INVESTIGATION OF THE SUITABILITY OF CONCRETE INFILLED BAMBOO FOR STRUCTURAL PERFORMANCE IN COMPRESSION FOR LOW-COST BUILDING

BY

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DECLARATION

I, OKUDA JAMES GOWON, hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person, nor materials which has been accepted for the award of any other degree of the university or other institute of higher learning, except where due acknowledgement has been made in the text and the reference list.

Signed………………………………………. Date……………………………………………

APPROVAL

The undersigned approve that they have read and hereby recommend for submission to the Directorate of Research and Graduate Training of Kyambogo University, a dissertation entitled: Investigation of The Suitability of Concrete Infilled Bamboo for Structural Performance in Compression for Low-Cost Building in fulfillment of the requirements for the award of Master of Science in Structural Engineering Degree of Kyambogo university.

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DEDICATION

To my Late Mother, Josephine Akidi-Okuda. I will always remember you!

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SYMBOL	DESCRIPTION	UNIT
A	Cross-Sectional Area of Plain Bamboo samples	mm^2
A_b, A_c	Area of Bamboo and Concrete infilled sections respectively	mm^2
ACI	American Concrete Institute	-
BRE	British Research Establishment	-
$BS:ISO$	British Standard: International Organization for Standardization	-
$CEDAT$	College of Engineering, Design, Art and Technology (Makerere University)	-
$CFST$	Concrete-filled steel tube	-
C_k	Coefficient between intermediate and long slender elements for axial compression	-
D_e, D_c	External Diameter of Bamboo and Diameter of concrete infilled in Bamboo respectively	mm
E	Elastic Modulus	N/mm^2
E_b, E_c	Modulus of Elasticity of Plane Bamboo and Concrete respectively	N/mm^2
$EC2$	Eurocode 2: Design of Concrete Structures-Part1-1: General rules and rules for Building	-
$EC3$	Eurocode 3: Design of Steel Structures-Part1-1: General rules and rules for Building	-
$EC5$	Eurocode 5: Design of Timber Structures-Part1-1: General rules and rules for Building	-
EI_{eff}	The effective flexural stiffness of the concrete infilled Bamboo column obtained from adding up the flexural stiffnesses of the individual components of the cross-section	N/mm^2
F_{ck}	Characteristic compressive strength of Concrete	N/mm^2
$F_{ck,c}$	Increased characteristic strength of concrete due to confinement	N/mm^2
$F_{y,b}, F_{y,c}$	Compressive strength of Bamboo and Concrete respectively	N/mm^2
I_b, I_c	second moment of area, or moment of inertia, of the Bamboo culm and Concrete section infilled in Bamboo respectively	mm^4
k	Coefficient of effective length based on support condition	-
L	Length of Bamboo samples	mm
$Le\ or\ L_{eff}$	Effective length of plane Bamboo or concrete infilled Bamboo culm sample lengths	mm
N_{ED}	Failure load capacity of Plane Bamboo and concrete infilled Bamboo culms at different sample lengths	N
$N_{pl,rk}$	Characteristic Plastic resistance of concrete filled Bamboo culms at different sample lengths	N
N_{Rd}	Axial load carrying capacity of concrete filled Bamboo culms at different sample lengths	N
r	Radius of gyration of Bamboo culms	mm
t	Bamboo culm samples wall thickness	mm
UTM	Universal Testing Machine	-

Greek Letters

SYMBOL	DESCRIPTION
ψ	Buckling reduction factor
Λ	Samples slenderness ratio
σ_y	Material compressive strength
γ_E	Material factor of safety

ABSTRACT

Various Engineering Scholars and Building construction materials and researchers have been doing experiments on investigating properties of Plain Bamboo, Concrete infilled Bamboo composite, and use of Bamboo to replace reinforcements in Concrete. Little has been disseminated on the Concrete infilled Bamboo with various concrete mix ratios. There are scarce and scanty documented and published information relating to the structural properties of Concrete infilled Bamboo as composite material. It is urgent to venture and understand through experimental investigations the Structural Properties of Concrete infilled bamboo to understand its structural properties to proof reliable usage when designing low-cost buildings, especially when considering axial compressive loading.

Bamboo grows fast, and its readily available natural resource, with proven high strength and low weight to height ratio. For decades, Bamboo has been used as a rural building construction, and with recent innovations for domestic furniture. With recent research and innovations to look for alterative building materials to substitute concrete and steel, Bamboo Mechanical and structural properties have proven ideal for construction especially for low-cost houses units. Its major short fall however remains buckling, which is limits their usage in buildings subjected to compressive loads.

This thesis outlines an experimental approach to investigate the properties, specifically the compressive strength when bamboo is infilled with concrete to form a composite material. Experimental investigation and results of the compressive strength of concrete infilled composite, with different concrete grades subjected to loads was experimentally investigated to appreciate the compressive strength of Concrete infilled Bamboo at different Bamboo samples lengths. This research mainly was based to assess the compressive strength of plane Bamboo, and concrete infilled Bamboo using varying concrete grades. The positive results from the experiment can outline an avenue and evidence for its suitability in expanding the usage of Bamboo as a construction material for low-cost shelter constructions.

In this research paper, the compressive strength of plane Bamboo and concrete infilled Bamboo with concrete grades C12/15, C16/20 and C20/25 was investigated. Overall, there was marked improvement on the compressive strength of Concrete infilled bamboo culms. For Experimental tests done on plain Bamboo, the failure load was found to be decreasing with increasing Bamboo sample lengths. The axial load capacity of plain Bamboo at 0.2m sample length is 26.4% more than that at 1m length. Concrete infilled Bamboo with C15, C20 and C25 led to an increment of 58.7%, 103% and 139.1% of the compressive strength capacity compared to plain bamboo culms sample test length at 1m respectively; and 54.4%, 77.6% and 100.8% at Sample lengths of 0.2m. Concrete infills greatly improves the load capacity of identical bamboo culms. The failure load capacity was increasing when Bamboo sample lengths were infilled with Concrete, and the Load carrying capacity increases when Bamboo was infilled with concrete of higher grades. Bamboo infilled with concrete grade C25 has a large failure load than that infilled with concrete grade C20 and C15, signifying a higher ductility behaviour. From the study therefore, it can be concluded that concrete infill in bamboo can delay the buckling of the culms, and thus significantly improves the compressive strength capacity and ductility.

There were observed differences between the experimental and the theoretical results of concrete infilled Bamboo. The difference in results could have come as experimental results were derived from actual laboratory experiments on the plain Bamboo and concrete infilled Bamboo under study. Theoretical “results" was just an application of the latest theories, formulae, and references on confined concrete to try to predict how it works, assuming its relative structural behaviour and performance.

Finally, this research can be a resource for reference and formulating further innovations in Structural Engineering design to use Concrete infilled Bamboo composite as a building materials properties understood for effective design, repeatability, adoption for conventional construction and maintenance to meet the current need for innovative and new building materials.

Key words:

Plain Bamboo, Concrete infilled Bamboo, Compressive strength.

CHAPTER ONE: INTRODUCTION

1.1 Background to the Study

The evergreen and naturally available local construction material, bamboo, has been used by humanity for ages. For decades, it has been used as an available and readily replenishable building construction materials by low-income individuals of most developing countries. Traditionally, bamboo has been used as a construction material in Africa, South Pacific, East and South Asia (M.A Dos Reis Pereira, T.Q.F. Barata, 2015) and by extension in the aesthetic and decorations.

A hollow and woody plant, Bamboo plant is estimated to be in about 1,500 species over the world. It is classified as grass family ***Gramineae*** and sub-family ***Bambusoideae***, with over 70 genera (Khalil, 2012). Almost all bamboo species are found in warm and moist tropical and temperate climates, though many species are found in diverse climates, ranging from hot tropical regions to cool mountainous regions and highlands. Bamboo grows fast, and ready for harvesting and use within 4-7 years (Ashby, 2016)

Predominantly, bamboo is a tropical and sub-tropical plant which is found in many countries. Its high rate of growth and replenishment when cut, high level of toxic gas and Carbon dioxide uptake and usage, varying usable diameter, varying usable length, and resistance to destructive environmental conditions makes it an ideal and distinctive materials with promising structural and mechanical properties which can make it ideal for innovative interest in structural Engineering. It is a readily available and regenerative natural resource at the disposal of Mankind.

Considering its high growth rate with ideal environmental and mechanical properties, Bamboo can be considered for as a potential building construction material with innovations. These properties and potential make bamboo an ideal construction material for different applications as structural members and components. With the current urge to arrest global warning, it becomes extremely vital to look for alternative greener economy, and reliable environmentally friendly construction materials for sustainable building construction development. Its vast availability and high growth rate have made it a construction material of interests from structural Engineers and researchers. The different species and with varying heights and diameter have made the usage of bamboo suitable for many buildings structural components for ages. Bamboo is known for its strength, durability and lightweight. The hollow circular and cylindrical shaped chambers make bamboo lighter. While the bamboo culm is the more ideal part used for construction, other people have used roots, leaves, and stems of the plant for medicine and food. For ages, Bamboo has been used as a construction material in the construction of traditional bridges, erection platforms and scaffolds, and more recently in modern building constructions and walling aesthetic, as shown in Figures 1.1 and 1.2 below.

Figure 1.1: Structural use of bamboo as scaffolds (left) and as a bridge (right)

Figure 1.2: Plain bamboo used as columns and trusses and as decorative walling material.

There are thousands of bamboo species, and hundreds of native species world over, especially in South America and Asia. Over decades, Bamboo is being used in construction, though its use and basic knowledge of its characteristics, repeatability and application in construction are still little known, with no definitive code of design produced (M.A Dos Reis Pereira, T.Q.F. Barata, 2015)**.** Like timber, Bamboo is a native local building material strength and low weight useful for structural members in building constructions. Bamboos generally have a modulus of elasticity approximately measured to be about 9 GPa. This is quite lower compared to timber, 20 GPa, steel, 200 GPa and concrete composite which is in the range of 30-50 GPa. However, it has a high measured compressive strength ranging between 40 to 80 MPa**.** These properties should trigger structural Engineering research on the utilization and adoption of bamboo in construction industry by documenting and properties of this "***green and Eco-friendly***" construction material in response to the declining forest cover due to lumbering for wood. Investigated structural performance of bamboo should give evidential data on its suitability for manufacturing the so-called 'Engineered bamboo' from ordinary bamboo applying modern technology.

Conventional usage of Concrete and steel for building construction is becoming expensive. The cost of production of these materials is constantly rising. Such construction requires good quality assurance and management, with skilled and experienced personnel to manufacture to prepare and assemble different components, for any truly successful results. The innovative use of Bamboo in construction should offer an alternative material to steel and concrete. However, this should come with a design code for repeatability and maintenance, especially for developing countries.

Innovative building construction materials like the usage of bamboo should alleviate the seeming over-dependence on conventional constructions in steel and concrete, coupled with rising cost of its production. This will also arrest the current global warming and environmental degradation that accompanies the production of cement and steel. Once regarded as ***'poor man's timber'*** is now being dubbed Green Gold for its vast environmental benefits such as alleviating pressure on tropical forests thereby mitigating climate change, curbing deforestation and being enhanced and used as structural members in buildings.

1.2 Problem Statement

With increasing world population and need for housing units, the demand and cost of construction materials for building has grown exponentially. Conventional usage of Concrete and steel for building construction is becoming expensive. The cost of production of these materials is constantly rising. Such construction requires good quality assurance and management, with skilled and experienced personnel to manufacture to prepare and assemble different components, for a safe and robust building component. These make housing constructions in concrete and steel very expensive and unsustainable for many low-income individuals. It is therefore necessary to explore innovations of using bamboo as a cheap, readily available, and sustainable material as building materials instead of the conventional use of concrete and steel. Besides, the Housing shortage world over due to the rising unaffordability of conventional building materials makes it logical to consider alternative technologies and research on different materials for their application in construction.

For ages, Bamboo has been used for traditional building constructions, and still it is being used in modern construction. Bamboos grows fast, maturing within a period between 4-7 years, and has good eco-friendly properties such as renewability and carbon dioxide fixation. It can easily get biodegraded. For most Civil Engineering construction works, conventional building materials like steel and cement are used in large quantities. The usage of these materials has greatly increased coupled with high pace infrastructural developments in cities. Various gas emissions and energy consumptions are related to the current global warming and environmental degradation is being related to manufacturing industry, with steel and cement production taking a greater share. Given the current level of emissions of toxic gases and the level of environmental pollution arising from conventional construction methods, adverse climatic changes continue to devastate humanity with great economic and social losses.

Bamboo is considered a structural building material with many advantages and is some of the ideal materials for future green building innovations increasingly brought to the attention of the Civil Engineering industry. The exploitation of the performance of bamboo composite as an option in building constructions as opposed to conventional construction in concrete and steel constructions should give the suitability of the material to achieve a low carbon construction system.

The compressive strength of bamboo is relatively high at 40-80 MPa. This property makes bamboo possess an important characteristic suitable for use as a structural material. It is a relatively stronger and lighter material that can be exploited as a cheaper structural material option for light weight building constructions. This property could be exploited for the suitability of bamboo as a material for building construction. If widely recognized and adopted by structure and architecture, composite bamboo performance parameters will be a cheaper option for manufactured building materials with an eco-resolution analysis to create an eco-living unit.

Taking advantage of the local abundant bamboo resources in Uganda, there is a need therefore to invest in the exploitation of bamboo as a new building material, particularly exploiting its high compressive strength to replace steel in structural members. With the extensive utilization of bamboo industrialization, the construction industry seems to have a broader prospect.

1.3 Objective of the Project

1.3.1 Main Objective

To investigate performance of concrete-infilled bamboo in compression.

1.3.2 Specific Objectives

I. To determine compressive strength of selected bamboo at different Bamboo sample heights
II. To determine compressive strength of Concrete infilled bamboo with different concrete grades at different bamboo sample heights
III. To derive a design method for concrete-infilled bamboo

1.4 Research Questions

Properties of bamboo, such as fire resistance, strength, durability, etc., are not yet fully disseminated; with no codes, standards and regulations readily available to Structural Engineers and building practitioners. Such documents need to be available for Structural Engineers, Construction materials Engineers and researchers for new building construction materials.

This research sought to assess key information towards appreciating the suitability of plain Bamboo and concrete infilled Bamboo as innovations in structural Engineering focusing mainly on experimentally observing values of its structural mechanical properties basing on:

I. Effects of heights on compressive strength of plain Bamboo, and possible limitation of height for structural use of bamboo in construction industry.

II. Effects of different concrete grades infilled in bamboo on the compressive strength of bamboo at different sample heights.
III. Possibilities of adoption of Bamboo against apathy, coupled with deep-seated psychological resentment of Engineers and Architects towards its use as a construction material.

All attempts towards adopting bamboo as a new construction material should aim in possibilities of usage and applications in its different forms. With a urge to source for a new construction material through modern technology and innovations towards green and eco-friendly Civil Engineering constructions, Engineers should aim to maintaining a good balance between the fundamental strength properties and practical of Bamboo usage in construction industry.

1.5 Justification

Bamboo is an indigenous construction material not well-known to Civil Engineers in Africa, particularly in Uganda. Lack of approved codes and standards and diverse published technical information lead to this local material as foreign and therefore unsafe to replace conventional building materials. Taking into consideration of the increasing cost of conventional materials in modern construction industry, searching for alternative materials for low-cost construction and global warming mitigation is urgent. Conventional housing constructions in concrete and steel have become very costly and expensive for many. To successfully reverse the current trend, Structural Engineers must continuously search for alternative materials that can be used aside from steel and concrete. One of these materials is Bamboo.

Bamboo is considered as a new building material because of its outstanding mechanical performances with a good reputation as an eco-friendly, highly replenishable local material because:

I. The building industry has long been responsible for global warming and environmental degradation directly due to the industrial processes of manufacturing conventional building materials like steel and concrete. Bamboo grows fast, with a maturity period between 4 to 7 years. It is renewable and has high levels of carbon dioxide fixation and storage. Bamboo is cheap and therefore can be considered an eco-friendly material as construction material. Its usage is anticipated to reduce over dependance on the use of timber and destruction of natural and artificial forest covers.

II. The compressive strength of bamboo is relatively high at 40-80MPa. This characteristic property makes bamboo suitable for use as a construction material, especially to members subjected to compressive load.

III. The cost of construction of concrete and steel structures is increasing. This makes housing constructions in conventional materials of steel and concrete very expensive and unattainable for many of the poorest. It becomes urgent therefore, to explore proven opportunities of using bamboo as a cheap, readily available, and sustainable material as building materials instead of traditional utilizations of concrete and steel.

There is a need therefore to conduct experimental investigation for the exploitation of bamboo as a building material, particularly to exploit its high compressive strength to replace steel. With a new definition of concrete-infilled bamboo as a structural member for low-cost construction in Civil Engineering context, mainly with clear and repetitive designs (instead of artesian Craftsmen) and the professional codes and standards (instead of traditional construction usage) a new approach of bamboo utilizations will open modern cultures an identity of bamboo-built society. This will outline a relationship between traditional bamboo usage and modern designers, linking traditional cultural identity and symbol to modernization using bamboo in Civil Engineering buildings.

1.6 Significance of the Research Project

With known excellent growth rate, environmental protection properties, mechanical strength properties, Bamboo has proven ideal for different applications in construction industry. These properties make Bamboo plant an important and reliable resource for generating an eco-friendly economy sustainable housing development. Given the high growth rate and biodegradability characteristics, bamboo can be taken as ideal eco-friendly economic investment to mitigate current global warming. This investigation of the structural suitability of bamboo-infilled concrete for low-cost construction reviewed should outline the value of bamboo in the prospects of structural Engineering given economic prosperity and ecological security. Besides this, bamboo is increasingly being considered for manufacturing the so-called “engineered bamboo” by applying modern technology.

1.7 Project Research Scope

The strength test for compression was experimental, conducted at Makerere University College of Engineering, Art, Design and Technology (CEDAT) Material Laboratory. The research project scope was mainly limited to the following:

1.7.1 Content Scope

The research thesis was aimed at investigation of the structural performance of concrete infilled Bamboo for low-cost building construction. The content scope included.

I. Identification of the sources of raw materials used for the experiment. The materials to be used for the experiment were selected bamboo species within Uganda, suitable aggregates, sand, cement, and water for concrete strength of different classes.
II. Laboratory test on selected concrete materials to appreciate their properties and suitability for the proposed experiments.
III. Preparation of selected bamboo for the concrete casting
IV. Design of concrete to the desired grades of C12/15, C16/20 and C20/25.
V. The casting of the designed concrete as infills in bamboo.
VI. Curing of the cast concrete
VII. Laboratory test for compressive strength of concrete-infilled bamboo and plain bamboo at bamboo test lengths of 1m, 0.8m, 0.6m, 0.4m and 0.2m
VIII. Comparison and analysis of laboratory test results
IX. Deduction and conclusion of the results of the laboratory test results.

1.7.2 Geographic Scope

This research thesis and experiments were conducted within Uganda, with the sourcing of selected Bamboo done from the known Bamboo producing Districts of Kasese, Kikuube, Masindi and Hoima. Laboratory tests of the structural property in Compression of plain and concrete-infilled bamboo were conducted at Makerere University College of Engineering, Art, Design and Technology (CEDAT) Material Laboratory.

1.7.3 Time Scope

This research started in July 2020, with research proposal identification and presentation.

1.8 Conceptual Framework

The project research concept was aimed to give an outline approach and principles criteria of the activities, strategies and available possibilities that would be carried out in accomplishing the objectives of the project. This research was intended to guide in developing a conceptualized and operational plan undertaken and the different tasks that were carried out to achieve the main objective of the research.

The approach of the research involved both quantitative and qualitative methods aimed at achieving the absolute objective of the project. The qualitative approach allowed greater understanding and analytical examination and explanations of un- insight and understanding of the strength parameters of plain bamboo and concrete-infilled bamboo.

Overall, the research was aimed at giving the details of:

i. Preparation of plain bamboo specimens in different lengths; 1m, 0.8m,0.6m, 0.4m and 0.2m
ii. The casting of designed concrete as infills in the different cut lengths of the bamboo.
iii. Laboratory investigation of the performance of plain bamboo in compression, shear and bending at different test lengths of; 1m, 0.8m,0.6m, 0.4m and 0.2m
iv. Performance of concrete bamboo-infilled concrete in compression, shear and bending at different lengths ranging from 1m, 0.8m,0.6m, 0.4m and 0.2m

Figure 1.3 below shows the research conceptual framework.

