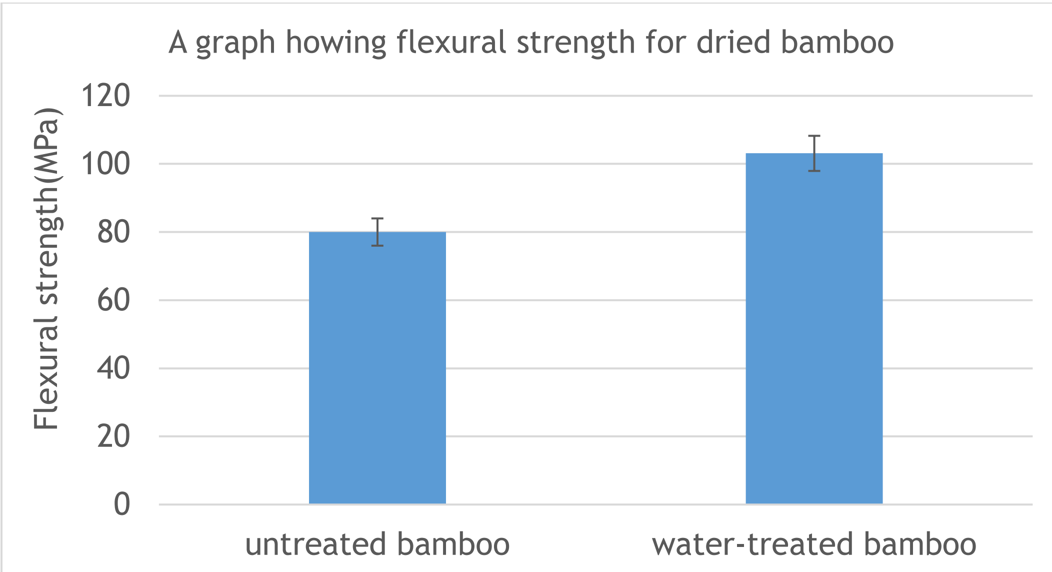
The reduction in mass loss that was observed, from about 22.5% in untreated bamboo to less than 15% in water-treated bamboo, can be directly attributed to the hydrothermal maceration of the easily degradable carbohydrates, which are mainly starch and simple sugars that are the main nutrient sources for decay fungi. The water-treatment process removes the carbon content of the material that is available for fungi, thus preventing the growth of fungi and the enzymatic breakdown of the cellulose and hemicellulose structural components.

4.4.4 Compressive strength



The compressive strength observed after treatment went up from about 40 MPa for untreated bamboo to 57.9 MPa for water-treated bamboo, which is due to the hydrothermal alteration of the lignocellulosic microstructure. The process allows the partial removal of hemicelluloses and the plasticizing moisture in the cell wall, which in turn, reduces intermolecular spacing, and promotes closer cellulose microfibrils' packing and stronger bonding by hydrogen. The cell wall structure becomes denser, more consolidated, and less compliant leading to higher stiffness and axial compression load-bearing capacity, as well as better stress transfer efficiency through the fiber matrix.

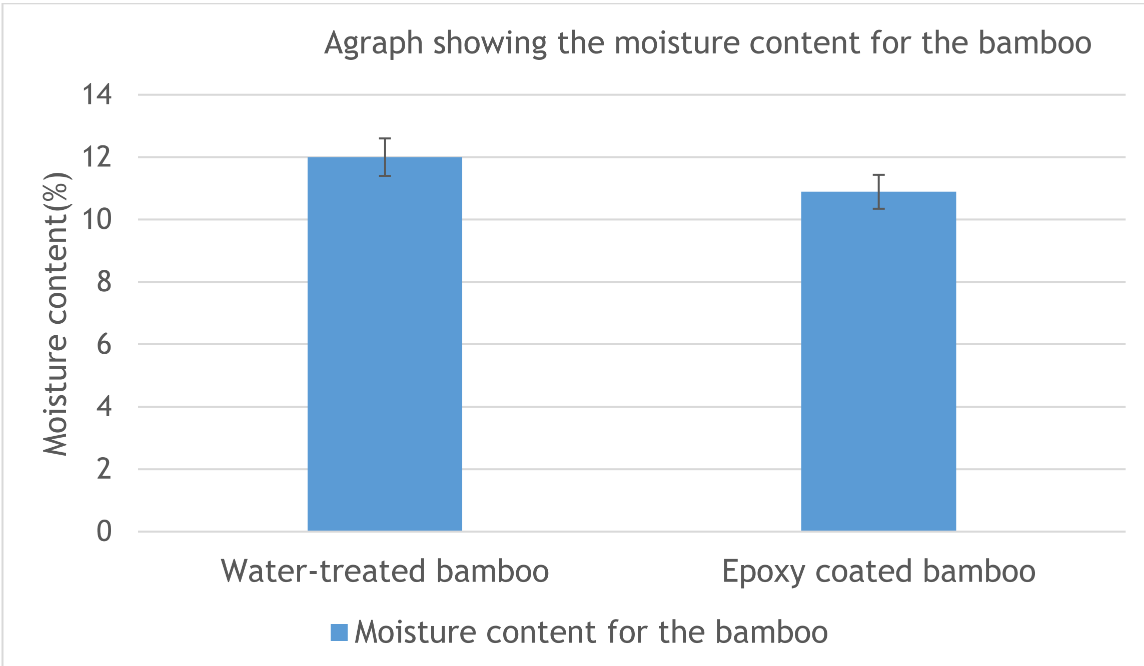
4.4.5 Flexural strength



The boost in flexural strength from untreated bamboo's slight being 80 MPa to water-treated bamboo's considerable being 103.1 MPa is due to microstructural consolidation and thermal treatment. The treatment lowers the moisture level of the material and at the same time, removes the non-crystalline hemicellulose which improves the bonding between the fibrils and thus the stress transfer between the microfibrils during bending is more efficient. The treatment therefore culminates in the outer fibers being more stiff and stronger in tension thus, the material's ability to resist flexural deformation and failure increases significantly.

