DECLARATION

We hereby declare that, apart from the references of other people’s work which has been appropriately acknowledge, the research work was done solely by us and also under the supervision of Dr. Emmanuel Kwesi Arthur and Dr. Emmanuel Gikunoo. This work has never been presented or published in whole or in parts for any other degree in the university or elsewhere.

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DEDICATION

This work is dedicated to the Almighty God, our families, friends and loved ones for the love and support that saw us through to the end of this research.
ABSTRACT

Bamboo has been one of the most used biodegradable natural plant fibre in the past decades due to its high bending strength, low cost, biodegradability, renewability (abundance in nature), and it low weight to strength as well. In view of the properties of bamboo, it has gained several use in different engineering field recently, as such, the use of its fibres as reinforcement in composite materials for high mechanical strength, good thermal insulation and low weight to strength ratio. This project work was therefore carry out to investigate the thermal conductivity and the acoustic properties of an alternative roofing material made of bamboo-polyester fibre composite. Bamboo reinforcement (particulates and fibres) of different volume fractions (0.1, 0.2, 0.3 and 0.4) were reinforced into a polyester matrix.

After the thermal conductivity and the acoustic test were conducted, the results obtained depicted that, the thermal conductivity of the composite roofing decreased as the percentage of the reinforcement increased as whiles the sound absorption decreases with increasing reinforcement percentage.
ACKNOWLEDGEMENT

The greatest of our acknowledgement goes to the almighty God for seeing us through this work. We also want to say a big thank you to our supervisors, Dr. Emmanuel Kwesi Arthur and Dr. Emmanuel Gikunoo for all their assistance offered and consistence supervision during the work. We would also like to express our special gratitude and thanks to Mr. Felix Ati of Materials Engineering Laboratory, Mr. Francis Amuzu of the Strength of Materials Laboratory and Mr. Geshon of the wood workshop for their help during the fabrication and test of our work. Our appreciation also goes to our families, friends and loved ones who contributed in various ways to make this work a success. We are also grateful to other laboratory for permitting us to use their laboratory for our work.

Finally, we would like to acknowledge the Materials Engineering Department at Kwame Nkrumah University of Science and Technology for inculcating into us an appreciation of our course of study through this work.
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CHAPTER ONE

INTRODUCTION

1.1. Background

Over recent years, traditional roofing materials such as metals and ceramics are increasingly being replaced by advanced composite materials; for example, Fibre Reinforced Polymers (FRP). Historically, copper was first used as roofing material for architectural buildings by the Romans in the early centuries. Centuries later, copper and its alloys were integral in European medieval architecture (Wayne, 2017).

Technology has advanced over the years which has led to the availability of other different roofing materials such as; aluminium, ceramics and Asbestos. According to (Zakikhani, Zahari et al. 2014) it is expected that, the use of fibre-polymer composite as roofing materials will expand in the near future due to their advantages such as; high strength, low weight, less sonorous, corrosion resistance, biodegradable, eco-friendly and cost effective, therefore replacement of traditional building materials with Fibre Reinforced Polymer (FRP) composite is a necessity.

Natural fibres base on their sources are divided into three categories; plant fibres (sisal, hemp, flax, bamboo, etc), animal parts involving protein (silk, hair, wool, etc) and minerals. The main parts of plant fibres are cellulose, hemicellulose, lignin and pectin (Zakikhani, Zahari et al. 2014). Bamboo as a natural fibre for reinforcement has recently attracted the attention of researchers (Sakaray, Togati et al.) because of their advantages over other established materials. They are environmentally friendly, abundantly available, cheap, high stiffness and have low density. Bamboo is a green plant belonging to the grass family of plants. It culms are hollow and also the intervals (nodes) contains several diaphragms which separates from
the internodes. Bamboo grows well in warmer moist regions or environments and also contains a larger amount of fibres. Bamboo is mainly made up of 70% cellulose and 20% of lignin. Bamboo in its greenish nature helps to reduce the amount of carbon dioxide in the atmosphere (Zakikhani, Zahari et al. 2014).