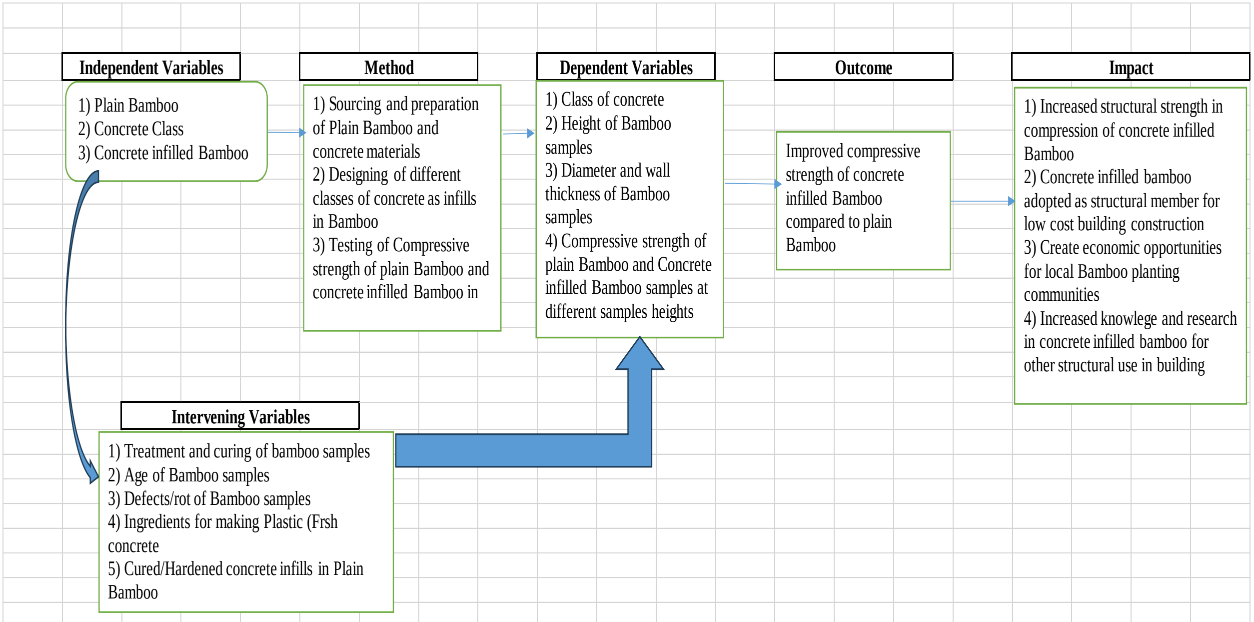

Figure 1.3: Conceptual framework for the research experiment

1.9 Chapter Summary

The objective of this research was to experimentally investigate structural performance of Concrete infilled Bamboo in compression for low-cost Building construction. A detailed overview of the study has been provided under the following components: - introduction, statement of the research problem, objectives of the research, significances and research scope being undertaken.

The evergreen and naturally available local construction material, bamboo, has been used by humanity for ages. For decades, it has been used as an available and readily replenishable building construction materials by low-income individuals of most developing countries. A hollow and woody plant, Bamboo is classified as grass family (Gramineae), sub-family ***Bambusoideae***, found in about 1,500 species over the world and over 70 genera.

With increasing world population and need for housing units, the demand and cost of construction materials for building has grown exponentially. Conventional usage of Concrete and steel for building construction is becoming expensive. The cost of production of these materials is constantly rising. Such construction requires good quality assurance and management, with skilled and experienced personnel to manufacture to prepare and assemble different components, for a safe and robust building component. These make housing constructions in concrete and steel very expensive and unsustainable for many low-income individuals. It is therefore necessary to explore innovations of using bamboo as a cheap, readily available, and sustainable material as building materials instead of the conventional use of concrete and steel. Besides, the Housing shortage world over due to the rising unaffordability of conventional building materials makes it logical to consider alternative technologies and research on different materials for their application in construction.

The exploitation of the performance of bamboo composite as an option in building constructions as opposed to conventional construction in concrete and steel constructions should give the suitability of the material to achieve a low carbon construction system. To alleviate the effects of global warming linked to the manufacture of conventional construction materials, using bamboo for low-cost construction can be taken as Eco-friendly. All attempts towards a new construction material should aim for possible application of bamboo in construction to maintain a balance between the traditional and innovative utilization of bamboo, a critical approach to meeting new challenges of technology and innovations is a task towards green and eco-friendly Civil Engineering constructions.

The research was experimental and investigative in a construction material laboratory. The research project was mainly limited to the following:

I. Identification of the type and source of bamboo for the proposed research,
II. Selection of appropriate concrete materials,
III. Designing an appropriate concrete class to be used for the experiment,
IV. Preparation of bamboo, including cutting to appropriate length and opening of the nodes,
V. Casting of concrete as infills in the cut bamboo lengths, curing of concrete infills in the bamboo,
VI. Laboratory testing and analysis of the plain bamboo and bamboo-infilled concrete.

Conclusive results of the experimental test on a plain and concrete-infilled bamboo would lead to innovation in structural and construction materials having the possibility to reduce over reliance on non-renewable materials like sand, cement, etc. that are used globally for construction. This would of non-renewable materials.

Once regarded as ***'poor man's timber'***, bamboo has the potential to form a composite construction material and is dubbed as Green Gold for its vast environmental benefits such as alleviating pressure on tropical forests thereby mitigating climate change, curbing deforestation and enhancing used as structural members definitely help to lower the related environmental degradation associated with the extraction and production of conventional building materials used in construction.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The construction industry is one of the greatest contributors to the development of any country, with building materials taking over 35% cost of construction. With constructions and infrastructure sector taking center stage for the development of the country, the demand on the conventional construction materials will exponentially grow. The cost of manufacturing of conventional building material like cement and steel is steadily increasing, therefore having a direct effect on the construction projects (Mogbo, 1999). Studies conducted on the increasing cost of construction reported cost of materials directly influence the cost of construction. In developing countries, the cost of production of cement and steel is quite expensive (Sarfo-Ansah, 2010), and over the last few decades raw materials for production has been exhausted. Looking for new materials and deducing the costs of production of construction materials should be urgent. Increasing population growth is anticipated to increase resource demand for infrastructure development. Principally, the cost of predominant conventional materials (cement, gravel, steel reinforcements and sand) has become expensive and this is anticipated to slow the construction of buildings in Uganda and other low-income countries. The urge to provide immediate alternative low-cost and practical building materials solutions has therefore become more acute (Kereli, 2001).

Alternative materials for building constructions can be got from local indigenous materials that are locally produced and manufactured, naturally occurring, and abundant in a country (Cunningham, W.F., Cunningham, M.A., 2002). These materials are produced within the vicinity or environment where they will be used, or they are available on the same site where they will be used (Pearce, 2001). Indigenous materials suffer from the widespread but generally erroneous belief that it is *"native"*, requiring no processing between harvesting and usage (Owusu, 2001).
As outlined by (Fadairo, G., Olotuah, A.O., 2013), three distinct identification of construction materials based on their production methods:

1) The traditional materials: these are non-manufactured materials locally available within the environment. These materials have been used for ages and can be locally produced and assembled using locally available tools. Traditional materials include bamboo, stabilized mud, straw, laterite, gravel, thatch, Raphia palm, etc.

2) Manufactured construction materials: These are industrially produced materials like cement, steel, PVC Pipes, and glass.
3) Innovative materials: These are materials manufactured through innovations as alternatives to conventional building materials. Examples of innovative materials include fibre-based concrete, and ferro-cement products.

2.2 Performance Indicators of Bamboo as a Building Construction Material

The evergreen and naturally available local construction material, bamboo, has been used by humanity for ages. For decades, it has been used as an available and readily replenishable building construction materials by low-income individuals of most developing countries. Traditionally, bamboo has been used as a construction material in Africa, South Pacific, East and South Asia (M.A Dos Reis Pereira, T.Q.F. Barata, 2015)**.** Compared to other native construction materials, bamboo has a circular cross section with varying diameter and usable heights. Because of its circular cross section and culm wall thickness, bamboo can be adopted for construction owing to its high tensile strength, height and compressive strength. This confirms the proposed usage of bamboo as building construction material. Also, the torsional and tensile property of bamboo can be used to absorb shocks from seismic and aerodynamic forces.

It is a fact that there are some bamboo buildings (some of them are relatively big and long spanned) erected around the world. In dealing with bamboo as a construction material, there are still many aspects that are not clear and established. The aspect of durability is also still raising the question of the anticipated construction of Engineering structures using bamboo as a construction material. Other aspects hindering usage of bamboo as construction materials are building codes, methods for testing, product standardization, and calculation procedures for structural members and joints. The main obstacle to the large-scale integration and application of Bamboo in structural Engineering is little information about its interaction with concrete, fire resistance and structural strength. In studies on the design process of those buildings, at a certain level, the engineering team applies a combination of experimental study, engineering judgments, and best practices experiences.

The growing infrastructure and construction industry has created a high demand for suitable building materials and products. The performance of bamboo and suitability as a structural material will be used to produce alternative structural member composites with standards, therefore reducing the over dependance on variable building materials. All attempts in bamboo research should aim at developing alternative structural elements for use in low-cost buildings. It seems evident that in using bamboo, every time one must find out its properties which seem to be difficult to apply on an actual worksite.

2.3 Innovations in Bamboo Industry

Traditionally, bamboo has been used for building construction in Africa, South Pacific, East and South Asia for thousands of years and still, it is a popular construction material for the construction of traditional bridges, erection platforms and scaffolds, and more recently in modern building constructions and walling aesthetic and many unique and conventional constructions around the world. Figure 2.1 below shows the construction of a foot bridge using Bamboo.

Figure 2.1, Left and right: Traditional innovation of the use of bamboo as a foot bridge.

Recently, innovations in the usage of Bamboo have outlined its potential to be adopted as for structural cladding and aesthetics, low-cost materials for construction compared to timber. More research in the Bamboo industry is anticipated to have a direct contribution to the growth of the construction industry in achieving very high "value addition" and utilization rates.

Figure 2.2 below shows Engineering innovations of joining Bamboo to be used as a structural member in Building construction.

Figure 2.2: Jointing and connections of bamboo culms.

Traditionally, bamboo has been used as fabric and flooring materials and more recently to fabricate unique furniture pieces, including beds, dining tables and chairs for living rooms. It is easy to produce and assemble, strong, long lasting, and cheap. The usage of bamboo blends local cultures and heritage of these unique natural resources and modern construction and furniture manufacturing. Figure 2.3 below shows the utilization of Bamboo for making Household furniture.

Figure 2.3: Bamboo usage as domestic furniture

Surprisingly however, the proposed structural use of Bamboo in building material construction is not being fully embraced by key professionals in the construction industry, including Architects, Structural Engineers and Quantity Surveyors. There seems to be over reliance on manufactured building materials on assumption that local materials cannot substitutes or be developed to have a comparative advantage. An understanding of the short comings of traditional materials and its salient characteristics, can guide in ways to use them with confidence and applying proven knowledge and skills (Cather, 2001).

2.4 Properties of Bamboo

Bamboo has some properties that determine its appropriate applications as a construction material. These properties also assist researchers, design engineers, architects, material scientists and other industrial users to know where to apply them. A review of the physical properties, mechanical properties, and critical structural equations for analysis of bamboo structures has become urgent for researchers in structural Engineering for standardization of testing procedures and development of codes for references.

2.4.1 Physical Properties of Bamboo

Bamboo is classified as grass family (Gramineae), sub-family ***Bambusoideae***, with over 70 genera divided into about 1,500 species over the world (Khalil, 2012). It can grow to heights ranging from a few centimeters to over 30m, with diameter ranging between 3 mm to over 25 cm. The plant has stems which are hollow but very strong, except for partitions at the nodes; these two qualities provide great popularity and usefulness of bamboo in everyday life. The main components of a bamboo plant include rhizomes, roots, culms, branches, leaves, and flowers. Compared to other plants, Bamboo It has a stem, branches, and leaves. The anatomically and morphologically difference between Bamboo and other plants is its hollow culms, no bark and year rings. At maturity period, bamboo does not increase in diameter. Figure 2.4 below shows the anatomical structure of the Bamboo plant.

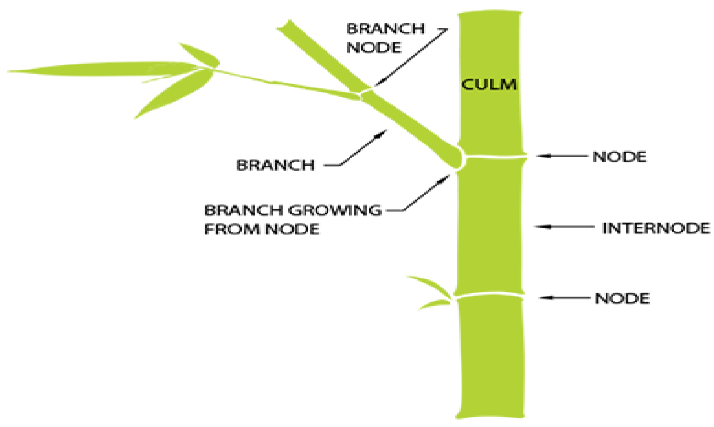

Figure 2.4: Bamboo Anatomical Structure.

The properties of bamboo in the longitudinal direction are completely different to that in the transverse direction, making it an anisotropic material. Longitudinally, bamboo is made of strong and stiff cellulose fibres. In its transverse cross section, bamboo consists of soft and brittle lignin. Being an anisotropic material, Bamboo can be considered as “mono-sided” reinforced with low torsional strength capacity.

Strength properties of bamboo have already been tested by researchers around the world and present outstanding results which are in many cases much superior to conventional building materials. However, building code standards require more than the strength properties of material alone, other properties to consider are durability, fire Safety, environmental Impact, user Safety, and energy efficiency.

2.4.2 Strength Properties of Bamboo

Strength tests on bamboo has been conducted according to **BS ISO 22157:2019 ISO 22157:2019** standards. Bamboo is an anisotropic material, having mechanical properties that vary in the longitudinal, radial, and transverse directions. Bamboo consists of many different species with different structural and mechanical properties. One single bamboo species can show very different test results depending on the age and moisture content of the tested bamboo pole, its origin (soil, altitude, climate conditions), and the part of the stem that is tested (bottom, middle or top part of the "tree"). Bamboo is a relatively stronger and lighter material. The strength of bamboo greatly depends on the Species being used, level of moisture content, culm diameter, culm wall thickness, inter-node distance, height section being used and age of the plant at the time of harvesting.

The compressive strength of culms increases with height while bending strength has the opposite pattern. Bamboo shrinks more than wood when it loses water. It shrinks in the cross sections between 10–16%, and the wall thickness is also about 15–17%. Bamboo has an enormous elasticity which makes it a suitable building material and is environmentally friendly for areas with quakes. Furthermore, bamboo has a relatively low weight and can be transported easily and utilized at any given distance across the globe. The strength properties of bamboo and its use in developing countries have led to its empirical use as reinforcement in concrete structures. For design purposes, the following strength test should be highlighted:

I. Bending strength test to predict the deflection.

II. Shear strength test to design joints and connection systems.

Bamboo Shear occurs parallel to the grain and perpendicular to the grain.

Despite these known strength properties, there is a growing concern about the adoption of bamboo in building construction industry. The mechanical performance study of bamboo-infilled concrete as a construction material is still inadequate. Also, the structural behaviour of bamboo is not quite understood as conventional construction materials, which results in difficulties to predict the performances of bamboo-infilled concrete as structural members. Critical properties such as fire resistance, strength properties, durability, etc., that affects the strength of bamboo are not yet fully disseminated; with no codes, standards and regulations readily available to Structural Engineers and building practitioners. There is therefore need for regulations and standards.

2.5 Global Distribution of Bamboo

Traditionally, bamboo has been used as a construction material in Africa, South Pacific, East and South Asia (M.A Dos Reis Pereira, T.Q.F. Barata, 2015) and by extension in the aesthetic and decorations. A hollow and woody plant, Bamboo plant is estimated to be in about 1,500 species over the world in about 70 genera covering an approximate area of about 22 million m^2. Most of these species are found in tropical and subtropical regions with good monsoon climate and water and heat conditions, and a few are grown in temperate and even sub-arctic regions. China, India, and Japan are the best countries for bamboo production. In European, there is no natural distribution of bamboo species. Britain, France, Germany, Holland, and other countries in Europe started the introduction and cultivation of bamboo and grow well. As shown in Figure 2.5, about 65% of bamboo are gowned in Asia (Paridah, 2013).

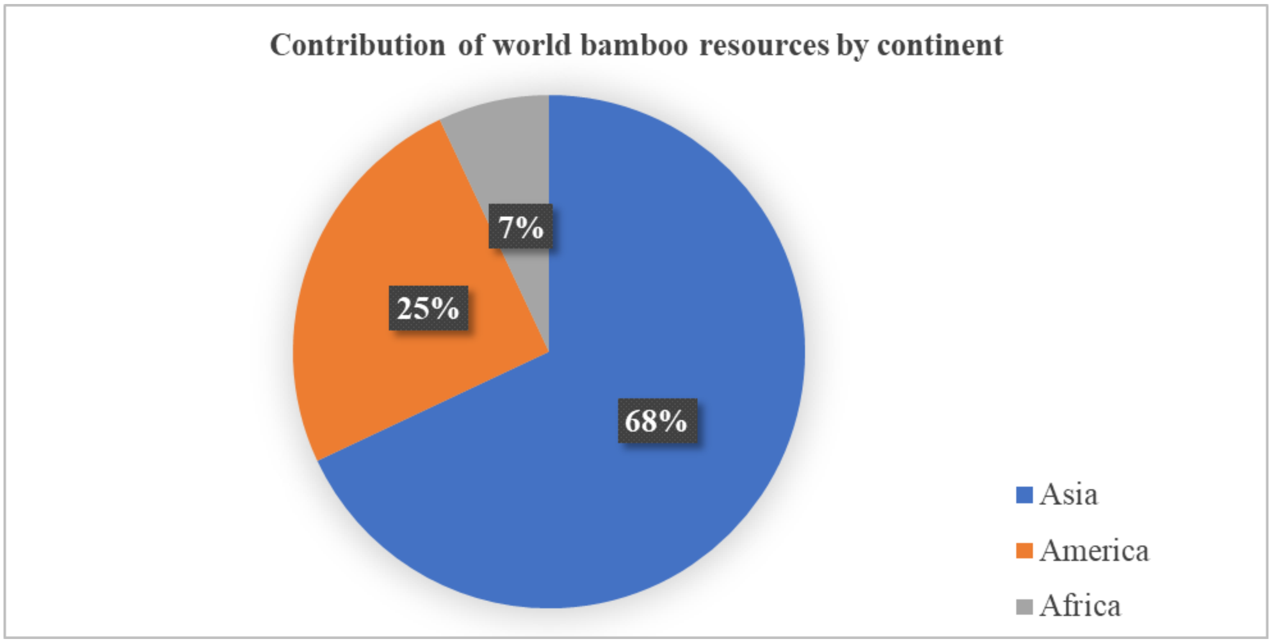

Figure 2.5: Contribution of world bamboo resources by continent

2.6 Suitability of Bamboo in the Construction Industry

Because of those unique characteristics, the construction industry always tends to keep an eye on bamboo as a construction material. With infrastructure development sustainability of construction materials has become a key issue in the last years. Extreme industrial processes and high Costs of production has been associated with environmental degradation related to the manufacture of non-renewable material. Relatively, some of the Problems associated with the commonly manufactured building construction material like cement and steel around the globe, putting much pressure on the environmental due to load of building materials. The building industry is now known to be one single factor causing a considerable part of the annual environmental damage and thus can be assumed to take up the responsibility contributing to sustainable development. Finding a more environmentally benign ways of construction and building becomes quite urgent. One of the directions for solutions is to look for alternative building material with urge for easy recycling, reuse, low pollution production, or use of replenishable resources.

The suitability of bamboo as a constructional material can be summarized as shown in Figure 2.6 below.

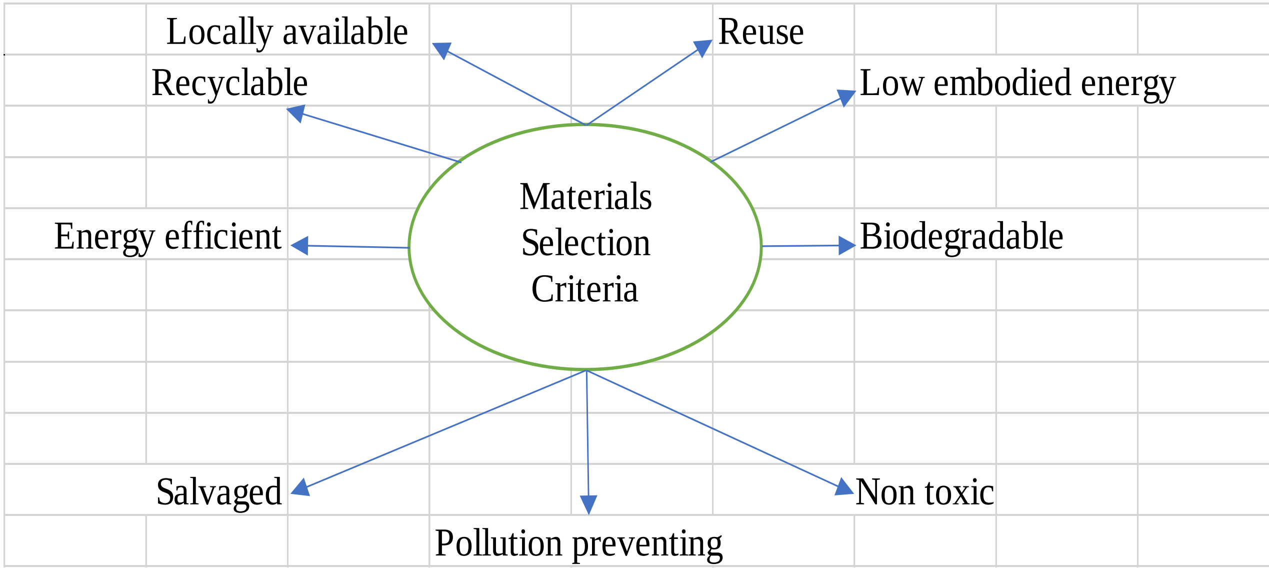

Figure 2.6: Diagrammatic illustration of the Suitability of bamboo in low-cost and environmentally friendly Civil Engineering works.