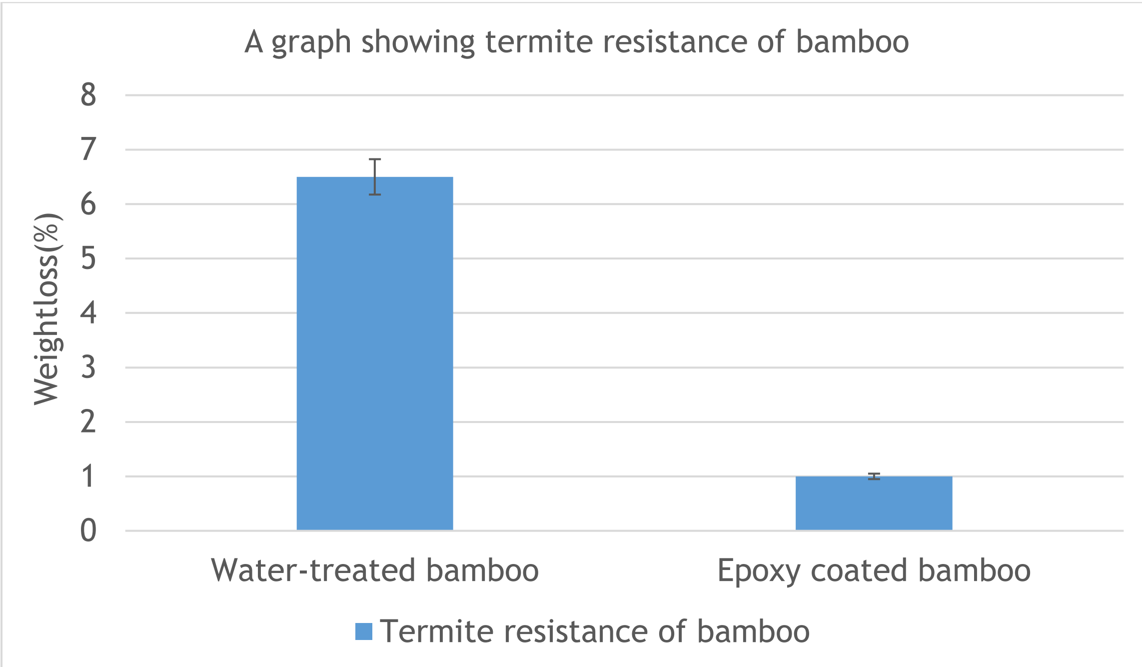
4.5 Results for the last objectives

4.5.1 Moisture Content



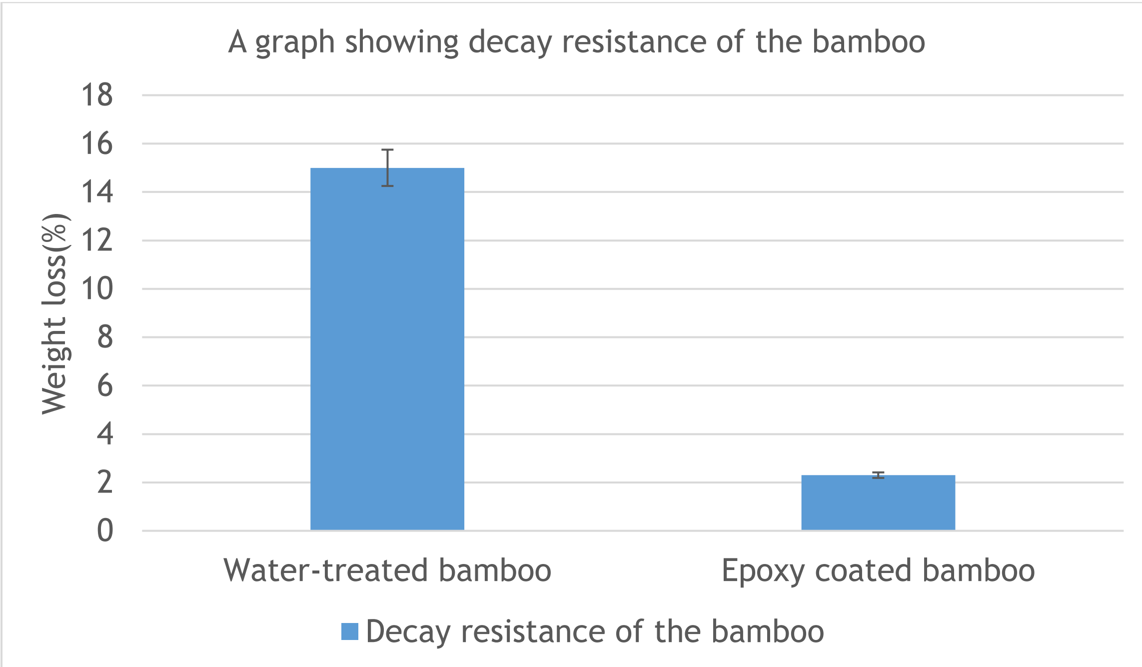
The dual-stage barrier mechanism created is responsible for the observed decrease in equilibrium moisture content of about 1% from water-treated bamboo to epoxy-coated bamboo. The first stage of hydrothermal treatment removes hygroscopic hemicelluloses and decreases hydroxyl group availability, while the second stage of epoxy coating forms a continuous, hydrophobic polymer film on the surface of the material. The epoxy film created acts like a physical barrier that strongly prevents the diffusion and adsorption of water into the lignocellulosic cell wall, thus lowering the material's hygroscopicity even further and making it more stable dimensionally in humid conditions.

4.5.2 Termite resistance



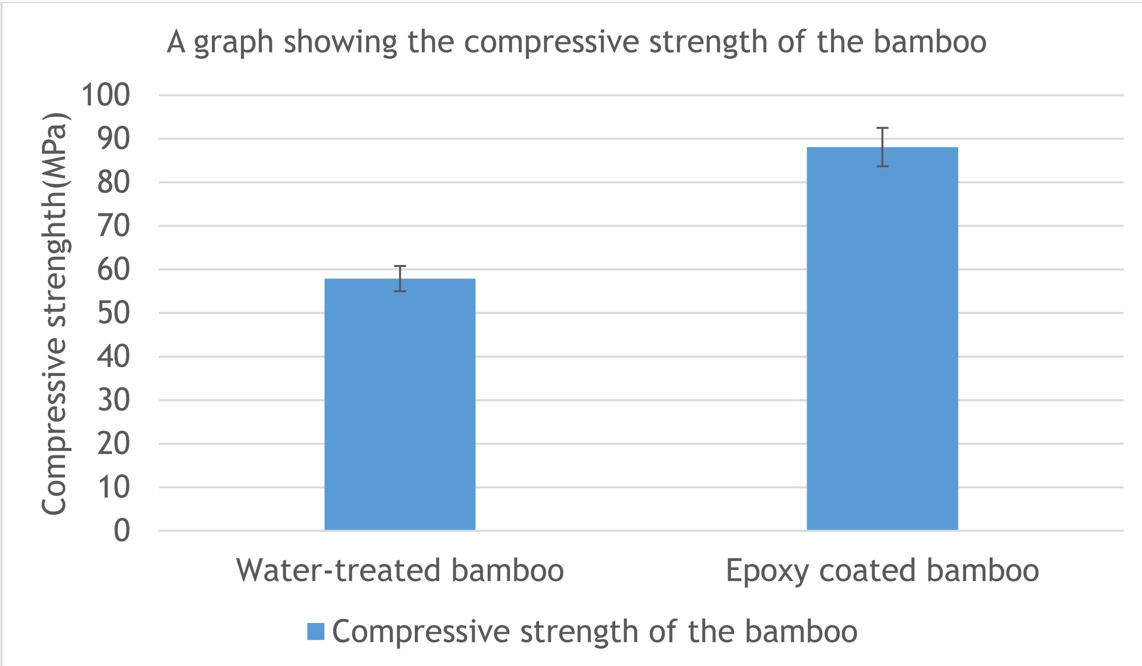
The results show that the bamboo coated with epoxy is much more resistant to termites than the bamboo treated with water, which is due to the creation of a continuous, impermeable barrier of polymer that physically stops the insect's mandibles from getting to the lignocellulosic material. At the same time, the water treatment reduces the availability of the food sources but the epoxy coating gives the total defense by not only sealing the surface irregularities but also blocking the mechanical penetration and olfactory detection cues, thus, providing the protection through surface encapsulation.