Figure 1.1; image of green bamboo plant

Polyester is a thermoset polymer which is relatively tough, easy to process and have moderate temperature processing capabilities. These properties of polyester resins are mainly because of the existence of a three-membered (i.e two carbon and an oxygen) cyclic bonded ring known as oxirane group in their chemical structures (Biswas et al, 2014). Advantages of polyester are; good adhesive properties, good resistance to chemical and heat, excellent bonding and gap filling property. These properties make polyester resin good to be used as a matrix for fibre reinforced polymer composite in this application.

Utilization of polyester-bamboo fibre reinforced composite as a roofing material to substitute for the traditional roofing materials like aluminium, steel and ceramic which have disadvantages such as; high thermal conductivity, highly corrosive, high cost of extraction, high density and highly sonorous has become a major concern to engineers. Research have
been done by (Zakikhani, Zahari et al. 2014) on some physical and mechanical properties of polyester-bamboo reinforced composites but to the best of our knowledge, little information is available on the thermo-physical property of polyester-bamboo reinforced composite. This study requires the investigation on the thermal and acoustic properties of alternative roofing material made of polyester-bamboo fibre reinforced composite.

1.2 Problem Statement

Metallic roofing sheets, which are the most common roofing sheets in recent times mostly corrode with time because of their electrochemical reactions with the environment (atmospheric moisture), corrosion create pores in the roofing sheet causing drainage during rainfall and also cause roofing sheet to lose their aesthetic purpose. Aside the metal roofing being corrosive, they produce noise during rain fall (highly sonorous) and also because of their excellent thermal conductive property, they dissipate heat into rooms during the day as a result, increasing room temperature. This incur extra cost to fix air conditioners in rooms to stabilize the room temperature and also to replace roofing materials when they cause drainage during rainfall as a result of corrosion.

However, because of these problems with metallic roofing sheets, people have patronized ceramic roofing materials. Problem with ceramic roofing materials are their brittle nature and their weight. Because ceramic roofing sheets are very heavy, most building using ceramic roofing materials incur cost for their load bearing.

The use of polyester-bamboo reinforced composite as an alternative roofing sheets would be a best solution for these problems because of their properties such as; low weight, corrosion
resistance, less sonorous and poor thermal conductivity.

Figure 1.2 (a) Ceramic roofing (b) Corroded metallic roofing sheet

1.3 Aim and Objectives

The main aim of this project is to determine the thermal conductivity and acoustic properties of an alternative roofing material made of polyester-bamboo fibre composites.

Other specific objectives of this project are;
• To determine the chemical resistance of the bamboo-polyester roofing (corrosion resistance).

• To investigate the water absorptivity of bamboo-polyester roofing sheet.

• To determine the flexural strength of bamboo-polyester roofing sheet.

• To determine the thermal conductivity of bamboo-polyester roofing sheet.

• To determine the acoustic property of bamboo-polyester roofing sheet.

1.4 Justification

Roofing sheets which exist in our environment made of metallic materials and ceramic materials have high thermal conductivity, highly sonorous, prone to corrosion and expensive extraction of raw materials. Ceramic roofing materials have high weight which increases the load bearing of the building and also brittle in nature.

Therefore, an alternative composite roofing material made of polyester-bamboo fibre/particulates which has high strength to volume ratio, light weight, renewability of raw materials (bamboo) and environmental friendly would be applicable. Other additives added to polyester-bamboo composite material would enhance the roofing sheet to be water resistant and also chemical resistant.

1.5 Scope of Study

This report is categorized into five major chapters which is made of; introduction, literature review, proposed methodology, result and discussion and also conclusion and recommendation respectively.

The introduction of the report includes the background study of polyester-bamboo composite, problem statement, aim and objective, justification as well as the scope of study. Chapter two being the literature review on fabrication of an alternative roofing sheet made of polyester-
bamboo. The chapter three contains the materials and methods that is used for the fabrication of the roofing sheet, extraction of the raw materials (bamboo fibre/particulates) and the characterization of the roofing sheet (thermal conductivity, acoustic properties, flexural test, fire resistant, corrosion resistant and also water absorptivity).