Even though bamboo has such unique characteristics it is not being used on a mass scale. The proposed adoption for its widespread use to substitute conventional building construction materials like steel and concrete should be addressed by builders, Engineers, and researchers.

2.7 Sustainability of Bamboo in the Construction Industry

Conventional usage of Concrete and steel for building construction is becoming expensive, considering increasing world population and need for more housing units, making the demand and cost of construction materials for building to grow exponentially. With increasing population in towns and cities therefore, it is a concern consumer affecting demand, putting more pressure on global natural resources. The cost of production of these materials is constantly rising. Such construction requires good quality assurance and management, with skilled and experienced personnel to manufacture to prepare and assemble different components, for a safe and robust building component. These make housing constructions in concrete and steel very expensive and unsustainable for many low-income individuals. It is therefore necessary to explore innovations of using bamboo as a cheap, readily available, and sustainable material as building materials instead of the conventional use of concrete and steel. Besides, the Housing shortage world over due to the rising unaffordability of conventional building materials makes it logical to consider alternative technologies and research on different materials for their application in construction. Increased demand per capita is causing three main interrelated environmental problems:

I. Resources depletion,
II. Environmental deterioration
III. human health concerns, and
IV. environmental degradation

Given the current demand for low-cost constructions, the sustainability of bamboo in building constructions is appreciated by the following:

1) Accessibility

With increasing demands for new buildings, the demand for concrete and steel reinforcement products as construction materials is increasing. However, as the cost of conventional construction in concrete and steel is increasing, it is therefore necessary to exploit the opportunity for new building materials other than of traditional use of conventional building materials like concrete and steel. In addition, properties such as faster growth rate, renewability, biodegradability, and carbon sequestration comparable to that of wood makes bamboo to environmental characteristics vital to alleviate the effect of climate change. Bamboo can grow completely within short time duration and can be harvested within a period of between 4 to 7 years (Ashby, 2016). It grows almost anywhere around the world and can be considered a cheap material for Building construction. Bamboo is a sustainable natural material which has unique and important characteristics when compared with other timber. Bamboo is considered an eco-friendly material accessible to all.

2) Serviceability

The use of bamboo which is fast growing and ecologically friendly material for structural applications is being considered quite appropriate. The tensile strength of bamboo is quite high and can reach up to 125 MPa. This makes bamboo an appropriate alternative to steel in tensile loading applications. Bamboo has excellent mechanical properties.

3) Workability

The cost of modern building construction is increasing, putting high demand on resources concrete and steel reinforcement products used as building materials. With increasing cost of these materials, it is becoming necessary to explore alternative new building materials instead of traditional utilizations of concrete and steel reinforcement.

The interrelation of the different aspects of bamboo sustainability in the construction industry is shown in the Figure 2.7 below.

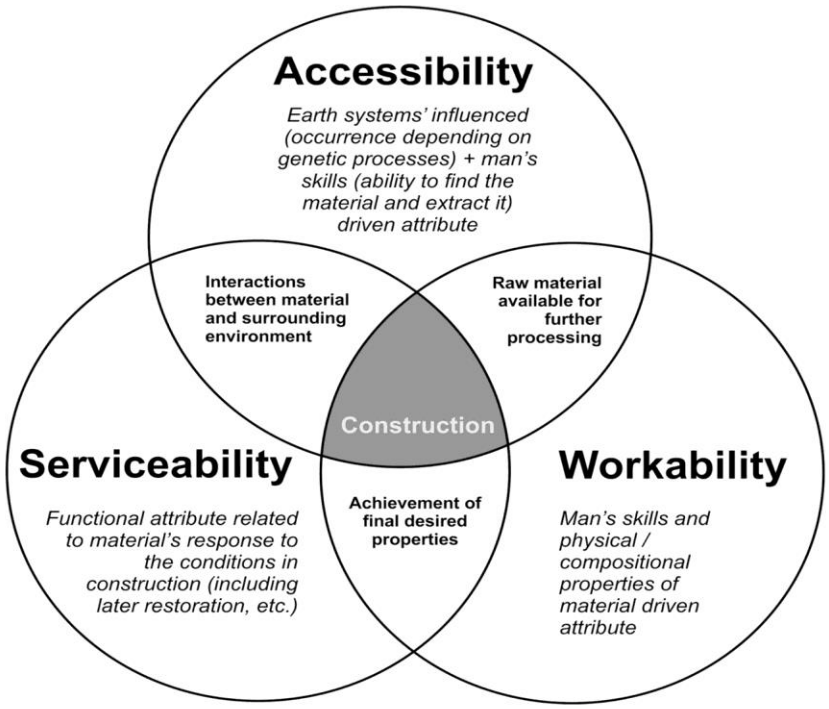

Figure 2.7: Sustainability of bamboo in construction.

2.8 Advantages and Disadvantages of Bamboo

Previous research on bamboo has revealed structural and mechanical properties of importance that could enhance research and innovations for new construction materials. These properties include:

I. Superior structural strength in bending, compression, and shear, which makes bamboo use ideal and suitable for low-cost construction.
II. Its circular form and hollow sections make bamboo a light building material**,** which is easy to handle, transport and store. Another advantage of the circular shape of bamboo

makes it ideal for it to be used in combination with other types of construction materials, like reinforcing steel and concrete as a composite material.

III. In each of its nodes, bamboo has a dividing or transverse wall that maintains strength and allows bending thus preventing rupturing when bent. Because of this characteristic bamboo construction offers superior earthquake-resistance

Bamboo has been used in construction for decades because of the following advantages:

I. Tensile strength: Bamboo has higher tensile strength than steel because its fibres run axially.
II. Fire Resistance: The capability of bamboo to resist fire is very high and it can withstand temperatures up to 4000 C. This is due to the presence of a high value of silicate acid and water. The property of high silicate acid by bamboo makes it have an abnormal flame resistibility.
III. Elasticity features.
IV. Low weight allowing easier for transportation and construction.
V. Unlike other building materials like cement and asbestos, bamboo poses no danger to health.
VI. Bamboo is easy to cut, handle, repair, reposition and maintain, without the need for sophisticated tools or equipment, quite cheap and easily available in ample quantity.
VII. Bamboo is non-polluting and does not have crusts or parts that can be considered waste.
VIII. The natural surface of the bamboo is smooth, and clean, with an attractive color which does not require painting, scraping, or polishing.

However, some disadvantages that makes the effective use bamboo in the construction industry not feasible in conventional construction includes:

I. The bamboo nodes possess the point of structural weakness. The weakness of bamboo perpendicular to the fibres makes hollow bars prone to crushing or splitting during transportation, handling, and erection. Bamboo bars must be handled with additional care not required for steel bars.

II. There is no known research addressing methods of splicing or the behaviour of splices in bamboo reinforcing bars. Like steel, bamboo bars are practically limited to about 6 m in length. Bamboo has its natural shape, which is not uniform, tapering with height.
III. Bamboo construction has no detailed codes.
IV. Bamboo is easily attacked by fungi and insects.
V. Its behaviour at elevated temperatures or in fire conditions is unknown.
VI. Bamboo is known to creep under the effects of sustained loads.

Bamboo has irregular dimensions and inhomogeneous material structure and thus is not easy to be processed by machines and is incompatible with the standardized industrial connecting components. Moreover, bamboo's easily split canes are difficult to be treated with nails and screws which are normally used for wood. Such shortages restrict the use of bamboo in the industrial context.

2.9 Durability of Bamboo Structures

Rot and deterioration directly are the main concern relating to the durability of bamboo, making it to be considered a ***"Poor Man's timber"***. Many bamboo structures do not last and will deteriorate in as few as 3-6 months following construction. (Kaminiski, 2016). Durability of bamboo structures depend strongly on the preservative treatment methods following basic requirements and their chemical composition. This will also depend on the level of maintenance medium which includes prompt response to leakage from the roof, prohibition of crack propagation, bolt tightness, regular waterproofing and the type of waterproof material. Species, culm length, culm wall thickness and culm age during harvesting greatly influences the durability of bamboo structures.

2.9.1 Bamboo Insect Infestation

Compared to timber, Bamboo is more susceptible to decay (Janssen, 2000). Unlike timber varieties, bamboo has no toxic deposits to attract insects and beetles. This makes thinned walled bamboo culm prone to rot and insect infestation and biodegradation, affecting its durability. There are three causes of decay:

I. Beetle attack
II. Termite attack and
III. Fungal attack (rot).

Powder post beetles are known to bamboo culm, leaving only a thin outer shell with their Larvae surviving on starch and sugars in the parenchyma cells found in the culm.
Figure 2.8 shows a Beetle Bored Bamboo Culm.

Figure 2.8: Bamboo culm bored by beetle.

Often attack becomes visible only at a late stage of deterioration, when wood termites build their nests inside the bamboo culm parts after boring. Termites attack bamboo mostly at the section in contact with the ground and extends upwards with gnawing inside the bamboo culm. Termite-resistant concrete, steel, or masonry foundation can act as appropriate barrier for termites' infestation from the ground. Figure 2.9 below shows termites infested Bamboo culms.

Figure 2.9: Bamboo attack by termites

The large amount of starch present in bamboo makes it highly attractive to mould and fungi, termites, and powder-post beetles. They cause much damage during drying, storage, and subsequent use. Ideally, untreated bamboo last between 2-6 years internally, and not more a year if exposed to water (Kaminiski, 2016).

2.9.2 Preservation of Bamboo

There are various methods for treating of bamboo to enhance its durability. The choice of these methods can be guided basing on:

I. State of bamboo; green or dry
II. The anticipated durability period expected of the bamboo structure.
III. The shape of the bamboo to be treated.
IV. Level of exposure of the bamboo to weather
V. Proposed use of the bamboo
VI. Scale of Operations of the treatment plant
VII. Availability of resources (machinery, chemicals, time.)

Treating bamboo can increase its service life radically, to the extent that there is no distinguishable life limit when well-treated and used in a well-protected manner. the treatment of bamboo serves as an effective and affordable option for increasing its durability and longevity. For all bamboo and timber constructions, longevity is assumed to depend on the species, thickness, length, and age during harvesting.

To avoid decay and improve longevity, two design principles can be taken:

1) Durability by design, taking into consideration elevation of the structure above the ground, applying damp-proof membranes, good drip details, good roof overhangs, and waterproof coatings for the walls.

2) Protection against insects and termites as appropriate.

Both principles can be applied as one might be inadequate to protect against rot. As shown in Figure 2.10 below, chemical treatment can get washed out if exposed to water (Kaminiski, 2016).

Figure 2.10: Boron-treated bamboo culms splitting and bleaching when exposed to sun and rain.

It should be noted that curing methods ensure satisfying results though with uncertainties about the advantages. Bamboo treated using Boron for some times with promising results. Its only shortfall is being toxic for the treatment workers and the end user. It is therefore less appropriate for developing countries, where bamboo is currently mostly used. Copper azole is being used to substitute the use of boron.

Traditional bamboo treatment, like placement in water and exposure to smoke provide very limited protection against beetles. There is little evidence to show they are effective against termites and rot and are therefore it cannot be adopted in modern construction.

Even with treatment and curing, whole bamboo or split bamboo should receive a waterproof coating to reduce the ingress of water and therefore its swelling. Without coating, bamboo culm might swell and damaged. Different types of coating materials are available as preferred. Native latex, coal tar, paint, dilute varnish, and water glass (sodium silicate) are other suitable coatings.

2.9.3 The Importance of Bamboo Preservation

Most counties where bamboo is being used for construction a lack knowledge on treatment and preservation of bamboo. Most bamboo structures in rural areas are untreated. Early harvesting, or use of the wrong species makes the structures to deteriorates within a short period of time. This circle of failure from harvesting to construction and deterioration seems to be the major reason why bamboo is still considered a *“**poor man's timber”.*** Lack of professionals and treatment facilities exacerbates the already little knowledge on the need to preserve bamboo. This highlights the incorrect use affect the importance of bamboo, but it also puts heavy pressure on the resource, since frequent replacement is necessary.

2.9.3.1 Traditional Methods of Preservation of Bamboo

There are common simple and cost-effective methods in the treatment and conservation of bamboo without the use of chemicals or any special equipment. The following are some of the traditional methods used for the preservation of bamboo.

I. Curing Method: cut bamboo culms are stored in shade by stacking to allow aeration between the stacked bamboo. The aeration leads to loss of starch contents in bamboo culms.
II. Smoke Treatment: The Process of Smoke treatment of bamboo allows a layer coating of soot to cover the culms.
III. Water Soaking Method: Bamboos are placed on stagnant or running water or water ponds from a few weeks to a few months to leach out the starch, sugar and other water-soluble contents.
IV. Heat Treatment Method: Bamboo is exposed to heat in this method by baking or torching them. This method is very useful for the straightening of bamboo.

2.9.3.2 Chemical Methods of Preservation of Bamboo

Tradition method of bamboo preservation is not effective with very short period before the culms decay. Chemical preservation employs special equipment with effective absorption for long-term protection. Chemical preservatives can protect bamboo against biological attacks and degradation, though their selection and application should be carefully employed, owing to the health hazards and environmental safety requirements.

Two different types of chemical preservation of bamboo can be employed namely, non-fixing and fixing-type preservatives. With non-fixing preservatives, the bamboo leaches out when exposed to rain. This chemical treatment is not ideal for structures suited outdoor. The chemicals consist mainly of boron salts dissolved in water, which are effective against borers, termites, and fungi (except soft rot fungi). After treatment, the water evaporates leaving the salts inside the bamboo. Curing bamboo with borax and boric acid is the most popular bamboo preservation method (for indoor use) around the world because it is effective and more environmentally friendly than other wood preservatives (Ya-Mei, W., Xi-Ming, W., Jun-Liang, L., 2011).

2.10 Fire Resistance of Bamboo

Fire resistance of bamboo is one of the aspects that have not yet been stated clearly. It is kind of similar to some requirements for wooden nonstructural elements. No standard test has been established for bamboo. The behaviour of bamboo when subjected to fire is quite similar to timber, charring at a slow and predictable rate, assumed at approximately 0.6mm/minute. Like timber, bamboo is also a poor conductor of heat. When bamboo plants or stalks are in a dried state, they are very flammable. This is also true when bamboo is green. Bamboo has an internal membrane that is combustible. Therefore, it is important to study the fire behaviour and flame-retardant properties of bamboo.

2.11 Concrete

Concrete can be taken as one single most important component used in civil engineering constructions activities. Structural members like beams, columns, slabs, foundations are constructed using concrete, either pre-cast or cast insitu. Vital ingredients for the manufacture of concrete includes cement, water and aggregates (sand and coarse aggregates). Following the mixing protocol, concrete can be manually mixed of mixed in a concrete mixer. After placing, the concrete is compacted and cured as it hardens. Concrete strength is known to increase with age. (Neville, 2011)

2.11. Concrete Ingredients

Sand, coarse aggregates, cement and water, are convention ingredients for the production of concrete, with additives and admixtures added to improve its strength and properties as deemed necessary. Proportion and ingredient properties are the factors that determine the strength and durability of concrete.

2.11.1 Water

Water is a necessary ingredient in concrete to allow hydration process and binding of other constituent concrete ingredients (Neville, 2011). Relatively, the strength of concrete is linked to the water cement ratio during concrete mixing. Water is also used for concrete curing after placement. It has been experimentally proved that water cement ratio defines the degree of concrete strength, with concrete curing attributed to production of high-quality concrete.

2.11.1.2 Portland cement

Portland cement is one of the basic ingredients of concrete production. It is used to form a paste when mixed with water and aggregates. It is manufactured through closely controlled chemical combination of calcium, silicon, aluminum and other ingredients. When mixed with water, heat is released through a chemical exothermic reaction (Shirke, 2014).

2.11.1.3 Aggregates

Aggregate is an inert concrete material used as fillers, occupying between 65 to 75% of the concrete volume (Neville, 2011). Fine aggregates, also commonly known as sand or crushed stones should have grains not passing through the number 4 sieve. Find aggregates also include clay and silt, though it is not ideal to be used for concrete production. Coarse aggregates include particles measuring above the 4.75mm sieve limit. Coarse aggregates can be gravel or crushed/processed natural stone. Concrete grade is typically improved by using quality fine and coarse aggregates with a designed amount of water needed for a concrete mix (Ali, 2014).

2.11.3 Concrete Design Mix

Desired workability, strength and durability of concrete depends on the water cement ratio, quality and quantity of coarse and fine aggregates, type of cement with admixtures if any in their designed proportions. Water cement ration defines the strength and concrete quality in a freshly mixed concrete. The quantity of water determines the workability, and the anticipated rate of concrete hardening and designed durability. Different methods with empirical relationships, graphs and charts are available for reference during constitute mix design. American Concrete Institute (ACI) and British Research Establishment (BRE) are the two methods commonly used in designing mix for concrete.

2.14 Chapter Summary

Infrastructure sector is one single greatest contributor to the development of any country, with building materials taking over 35% cost of construction. With constructions and infrastructure sector taking center stage for the development of the country, the demand on the conventional construction materials will exponentially grow.

Traditionally, bamboo has been used as a construction material in Africa, South Pacific, East and South Asia for thousands of years and still, it is a popular construction material. Structurally, Bamboo has been used for ages as a building material, construction of traditional bridges, erection platforms and scaffolds, and more recently in modern building constructions and walling aesthetic and many unique and conventional constructions around the world.

Innovative building construction materials like the usage of bamboo should alleviate the seeming over-dependence on conventional constructions in steel and concrete, coupled with rising cost of its production. This will also arrest the current global warming and environmental degradation that accompanies the production of cement and steel. Once regarded as ***'poor man's timber'*** is now being dubbed Green Gold for its vast environmental benefits such as alleviating pressure on tropical forests thereby mitigating climate change, curbing deforestation and being enhanced and used as structural members in buildings.

Because of those unique characteristics, the construction industry always tends to keep an eye on bamboo as a construction material. With infrastructure development sustainability of construction materials has become a key issue in the last years. Problems associated with the industrial processes and manufacture of building construction material like cement and steel around the globe includes rise in cost, environment degradation and pollution. This has made the building industry as one sector causing a considerable environmental pollution.

CHAPTER 3: METHODOLOGY

3.1 Introduction

A detailed explanation and processes of the various steps undertaken during the study is highlighted in this chapter. The research methodology outlines the sourcing of bamboo samples, samples preparation and determination of general properties of concrete: its constituent materials, sieve analysis and concrete cubes crushing strength test for the designed concrete grades, concrete infilled bamboo samples preparation and crushing of plain bamboo and concrete infilled bamboo to determine its compressive strength.

Methodology of this study aimed to deduce results of vital structural parameters for the utilization of bamboo composite in the building structure field as a green building material. The explored methodologies for experimental studies on the structural properties of natural bamboo-infilled with concrete in comparison to that of plain bamboo provide measured results that would guide for the use of bamboo as structural members in buildings. Compressive strength tests were performed to investigate the failure load capacity of plain bamboo and bamboo-infilled concrete. The compressive strength results may guide more in adoption, with innovation for the use of bamboo in building constructions.

To study the structural performance of plain bamboo and concrete infilled bamboo in compression, several samples of different lengths were analyzed. The independent variables of the experimental study were:

I. Plain Bamboo at samples lengths; and
II. Different Concrete classes infilled Bamboo at the lengths of the corresponding samples.

The Dependent variable was the compressive strength of the plain bamboo and Concrete-infilled Bamboo columns. The influence of these variables on the mechanical (compressive strength) of plain bamboo and concrete-infilled bamboo with different concrete grades was experimentally assessed.

3.2 Experimental Set-up (Research Design)

Through laboratory experimental investigations, several specimens of plain bamboo and bamboo filled - concrete columns at different sample lengths were subjected to axial compression. The concrete materials mixing for the experiment was conducted within Civil Engineer Construction materials laboratory-College of Engineering, Design, Art, and Technology (***CEDAT***) of Makerere University, Kampala. The research methodology was taken as outlined in the flow chart in Figure 3.1 below.