4.5.3 Decay resistance



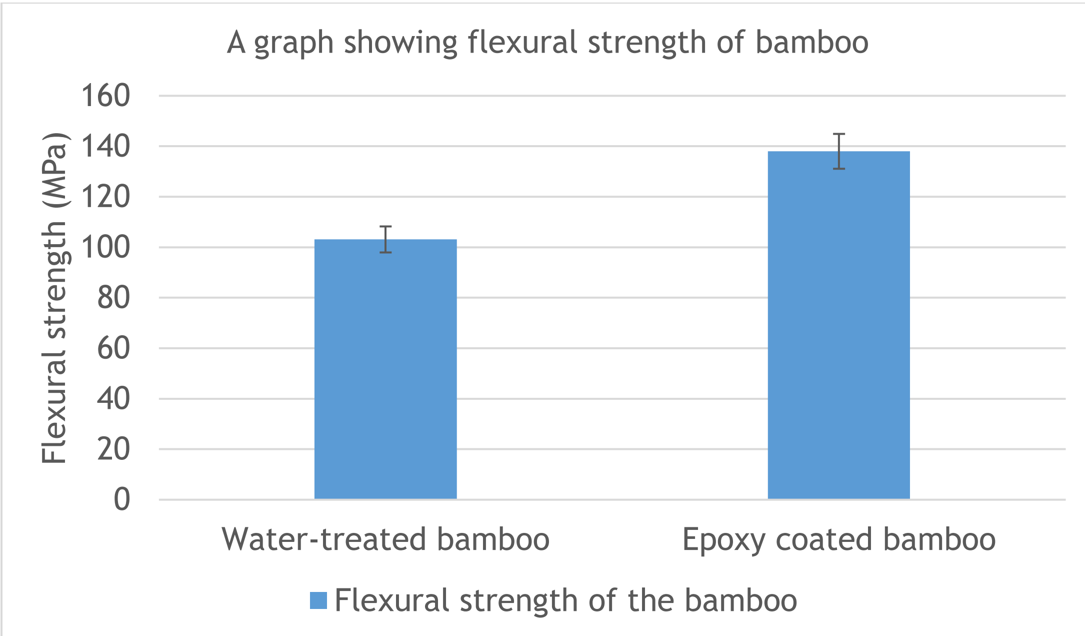
The observed decay resistance of epoxy-coated bamboo is much better than that of water-treated bamboo due to the formation of an impermeable polymeric barrier which not only prevents the entry of moisture during the process but also protects the substrate physically from fungal hyphae. The water treatment however reduces nutrient availability by the leaching of soluble carbohydrates whereas the epoxy coating provides a much more thorough protection by making the conditions necessary for fungal enzymatic activity and spore germination to be totally excluded, thus offering superior protection through environmental exclusion.

4.5.4 Compressive strength



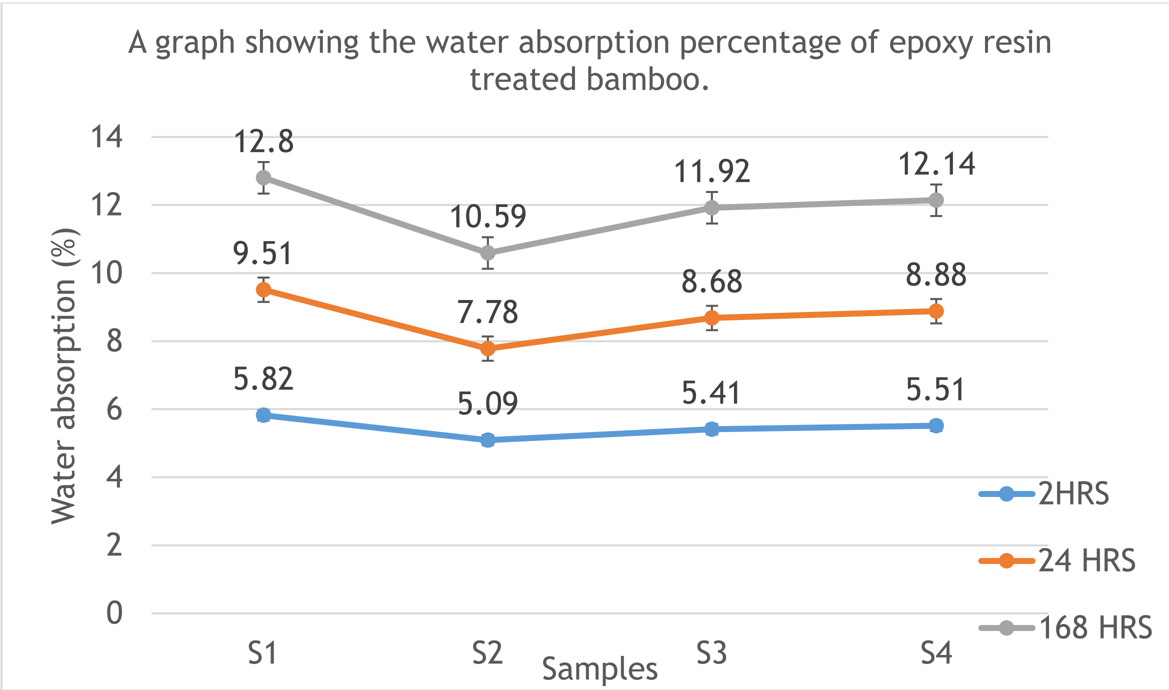
The epoxy layer does not enhance the bamboo's natural compressive strength of the cellular structure but instead, it superimposes a layer of strength outside the specimen that restrains it sideways, thus inhibiting the occurrence of buckling and allowing the load to be distributed more evenly. In contrast, the water treatment alters the cell wall matrix which in turn increases the value of the stiffness of the cell walls, while the epoxy coating also serves as a mechanical barrier, leading to a higher total measured compressive load capacity under axial load at the same time.