The result obtained in the characterization of the roofing sheet and the analysis of the data is incorporated in chapter four. The last chapter of the report is made of the conclusion and recommendations.
CHAPETR TWO

LITERATURE REVIEW

2.0. Introduction

Natural fibres obtained from plants are called cellulosic fibres. Also, natural fibres such as bamboo fibres are been understood to have a good potential in the future as a replacement for synthetic fibres. Some of the advantages of bamboo fibres are low cost, abundance of it source, renewability, good thermal properties and acceptable specific strength properties (Manickavasagam, Ramnath et al.). These properties make bamboo fibres as reinforcement in synthesizing composite material with a polymer matrix a suitable alternative material for roofing sheet.

(Zakikhani, Zahari et al. 2014) conducted a research to investigate bamboo fibre extraction and its reinforced polymer composite material. Bamboo structure was studied and three different bamboo fibre extraction methods were also done; mechanical, chemical and combination of both. The dried bamboo culms were cut into strip using a knife which was then soaked in 1N of NaOH solution for 72 hours in other to facilitate any of the extraction process said above. The composite was synthesized by pressing the moulded bamboo strips into the polyester resin under high pressure. The prepared composite was cured in an oven at 80°C for four and half hours. (Lu, Jiang et al. 2013), this paper shows an effect of surface modification of bamboo cellulose fibres on mechanical properties of cellulose/polyester composites. Bamboo cellulose fibres were treated with NaOH aqueous solution and silane coupling agent, respectively before they were applied into polyester composites.

(Besi 2013), this paper review the mechanical properties of bamboo fibre reinforced polymer composite. It was observed that, the mechanical properties of the bamboo reinforced composite increased with cellulose content, which was influenced by factors such fibre...
volume fraction, fibre length, fibre aspect ratio, fibre-matrix adhesion and fibre orientation. (Sreenivasulu and Reddy 2014), in this evaluated the mechanical properties of bamboo fibre reinforced composite materials such as tensile strength and flexural strength of short bamboo fibres. Hand lay-up technique was used in synthesizing the composite for characterization. In this paper, the flexural test was determined by using a universal testing machine. (Mounika, Ramaniah et al. 2012), in this paper conducted a test on the thermal conductivity of bamboo fibre reinforced composite by a guarded heat flow meter method in accordance with ASTM E1530-99. Different fibre orientation and volume fractions of samples were used. (Mohapatra, Mishra et al. 2014), experimentally also studied the thermal conductivity of teak wood dust reinforced polyester composite using Lee’s apparatus method.

(Farid, Purniawan et al. 2017) in this paper conducted an acoustic test on wideband bamboo based polymer composite. The analysis on the composite (sound absorption) was conducted as per ASTM E1050. (Liu, Chen et al. 2014), conducted several test on bamboo fibre composite which included water absorption test. (Prabhu, Joel et al. 2017), experimentally studied the flexural strength of a polyester-bamboo fibre composite

2.1. Roofing sheet

Roofs can be one of the most character defining features of historic buildings, it is part of a building envelope, and it is the covering on the uppermost part of a building or a shelter which provides protection from animals and weather, notably rain or snow, but also heat, wind and sunlight.

Originally, roofing sheets were made of copper in the 3rd century B.C, but technology has advanced over the years which has led to the availability of other roofing materials like; ceramics, wood, asphalt, asbestos, iron and aluminium (Wayne, 2007)

The development of new materials for roofing sheets was as a result of some disadvantages found on the original roofing materials. Researchers found out that copper which was the
original roofing materials in the 3\textsuperscript{rd} century was a very good conductor of heat and also produces noise when it rains.

Technology is advancing year after year, new materials are being developed for roofing sheets, from metals to ceramics and now to composites (Fibre-Reinforced Polymer) which has over the years attracted the attention of engineers because of their significant properties which are; stiffness, fire resistance, light weight, bio degradable and less sonorous.