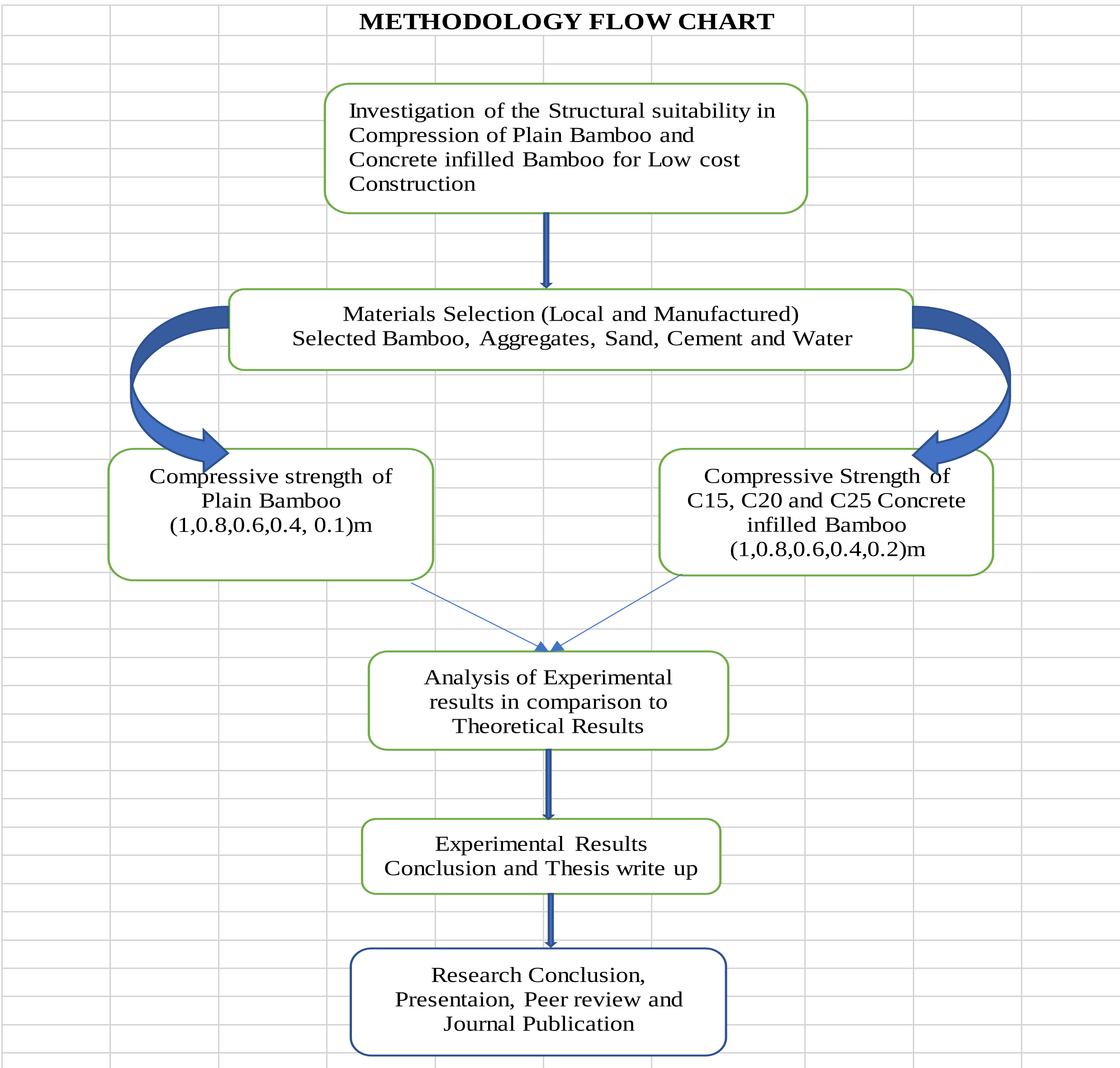

Figure. 3.1: Methodology flow chart

3.2.1 Research approach

An experimental program was designed to investigate the effect of different concrete grades on the compressive strength properties at different Bamboo sample lengths. A total of 4 samples of Bamboo at lengths of (0.2, 0.4, 0.6, 0.8 and 1) m were prepared for plain Bamboo and concrete-infilled Bamboo with different concrete grades (C12/15, C16/20 and C20/25) and tested to determine its compressive strength.

3.2.2 Sample coding

To ease identification throughout the research process, Bamboo samples were assigned a unique identification code typical of the sample lengths and class of concrete; for example, Plain bamboo and concrete-infilled bamboo at bamboo sample length 1m was assigned codes 1, 2, 3 and 4 for the four samples for experimental analysis in compression.
Table 3.1 presents the corresponding Plain Bamboo and concrete-infilled bamboo sample lengths and concrete classes.

Table 3.1 Plain Bamboo and concrete-infilled bamboo sample lengths and concrete classes

Parameter	Bamboo Sample Length (M)	Plain Bamboo Samples	C12/15 Concrete-infilled Bamboo samples	C16/20 Concrete infilled Bamboo Samples	C20/25 Concrete infilled Bamboo Samples
Compressive strength	0.2	4	4	4	4
	0.4	4	4	4	4
	0.6	4	4	4	4
	0.8	4	4	4	4
	1.0	4	4	4	4

3.3 Samples Collection

3.3.1 Materials

The materials used were Bamboo Culms, cement, coarse and fine aggregates, and water.

3.3.2 Selection of Bamboo Culms

Selected bamboo species within Uganda were sourced for the experiments. The culms selection was representative of the sub-regions of Uganda where bamboo growth is known at the commercial level. This was deliberately done such that the total test results would be used to appreciate the variation in the test results of the samples. Figure 3.2 below shows the selection and cutting of Bamboo culms for the research experiments.

Figure.3.2 Left: Examining the Bamboo for Selection and Right: Cutting the bamboo samples at desired length for transportation to the Laboratory for the experiment.

Bamboo culms was randomly selected from different clumps got from different localities. Great emphasis was made on the diameter of the bamboo; approximately 100mm in diameter, symmetrical uniformity of the diameter at the proposed cutting lengths and the age of the bamboo species. As shown in Figure 3.3 below, the cut Bamboo culms were transported for curing, samples cutting to the desired length and node opening.

Figure 3.3: Bamboo samples transportation.

The Bamboo selected for the research was ***Bambusa Vulgaris*** (commonly known as Golden Bamboo). Bamboo samples were sourced from Kasese, Hoima, Kikuube and Masindi Districts.

All samples were between 5-7 years old, and not less than 100mm in external diameter. Broken, damaged and discoloured culms were discarded. Bamboo samples were taken from the districts above because the species would present similar properties for the experiment since the different localities have similar weather condition that would present similar growth conditions for the bamboo.

3.3.2.1 Tools and Equipment for Bamboo Sample Preparation

The selected bamboo culms were cut to sizable lengths using a panga knife that would allow transportation from the farm to the laboratory using a vehicle. These culms were then cut to the required test lengths.

The sourced bamboo was cut in the experimentally designed lengths measured as 1m, 0.8m, 0.6m, 0.4m and 0.2m. A calibrated tape measure and cutting device using a hand saw was used to cut the bamboo culms. As shown in Figure 3.4, the Bamboo Culm nodes were opened by boring through the nodes with a sharpened steel reinforcement bar to create a hollow cylindrical and circular section for concrete infill.

Figure 3.4: Cutting the bamboo samples to the desired lengths and Right: Opening the bamboo Culms using an improvised chisel and hammer.

3.3.2.2 Bamboo Samples Curing

Green Bamboo contains starch and sugar, making it susceptible to attack from insects, termites, borers, powder post beetles, and fungi decay. The treatment of bamboo was vital to increase its longevity by protecting the bamboo from insect attack. The pre-treatment of bamboo serves as an effective and affordable option for increasing its durability and longevity. Species, wall thickness, culm length, and age of the bamboo being used are some factors that affects the actual longevity may of bamboo.

Physical method of Curing Bamboo culms

The curing of the bamboo samples was done in a temporary shade made using plastic sheeting. care was taken to:

I. Keep the culms away from direct soil.
II. Avoid direct sunlight.
III. Ensure proper air ventilation between the culms while drying.

The bamboo culms were stacked horizontally. The culms were rotated every day to ensure uniform drying.

Chemical Treatment of Bamboo Culms

Availability of resources and machinery, and hazards related to other known chemicals like Boric acid limited the pre-treatment options to known chemicals using an anti-termite chemical shown in Figure 3.5 below.

Figure 3.5: Anti-termite chemical used for the treatment of bamboo samples.

The anti-termite solution used was an organophosphate-based broad-spectrum insecticide containing chlorpyrifos 480gm per litre as an active ingredient. This known chemical has been effectively used as a fungicide and insecticide for the preservation of timber against termite infestation. 200ml anti-termite solution was mixed with 20 litres of water. The solution had Bamboo soaked for one day before drying on a rack within a room temperature for one day and delivery to the laboratory.

The effectiveness of this chemical treatment was experimented by exposure of the bamboo samples not treated and that was soaked in the solution to termite infestation. After 1 week of exposure, the one soaked in the anti-termite solution was not infested with termites. The analysis of the level of infestation gave an appropriate treatment option.

3.3.3 Cement

Type I Ordinary Portland Cement (OPC) was used for the different concrete classes as infill in bamboo. For this research, CEM II 32.5N - OPC, manufactured by Tororo Cement Limited was used.

3.3.4 Aggregates

Crushed aggregates were obtained from China Railways seventh Group (CR7G) project site at Howa Quarry-Kikuube District. For this research aggregates not exceeding 19 mm.

Sand (25% crushed sand (quarry dust) and 75% Lake sand) were obtained from CR7G quarry site and Gabba Beach respectively.

3.3.5 Water

Ordinary portable water was obtained from National water and sewerage corporation tape stand at Makerere University materials Laboratory was used.

3.4 Material Tests

3.4.1 Test on Cement

The cement used for the experiment was of class CemIV/B 32.5N, manufactured by Tororo Cement Ltd. Physical, Chemical and Strength tests were conducted at China Railways Seventh

Group (CR7G) materials laboratory at Howa-Kikuube District and are summarized according to the test procedures and specifications in the Tables below.

3.4.1.1 Physical Test

The physical Test of Cement was conducted according to the Test reference shown in Table 3.2 below.

Table 3.2: Specification and reference for Physical Tests Procedure

S/No	Test	Unit	Test Reference
01	Initial setting time	Minutes	EN 196-3:2005
02	Final setting time	Minutes	EN 196-3:2005
03	Consistency	%	EN 196-3:2005
04	Soundness	mm	EN 196-3:2005

3.4.1.2 Chemical Test

The Chemical Test of Cement was conducted according to the Test reference shown in Table 3.3 below.

Table 3.3: Specification and reference for Chemical Tests Procedure

S/No	Test	Unit	Test Reference
01	Chloride content as Cl^-	%	EN 196-2:2005
02	Sulphate content as SO_3	%	EN 196-2:2005

3.4.1.3 Strength Test

Table 3.4: specification and reference for Strength (Mortar Prism) Tests Procedure

S/No	Test	Unit	Test Reference
01	7-days strength	Mpa	EN 196-1:2010
02	28-days strength	Mpa	EN 196-1:2010

3.4.1.4 Tests on Course and Fine Aggregates

The physical properties that were useful for mix computations were aggregate type, sieve analysis, specific gravity, absorption, moisture content and unit weight. Tables 3.5 and 3.6 shows the sieve analysis specification for fine and coarse aggregates that were used for the Concrete design.

Table 3.5: Grading Reference of Fine Aggregates (CR7G-Howa Quarry)

Percentage Passing, (%)								
Sizes (mm)	Sieve size	4.75 No.4	2.36 No.8	1.18 No.16	600 No.30	300 No.50	150 No.100	75 No.200
	ASTM C33/C33M-18, (2018)	95~100	80~100	50~85	25~60	5~30	0~10	0~3.0

Table 3.6: Grading Reference of Coarse Aggregate (CR7G-Howa Quarry)

Aggregate Sizes	Percentage Passing (%)					
	Sieve size	19	12.5	9.5	4.75	2.36
	ASTM C33/C33M-18, (2018)	90- 100	/	20-55	0-10	0-5

Table 3.7: Physical properties- coarse and fine aggregates (CR7G-Howa quarry)

Test Item	**Specification**
	ASTM C33/C33M-18, (2018)
Fineness modulus, FM	2.3~3.1
Water Absorption %	≤3
Saturated surface dry apparent density, (g/cm3)	(sand) ≥ 2.5
	(Agg.) ≥ 2.55
Mica content (%)	≤ 2
Fines < 0.075 mm (%)	≤ 3
Flakiness Index, %	< 25
Elongation Index, %	

3.5 Concrete Mix Design, Compaction, Finishing and Curing

The Nominal concrete mix design selected for concrete-infilled bamboo was C12/15, C16/20, and C20/25.

3.5.1 Concrete Mix Design Preparation

Concrete mix was prepared based on philosophy that concrete should provide both adequate durability and strength of the structure. Conventional concrete materials: Sand (quarry dust and lake sand) and aggregates were obtained from China Railway seventh group (CR7G) quarry site for the ongoing road construction works at Howa-Kikuube District and Gabba Beach-Kampala. Tororo Cement, of strength class 32.5N manufactured by Tororo Cement Limited, was used for the experiment. Water used for concrete mixing was sourced from National water and sewage corporation tap stand at Makerere University Material Laboratory.

3.5.2 Mixing Protocol

The mixing protocol for plain concrete complied with (ACI 211.1-91, 2002), provides two methods of mixing: (1) Wet mixing (applies to hand mixing), and (2) Dry-compacted mixing. The wet mixing protocol was adopted for the study.

During mixing of concrete, the following precautions were considered.

I. Mixing protocol: the mixing protocol was Sand-Cement-Aggregates-Water.
II. Mixing time: Mixing of sand and cement was done over a period until the formation of a homogeneous composite.

3.5.3 Concrete Materials Mix Proportions

Appendix A shows Tables with the summary of the values computed concrete mixes following procedures in the manual for the standard used for plain concrete (ACI 211.1-91, 2002).

3.5.4 Production of Trial Mix

A trial mix for concrete materials proposition was conducted before final casting of concrete as infills in bamboo. 4 concrete cube samples measuring 150mmX150mmX150mm was cast, cured and crushed after 7, 14 and 28 days. Procedures outlined in BS and ASTM was used for

Concrete mixing. The concrete mixing protocol included Sand and Cement mixed to uniformity, coarse aggregates and water.

3.5.5 Slump Test

Tests on fresh concrete were conducted to ensure adherence to research quality requirements. The checks that were done include: slump, ambient temperature and concrete temperature measurements. Reference was made to ASTM C143/C143M-20, (2020) for slump test on concrete mix.

Slump test aimed to check that the concrete mix is ideal, workable, cohesive, and easy to place and compact. These properties were achieved by trial and error with the selected Concrete materials. Workability was assessed by use of a slump test, and this was useful in arriving at a suitable mix. A conical metallic Mould, placed and anchored on the larger diameter base was filled with concrete in three layers. Tamping of the concrete layers and sides of the mould was done with rod. After carefully removal of the cone, conical shaped molded concrete was realized. As shown in Figure 3.6 below, the height difference between the mould and the concrete cone was measured to give the slump.

Figure 3.6: Performing slump tests for the concrete mix design.

For this research, a normal strength mix and a workability test were a guide to the water content of the mix, and therefore its strength, as well as a measure of the fluidity of the mix.

3.5.6 Concrete Strength Test

A trial mix for concrete materials proposition was conducted before final casting of concrete as infills in bamboo. 4 concrete cube samples measuring 150mmX150mmX150mm was cast, cured and crushed after 7, 14 and 28 days. To prevent the adhesion of concrete, moulds were lubricated on the interior surface. The concrete cubes were then cured for 28 days by placing them on stagnant water pool. After 28 days, concrete cubes were crushed to determine its compressive strength.

Compressive strength test standard procedures prescribed in BS EN 12390-3 (2009). A Universal Testing Machine (UTM) of 3000 KN maximum capacity was used. Standard cubes with dimensions 150 mm conforming to BS EN 12390-1 (2012), were tested at 14 and 28 days. Samples were tested with the loading rate maintained within the range of 0.6 ± 0.2 MPa/s, corresponding to 9 ~ 18 KN/s. The crushing load recorded in (KN) was used to calculate the compressive strength of concrete using equation below.

$$f_c = \left(\frac{P}{bd}\right)$$

Where; f_c- Compressive cube strength (N/mm^2); P- failure load (N), b- width, and d - depth; all in mm.

Figure 3.7: Preparation and curing of concrete cubes for compressive strength test.

3.6 Casting and Curing of Concrete Infilled Bamboo

The designed concrete mix ration was then cast on the cut lengths of the bamboo as infills. Compaction of the concrete in the bamboo was done by reinforcement bars and tampering of the bamboo walls to allow full compaction. As shown in Figure 3.7 below, the bottom of cut bamboos were covered with a metallic plate as concrete casting and compaction was ongoing. The cast concrete as infills in bamboo were cured at the exposed ends of the concrete using a moist cloth.

Figure 3.8: Casting designed concrete mix into the hollow bamboo. Left: Cast concrete setting in the hollow bamboo before curing.

3.7 Laboratory Test Procedure

Complex equipment and instrumentation used for research in bamboo are available to only a handful of bamboo researchers and institutions. The compressive strength tests of Plain bamboo and concrete-infilled bamboo were limited by access to complex test apparatuses. Nonetheless, testing using UTM following the test reference was adopted to allow repeatability and minimize inter-laboratory movement to the greatest extent possible. A compressive strength test using the UTM method was adopted taking into consideration:

I. Minimal specimen preparation using readily- available hand tools.
II. Test procedures that do not require a complex test apparatus; and,
III. Applying compression forces.

The compressive strength test on plain bamboo and concrete-infilled bamboo was performed with reference to ***BS ISO 22157:2019.***

3.7.1 Compressive Strength Test: Clause 10: *BS ISO 22157:2019*

Compression tests parallel to the fibre were made on the test specimens. The plain bamboo and concrete-infilled bamboo specimens were placed such that their axis is aligned with the loading axis of the UTM.

As shown in Figure 3.8, between both the steel plates of the machine and both ends of the specimen, an intermediate layer was placed to minimize friction and provide radial restraint at the specimen ends. A small load was applied to seat and hold the specimen in position. The end planes of the specimen were made parallel to each other and perpendicular to the long axis of the specimen.

The maximum applied load, at which the specimen fails, was recorded.

Figure 3.9: Conducting Compressive strength Test on the bamboo infilled concrete samples.

3.8 Presentation of Test Results

The test results from the UTM Scale guage were preseneted in the table below.

Table 3.8: Table used for Recording Laboratory Test Results

Sample Code	Sample Diameter *De* (mm)	Sample wall thickness *t* (mm)	Average sample Diameter *De* (mm)	Average sample wall thickness *t* (mm)	Sample Area (mm^2)	Failure Load (KN) Per Sample Length				
						1m	0.8m	0.6m	0.4m	0.2
1										
2										
3										
4										

3.9 Analysis of Test Results

3.9.1 Determination of Bamboo sectional properties

Cross-Sectional area, *A*

The cross-sectional area of the bamboo Culm was determined from ***Clause 3.3 and 4: BS ISO 22157:2019.***

$$A = \left(\frac{\pi}{4}\right) X\left[D_e{}^2 - (D_e - 2t)^2\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .. Eqn. 3.1$$

For Concrete infilled Bamboo, the cross-sectional area is given by:

$$A = \left(\frac{\pi}{4}\right) X\left[D_e{}^2\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .. Eqn. 3.1b$$

3.9.1.2 Radius of Gyration, r

The radius of gyration was calculated from the equation below

$$r = \sqrt{\frac{I}{A}} = 0.25\sqrt{\left[\boldsymbol{De^2} + (\boldsymbol{De} - \boldsymbol{2t})^2\right]} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .. Eqn. 3.2$$

For concrete-infilled Bamboo Samples, the Radius of Gyration is given by;

$$r = \sqrt{\frac{I}{A}} = 0.25\sqrt{[De^2]} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots .. Eqn. 3.3$$

Where $De \text{ and } t$ can be taken as the external diameter and wall thickness respectively.

Second Moment of Area, I (mm^4)

The second moment of area of plane Bamboo samples was taken from ***Clause 4, BS ISO 22157:2019,*** given by;

$$\mathrm{I} = \pi \frac{\left(D_e{}^4 - (D_e - 2t)^4\right)}{64} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots .. Eqn. 3.4$$

For concrete-infilled Bamboo samples, the second Moment of Area is given by;

$$\mathrm{I} = \pi \frac{\left(D_e{}^4\right)}{64} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots Eqn. 3.5$$

Where D_e is the External diameter of the bamboo samples and t is the bamboo samples wall thickness.

Determination of Effective Length Le

$$Effective\ length,\ Le = kL \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots . Eqn. 3.6$$

Where:

K *is* Coefficient of effective length, *based on the support condition.*

L *is the sample test length* (mm).

The Figure in Appendix B.1.3 was used to determine the effective length Coefficient, *k*.

3.10 Samples Classification

3.10.1 Slenderness Classification of Samples

Bamboo culms is classified as short, intermediate or long depending on boundary condition relating to the slenderness ratio λ and the boundary coefficient C_k given in table 3.9 below.