4.5.5 Flexural strength



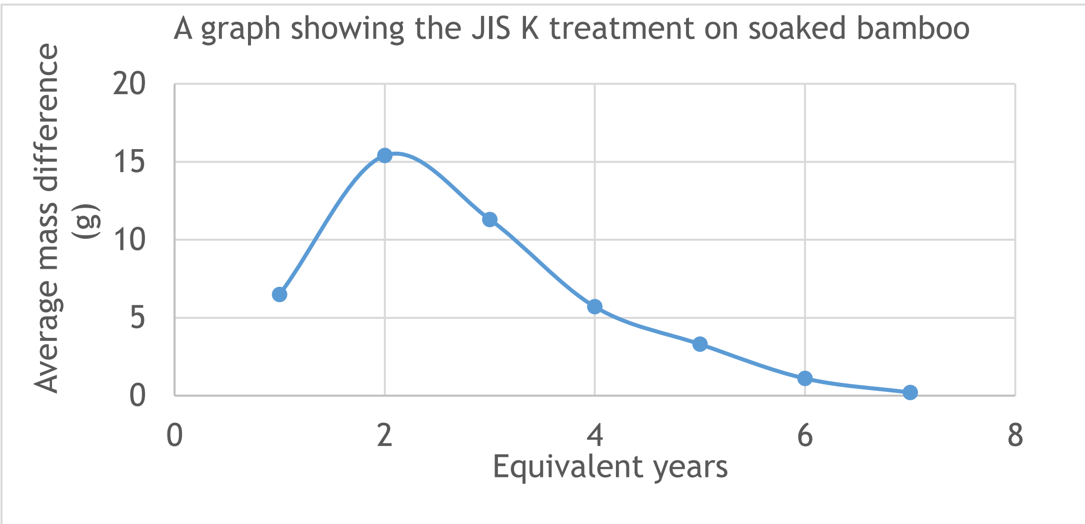
The considerable rise in the flexural strength of epoxy-coated bamboo in comparison with water-treated bamboo is attributed to the composite beam behavior. The epoxy coating that is applied to the tension side of the bamboo during bending works as a strong skin that carries a large part of the tensile load, so the neutral axis is shifted and the stress on the outermost bamboo fibers is reduced. Water treatment, on the other hand, increases the inherent stiffness of the lignocellulosic matrix, while the epoxy coating gives additional tensile reinforcement and crack-bridging, thus, the section modulus and overall bending moment capacity become effective being increased.

4.5.6 **Water absorption**

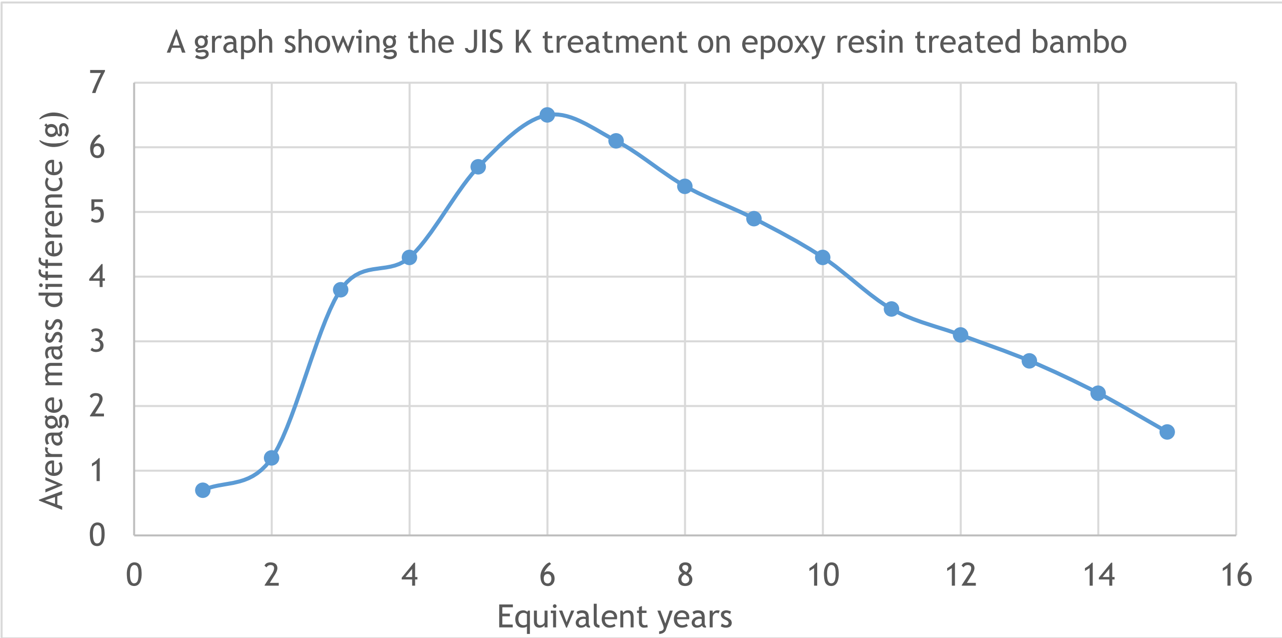


The findings suggest that the treatment with epoxy resin has an impact on the water absorption of bamboo, which varies by the method of treatment. For all soaking periods (2, 24, and 168 hours), it is the impregnation method that determines to a large extent the reduction of absorption which was produced by the treatment. The two S3 and S4 samples showed the lowest total absorption, thus, the more intensive epoxy penetration and curing process is able to build up a stiff and lasting obstructor in the bamboo's porous structure. This barrier works by sealing off cell lumens and filling capillaries, hence, being a limit to both the initial capillary uptake and the long-term diffusion of water molecules into the hygroscopic cell walls. On the other hand, the uplifted absorption in S1 and S2 indicates poor resin loading as a cause, thereby inferring that the extent of the composite formation between the epoxy matrix and the bamboo fibers is of utmost importance for the application of the material's dimensional stability and moisture resistance.

4.6 JIS-K Aging treatment



JIS K treatment is a standardized preservative treatment and the results reveal there is a significant trend in average mass change of soaked bamboo during simulated aging of up to eight years of equivalent time. First, there is a low degree of mass difference in treated bamboo meaning that the JIS K treatment is an efficient measure to curb the absorption and subsequent deterioration of bamboo due to moisture uptake at an early stage. The progressive increase in mass, as equivalent years are accumulated indicating some long term damage to the protective barrier of the treatment, probably by cyclic wetting drying stresses, micro-cracking and loss of treatment preservative elements.



JIS K preservative treatment impregnated with epoxy resin leads to a considerably stabilized mass profile over extended aging as indicated by the fact that the average difference in mass across the corresponding 16 year range is minimal. This synergy implies that preliminary sealing of the porous microstructure of the bamboo by the epoxy resin defines the initial reduction of water intake, and formation of a stable substrate, and the second JIS K treatment offers the long-lasting biocidal and environmental protection against decay organisms. The mass change trend is flat, with good long term dimensional and hygroscopic stability being achieved which is important because of the extensively used composite treatment approaches, in which a polymer matrix is coupled with a chemical preservative. The results support the significance of the depth of treatment, retention and exposure to the environment in the control of engineered bamboo materials service life and implies that mass change can serve as an efficient method of effectively extending the service life of bamboo in the wet and exterior environment, as both physical water and biological degradation pathways are inhibited simultaneously.

4.7 Design.

Material: Bambusa vulgaris culms

4.7.1 Roof assembly based on section A in 4.7.1 drawing

The design takes advantage of a stratified drainage, ventilation and structural support with timber roof wall plates and frame of 100x75 mm. The treated timber profiles (100x75mm) installed in form of battens (purlins) to form a ventilated box on top of the clay layer. It is required to have a layer of 200mm depth of clay, which is to be graded and compacted with a slope on which water can drain, and maintained to dry through the ventilated cavity beneath the bamboo. Culms of bamboo treated, and laid across the battens in the form of a roof cover.

4.7.2 Culm Layout and Specification of Bamboo Culm.

The pattern layout used to lay the culms consists of the tightly spaced pattern on the 100x75 mm timber battens with a spacing that is of high density cover to give maximum coverage and water proofing. The recommended culm diameter is 50-90 mm according to common structures. Culms should be attached straps or bolts to the battens, so that they can move slightly.