2.1.1. Roofing materials

Roofing material is the outer most layer on the roof of a building sometimes self- supporting, but generally supported by an underlying structure. Types of roofing materials which are commercially available ranges from natural products such as thatch and slate to commercially produced products such as tiles and polycarbonates sheeting. There are different types of roofing sheets, they are;

1. **Asphalt composition shingles**: they are composite roofing sheet product made from either a fiberglass or a cellulose mat, and asphalt and minerals, as opposed to a single material, such as wood shingles or clay tiles

![Asphalt composition shingles](https://e3rr.com/roof-shingles-made-theyre-made)

Figure 2.1 (a): Asphalt composition shingles

(Source: https://e3rr.com/roof-shingles-made-theyre-made)
2. **Corrugated roofing sheets**: is a building material composed of sheets of hot-dip galvanized mild steel, cold-rolled to produce a linear corrugated pattern in them. The material used is actually steel, and only surviving vintage sheets may actually be made up of iron. The corrugations increase the bending strength of the sheet in the direction perpendicular to the corrugations, but not parallel to them.

![Corrugated roofing sheet](https://www.bushburycladding.co.uk/corrugated-steel-roofing-sheets)

Figure 2.1 (b): Corrugated roofing sheet

(Source: [https://www.bushburycladding.co.uk/corrugated-steel-roofing-sheets](https://www.bushburycladding.co.uk/corrugated-steel-roofing-sheets))

3. **Polycarbonate roofing sheets**: they are roofing sheets made from a group of thermoplastic polymers containing carbonate groups in their chemical structures. Polycarbonates used as roofing sheets are strong, tough materials, and some grades are optically transparent. They are easily worked, moulded, and thermoformed.
Figure 2.1 (c): Polycarbonate roofing sheet


4. **Stone coated roofing sheets**: This is made from steel or some other metal; the metal is then coated with stone chips and attached to the steel with an acrylic film. The goal is a more durable roof that still retains the aesthetic advantages of a more traditional roofing material
Figure 2.1 (d): Stone coated roofing sheet


5. **Wood shingles**: they are roof covering consisting of individual overlapping elements. These elements are typically flat, rectangular shapes laid in courses from the bottom edge of the roof up, with each successive course overlapping the joints below. Shingles are made of wood.

Figure 2.1(e): Wood shingles
6. **Tiled roofing sheets**: They are designed mainly to keep out rain, and are traditionally made from locally available materials such as terracotta or slate.

![Tile roofing sheet](http://www.amersonroofing.com/tile-roofs.php)

Figure 2.1 (f): Tile roofing sheet

7. **Slate roofing sheets**: They are type of roof shingle, or more specifically a type of roof tile, which are installed by a slater. Slate has two lines of breakability — cleavage and grain — which make it possible to split the stone into thin sheets. When broken, slate retains a natural appearance while remaining relatively flat and easy to stack.

![Slate roofing sheet](http://www.amersonroofing.com/tile-roofs.php)

Figure 2.1 (g): Slate roofing sheet
2.1.2 Shapes of roofing sheets

Roofing sheets differ greatly from region to region, the main factors which influence the shape of roofs are climate and materials available for roof structure and outer covering, roof shapes vary from almost flat to steeply pitched. They can be arched or domed; a single flat sheet or complex arrangements of slopes, gables and hips; or truncated to minimize the overall height. The various shapes include:

1. **Flat shape**: These are found in traditional buildings in regions with low precipitation. Modern materials which are highly impermeable to water make possible the very large low-pitched roofs found on large commercial buildings. Although called flat but they are generally pitched.

2. **Gable**: Simple roof design shaped like an inverted V

3. **Hipped shape**: A hipped roof is sloped in two pairs of directions compared to the pair of direction for a gable roof.

4. **Mansard**: A roof with the pitch divided into a shallow slope above a steeper slope. The deep slope may be curved.

5. **Gambrel**: A roof similar to a mansard but sloped in one direction rather than both

6. **Shed roof**: A roof having only one sloping plane and no hips, ridges or valleys.

7. **Dutch gable**: A hybrid of hipped and gable with the gable at the top and hipped lower down.

8. **Salt box**: A gable roof with one side longer than the other, and thus closes to the ground unless the pitch on the other side is altered.
9. **Bonnet roof**: A reversed gambrel or mansard roof with the lower position at the lower pitch than the upper position.