Table 3.9 Bamboo Samples Section classification

Culmn Classification	Measured Slenderness range
Short	$\lambda < 30$
Inter-mediate	$30 < \lambda < C_k$
Long	$C_k < \lambda < 150$

(Adopted from: "Asociación Colombiana de Ingeniería Sísmica (AIS) (2010) NSR-10: Reglamento Colombiano de construcción sismo resistente. Titulo G: Estructuras de madera y estructuras de guadua. Bogota, AIS")

Theoretically, the slenderness ration λ was taken from the equation given by:

$$\lambda = \left({}^{Le}/_{r}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Eqn. 3.7$$

Where:

$Le = Effectice\ length\ (mm),$

$r = Radius\ of\ gyration\ (mm)$

The boundary coefficient between intermediate and long slender elements for axial compression was taken from the equation given by:

$$C_k = \pi * \sqrt{\frac{E_{0.05}}{\gamma_E * \sigma_y}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Eqn. 3.8$$

For plain Bamboo samples, the theoretical boundary coefficient of the slenderness value of the Bamboo test sample length was modified, given by:

$$C_k = \pi * \sqrt{\frac{E_b}{\gamma_E * \sigma_y}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Eqn. 3.9$$

$$But, \sigma_y = \frac{F_y}{A}\ (N/mm^2)$$

Using the principle of superposition, the modified boundary coefficient of the slenderness value of Concrete infilled Bamboo samples at different test lengths is given by:

$$C_k = \pi x\left(\sqrt{\frac{E_c + E_b}{1.5\sigma y}}\right) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots Eqn. 3.10$$

σy is the axial compressive failure load of concrete infilled Bamboo.

From Experiments, the elastic modulus of concrete was taken from the equation from EN 1992-1,

$$E_c = 4700\sqrt{F_{ck}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots .. Eqn. 3.11$$

Where;

F_{ck} is the characteristic cylindrical strength of Concrete used as infills in Bamboo Culms.

3.11 Theoretical Compressive Load Capacity of Plain Bamboo Sample

3.11.1 Buckling Coefficient of Plain Bamboo Test Samples

From previous experiments on the "Column buckling of structural bamboo" conducted by Yu et al., the designed and measured compressive strength buckling reduction factors were found to have values between **0.14–0.65** and 0.23–0.91 for 1000-2000 mm length bamboo columns, respectively, whereas they were 0.29–0.67 and 0.36–1.31 for 400-800 mm length.

From $\sigma_y = \frac{N_{ED}}{A} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots .. Eqn. 3.12$

Where;

N_{ED} is the compressive failure load, taken from the UTM scale reading and A is the sample's cross-sectional area.

The Theoretical loading capacity of Plain bamboo samples is given by;

From $N_{RD} = P = \psi A\sigma_y \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots .. Eqn. 3.13$

Where ψ is the buckling reduction factor.

Using the principle of super-position, the designed load capacity of Concrete infilled Bamboo samples is given by:

$$N_{Rd} = F_{ck} x A_c + F_{y,b} x A_b \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; Eqn. 3.14$$

Where F_{ck} and A_c is the characteristic cylindrical strength of Concrete and Area of Concrete respectively and $F_{y,b}$ and A_b is the yield strength and Area of Bamboo respectively.

$$I_b = \pi \frac{\left(D_e{}^4 - (D_e - 2t)^4\right)}{64} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; Eqn. 3.22$$

From previous experiments, the elastic modulus for class of Bamboo with culm wall thicknesses between **19 mm to 20 mm is *18,140 MPa***. Therefore, the apparent or effective modulus of bamboo is taken as E=18,140 N/mm^2.

Therefore, $E_b = 18{,}140 \text{ N}/mm^2$.

CHAPTER 4: RESULTS AND ANALYSIS

4.0 Introduction

Results of the tests conducted for this research, their analysis and discussions are recorded in this chapter. Compression tests of both Plain Bamboo and Bamboo infilled concrete samples at different lengths were analyzed to appreciate the load-carrying capacity and deformation under Loading.

4.1 Concrete Materials and Mix Design

Concrete mix design was vital for the research as the concrete grade was formed from independent variables. Vital materials in all concrete construction activities namely Cement, water and aggregates (fine and coarse) were the main components of concrete. From the trial mix, concrete ingredients including water, coarse and fine aggregates and cement were selected in measured proportions for the required concrete strength. The workability test was conducted to check the water cement ratio to enable easy placement and compaction of the design concrete mix in bamboo columns, also considering strength and durability of concrete depends on the water content. Some of the measures taken during concrete mix design included type of cement, concrete grade, aggregate sieve analysis, Water-cement ratio and workability. Concrete cube crushing strength test were conducted after 28.

4.1.1 Concrete materials test Results

4.1.1.1 Test results on Cement

Tests conducted on Type I Ordinary Portland Cement (OPC): CEM II 32.5N - OPC, manufactured by Tororo Cement limited used for the different concrete classes as infill in bamboo gave the following results summarized in tables 4.1, 4.2 and 4.3.

Table 4.1 Cement Physical test results

S/No	Test	Unit	Results	Specification: Uganda Standard 310-1:2001 for strength class CemIV:32.5N
01	Initial setting time	Minutes	142	≥75
02	Final setting time	Minutes	348	≤600
03	Consistency	%	26	-
04	Soundness	mm	1.2	≤10

Table 4.2 Chemical Tests results

S/No	Test	Unit	Results	Specification: Uganda Standard 310-1:2001 for strength class CemIV:32.5N
01	Chloride content as	%	0.04	≤0.1
02	Sulphate content as	%	2.36	≤3.5

Table 4.3: Strength (Mortar Prism) Tests results

S/No	Test	Unit	Results	Specification: Uganda Standard 310-1:2001 for strength class CemIV:32.5N
01	7-days strength	Mpa	23.4	≥16
02	28-days strength	Mpa	49.6	≥32.5/≤52.5

4.1.1.2 Aggregates test results

Aggregates physical properties useful for mix computations were aggregate type, sieve analysis, specific gravity, absorption, moisture content and unit weight. Table 4.4 shows the grading results of fine aggregates.

Table 4.4: Grading Results of Fine Aggregates

Percentage Passing, (%)								
Sizes (mm)	Sieve size	4.75 No.4	2.36 No.8	1.18 No.16	600 No.30	300 No.50	150 No.100	75 No.200
0 ~ 4.75	Results	97.7	85.2	74	37.4	18.0	7.3	5.0
	ASTM C33/C33M-18, (2018)	95~100	80~100	50~85	25~60	5~30	0~10	0~3.0

Using the results from sieve analysis in Table 4.4 above, the grading sieve analysis results is represented in Figure 4.1 below.

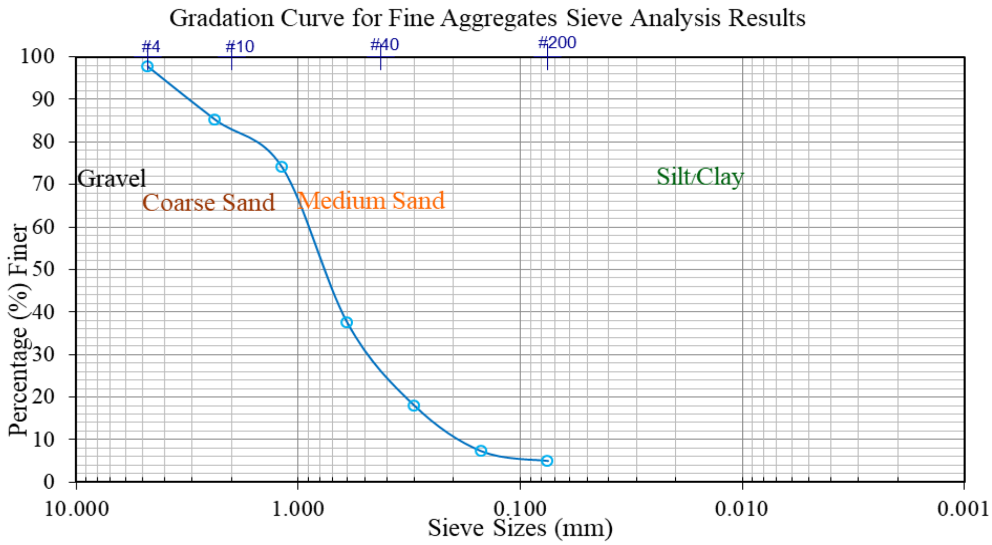

Figure 4.1: Gradation Curve for Fine aggregates sieve analysis

From Figure 4.1 above, the sand samples did not contain silt/Clay.

The results of the sieve analysis of coarse aggregates were represented in Table 4.5 below.

Table 4.5: Grading Results of Coarse Aggregate

Aggregate Sizes	Percentage Passing (%)					
	Sieve size	19	12.5	9.5	4.75	2.36
4.75-19	Test Results	100	76.2	50.4	3.6	0.45
	ASTM C33/C33M-18, (2018)	90- 100	/	20-55	0-10	0-5

From the sieve analysis results in Table 4.5 above, the test results of the sieve analysis are represented in Figure 4.2 below.

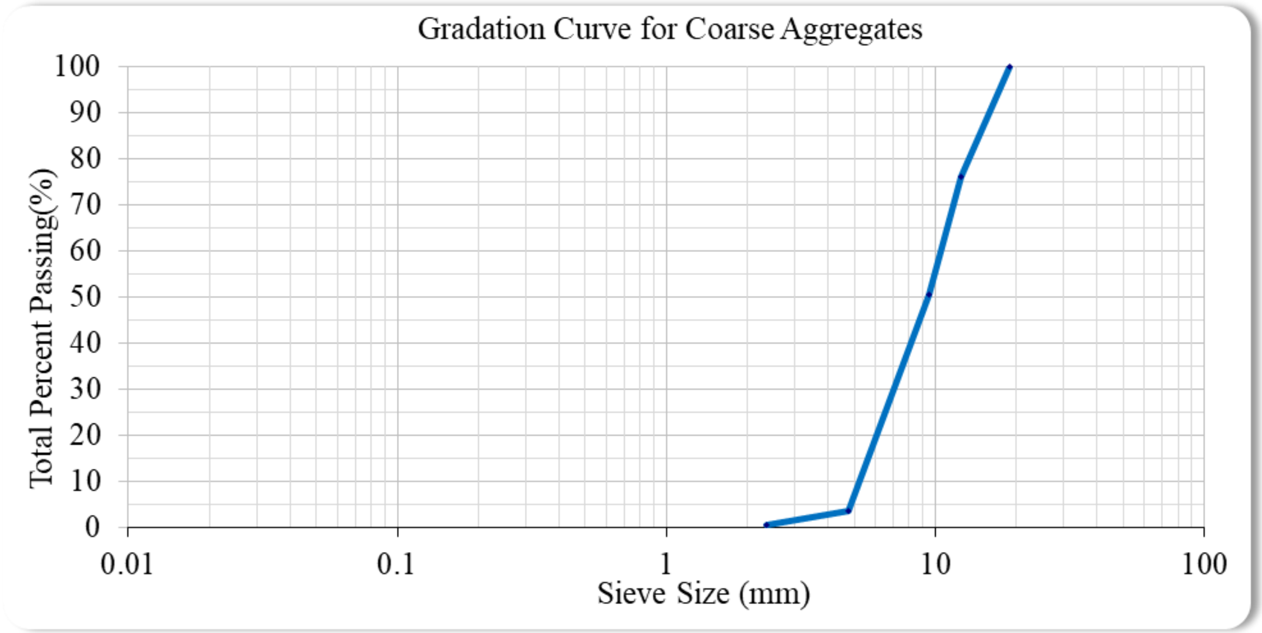

Figure 4.2: Gradation curve for coarse aggregates sieve analysis results

From Figure 4.2 above, the maximum aggregate sizes were found to be 19mm.

From Tables 4.3, 4.5 and Figures 4.1 and 4.2, the sand and aggregates fall within acceptable values for the experiment.

Table 4.6 shows the results of the Test conducted on the physical properties of fine and coarse aggregates.

Table 4.6: Physical properties- coarse and fine aggregates Test results

Test Item	**Specification**	**Test Results**	
	ASTM C33/C33M-18, (2018)	Fine Aggregates 0-4.75(mm)	Coarse Aggregates 4.75-19(mm)
Fineness modulus, FM	2.3~3.1	2.86	
Water Absorption %	≤3	0.61	0.37
Saturated surface dry apparent density, (g/cm3)	(sand) ≥ 2.5	2.80	
	(Agg.) ≥ 2.55		2.85
Mica content (%)	≤ 2	0.00	
Fines < 0.075 mm (%)	≤ 3	2.74	
Flakiness Index, %	< 25		9.50

Elongation Index, %			11.60

4.1.2 Concrete Mix Slump test

The measured slump values for concrete grades C12/15, C16/20 and C20/25 were recorded in table 4.7 below.

Table 4.7: Slump test results of different concrete grades

Concrete Grade	Slump (mm)	Acceptable Slump limits (mm)
C12/15	25	15-25
C16/20	25	15-25
C20/25	20	15-25

From Table 4.7, the recorded slump for the different concrete mix designs recorded values between 20-25mm, well within acceptable slump ranges between 15 to 25 mm.

4.1.3 Compressive Strength Test on Concrete Cubes

The determine concrete mix design characteristic strengths test after 14 and 28 days were recorded in table 4.8 below.

Table 4.8: Concrete Cubes Compressive Strength Test results of Different Concrete Design mix

C15 Concrete Design Mix								
Test Duration	**14 Days**				**28 Days**			
C15 Cube Code	A-15-1	A-15-2	A-15-3	A-15-4	A-28-1	A-28-2	A-28-3	A-28-4
C15 Cube Strength (N/mm^2)	12	15	15	15	15	16	16	17
C15 Average Cube Strength (N/mm^2)	**14.25**				**16**			
C20 Concrete Design Mix								
C20 Cube Code	B-15-1	B-15-2	B-15-3	B-15-4	B-28-1	B-28-2	B-28-3	B-28-4
C20 Cube Strength (N/mm^2)	18	21	21	23	21	24	24	23
C20 Average Cube Strength (N/mm^2)	**20.75**				**23**			
C25 Concrete Design Mix								
C25 Cube Code	C-15-1	C-15-2	C-15-3	C-15-4	C-28-1	C-28-2	C-28-3	C-28-4
Cube Strength (N/mm^2)	24	25	25	25	26	29	27	27
C25 Average Cube Strength (N/mm^2)	**24.75**				**27.25**			

From Table 4.8, The determined results for the concrete strength test conducted on the different mix design after 14 and 28 days was closely marching the targeted compressive strength. It is therefore noted the calculated proportions achieved the concrete ingredients mix ration, indicated ***in Appendix A, Tables A1.1, A1.2 and A1.3.***

4.2 Compression: Plain Bamboo

4.2.1 Plain Bamboo Samples Section Properties

4.2.1.1 Samples Dimensions for Compression Test

Preliminary measurements were done on the Bamboo culms to determine the Bamboo culm external diameter and wall thickness. Table 4.9 below shows the results of the average external diameter and the wall thickness used for compressive strength analysis.

Table 4.9: Plain Bamboo Samples dimension for compressive strength test.

	Samples Code	Bamboo Samples External Diameter *De* (mm)	Bamboo Samples Wall Thickness *t* (mm)	Average Samples External Diameter (mm)	Average Samples Wall Thickness (mm)
Plain Bamboo Samples	1	100	20	100.75	20.25
	2	101	19		
	3	101	21		
	4	101	21		

Results from table 4.9 above the Bamboo culm external diameter and wall thickness used for compressive strength analysis was taken to be representative of the Bamboo samples used for the experiment.

4.2.1.2 Sectional Properties of Plain Bamboo Samples.

Equations 3.1 and 3.3 was used for the computation of Cross-Sectional Area, (A) Radius of Gyration, r for plain Bamboo samples (Appendix B). The results of the sectional properties of Plain Bamboo samples at different length are as recorded in table 4.10.

Table 4.10: Sectional Properties of Plain Bamboo Samples

Sectional Property	Symbol	Unit	Value
Cross Sectional Area	A	mm^2	5121
Radius of Gyration	R	mm	29.34

4.2.1.4 Determination of Effective Length

The effective length ***Le*** was determined from equation 3.6 and Figure. A.1 in Appendix C. The Coefficient of effective length, ***k*** considering the loading mode of the Bamboo held within the compressive test machine (UTM) was taken as 1. This is because the loading condition provided a non-sway mode, where effectively, the Bamboo culm was held in position at both ends, not restrained in direction at either end. The effective length of Plain Bamboo samples was determined as summarized in table 4.11 below.

Table 4.11 Effective length of Plain Bamboo samples

Effective Length, *Le* (m)					
Sample length (m)	1	0.8	0.6	0.4	0.2
Effective length (m)	1	0.8	0.6	0.4	0.2

4.2.1.5 Slenderness Ratio

From equation 3.7, the slenderness ratio of plain Bamboo samples at different lengths is summarized in table 4.12.

Table 4.12 Slenderness ratio of Plain Bamboo samples in compressive.

Effective Length, Le(mm)	1000	800	600	400	200
Radius of Gyration, r (mm)	29.34	29.34	29.34	29.34	29.34
Slenderness Ratio λ	34.083	27.267	20.450	13.633	6.817

From Table 4.12 above, the slenderness ratio is observed to be decreasing with decreasing Bamboo sample length.

4.3 Analysis of Experimental Test Results.

4.3.1 Plain Bamboo Samples Slenderness Classification.

The slenderness boundary coefficient is used to classify members as short, intermediate or slender, depending on the slenderness ratio. From the slenderness ratio of the plain Bamboo samples obtained in table 4.12, and using equation 3.8, the slenderness boundary coefficient of plain Bamboo samples under compressive load was recorded in table 4.13 below.

Table 4.13 Experimental boundary coefficient of slenderness value per sample length

Effective Length *Le (mm)*	1000	800	600	400	200
Modulus of Elasticity, *E (N/mm²)*	18,140	18,140	18,140	18,140	18,140
Average Failure Load *(N)*	92,000	98,000	110,000	117,000	125,000
Average Area, *A(mm²)*	5121	5121	5121	5121	5121
Average Compressive Strength, σ *(N/mm²)*	17.97	19.14	21.48	22.85	24.41
Slenderness Boundary Coefficient, C_k	81.51	79.97	74.54	72.27	69.93

From Tables 3.9 and 4.12 and 4.13; the experimental results of the slenderness ratio of Plain Bamboo Test samples at lengths 800mm, 600mm, 400mm and 200mm are classified as short (Stocky) samples, whereas Test samples at 1000mm length can be classified as Inter-mediate (Slender) samples.

4.4.1 Theoretical Compressive Load Capacity of Plain Bamboo Sample

4.4.1.1 Buckling Coefficient of Plain Bamboo Test Samples

The Theoretical loading capacity of Plain bamboo samples is given taken from

$$N_{RD} = P = \psi A \sigma_y$$

From research and publications, it can be deduced that the designed and measured compressive strength buckling reduction factors values range between **0.14–0.65** and 0.23–0.91 for 1000-2000 mm length bamboo columns, respectively and **0.29–0.67** and 0.36–1.31 for 400-800 mm length (Yu et al, 2002). The buckling reduction factor for the plain Bamboo samples was got through interpolation. Therefore, the theoretical loading capacity, the slenderness boundary Coefficient, *Ck* and the failure stress of the plane bamboo at different samples is given in Table 4.14 below.

Table 4.14 Theoretical loading capacity of Plain Bamboo Samples

Plain Bamboo					
Effective Length, *Le(mm)*	1000	800	600	400	200
Average Failure Load, *(N)*	92,000	98,000	110,000	117,000	125,000
Average Area, *A(mm²)*	5121	5121	5121	5121	5121
Buckling Reduction Factor Ψ	0.3	0.32	0.35	0.38	0.41
Loading Capacity *P(KN)*	92.18	98.32	107.54	116.76	125.98
Failure Stress *(N/mm²)*	18	19.2	21.0	22.8	24.6

From table 4.14 above, the theoretical load capacity of plain Bamboo was taken by considering the following:

- Being a natural product, the compressive strength and other mechanical properties of bamboo vary by location, age, and type of species. The compressive strength of bamboo is situated between 40 and 80 N/mm^2 which is twice to four times the value of most timber species. These Mechanical properties were tested according to ISO 22157 standards at the *Los Andes University in Bogota, Colombia* in 2010.

Taking the average compressive strength of bamboo from:

$$\sigma_y = \frac{40+80}{2}\ (N/mm^2)$$

Therefore, taking $\sigma_y = 60\ (N/mm^2)$

The experimental and theoretical loading capacity of Plain Bamboo samples is summarized in Table 4.15 below.

Table 4.15 Average Experimental and Theoretical Failure load of plain bamboo

	Sample Code	Sample Diameter D(mm)	Sample wall thickness (mm)	Average sample Diameter D (mm)	Average sample wall thickness (mm)	Sample Area (mm^2)	Failure Load (KN) Per Sample Length				
							1.0m	0.8m	0.6m	0.4m	0.2m
PLAIN BAMBOO	1	100	20	100.75	20.25	5121	92	97	109	116	125
	2	101	19				92	98	110	117	124
	3	101	21				93	98	110	117	125
	4	101	21				92	98	110	117	125
					Average Failure load (KN)		92	98	110	117	125
					Theoretical Failure Load (KN)		92.2	98.3	107.5	116.8	126

From Table 4.15, a graph of Experimental and theoretical failure load against test length is plotted in Figure 4.3 below.