4.7.3 Basic Calculations of Roof Loads.

4.7.3.1 Specifications

1. Roof Slope 30°-45°.

2. Density of Treated Bamboo is 800-1200 kg/m3
3. Safety Factor of 1.5 is to be used in case of variation in material.

4.7.3.2 Load Estimates; Dead load

1. Bamboo Culms of 80mm in diameter = 0.9 kN/m^2
2. Clay Layer of 200mm, moist = 3.6 kN/m^2
3. Timber Battens and structure= 0.3 kN/m^2.
4. Total Dead Load (DL) = 4.8 kN/m^2

4.7.3.3 Live Load

Maintenance Load (ASCE 7) = 0.6 kN/m^2

Wind Load in a moderate wind area could give a net uplift or suction pressure of 0.5-0.8 kN/m2 (can only be calculated in site specific detail) and take the more critical case.

4.7.3.4 Structural Sizing to Support batten (100x75 mm Timber)

The Span of Battens is assumed to bridge bigger rafters or trusses approximately 1.2 m span.

The Load on Batten supports a width of tributary of approximately 0.6m (between tributaries).

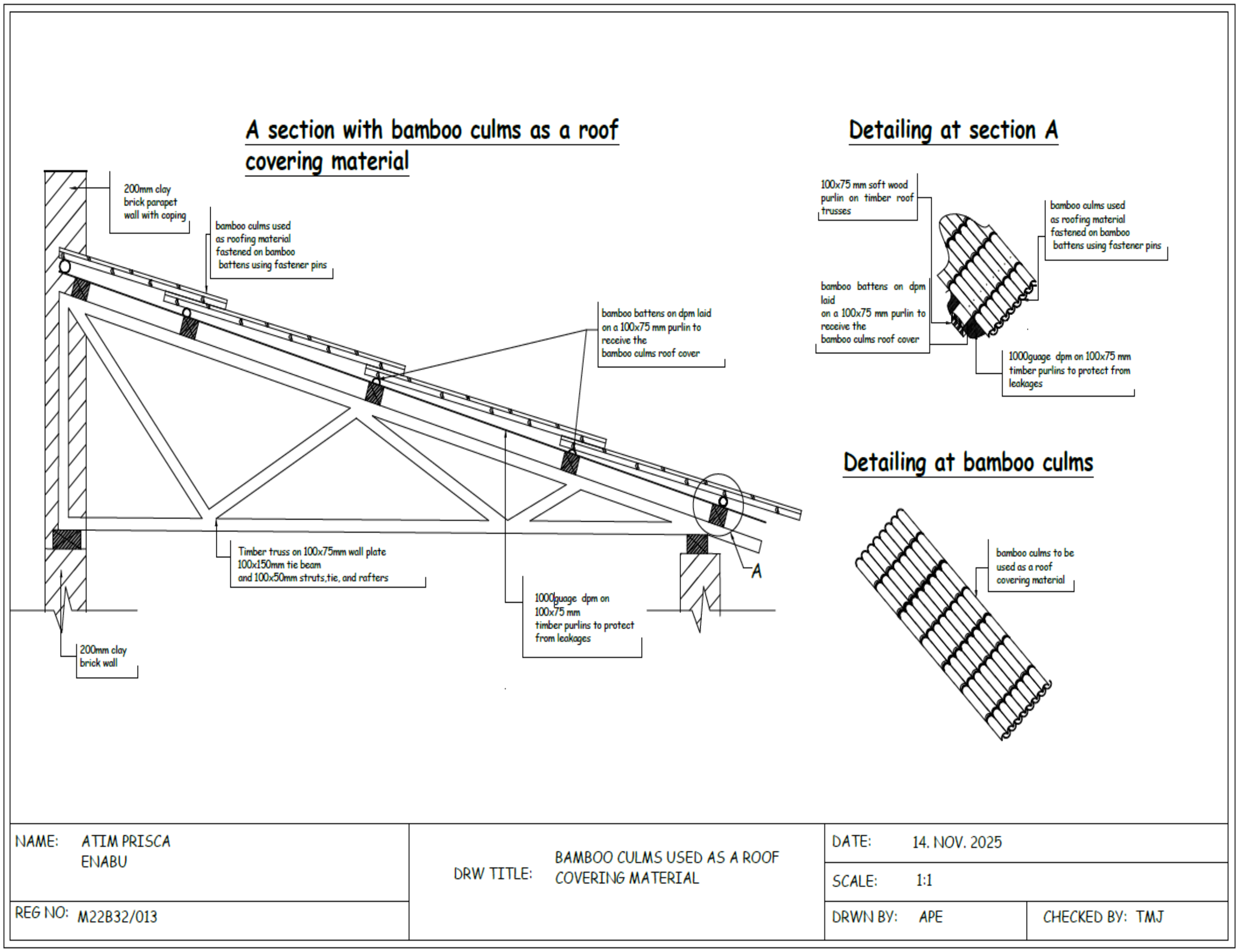
Batten total load per meter = (4.8 + 0.6) x 0.6 kN/m^2 = 3.24 kN/m^2

For the case of using a simply supported beam, maximum Bending Moment, M = (w x L2) / 8 = (3.24x1.22) / 8 = 0.58 kNm

Required Section Modulus, Sreq = M/sallowable = (0.58x106Nmm)/(24 N/mm2)=24,167mm^3.

Actual Section Modulus, S = (bxh2)/6 = (751002)/6=125,000mm3. 125,000 >> 24,167 required. These means that battens used of 100x75 mm, are sufficient in the presumed span and load.

4.8 Drawings


A section with bamboo culms as a roof covering material
200mm clay brick parapet wall with coping
bamboo culms used as roofing material fastened on bamboo battens using fastener pins
bamboo battens on dpm laid on a 100x75 mm purlin to receive the bamboo culms roof cover
Timber truss on 100x75mm wall plate 100x150mm tie beam and 100x50mm struts,tie, and rafters
1000guage dpm on 100x75 mm timber purlins to protect from leakages
200mm clay brick wall
A
Detailing at section A
100x75 mm soft wood purlin on timber roof trusses
bamboo culms used as roofing material fastened on bamboo battens using fastener pins
bamboo battens on dpm laid on a 100x75 mm purlin to receive the bamboo culms roof cover
1000guage dpm on 100x75 mm timber purlins to protect from leakages
Detailing at bamboo culms
bamboo culms to be used as a roof covering material
NAME: ATIM PRISCA ENABU
REG NO: M22B32/013
DRW TITLE: BAMBOO CULMS USED AS A ROOF COVERING MATERIAL
DATE: 14. NOV. 2025
SCALE: 1:1
DRWN BY: APE
CHECKED BY: TMJ

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

This research showed that bamboo as a roofing material can be improved greatly in terms of durability and performance with the use of epoxy resin treatment. By comparing untreated, traditionally treated and epoxy resin treated bamboo samples, the study established that the modern chemical treatment was superior to the conventional preservation systems in all the important areas of the material performance.