10. **Butterfly roof**: A V-shaped roof resembling an open book. A kink separates the roof into two parts running towards each other at an obtuse angle.

11. **Tented roof**: A type of polygonal hipped roof with steeply pitched slopes rising to a peak.

![Image of various roof shapes](http://dcacademy.info/roof-structure-types/roof-structure-types-roofing-commercial-roof-construction-types/)

**Figure 2.1 (h): Image of the various shapes of roofs**

(Source; http://dcacademy.info/roof-structure-types/roof-structure-types-roofing-commercial-roof-construction-types/)

### 2.2 Composite

The term composite materials were firstly used in 1950s and it has been used domestically from about 1960s. Composite can be defined as a multi-phase combination material of two or
more component materials with different properties and different through compounding processes, without maintaining the main characteristics of the original components, but also shows new characters which are not possessed by any of the original components (Wang, Zheng et al. 2011).

Composites are produced when two or more materials or phases are used together to give a combination of properties that cannot be attained by the individual materials (Askeland, Fulay et al. 2010). Composite materials have gain a lot of engineering applications and may be selected to give unusual combination of properties due to its ability to resist corrosion, light weight, high-temperature performance, stiffness and hardness. It is made up of a matrix and reinforcement (fibre/particulate). These materials brought together to form the composite material, which possesses different physical and chemical properties. This helps to attain the desired properties. Depending on the type of composite to be produced, different materials are used as the matrix and the reinforcement.

Composites makes up a very broad and important class of engineering materials. Annually in the world, production of composites is about 10 million metric tons and the market has in the recent years been growing at 5-10% per annum (Hull and Clyne 1996).

2.2.1 Matrix

Matrix is the soft continuous phase of a composite. It embodies ceramic matrix, metal matrix and polymer matrix. The matrix is much weaker and less stiff than the reinforcement in a composite. For natural composites, the cellulose molecules contain lignin which is the matrix and others also have collagen as a matrix (Hull and Clyne 1996).

The matrix has two major roles in a composite; transfer and distribute load to the reinforcement and also protect the reinforcement phase. Other important functions of matrix in the composite is that, it supports the reinforcement in position, prevent cracks from
propagating throughout the composite and also prevent the reinforcement from environmental
damage such as corrosion. Most matrix usually determines the electrical, chemical behaviors
and the highest temperature which the composite material can be used (Askeland, Fulay et al.
2010). The matrix determines the in plane shear strength, damage tolerance of the composite
and processability of composite. The function of the matrix is to enhance the transverse
properties of the laminated composites, improves impact and fracture resistance of composite
and inter-laminar shear.

2.2.2 Reinforcement

Reinforcement is the load bearing phase of a composite material. It does not always have to
be in the form of a long fibres. It can possess forms such as particles, flakes, short fibres,
whiskers, continuous fibres or sheet. Due to the stiffer and the strong nature of fibres, they
are mostly used for engineering applications. Reinforcement possess properties such as high
strength and high stiffness with low density which makes it suitable for engineering
applications.

The primary function of the reinforcement phase is to carry the applied load and also to
transfer strength to the soft matrix phase.

Reinforcement can be grouped into natural and artificial sources. Examples of natural
reinforcement are cotton, wool, hair, oak tree fibres, bamboo fibres and silk. Examples of
artificial reinforcement are glass fibres, carbon fibres, Kevlar aramid fibres, Gel-Spun
polyethylene fibres, glass fibres (stiffer and lighter), boron, silicon carbide and alumina (high
strength and stiffness) (Chawla 2012).

2.3 Types of composite

Composite materials can be named according to the type of reinforcement used or the type of
matrix used.
2.3.1 Based on reinforcement

Composite classification based on the reinforcement used can be grouped basically into three. These are particulate composite, fibre reinforced composite and laminar composite.

These groups can be subdivided. The table shows the classification based on the type of reinforcement used in the composite material (Callister Jr and Rethwisch 2012).