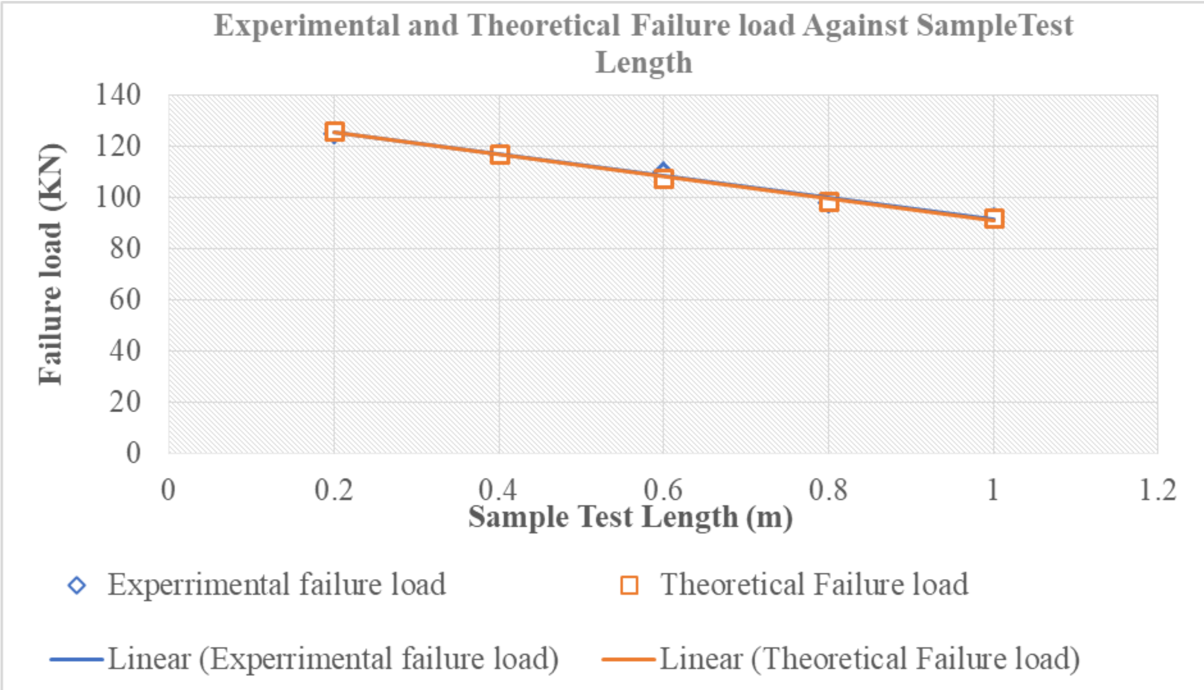

Figure 4.3: Graphical representation of failure load verses the sample test length.

4.5 Compression: Concrete Infilled Bamboo

4.5.1 Compression: C12/15 Concrete Infilled Bamboo

4.5.1.1 Samples Dimensions for C12/15 Concrete Infilled Bamboo Compression Test

From preliminary measurements on the Bamboo culms samples for C12/15 Concrete infilled compressive test experiment, the measured external diameter and the culm wall thickness were recorded in Table 4.16 below.

Table 4.16: C12/15 Concrete infilled Bamboo Samples dimension for compressive strength test

	Samples Code	Bamboo Samples External Diameter *De* (mm)	Bamboo Samples Wall Thickness *t* (mm)	Average Samples External Diameter (mm)	Average Samples Wall Thickness (mm)
C12/15 Concrete Infilled Bamboo Samples	1	100	19	100	18.25
	2	100	18		
	3	99	18		
	4	101	18		

4.5.1.2 Sectional Properties of C12/15 Concrete infilled Bamboo Samples.

Equations 3.1b and 3.4 was used for the computation of Cross-Sectional Area, **A** Radius of Gyration, r for C12/15 Concrete infilled Bamboo samples (Appendix B). The computation of Cross-Sectional Area, **A** Radius of Gyration, r for C12/15 Concrete infilled Bamboo is summarized in Table 4.17 below.

Table 4.17: Sectional Properties of C12/15 Concrete infilled Bamboo Samples

Sectional Property	Symbol	Unit	Value
Cross-Sectional Area	A	mm^2	7854
Radius of Gyration	R	mm	25

4.5.1.3 Determination of Effective Length

From equation 3.6 and Figure. 3.7, and taking the Coefficient of effective length *k* as 1, the effective length of C12/15 Concrete infilled Bamboo samples at different lengths was recorded in Table 4.18 below.

Table 4.18 Effective length of C12/15 Concrete infilled Bamboo samples

Effective Length, *Le* (m)					
Sample Length (m)	1.0	0.8	0.6	0.4	0.2
Effective Length (m)	1	0.8	0.6	0.4	0.2

4.5.1.4 Slenderness Ratio

Using equation 3.7, the slenderness ratio of C12/15 Bamboo samples at different lengths is summarized in table 4.19 below.

Table 4.19 Slenderness ratio of C12/15 Concrete infilled Bamboo samples in compressive.

Effective Length, Le(mm)	1000	800	600	400	200
Radius of Gyration, r (mm)	25.00	25.00	25.00	25.00	25.00
Slenderness Ratio λ	40.00	32.00	24.00	16.00	8.00

From table 4.19 above, the slenderness ratio is observed to decrease with decreasing concrete infilled Bamboo sample lengths.

4.5.1.5 Samples Slenderness Classification of C12/15 Concrete infilled Bamboo Samples

From the slenderness ratio of C12/15 Concrete infilled Bamboo samples obtained in table 4.19, and using equation 3.8, the slenderness boundary coefficient of plain Bamboo samples under compressive load was recorded in table 4.20 below.

Table 4.20 Boundary coefficient of slenderness value per sample length of C12/15 Concrete infilled Bamboo

Effective Length *Le*, mm	1000	800	600	400	200
Failure Load *(N)*	146,000	166,000	177,000	186,000	193,000
Elastic Modulus of Bamboo E_b (N/mm^2)	18,140	18,140	18,140	18,140	18,140
Elastic Modulus of Concrete E_c (N/mm^2)	16,281.3	16,281.3	16,281.3	16,281.3	16,281.3
Cross-sectional Area, A mm^2	7,854	7,854	7,854	7,854	7,854
Failure Stress σy (N/mm^2)	18.59	21.14	22.54	23.68	24.57
Slenderness Boundary Coefficient, C_k	110.38	103.52	100.24	97.80	96.01

From Tables 3.9, 4.19 and 4.20, the derived results of the slenderness ratio for C12/15 concrete infilled Bamboo Test samples at lengths 600mm, 400mm and 200mm are classified as short (Stocky) samples, whereas Test samples at 1000mm and 800mm length can be classified as Inter-mediate (Slender) samples.

From Tables 4.8, 4.13 and 4.20; the failure stress of C12/15 Concrete cubes, Plain Bamboo samples at different lengths and C12/15 Concrete infilled Bamboo at different lengths was summarized in Table 4.21 below.

Table 4.21 Failure stress results of Plain Bamboo, C12/15 Concrete infilled Bamboo and C12/15 Concrete Cubes.

Failure Stress of Test Samples	Sample Length (m)				
	1.0	0.8	0.6	0.4	0.2
Plain Bamboo (Experimental Failure Stress) (N/mm^2)	17.97	19.14	21.48	22.85	24.41
C12/15 Concrete infilled Bamboo (Experimental Failure Stress) (N/mm^2)	18.59	21.14	22.54	23.68	24.54
Percentage Stress Contribution due to C12/15 Concrete infills in Bamboo	3.34	9.46	4.70	3.51	0.53
C12/15 Concrete Cubes (N/mm^2)	16				

From Table 4.21 above, it is seen that the stress contribution of C12/15 Concrete as infills in Bamboo is negligible. The failure stress of C12/15 Concrete infilled Bamboo is therefore assumed to be taken by Bamboo.

A graph of failure stress for plain Bamboo and C12/15 Concrete infilled Bamboo is plotted as shown in Figure 4.4 below.

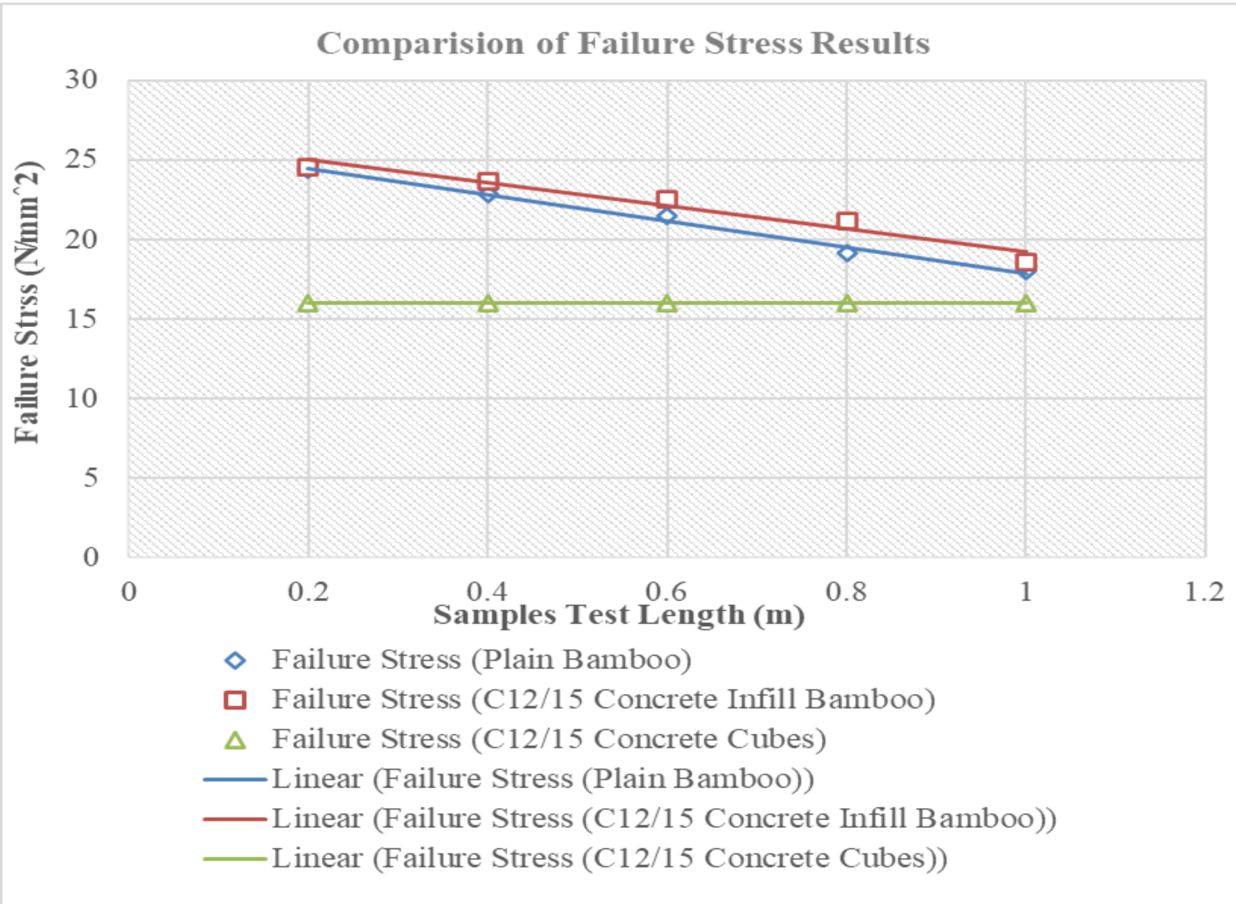

Figure 4.4: Failure stress Results of Plain Bamboo, C12/15 Concrete infilled Bamboo and C12/15 Concrete cubes

4.5.1.6 Analysis of Experimental Test Results of Concrete-Infilled Bamboo

A summary of the failure load of different concrete strength infilled bamboo at different test lengths is in the table below.

Table 4.22 Failure load of different concrete strength infilled bamboo and Plain Bamboo

Effective Length Le (mm)	FAILURE LOAD (KN)						
	Plain Bamboo (A)	Concrete Filled Bamboo			B-A	C-A	D-A
		C12/15 (B)	C16/20 (C)	C20/25 (D)			
1000	92	146	187	220	54	95	128
800	98	166	195	225	68	97	127
600	110	177	206	236	67	96	126
400	117	186	214	243	69	97	126
200	125	193	222	251	68	97	126

From Table 4.22, it is seen that the failure load attributed to concrete remains almost constant at different Concrete infilled Bamboo sample lengths for Grade C16/20 (Column C-A) and Grade C20/25 (Column D-A). However, for low concrete Strength of C12/15, the Failure load is quite low (Column B-A). Therefore, concrete grade influences the failure load capacity of concrete infilled Bamboo.

A graph of the Failure load capacity of Bamboo samples infilled with concrete of different classes obtained from Table 4.22 above is drawn as in figure 4.5.

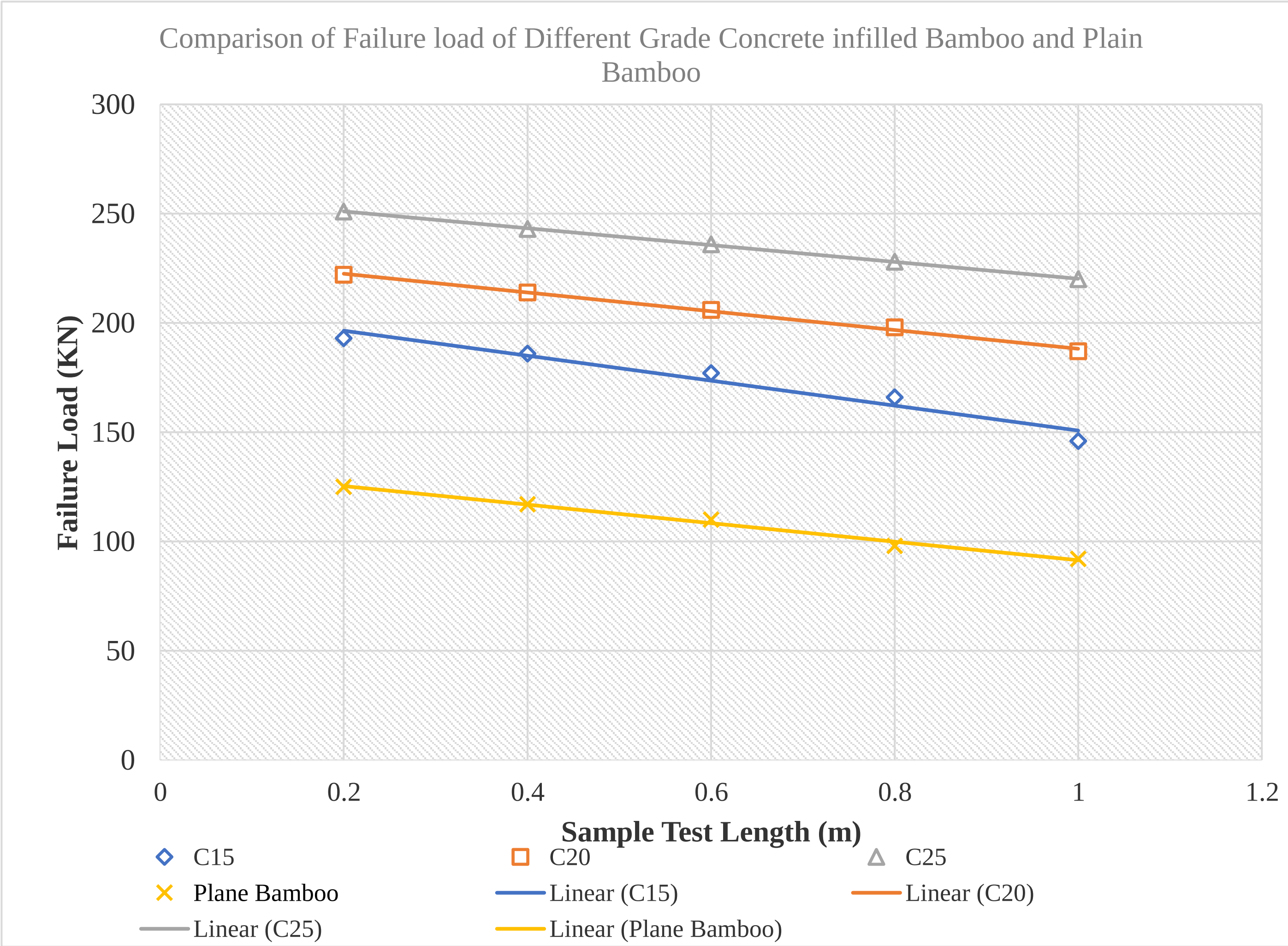

Figure. 4.5 Failure load of Different concrete class infilled bamboo and plain Bamboo against Sample test lengths

4.5.1.7 Design Values of compressive load of C12/15 Concrete infilled bamboo

The designed compressive load capacity of C12/15 Concrete infilled Bamboo is given by the equation below.

$$N_{RD,C12/15} = 0.688F_{ck}xA_c + F_{y,b}$$

4.6 Compression: C16/20 Concrete Infilled Bamboo

4.6.1 Samples Dimensions for C16/20 Concrete Infilled Bamboo Compression Test

From preliminary measurements on the Bamboo culms samples for C16/20 Concrete infilled compressive test experiment, the measured external diameter and the culm wall thickness were recorded in Table 4.23 below.

Table 4.23 C16/20 Concrete infilled Bamboo Samples dimension for compressive strength test

<table>
<tr><th rowspan="5">C16/20 Concrete Infilled Bamboo Samples</th><th>Samples Code</th><th>Bamboo Samples External Diameter De (mm)</th><th>Bamboo Samples Wall Thickness t (mm)</th><th>Average Samples External Diameter (mm)</th><th>Average Samples Wall Thickness (mm)</th></tr>
<tr><td>1</td><td>100</td><td>20</td><td rowspan="4">99.75</td><td rowspan="4">19.25</td></tr>
<tr><td>2</td><td>100</td><td>20</td></tr>
<tr><td>3</td><td>100</td><td>18</td></tr>
<tr><td>4</td><td>99</td><td>19</td></tr>
</table>

4.6.2 Sectional Properties of C16/20 Concrete infilled Bamboo Samples.

Equations 3.1b and 3.3 were used for the computation of Cross-Sectional Area, **A** Radius of Gyration, r for C16/20 Concrete infilled Bamboo samples (Appendix B). The computation of Cross-Sectional Area, Radius of Gyration, r for C16/20 Concrete infilled Bamboo is summarized in Table 4.24 below.

Table 4.24: Sectional Properties of C16/20 Concrete infilled Bamboo Samples

Sectional Property	Symbol	Unit	Value
Cross-Sectional Area	A	mm^2	7815
Radius of Gyration	R	mm	24.94

4.6.3 Determination of Effective Length

From equation 3.6 and Figure. 3.7, and taking the Coefficient of effective length *k* as 1, the effective length of C16/20 Concrete infilled Bamboo samples at different lengths was recorded in Table 4.25 below.

Table 4.25 Effective length of C16/20 Concrete infilled Bamboo samples

Effective Length, *Le* (m)					
Sample Length (m)	1.0	0.8	0.6	0.4	0.2
Effective Length (m)	1.0	0.8	0.6	0.4	0.2

4.6.4 Slenderness Ratio

Using equation 3.7, the slenderness ratio of C16/20 Bamboo samples at different lengths is summarized in table 4.26 below.

Table 4.26 Slenderness ratio of C16/20 Concrete infilled Bamboo samples in compressive.

Effective Length, Le(mm)	1000	800	600	400	200
Radius of Gyration, r (mm)	24.94	24.94	24.94	24.94	24.94
Slenderness Ratio λ	40.10	32.08	24.06	16.04	8.02

From table 4.26 above, the slenderness ratio is observed to decrease with decreasing concrete-infilled Bamboo sample lengths.

4.6.5 Samples Classification of C16/20 Concrete infilled Bamboo Samples

From the slenderness ratio of C16/20 Concrete infilled Bamboo samples obtained in table 4.26, and using equation 3.8, the slenderness boundary coefficient of plane Bamboo samples under compressive load was recorded in table 4.27 below.

Table 4.27 Boundary coefficient of slenderness value per sample length of C16/20 Concrete infilled Bamboo

Effective Length *Le*, mm	1000	800	600	400	200
Failure Load (N)	187,000	195,000	206,000	214,000	220,000
Elastic Modulus of Bamboo E_b (N/mm^2)	18,140	18,140	18,140	18,140	18,140
Elastic Modulus of Concrete E_c (N/mm^2)	18,800	18,800	18,800	18,800	18,800
Cross-sectional Area, A mm^2	7,815	7,815	7,815	7,815	7,815
Failure Stress σy (N/mm^2)	23.93	24.95	26.36	27.38	28.15
Slenderness Boundary Coefficient, C_k	100.78	98.70	96.02	94.22	92.92

From Tables 3.9, 4.26 and 4.27, the derived results of the slenderness ratio for C16/20 concrete infilled Bamboo Test samples at lengths 600mm, 400mm and 200mm are classified as short (Stocky) samples, whereas Test samples at 1000mm and 800mm length can be classified as Inter-mediate (long) samples.

From Tables 4.8, 4.13 and 4.20; the failure stress of C16/20 Concrete cubes, Plane Bamboo samples at different lengths and C16/20 Concrete infilled Bamboo at different lengths was summarized in Table 4.28 below.