The epoxy resin was used to create a hydrophobic and cross linked polymer framework in the cellular structure of the bamboo that essentially reduced the water uptake, growth of fungal organisms and termites. Aging tests in a laboratory, which mimicked up to 16 years of environmental exposure revealed that the epoxy resin treated bamboo retained not only dimensional stability but also not more than 2% of its mass, which implied a service life of 15-20 years which was a significant improvement over the 6 months to 3 years' service life of traditionally treated bamboo.

Furthermore, the work on the bamboo roof interlock system with the treatment of culms and a clay layer base and timber battens was structurally sound and climate appropriate. Its design also favored ventilation, drainage and simplicity in installing, which was applicable in informal and formal settlement.

5.2 RECOMMENDATION

Implement epoxy resin treatment as a common preservation technique on bamboo in roofing in tropical areas that have high humidity. Try supplementing epoxy resin with a secondary preservative like borate based and see how it works on bamboo properties and establish localized epoxy recipes with resins and hardeners locally available to enhance accessibility. Roof pitches and overhangs should be sufficient to facilitate water flow.

UNBS ought to come up and embrace a national standard on treated bamboo construction material with performance standards on the absorption properties of water, resistance to decay, mechanical strength and fire resistance check. Training should be encouraged among artisans on the contemporary methods of treating bamboo and roofing by local governments and the Non-Government Organizations. Also get the environmental implication and life-cycle analysis of epoxy-treated bamboo as opposed to the traditional roofing materials, carry out field testing over the long term to confirm the accelerated aging models and service life forecasting models.

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APPENDIX 1: PICTURES OF MATERIALS AND ACTIVITIES

Figure 8: Bamboo eaten by termites

Figure 7: Culture chambers set up for experiments

Figure 10: Termites eating bamboo

Figure 9: Specimens for different tests

Figures 11: Bamboo before and after JIS K test

Figure 12: Showing a bamboo roof sample after treating with epoxy resin

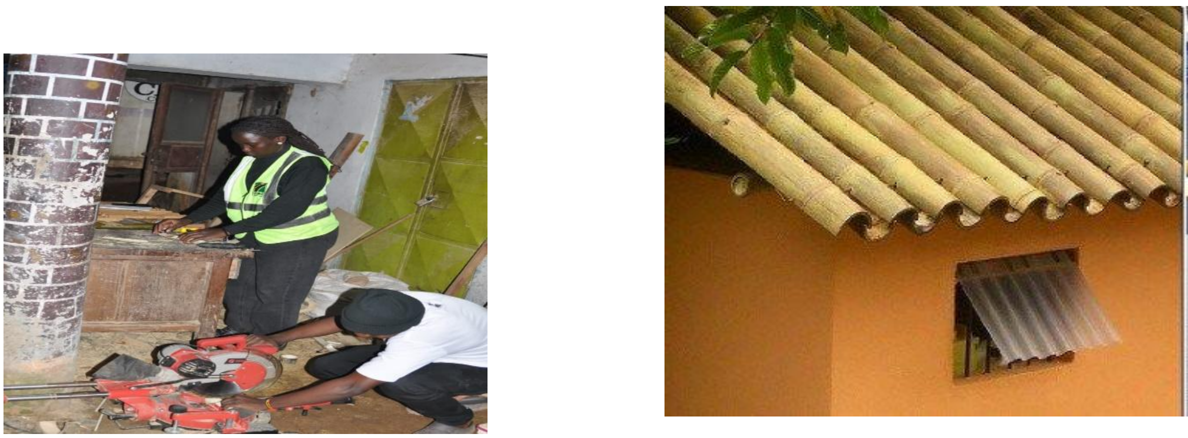

Figure 13: Sample preparation

Figures 14: Weighing of bamboo culm pieces and oven for drying samples

APPENDIX 2: PICTURES OF ORIGINAL LABORATORY TESTS COPIES.

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Wakiso, Uganda
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Email: info@getlab.co.ug
Web: www.getlab.co.ug

TEST CERTIFICATE

STUDENT NAME : **Atim Prisca Enabu**

PROJECT: **Assessing the use of bamboo as a sustainable building material for roof covering in developing areas in Uganda**

Issue Date: 29-Sep-25

Narrative Description:
Three (3) Sample of Bamboo were Delivered to the Laboratory by the Client

Serial No: **P2025255-1**

Test Report: GETL/TR/APE/25/001

Received Date: 26-Aug-25

Location: N/A

Test Date: 5-Sep-25

SUMMARY OF THE LABORATORY TESTS ON BAMBOO

SNo.	Test Parameter	Unit	Test Method	Specifications	Top, A	Middle, B	Bottom, C
1	Direct Moisture Content	%	ASTM D4442	15	12.69	12.77	12.87
Remarks							

Prepared by: Laboratory Engineer(Y.B)

Checked by: Senior Laboratory Engineer(OTA)

Approved by: Technical Manager(Eng.Dr.S.B)

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Wakiso, Uganda
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Web: www.getlab.co.ug

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STUDENT NAME : **Atim Prisca Enabu**

PROJECT: **Assessing the use of bamboo as a sustainable building material for roof covering in developing areas in Uganda**

Issue Date: 29-Sep-25

Narrative Description:
Three (3) Sample of Bamboo were Delivered to the Laboratory by the Client

Serial No: P2025255-2

Test Report: GETL/TR/APE/25/002

Received Date: 26-Aug-25

Location: N/A

Test Date: 5-Sep-25

SUMMARY OF THE LABORATORY TESTS ON BAMBOO

SNo.	Test Parameter		Unit	Test Method	Specifications	A	B	C
1	DECAY RESISTANCE	Weight Loss	%	ASTM D2017	-	13.40	13.29	11.86
		Decay Resistance Class	-		-	B	B	B
		Remarks						

Prepared by :
Laboratory Engineer(Y.B)

Checked by:
Senior Laboratory Engineer(OTA)

Approved by:
Technical Manager(Eng.Dr.S.B)

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Email: info@getlab.co.ug
Web: www.getlab.co.ug

TEST CERTIFICATE

STUDENT NAME : **Atim Prisca Enabu**

PROJECT: **Assessing the use of bamboo as a sustainable building material for roof covering in developing areas in Uganda**

Issue Date: 29-Sep-25

Narrative Description:
Three (3) Sample of Bamboo were Delivered to the Laboratory by the Client

Serial No: P2025255-3

Test Report: GETL/TR/APE/25/003

Received Date: 26-Aug-25

Location: N/A

Test Date: 5-Sep-25

SUMMARY OF THE LABORATORY TESTS ON BAMBOO

SNo.	Test Parameter		Unit	Test Method	Specifications	A	B	C
1	TERMITE RESISTANCE	Weight Loss	%	ASTM D3345	-	6.60	5.62	7.38
		Rate Of Damage	-		-	Heavy	Heavy	Moderate attack penetration
Remarks								

Prepared by :
Laboratory Engineer(Y.B)

Checked by:
Senior Laboratory Engineer(OTA)

Approved by:
Technical Manager(Eng.Dr.S.B)

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BAMBOO: WATER ABSORPTION. (REF: ASTM D570)