Table 4.28 Failure stress results of Plane Bamboo, C16/20 Concrete infilled Bamboo and C16/20 Concrete Cubes.

Failure Stress of Test Samples	Sample Length (m)				
	1.0	0.8	0.6	0.4	0.2
Plane Bamboo (Experimental Failure Stress) (N/mm^2)	17.97	19.14	21.48	22.85	24.41
C16/20 Concrete infilled Bamboo (Experimental Failure Stress) (N/mm^2)	23.93	24.59	26.36	27.38	28.15
Percentage Stress Contribution due to C16/20 Concrete infills in Bamboo	24.91	22.16	18.51	16.54	13.29
C16/20 Concrete Cubes (N/mm^2)	23				

From Table 4.28 above, it is seen that the stress contribution of C16/20 Concrete as infills in Bamboo increases with length. The failure stress of C16/20 Concrete infilled Bamboo is therefore assumed to reduce the buckling of Bamboo, therefore increasing its load-carrying capacity.

A graphical representation of failure stress for plane Bamboo and C16/20 Concrete infilled Bamboo is plotted as shown in Figure 4.4.

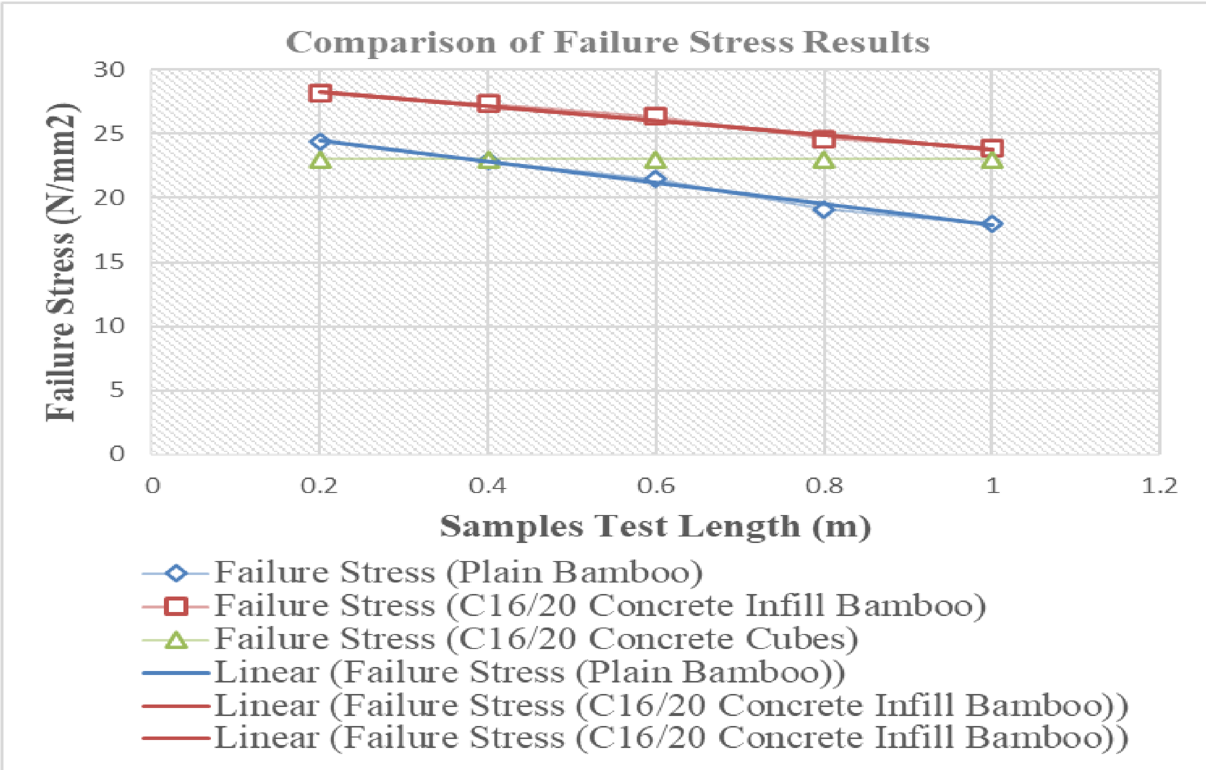

Figure 4.6: Failure stress Results of Plane Bamboo, C16/20 Concrete infilled Bamboo and C16/20 Concrete cubes

4.6.6 Design Values of compressive load of C16/20 Concrete infilled bamboo

The designed compressive load capacity of C16/20 Concrete infilled Bamboo is given by the equation below.

$$N_{RD,C16/20} = 0.776F_{ck}xA_c + F_{y,b}$$

4.7 Compression: C20/25 Concrete Infilled Bamboo

4.7.1 Samples Dimensions for C20/25 Concrete Infilled Bamboo Compression Test

From preliminary measurements on the Bamboo culms samples for C20/25 Concrete infilled compressive test experiment, the measured external diameter and the culm wall thickness were recorded in Table 4.29 below.

Table 4.29 C20/25 Concrete infilled Bamboo Samples dimension for compressive strength test

<table>
<tr><td rowspan="5">C20/25 Concrete Infilled Bamboo Samples</td><td>Samples Code</td><td>Bamboo Samples External Diameter De (mm)</td><td>Bamboo Samples Wall Thickness t (mm)</td><td>Average Samples External Diameter (mm)</td><td>Average Samples Wall Thickness (mm)</td></tr>
<tr><td>1</td><td>95</td><td>21</td><td rowspan="4">97.5</td><td rowspan="4">20.25</td></tr>
<tr><td>2</td><td>95</td><td>20</td></tr>
<tr><td>3</td><td>99</td><td>20</td></tr>
<tr><td>4</td><td>101</td><td>20</td></tr>
</table>

4.7.2 Sectional Properties of C20/25 Concrete infilled Bamboo Samples.

Equations 3.1b and 3.3 was used for the computation of Cross-Sectional Area, **A** Radius of Gyration, r for C16/20 Concrete infilled Bamboo samples (Appendix B). The computation of Cross-Sectional Area, **A** Radius of Gyration, r for C20/25 Concrete infilled Bamboo is summarized in Table 4.24 below.

Table 4.30: Sectional Properties of C20/25 Concrete infilled Bamboo Samples

Sectional Property	Symbol	Unit	Value
Cross-Sectional Area	A	mm^2	7466
Radius of Gyration	R	mm	24.38

4.7.3 Determination of Effective Length

From equation 3.6 and Figure. 3.7, and taking the Coefficient of effective length *k* as 1, the effective length of C20/25 Concrete infilled Bamboo samples at different lengths was recorded in Table 4.31 below.

Table 4.31 Effective length of C20/25 Concrete infilled Bamboo samples

Effective Length, *Le* (M)					
Sample Length (M)	1	0.8	0.6	0.4	0.2
Effective Length (M)	1	0.8	0.6	0.4	0.2

4.7.4 Slenderness Ratio

Using equation 3.7, the slenderness ratio of C20/25 Bamboo samples at different lengths is summarized in table 4.32 below.

Table 4.32 Slenderness ratio of C20/25 Concrete infilled Bamboo samples in compressive.

Effective Length, Le(mm)	1000	800	600	400	200
Radius of Gyration, r (mm)	24.38	24.38	24.38	24.38	24.38
Slenderness Ratio λ	41.02	32.81	24.61	16.41	8.20

4.7.5 Samples Classification of C20/25 Concrete infilled Bamboo Samples

From the slenderness ratio of C20/25 Concrete infilled Bamboo samples obtained in table 4.32, and using equation 3.8, the slenderness boundary coefficient of plain Bamboo samples under compressive load was recorded in table 4.33 below.

Table 4.33 Boundary coefficient of slenderness value per sample length of C20/25 Concrete infilled Bamboo.

Effective Length *Le*, mm	1000	800	600	400	200
Failure Load (N)	220,000	225,000	236,000	243,000	251,000
Elastic Modulus of Bamboo E_b (N/mm^2)	18,140	18,140	18,140	18,140	18,140
Elastic Modulus of Concrete E_c (N/mm^2)	21,019	21,019	21,019	21,019	21,019
Cross-sectional Area, A mm^2	7,466	7,466	7,466	7,466	7,466
Failure Stress σy (N/mm^2)	29.47	30.14	31.61	32.55	33.62
Slenderness Boundary Coefficient, C_k	93.50	92.46	90.28	88.97	87.54

From Tables 3.9 and 4.32 and 4.33, the derived results of the slenderness ratio of C20/25 concrete infilled Bamboo Test samples at lengths 600mm, 400mm and 200mm are classified as short (Stocky) samples, whereas Test samples at 1000mm and 800mm length can be classified as Inter-mediate (Slender) samples.

From Tables 4.8, 4.13 and 4.33; the failure stress of C20/25 Concrete cubes, Plain Bamboo samples at different lengths and C20/25 Concrete infilled Bamboo at different lengths was summarized in Table 4.34 below.

Table 4.34 Failure stress results of Plain Bamboo, C20/25 Concrete infilled Bamboo and C20/25 Concrete Cubes

Failure Stress of Test Samples	Sample Length (m)				
	1.0	0.8	0.6	0.4	0.2
Plain Bamboo (Experimental Failure Stress) (N/mm^2)	17.97	19.14	21.48	22.85	24.41
C20/25 Concrete infilled Bamboo (Experimental Failure Stress) (N/mm^2)	29.47	30.14	31.61	32.55	33.62
Percentage Stress Contribution due to C20/25 Concrete infills in Bamboo	39.0	36.50	32.05	29.80	27.40
C20/25 Concrete Cubes (N/mm^2)	27.25				

From Table 4.34 above, it is seen that the stress contribution of C20/25 Concrete as infills in Bamboo increases with length. The failure stress of C20/25 Concrete infilled Bamboo is therefore assumed to reduce the buckling of Bamboo, therefore increasing its load-carrying capacity.

A graph of failure stress for plane Bamboo and C20/25 Concrete infilled Bamboo is plotted as shown in Figure 4.7 below.

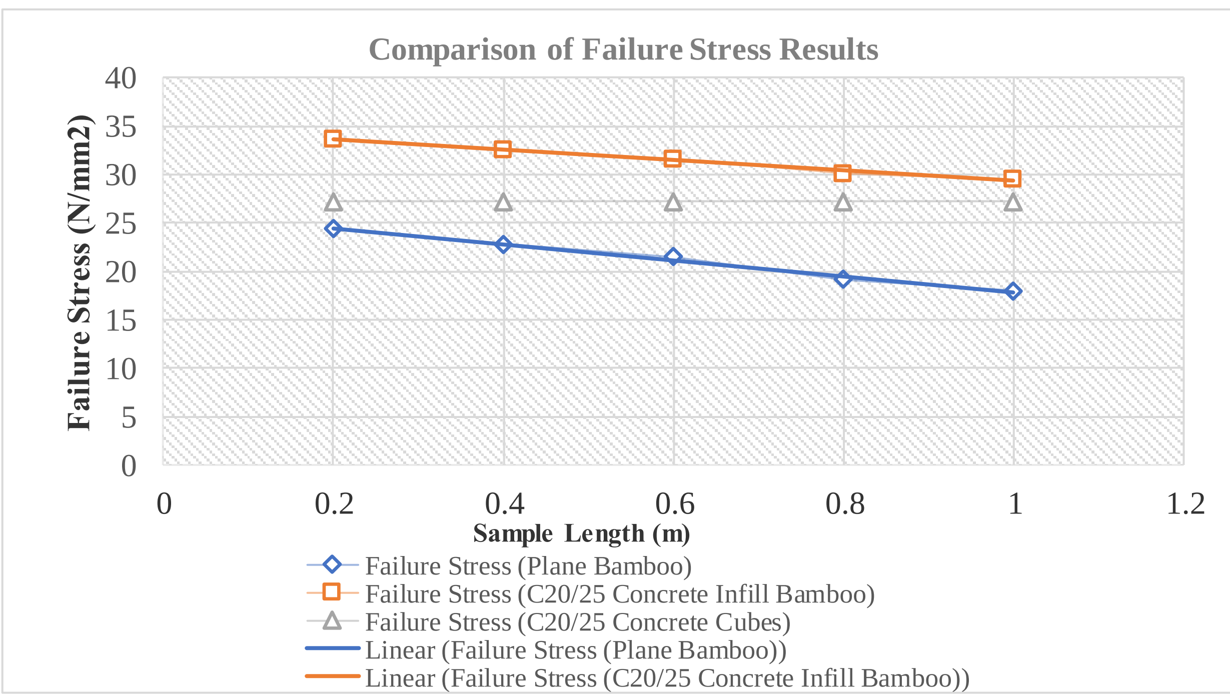

Figure 4.7: Failure stress Results of Plain Bamboo, C20/25 Concrete infilled Bamboo and C20/25 Concrete cubes.

4.7.6 Design Values of compressive load of C20/25 Concrete infilled bamboo

The designed compressive load capacity of C20/25 Concrete infilled Bamboo is given by the equation below.

$$N_{Rd} = 0.807 F_{ck} x A_c + F_{y,b}$$

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.0 Introduction

The research study relates to investigation of compressive strength of Plain Bamboo and concrete-infilled bamboo by recording the failure load capacity under loading using UTM. The Compressive failure load capacity variation of bamboo samples at varying lengths with different concrete grades was to experimentally investigate, and thus appreciate the structural suitability of composite material of Plain Bamboo infilled with Concrete which could promote the use of eco-friendly materials and reduce the cost of construction using conventional materials: Concrete and steel.

5.1 Visual Experimental Observations

There were virtually the same behaviours observed in all samples between the loading and failure process on Plain and Concrete infilled Bamboo culm samples. Between the loading and failure stages, cracking sounds followed by bursting of bamboo culms were hard. For concrete-infilled bamboo samples, failure was sudden after bamboo culm bursting and concrete crushing. This can be attributed to bamboo culms losing their load-bearing capacity at peak loading, thereby suggesting that all failure modes were due to column crushing.

5.2 Conclusions

Bamboo has been a sustainable building material with Culms showing promising Physical and mechanical strengths which can be employed as structural members in Building construction. Bamboo has high growth rate, easily planted and harvested within a relatively short time between 4-7 years, and it can be regenerated. These characteristics are very suitable for low-cost building construction.

Conclusively therefore, the compressive strength capacity of plain Bamboo and concrete infilled Bamboo with concrete grades C12/15, C16/20 and C20/25 was investigated gave notable increment in load-carrying capacity when the Bamboo culms are infilled with plain concrete. The following conclusions can be made from the study:

1) For Experimental tests done on plain Bamboo, the compressive strength was found to be decreasing with increasing Bamboo sample lengths. The axial load capacity of plane Bamboo at 0.2m sample length is 26.4% more than that at 1m length.
2) Concrete infilled Bamboo with C15, C20 and C25 led to an increment of 58.7%, 103% and 139.1% of the failure load capacity compared to that of the plain bamboo culms sample test length at 0.2m respectively; and 54.4%, 77.6% and 100.8% at Sample lengths of 1m. The compressive load capacity was found to be increasing when Bamboo sample had Concrete infilled, and notable increase in load carrying capacity when infilled with concrete of higher grades. It can be noted that concrete can increase greater compressive load when infilled in Bamboo than plain bamboo culms.
3) Bamboo infilled with concrete grade C25 has a larger compressive strength than Bamboo infilled with concrete grade C20 and C15, signifying a higher ductility behaviour. The study, therefore, concludes that concrete not only delays the buckling of bamboo but also significantly improves the load-carrying capacity and ductility depending on the grade used to fill bamboo.

There were observed differences between the experimental and the theoretical results of concrete infilled Bamboo. The difference in results could have come as experimental results were derived from actual laboratory experiments on the plain Bamboo and concrete infilled Bamboo under study. Theoretical "results" was just an application of the latest theories, formulae, and references on confined concrete to try to predict how it works, assuming its relative structural behaviour and performance.

On the Laboratory experimentation and observation side, it was difficult to design an approach that would eliminate all sources of error. Sample sizes might have been too few, UTM equipment at *CEDAT* Materials laboratory not as precise as desired, and interpretations of data were skewed by assumptions and visual consciousness.

Theoretically, the potential for error in results could have come by several means. The assumptions made for analyzing the theoretical values could simply be wrong or parts of it based on posited factors that are to some extent erroneous. We might have lacked accurate math formulae or employed it incorrectly. Also, measures or constants upon which calculations are based might be taken by other researchers as arbitrary or based on their few observations.

Therefore, the theoretical results can vary based on the work of best approximations and limitations as a “perfect theory” as relativity is subject to question as to its application.

5.3 Recommendations

Bamboo infilled concrete has proven to poses an enormous potential for adopted in the building industry, as deduced in this study. Besides the conclusive evidence of the property of concrete infilled bamboo in the study, the knowledge about jointing or connection system has not been fully disseminated. It is therefore necessary to undertake further studies on bamboo, relating to its sustainability as a construction material, with focus on preservation and connections. With the urge to alleviate the effects of global warming, this research becomes critical should conventional construction materials production lower, owing to its environmentally unfriendly production and chemical ingredients negative impact to the environment.

This research thesis done on concrete-filled bamboo was experimental, focusing majorly on the compressive strength capacity. More experimental study should be conducted to deduce structural strength parameters which could affect the ultimate strength concrete infilled Bamboo as a composite material that could be adopted for building construction. Therefore, the following recommendations are made for further research.

I. Similar experiments on longer Bamboo Culm lengths between 1m to 1.5m for Bamboo samples infilled with different concrete grades.
II. Similar experiments by axially placing reinforcements of 12mm Diameter within the hollow Bamboo culms before infilling with concrete.
III. Similar experiments to appreciate the performance with the same sample lengths joined with couplers.
IV. Similar experiment on a bundle of plain bamboo (2, 3, 4 and 6 bundles) and concrete infilled bamboo at different lengths and concrete grades.
V. There would be an interest need to investigate the bending and shear strength capacity of the plane bamboo and concrete infilled culms at similar sample lengths.
VI. Innovation for a suitable of coating material on Bamboo to counter fire resistance and adverse weather conditions.

Concrete infilled Bamboo has proven strength and can be recommended for the construction industry, especially for building under less loads such as in low-cost houses. Concrete infilled bamboo composite is an alternative building material other than steel and concrete. Therefore, we can use bamboo reliably and responsibly.