Project:	RESEARCH ON ASSESING THE USE OF BAMBOO AS A SUSTAINABLE BUILDING MATERIAL FOR ROOF COVERING IN DEVELOPING AREAS IN UGANDA.		
Client:	M/s Atim Prisca Enabu.		
Location.:	N/A	Sampling date	11-11-25
Sample Description.:	Bamboo	Tested By:	Prisca

	CONDITIONING AT 2 HOURS				CONDITIONING AT 24 HOURS				CONDITIONING AT 7 DAYS			
Sample Reference:	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4
Weight of Dry Sample (g)	19.77	19.27	20.13	18.7	19.77	19.27	20.13	18.7	19.77	19.27	20.13	18.70
Weight of Saturated Wet Sample. (g)	20.92	20.25	21.22	19.73	21.65	20.77	21.88	20.36	22.30	21.31	22.53	20.97
Water Absorption	5.82	5.09	5.41	5.51	9.51	7.78	8.69	8.88	12.80	10.59	11.92	12.14
AVERAGE WATER ABSORPTION (%)	8.68											

REMARKS/ OBSERVATION:

Checked by:

Laboratory Engineer (N.S)

Senior Laboratory Engineer (O.T.A)

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BAMBOO: DECAY RESISTANCE (Ref: ASTM: D2017)

Project:	RESEARCH ON ASSESING THE USE OF BAMBOO AS A SUSTAINABLE BUILDING MATERIAL FOR ROOF COVERING IN DEVELOPING AREAS IN UGANDA.		
Client:	M/s Atim Prisca Enabu.		
Tested By	Prisca.		
Sample Description.:	Bamboo	Testing Date:	26-Aug-25

Sample Reference:	D1	D2	D3
Initial oven-dry mass-M_1(g)	391	435	408
Final oven-dry mass -M_2(g)	381	427	398
Resistance $(M_1-M_2)/M_1*100$	2.56	1.84	2.45
Decay Resistance (%)	2.3		

REMARKS/ OBSERVATION:

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Checked by:

Laboratory Engineer (N.S)

Senior Laboratory Engineer (O.T.A)

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BAMBOO: MOISTURE CONTENT - (REF: ASTM D4442)

Project:	RESEARCH ON ASSESING THE USE OF BAMBOO AS A SUSTAINABLE BUILDING MATERIAL FOR ROOF COVERING IN DEVELOPING AREAS IN UGANDA.		
Client:	M/s Atim Prisca Enabu.		
Location.:	N/A	Sampling date	11-11-25
Sample Description.:	Bamboo	Tested By:	Prisca

Sample Reference:	S1	S2	S3	S3	S4	S5	S6	S8
Original Mass	17.02	19.25	20.08	14.65	14.41	18.85	13.07	16.17
Dry Mass	15.16	17.16	17.89	13.05	12.84	16.80	11.65	14.41
Moisture Content	10.95	10.86	10.91	10.92	10.90	10.88	10.86	10.88
AVERAGE MOISTURE CONTENT (%)	10.89							

REMARKS/ OBSERVATION:

Checked by:

Laboratory Engineer (N.S)

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P. O. Box 100001, Kasangati

Senior Laboratory Engineer (O.T.A)

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BAMBOO: TERMITE RESISTANCE (Ref: ASTM: D3345-74)

Project:	**RESEARCH ON ASSESING THE USE OF BAMBOO AS A SUSTAINABLE BUILDING MATERIAL FOR ROOF COVERING IN DEVELOPING AREAS IN UGANDA.**		
Client:	**M/s Atim Prisca Enabu.**		
Tested By	Prisca.		
Sample Description.:	Bamboo	Testing Date:	26-Aug-25
Sample Reference:	T1	T2	T3
Oven-dry mass Before - W1(g)	423	409	439
Oven-dry mass After - W2(g)	419	405	434
Resistance (W1-W2)/W1*100	0.95	0.98	1.14
Resistance (%)	1.0		

REMARKS/ OBSERVATION:

Checked by:

Laboratory Engineer (N.S)

Senior Laboratory Engineer (O.T.A)

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Tel: +256 (0) 392 175 883
Email: info@getlab.co.ug
Web: www.getlab.co.ug

TEST CERTIFICATE

CONTRACTOR: M/s Atim Prisca Enabu.

PROJECT: RESEARCH ON ASSESING THE USE OF BAMBOO AS A SUSTAINABLE BUILDING MATERIAL FOR ROOF COVERING IN DEVELOPING AREAS IN UGANDA.

Narrative Description:
One(1) set of Bamboo (4No.) were delivered at the laboratory by the client

Issue Date: 24-Nov-25

Date Recieved: 14-Nov-25

Test Date: 18-Nov-25

Location: N/A

ULTIMATE COMPRESSIVE STRENGTH OF BAMBOO. (EPOXY RESIM TREATED)

REF: ISO 22157-1:2004.

		Volume (C5, C6)	0.0000893	0.0000783	m³			Area (C5, C6)	0.000893	0.000783	m2		
SNo.	Lab.Sample Ref.		Client's Ref.	Specified Concrete Strength	Date		Age (Days)	Weight After Drying	Density	Crushing Load	Ultimate Compressive Strength	Mean Strength	Remarks
					Casting	Testing		(kg)	(kg/m³)	(kN)	(MPa)	(MPa)	
1			C5	N/A	N/A	18-Nov-25	N/A	0.05	940.8	78.4	87.8	88.1	Average Strength Meets The Specified Limits Of 60 - 90MPa
2			C6		N/A	18-Nov-25	N/A	0.06	807.2	69.2	88.4		

Prepared by:
Laboratory Engineer (J.B)

Checked by:
Senior Laboratory Engineer (O.T.A.)

Approved by:
Technical Manager (Dr. S.B.)

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5 NS Not specified

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Tel: +256 (0) 392 175 883
Email: info@getlab.co.ug
Web: www.getlab.co.ug

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CONTRACTOR: M/s Atim Prisca Enabu.

PROJECT: RESEARCH ON ASSESING THE USE OF BAMBOO AS A SUSTAINABLE BUILDING MATERIAL FOR ROOF COVERING IN DEVELOPING AREAS IN UGANDA.

Narrative Description:
One(1) set of Bamboo (4No.) were delivered at the laboratory by the client

Issue Date: 24-Nov-25

Location: N/A

Date Recieved: 14-Nov-25
Test Date: 18-Nov-25

ULTIMATE COMPRESSIVE STRENGTH OF BAMBOO (NATURAL CONDITIONING)

REF: ISO 22157-1:2004.

	Volume (C1,C2,C3,C4)	0.0001018	0.0000942	0.0000792	0.0001457	m^3	Area (C1,C2,C3,C4)	0.001018	0.000942	0.000792	0.001457	m2	
SNo.	Lab.Sample Ref.		Client's Ref.	Specified Concrete Strength	Date		Age (Days)	Weight After Drying	Density	Crushing Load	Ultimate Compressive Strength	Mean Strength	Remarks
					Casting	Testing		(kg)	(kg/m^3)	(kN)	(MPa)	(MPa)	
1			C1	NS	N/A	18-Nov-25	N/A	0.10	998.2	70.1	68.9	57.9	Average Strength Meets The Specified Limits Of 40 - 60MPa
2			C2		N/A	18-Nov-25	N/A	0.10	1008.5	67.0	71.1		
3			C3		N/A	18-Nov-25	N/A	0.06	709.6	37.1	46.8		
4			C4		N/A	18-Nov-25	N/A	0.10	719.3	65.5	45.0		

Prepared by: Laboratory Engineer (J.B)

Checked by: Senior Laboratory Engineer (O.T.A.)

Approved by: Technical Manager (Dr. S.B.)

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Notes:

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3. Interpretation of the results will be made at the request of the client/customer
4. NA - Not applicable
5. NS Not specified

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F/TR/08 ISSUE 02

GETLAB LTD
P.O. BOX 100001,Kasangati.
Plot 1234 ,Namirembe Hillside Road,Kitattika,Wakiso.
Tel: +256 (0) 392 175 883
Email: info@getlab.co.ug
Web: www.getlab.co.ug

TEST CERTIFICATE

CONTRACTOR: M/s Atim Prisca Enabu.

PROJECT: RESEARCH ON ASSESING THE USE OF BAMBOO AS A SUSTAINABLE BUILDING MATERIAL FOR ROOF COVERING IN DEVELOPING AREAS IN UGANDA.
Narrative Description:
One(1) set of Bamboo (4No.) were delivered at the laboratory by the client

Issue Date: 24-Nov-25

Date Recieved: 18-Nov-25

Location: N/A

Test Date: 18-Nov-25

FLEXURAL STRENGTH OF BAMBOO - ONE POINT LOAD. (REF: ASTM D198.)

EPOXY RESIN TREATED BAMBOO

	Volume (B3, B4, B5) 0.0000453	0.00005035	0.00003785		m³	Area =	0.000302	0.000337	0.000251	m²	m3	Length (m) 0.15		
S/No.	Lab.Sample Ref.	Client's Ref.	Specified Concrete Strength	Date		Age (Days)	Weight After Drying	Density	Crushing Load	Bending Moment	Section Modulus	Flexural strength Strength	Mean Strength	Remarks
				Casting	Testing		(kg)	(kg/m³)	(kN)	(Nm)	(m3)	(MPa)	(MPa)	
1		B4	N/A	N/A	18-Nov-25	N/A	0.05	1068.2	5.8	218	1.59E-06	136.4	138.0	Average Strength Meets The Specified Limits Of 110 -160MPa
2		B5		N/A	18-Nov-25	N/A	0.05	9159.2	4.9	184	1.38E-06	132.9		
3		B6		N/A	18-Nov-25	N/A	0.05	1251.0	4.2	158	1.09E-06	144.8		

Prepared by:
Laboratory Engineer (J.B)

Checked by:
Senior Laboratory Engineer (O.T.A.)

Approved by:
Technical Manager (Dr. S.B.)

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24 NOV 2025
Geotechnical Engineering & Technology Laboratory Ltd
P.O. Box 100001, Kasangati
KENAS

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YOUR RELIABLE ENGINEERING LABORATORY
P.O. BOX 100001,Kasangati.
Plot 1234 ,Namirembe Hillside
Road,Kitettika,Wakiso.
Tel: +256 (0) 392 175 883
Email: info@getlab.co.ug
Web: www.getlab.co.ug

TEST CERTIFICATE

CONTRACTOR: M/s Alim Prince Eraibe.

PROJECT: RESEARCH ON ASSESING THE USE OF BAMBOO AS A SUSTAINABLE BUILDING MATERIAL FOR ROOF COVERING IN DEVELOPING AREAS IN UGANDA.
Narrative Description:
One(1) set of Bamboo (4No.) were delivered at the laboratory by the client

Issue Date: 24-Nov-25

Date Recieved: 18-Nov-25

Location: N/A

Test Date: 18-Nov-25

FLEXURAL STRENGTH OF BAMBOO - ONE POINT LOAD. (REF: ASTM D198.)

NATURALLY SOAKED BAMBOO

	Volume (B3, B4, B5) 0.0000519	0.00003105	0.0000414		m³	Area =	0.000348	0.000207	0.000270	m²	m3	Length (m)	0.15	
S/No.	Lab.Sample Ref.	Client's Ref.	Specified Concrete Strength	Date		Age (Days)	Weight After Drying	Density	Crushing Load	Bending Moment	Section Modulus	Flexural strength Strength	Mean Strength	Remarks
				Casting	Testing		(kg)	(kg/m³)	(kN)	(Nm)	(m3)	(MPa)	(MPa)	
1		B1	N/A	N/A	18-Nov-25	N/A	0.05	1021.2	4.0	150	1.63E-06	92.1	103.1	Average Strength Meets The Specified Limits Of 70 - 120MPa
2		B2		N/A	18-Nov-25	N/A	0.05	1031.1	3.0	113	1.02E-06	110.1		
3		B3		N/A	18-Nov-25	N/A	0.05	1100.7	3.8	143	1.33E-06	107.2		

Prepared by: Laboratory Engineer (J.B)

Checked by: Senior Laboratory Engineer (O.T.A.)

Approved by: Technical Manager (Dr. S.B.)

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P. O. Box 100001, Kasangati

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BAMBOO: JIS Durability Test. (REF: JIS-K 1571)

Project:	RESEARCH ON ASSESING THE USE OF BAMBOO AS A SUSTAINABLE BUILDING MATERIAL FOR ROOF COVERING IN DEVELOPING AREAS IN UGANDA.
Client:	M/s Atim Prisca Enabu.
Location.:	N/A — Sampling d 04-11-25
Sample Description.:	Bamboo — Tested By: Prisca

	EPOXY RESIN TREATMENT														
Sample Reference:	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10	Y11	Y12	Y13	Y14	Y15
Average Mass Difference (g)	0.7	1.2	3.8	4.3	5.7	6.5	6.1	5.4	4.9	4.3	3.5	3.1	2.7	2.2	1.6

REMARKS/ OBSERVATION:

Checked by:

Laboratory Engineer (N.S)

Senior Laboratory Engineer (O.T.A)

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P. O. Box 100001, Kasangati

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BAMBOO: JIS Durability Test. (REF: JIS-K 1571)

Project:	**RESEARCH ON ASSESING THE USE OF BAMBOO AS A SUSTAINABLE BUILDING MATERIAL FOR ROOF COVERING IN DEVELOPING AREAS IN UGANDA.**						
Client:	**M/s Atim Prisca Enabu.**						
Location.:	N/A		Sampling date	04-11-25			
Sample Description.:	Bamboo		Tested By: Prisca				
	Naturally Soaked						
Sample Reference:	Y1	Y2	Y3	Y4	Y5	Y6	Y7
Average Mass Difference (g)	6.5	15.4	11.3	5.7	3.3	1.1	0.20

REMARKS/ OBSERVATION:

Checked by:

Laboratory Engineer (N.S)

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Geotechnical Engineering & Technology Laboratory Ltd
P. O. Box 100001, Kasangati

Senior Laboratory Engineer (O.T.A)