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APPENDICES

Appendix A: Concrete Mix Design Chart

Table A.1.1 Mix design ratio for C12/15 concrete

SUPERVISOR	STUDENT	LABORATORY
Dr. MICHEAL KYAKULA (PhD)	JAMES OKUDA GOWON-18/U/GMES/22095/PD	MAKERERE UNIVERSITY MATERIALS LABORATORY

C15 CONCRETE MIX DESIGN (C15/19mm Aggregates)							
Design DATE	5-Dec-21						
Mix Design	Slump Limits					25-100 mm	
Requirements	Nom.Max Size of Agg.					19mm	
(MoWHC-SERIES 6000)	Design Compressive Strengh (28days)					15 MPa	
	Trial Mix Mean Target Strengh(28days)			15 + (1.65X3.5)		20.78 Mpa	
	Max.water/cement ratio					0.5	
	Min.cement content					230	
Mix Design Data	Specific gravity of cement					3150	
(Lab test data)	Bulk specific gravity,SSD(5/20)				kg/m^3	2703	
	Bulk specific gravity,SSD(0/5)				kg/m^3	2613	
	Loose Unit weight (5/20)				kg/m^3	1445	
	Loose Unit weight (0/5)				kg/m^3	1673	
	Water abso.agg.(5/20)					0.37%	
	Water abso.sand(0/5)					2.00%	
	Adpoted water cement ratio					0.45	
	Cement used(32.5N) Tororo cement				kg/m^3	230	
Material sources	Cement (32.5)			Tororo Brand: Bought From Kampala			
	Coarse Aggregates			China Railway seventh Group Co. Ltd quarry at Howa			
	Sand (25% crushed sand & 75% Lake sand)			CR7G quarry site and Gabba Beach respectively			
	Water(Spring water)			NWSC Tap stand			
Batching weight per cum on apparent specific gravity and corrected weight	Absolute Vol. of cement			230/3150=	0.073	m^3	
	Water			105/1000=	0.1050	m^3	
	Entrupped air (considering) %			=	0.020	m^3	
	So total volume of paste			=	0.198	m^3	
	Therefore,soild volume of aggregate			=	0.802	m^3	
	Blending portion of 5/20 ,0/5			=	61%	39%	
	Therefore,vol.of 5/20			=	0.489	m^3	
	vol. of 0-5 (25% crushed & 75% Natural sand)			=	0.313	m^3	
Batching weight per cum	material	Volume	SG	Weight in kg per m^3		Corrected Weight in	
of concrete on SSD		m^3	kg/m^3	of concrete		kg per m^3 of concrete	
condition and	Cement	0.073	3150	230.0			230.0
corrected weight	Water	0.105	1000	105.0			119.2
	Coarse agg.(5-20)	0.489	2703	1322.3			1317.8
	Fine agg.(0-5/sand)	0.313	2613	817.3			807.5
	void	0.020					
	Total Wt.	1.00		2475			2475
Lab batch for	material			Weight in kg for		Final lab mix	
concrete cubes				lab batch		proportion,kg	
6cubes each 10 kg	Cement			5.58		5.58	
total fresh concrete	Water			2.55		2.89	
is 6*10=60kg	Coarse agg.(5-20)			32.06		31.95	
	FA 0-5 (25% Crushed sand & 75% Natural)			19.82		19.58 (4.895 c & 14.68 N)	
	Total Wt.			60.0		60.0	
	material	Weight in kg	Weight in 1 bag of cement	Density	Absolute volume in 1 bag of cement	Using agauge box of (0.3*0.4*0.3)=0.036m^3	
Site batching using agauge box of (0.3*0.4*0.3)=0.036m^3	Cement	230.0	50	1440.0	0.035	1 bag	
	Water	119.2	25.9	1000.0	0.026	26 Litres	
	Coarse agg.(5-20)	1317.8	286.5	1445.0	0.198	5.5boxes	
	Fine agg.(0-5)	807.5	175.6	1673.0	0.105	3boxes	
	Total Wt.	2475	538.0				
Test results	7^{th} day average compressive strength						Mpa
	28^{th} day average compressive strength						Mpa
	Observed slump Slump(mm)					75.0	
	W/C ratio					0.45	

Table A.1.2 Mix design ratio for C16/20 concrete

SUPERVISOR	STUDENT	LABORATORY
Dr. MICHEAL KYAKULA (PhD)	JAMES OKUDA GOWON- 18/U/GMES/22095/PD	MAKERERE UNIVERSITY MATERIALS LABORATORY

C20 CONCRETE MIX DESIGN (C20/19mm aggregates)

Design Date: 5-Dec-21

Mix Design Requirements (MoWHC-Series 600	Slump Limits		25-100 mm
	Nominal Max Size of Agg.		19mm
	Design Compressive Strengh (28days)		20 MPa
	Trial Mix Mean Target Strengh (28days)	20+(1.65x4)	26.6 Mpa
	Max.water/cement ratio		0.45
	Min.cement content		290 kg
Mix Design Data (Lab test data)	Specific gravity of cement		3150
	Bulk specific gravity,SSD(5/20)	kg/m³	2694
	Bulk specific gravity,SSD(0/5)	kg/m³	2640
	Loose Unit weight (5/20)	kg/m³	1597
	Loose Unit weight (0/5)	kg/m³	1496
	Water abso.agg.(5/20)		0.50%
	Water abso.sand(0/5)		0.64%
	Adpoted water cement ratio		0.45
	Cement used (32.5N) Tororo cement		300

Material sources	Cement (32.5 N)	Tororo Brand: Bought from Kampala
	Coarse Aggregates	China Railway seventh Group Co. Ltd quarry at Howa
	Lake sand (25% Crushed sand and 75% Lake sand)	CR7G quarry site and Gabba Beach respectively
	Water	NWSC Tap stand

Batching weight per cum of concrete on SSD condition and corrected weight	Absolute Vol. of cement	300/3150	0.095	m³	
	Water	135/1000	0.135	m³	
	Entrupped air (considering) 2%	=	0.020	m³	
	Total volume of paste	=	0.250	m³	
	Therefore,solid volume of aggregate	=	0.750	m³	
	Blending proportion of 5/20 ,0/5	=	61%		39%
	Therefore,vol.of 5/20 aggregate	=	0.457	m³	
	Vol. of 0/5 aggregate (25% Crushed and 75%Natural Sand)	=	0.292	m³	

Batching weight per c of concrete on SSD condition and corrected weight	Material	Volume m³	SG kg/m³	Weight in kg per m³ of concrete	Corrected Weight in kg per m³ of concrete
	Cement	0.095	3150	300.0	300.0
	Water	0.135	1000	135.0	146.1
	Coarse agg.(5-20)	0.457	2694	1232.1	1226.0
	Fine agg.(0-5)	0.292	2640	772.0	767.0
	void	0.020			
	Total Wt.	1.00		2439.1	2439.1

Lab batch for concrete cubes 6cubes each 10 kg total fresh concrete is 6*10=60kg	Materials	Weight in kg for lab batch	Final lab mix proportion,kg
	Cement	7.38	7.38
	Water	3.32	3.59
	Coarse aggte (5-20) mm	30.31	30.16
	Fine aggte (0-5) mm	18.99	18.87
	Total Wt.	60.0	60.0

Site batching using a gauge box of (0.3*0.4*0.3)=0.036 m^3	Materials	Weight in kg	Weight in 1 bag of cement	Loose densities	Absolute volume in 1 bag of cement	Using agauge box of (0.3*o.4*o.3)=o.o36m^3	
	Cement	300.0	50	3150.0	0.016	1Bag	bag
	Water	146.1	24.4	1000.0	0.024	24	litres
	Coarse agg.(5-20)	1226.0	204.3	1597.0	0.128	4	boxes
	Fine agg.(0-5)	767.0	127.8	1496.0	0.085	2	boxes
	Total Wt.	2439.1	406.5				

Test results	7th day average compressive strength		Mpas
	28th day average compressive strength		Mpas
	Observed Slump, mm	75.0	mm
	Water/Cement Ratio	0.45	

Table A.1.3 Mix design ratio for C20/25 concrete.

SUPERVISOR	STUDENT	LABORATORY
Dr. MICHEAL KYAKULA (PhD)	JAMES OKUDA GOWON-18/U/GMES/22095/PD	MAKERERE UNIVERSITY MATERIALS LABORATORY

C25 CONCRETE MIX DESIGN (C25/19mm Aggregates)							
Design DATE	5-Dec-21						
Mix Design	Slump Limits					25-100 mm	
Requirements	Nom.Max Size of Agg.					20mm	
(MoWHC-SERIES 6000)	Design Compressive Strengh (28days)					25 MPa	
	Trial Mix Mean Target Strengh(28days)			25 + (1.65X4.0)		31.6 Mpa	
	Max.water/cement ratio					0.5	
	Min.cement content					300	
Mix Design Data	Specific gravity of cement					3150	
(Lab test data)	Bulk specific gravity,SSD(5/20)				kg/m³	2691	
	Bulk specific gravity,SSD(0/5)				kg/m³	2637	
	Loose Unit weight (5/20)				kg/m³	1468	
	Loose Unit weight (0/5)				kg/m³	1531	
	Water abso.agg.(5/20)					0.39%	
	Water abso.sand(0/5)					0.55%	
	Adpoted water cement ratio					0.47	
	Cement used(32.5N) Tororo cement					380	
Material sources	Cement (32.5)			Tororo Brand: Bought from Kampala			
	Coarse Aggregates			China Railway Seventh Group Co. Ltd Quarry at Howa			
	Sand (25% crushed sand & 75% Lake sand)			CR7G Quarry site and Gabba Beach Respectively			
	Water(Spring water)			NWSC Tap stand			
Batching weight per cum on apparent specific gravity and corrected weight	Absolute Vol. of cement			380/3150	0.121	m³	
	Water			180/1000	0.1800	m³	
	Entrupped air (considering) %			2%	0.020	m³	
	So total volume of paste			=	0.321	m³	
	Therefore,soild volume of aggregate			=	0.679	m³	
	Blending portion of 5/20 ,0/5			=	61%	39%	
	Therefore,vol.of 5/20			=	0.414	m³	
	vol. of 0-5 (25% crushed & 75% Natural sand)			=	0.265	m³	
Batching weight per cum of concrete on SSD condition and corrected weight	material	Volume m³	SG kg/m³	Weight in kg per m³ of concrete		Corrected Weight in kg per m³ of concrete	
	Cement	0.121	3150	380.0			380.0
	Water	0.180	1000	180.0			188.1
	Coarse agg.(5-20)	0.414	2691	1115.2			1110.9
	Fine agg.(0-5/sand)	0.265	2637	698.7			694.9
	void	0.020					
	Total Wt.	1.00		2374			2374
Lab batch for concrete cubes 6cubes each 10 kg total fresh concrete is 6*10=60kg	material			Weight in kg for lab batch		Final lab mix proportion,kg	
	Cement			9.60		9.60	
	Water			4.55		4.75	
	Coarse agg.(5-20)			28.19		28.08	
	FA 0-5 (25% Crushed sand & 75% Natural)			17.66		17.56	
	Total Wt.			60.0		60.0	
Site batching using agauge box of (0.3*0.4*0.3)=0.036m³	material	Weight in kg	Weight in 1 bag of cement	Loose densities	Absolute volume in 1 bag of cement	Using agauge box of (0.3*o.4*o.3)=o.o36m³	
	Cement	380.0	50	3150.0	0.016	1 bag	
	Water	188.1	24.8	1000.0	0.025	25 Litres	
	Coarse agg.(5-20)	1110.9	146.2	1473.0	0.099	3 boxes	
	Fine agg.(0-5)	694.9	91.4	1697.0	0.054	1.5 boxes	
	Total Wt.	2373.9	312.4				
Test results	7th day average compressive strength						Mpas
	28th day average compressive strength						Mpas
	Observed slump (mm)					75	
	W/C ratio					0.5	

Appendix B: Plain Bamboo and Concrete Infilled Bamboo Sectional Properties

B.1.1 Plain Bamboo Cross-Sectional Area, $(\mathbf{A}\ (\boldsymbol{mm^2})$

$$A = \left(\frac{\pi}{4}\right) X[100.75^2 - (0.10075 - 2x20.25)^2]$$

$$A = 5121xmm^2$$

For C12/15 Concrete infilled Bamboo samples, the Cross-Sectional area is given by:

$$A = \left(\frac{\pi}{4}\right) X[100^2]$$

$$A = 7854xmm^2$$

For C16/20 Concrete infilled Bamboo, the Cross-Sectional area is given by:

$$A = \left(\frac{\pi}{4}\right) X[99.75^2]$$

$$A = 7814.8xmm^2$$

For C20/25 Concrete infilled Bamboo, the Cross-Sectional area is given by:

$$A = \left(\frac{\pi}{4}\right) X[99.75^2]$$

$$A = 7814.8xmm^2$$

B.1.2 Plain Bamboo Radius of Gyration, r

The radius of gyration is calculated from the equation below

$$r = \sqrt{\frac{I}{A}} = 0.25\sqrt{[\boldsymbol{De^2} + (\boldsymbol{De} - \boldsymbol{2t})^2]}$$

Where;

$De\ is\ the\ external\ Diameter\ of\ the\ test\ samples\ (mm)$

$t\ is\ the\ samples\ wall\ thickness\ (mm)$

Taking $r = 0.25\sqrt{[\boldsymbol{D^2} + (\boldsymbol{D} - \boldsymbol{2t})^2]}$

$$r = 0.25\sqrt{[\mathbf{100.75^2} + (\mathbf{100{,}75} - \mathbf{2} * \mathbf{20.25})^2]}$$

$$r = 29.34mm$$

For C12/15 Concrete infilled Concrete Bamboo, the radius of Gyration is given by;

$$r = \sqrt{\frac{I}{A}} = 0.25\sqrt{[\boldsymbol{D^2}]}$$

$r = 0.25\sqrt{[\mathbf{100^2}]}$

$r = 25mm$

For C16/20 Concrete infilled Bamboo, The radius of Gyration is given by;

$r = \sqrt{\frac{I}{A}}$ $=0.25\sqrt{[\boldsymbol{D^2}]}$

$r = 0.25\sqrt{[\mathbf{99.75^2}]}$

$r = 24.94mm$

For C20/25 Concrete infilled Bamboo, The radius of Gyration is given by;

$r = \sqrt{\frac{I}{A}}$ $=0.25[\boldsymbol{D^2}]$^1/2

Taking $r = 0.25[\boldsymbol{D^2}]$^1/2

$r = 0.25[\mathbf{97.5^2}]$^1/2

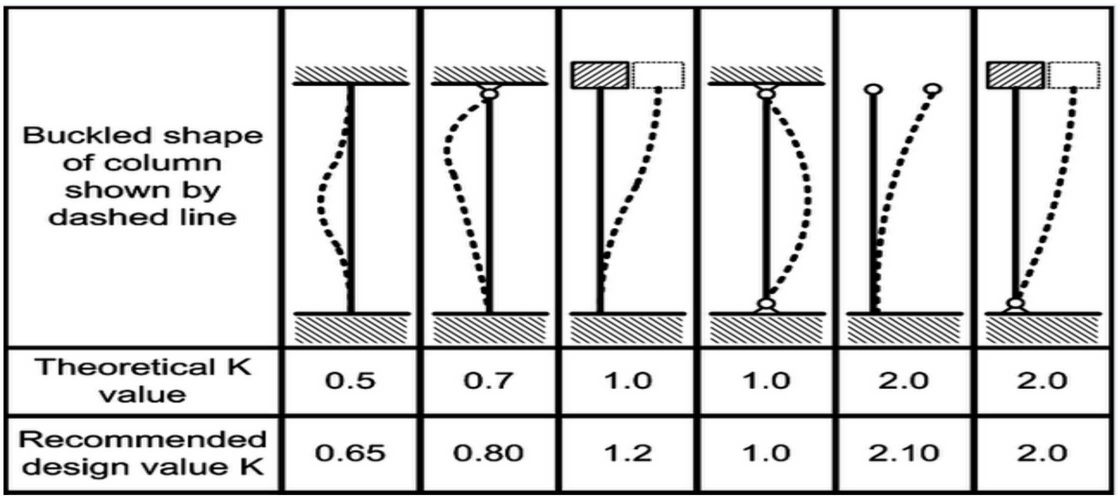
$r = 24.38mm$

Appendix C. Determination of Effective Length Le of Test Samples.

$Effective\ length,\ Le = kL$. Where:

$K\ is$ Coefficient of effective length, $based\ on\ the\ support\ condition.$

$L\ is\ the\ sample\ test\ length\ (mm)$



Buckled shape of column shown by dashed line						
Theoretical K value	0.5	0.7	1.0	1.0	2.0	2.0
Recommended design value K	0.65	0.80	1.2	1.0	2.10	2.0

Fig. A.1 Recommended design value of effective length Coefficient, k

For non-sway support condition, $K = 1$

Appendix D. Slenderness Classification of Plain Bamboo Samples

Bamboo can be classified as short, intermediate and long depending on the boundary condition relating to the slenderness ratio λ and the boundary coefficient C_k given in the table below.

Table 3.9 Bamboo Samples Section classification

Column Classification	Slenderness Ratio
Short	$\lambda < 30$
Intermediate	$30 < \lambda < C_k$
Long	$C_k < \lambda < 150$

Theoretically, the slenderness ratio λ was taken from the equation given by;

$$\lambda = \left({Le}/{r} \right)$$

Where:

$Le = Effectice\ length\ (mm)$,

$r = Radius\ of\ gyration\ (mm)$

The boundary coefficient between intermediate and long slender elements for axial compression was taken from the equation given by:

$$C_k = \pi * \sqrt{\frac{E_{0.05}}{\gamma_E * \sigma_y}}$$

For plain Bamboo samples, the theoretical boundary coefficient of the slenderness value of the Bamboo test sample length is given by:

$$C_k = \pi * \sqrt{\frac{E_b}{\gamma_E * \sigma_y}}$$

$$But, \sigma_y = \frac{F_y}{A}\ (N/mm^2);$$

Where F_y is the compressive failure load of Plain Bamboo, taken from the UTM reading and A is the average cross-sectional area of Plain Bamboo samples and Y_E is a material factor of safety. Its recommended value is given as 1.5.

From Experiments, the modulus of elasticity is found for class 7 samples with wall thicknesses of **19 mm to 20 mm at 18,140 MPa**.

Being a natural product, the compressive strength and other mechanical properties of bamboo vary by location, age, and type of species. The compressive strength of bamboo is situated between 40 and 80 N/mm^2 which is twice to four times the value of most timber species. The difference in results can be explained by the different test methods and samples that were used. However, the age and moisture content of bamboo samples have a significant influence on the compressive strength of bamboo. Bamboo with low moisture content has a higher compressive strength than bamboo with high moisture content.

From the literature, the theoretical value of the elastic modulus of bamboo relates to the assumption that bamboo is partly made of Cellulose. Taking the modulus of elasticity of 70,000 N/mm^2 for cellulose and assuming a bamboo fibre is 50% cellulose, the apparent or effective modulus of bamboo is taken as E=35,000 N/mm^2.

Taking the average compressive strength of bamboo from:

$$\sigma_y = \frac{(40+80)}{2} \ (N/mm2)$$

Therefore, $\sigma_y = 60N/mm2$

$$C_k = \pi * \sqrt{\frac{35{,}000}{1.5 * 60}}$$

C_k =61.95

Appendix D.1 Samples Classification of Concrete infilled Bamboo Samples

The boundary coefficient of slenderness value of Concrete infilled Bamboo samples at different test length is given by:

$$C_k = \pi x \left(\sqrt{\frac{E_c + E_b}{1.5\sigma y}} \right)$$

σy is the axial compressive failure load of concrete infilled Bamboo.

From Experiments, the modulus of elasticity of concrete is given by,

$E_{c,12/15} = 4700\sqrt{F_{ck}}$

$E_{c,12/15} = 4700\sqrt{12}$

$E_{c,12/15} = 16281.3$

$E_{c,16/20} = 4700\sqrt{F_{ck}}$

$E_{c,16/20} = 4700\sqrt{16}.$

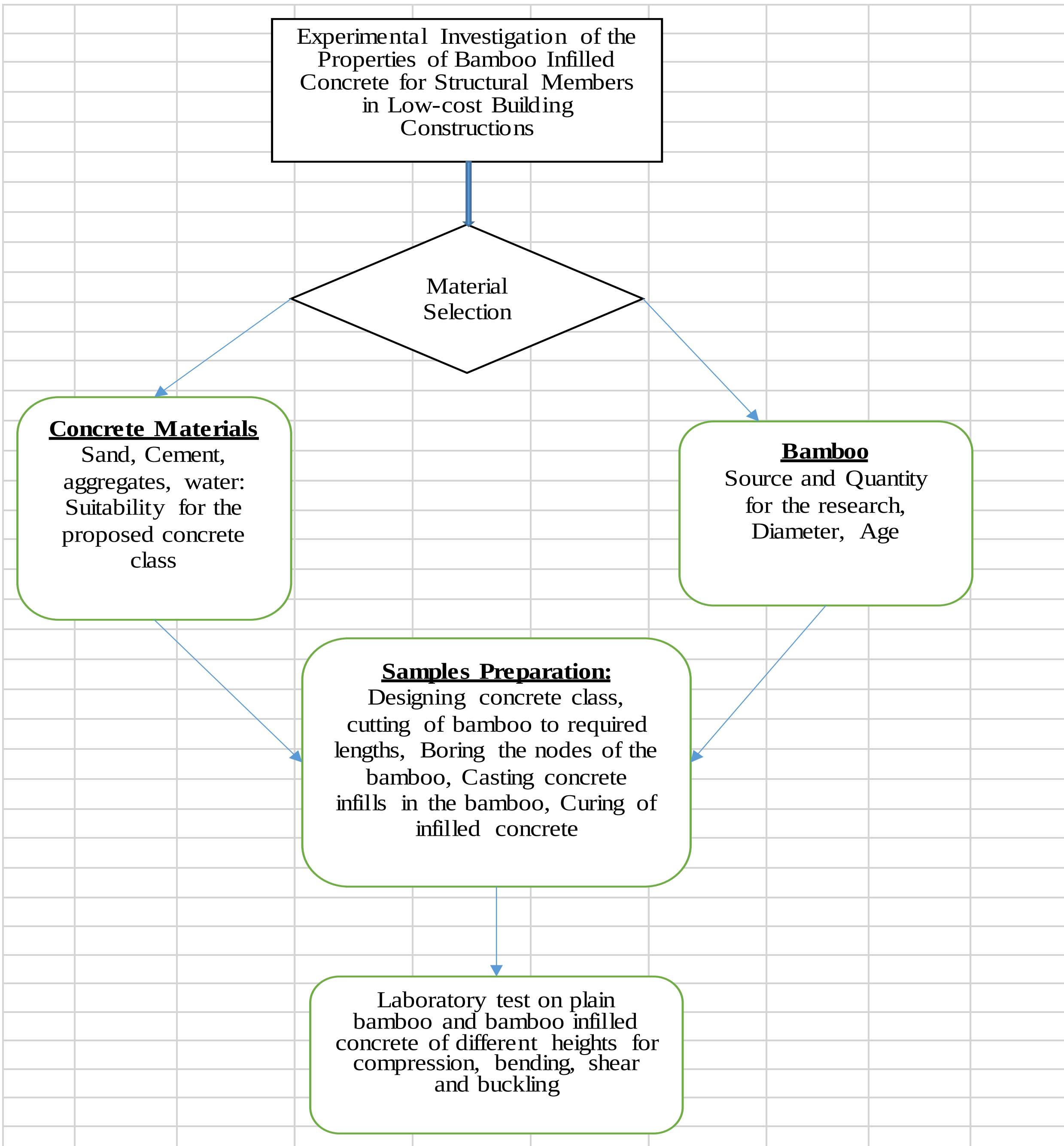
$E_{c,16/20} = 18800$

$E_{c,20/25} = 4700\sqrt{F_{ck}}$

$E_{c,20/25} = 4700\sqrt{20}$

$E_{c,20/25} = 21019$

Appendix E: Research Design Flow



Appendix F: Methodology Experimental Program