Figure 2.3: A schematic diagram showing the types of composite based on the type of reinforcement and its arrangement.

(Source: http://classes.mst.edu/civeng120/lessons/composite/materials/index.html)

2.3.2 Based on matrix

A matrix is a soft continuous phase of a composite. It protects the reinforcements from environmental attacks such as corrosion, it also prevents the reinforcement from abrasion and also from scratching. The matrix also binds the reinforcement together in position and also transfers the load to the reinforcements.
Composites types based on matrix can be classified into three depending on the material used as the matrix; metal matrix composites (MMC’s), ceramic matrix composites (CMC’s) and polymer matrix composites (PMC’s) (Askeland, Fulay et al. 2010).

Generally, metals and polymers are used as the matrix in composite materials since ductility is required. Polymers are used because of its good chemical resistance and therefore prevent the reinforcements from chemical attacks and have good adhesive properties which helps to bond the fibres together and also light in weight. Examples of polymers used as matrix includes phenolics, and polyesters. (Callister Jr and Rethwisch 2012)

Metals on the other hand possesses desirable engineering properties such as good strength, high toughness, creep and fatigue resistance, good electrical and thermal conductivity and also high temperature performance. Examples of metal matrix are aluminum, magnesium, copper and nickel (Askeland, Fulay et al. 2010).

Ceramic matrix composite has good properties at elevated temperatures and also lighter in weight as compared to that of metals. This makes ceramic matrix preferable to metal matrix. Ceramic matrix includes silicon carbides, silicon nitride, aluminum nitride and alumina (Lamon, Mazerat et al. 2015).

2.4. Rule of Mixtures

Rule of mixtures is a micromechanics model used to predict the properties of composites. It is a rough tool that considers the composite properties as volume-weighted averages of the component properties (Chawla 2012). It is most efficient only in some simple situation in engineering applications. It can be used to predict properties such as density, elastic modulus, tensile strength and thermal conductivity of a composite. Areas where more information about a composite property is required, this rule becomes restricted in terms of application.
The rule of mixture used to predict the elastic modulus of a composite in the longitudinal direction for continuous fibre reinforcement is given as:

\[ E_{cl} = E_f V_f + E_m V_m \]  \hspace{1cm} \text{Equation 1}

This rule of mixture is also known as the upper bound rule of mixture. It is assumed that the strain is equal for matrix, fibre and composite. That is isostrain.

For the transverse direction the stress is assumed to be the same for the fibre, matrix and the composite. That is isostress. The rule of mixture used to predict the elastic modulus of the composite in the transverse direction also known as lower bound is given below

\[ E_{ct} = \frac{E_m E_f}{E_m V_f + E_f V_m} \]  \hspace{1cm} \text{Equation 2}

For the above rules the fibres were assumed to be uniform in properties, length of fibre extends throughout the matrix and also fibres of approximately equal diameter.

Where \( E_{cl} \) is the modulus of the composite in the longitudinal direction with respect to the fibre arrangement, \( E_f \) is the modulus of the fibre, \( V_f \) is the volume fraction of the fibre, \( E_m \) is the modulus of the matrix, \( V_m \) is the volume fraction of the matrix.

Rule of mixture used to predict the thermal conductivity in the longitudinal direction is given below

\[ k_{cl} = k_f V_f + k_m V_m \]  \hspace{1cm} \text{Equation 3}

For the transverse direction it is given as

\[ k_{ct} = \frac{k_f k_m}{k_f V_f + k_m V_m} \]  \hspace{1cm} \text{Equation 4}
Where $k_{cl}$ and $k_{ct}$ are thermal conductivities of the composite in the longitudinal and transverse direction respectively, $k_f$ and $k_m$ are the thermal conductivities of the reinforcement and the matrix.

Rule of mixtures for the theoretical density of a composite in the longitudinal direction is given as

$$\rho_c = \rho_f V_f + \rho_m V_m \quad \text{ Equation 5}$$

Rule of mixtures can also be used to predict the properties of a composite reinforced with particulate accurately. For the density it is given as

$$\rho_c = \rho_1 V_1 + \rho_2 V_2 \quad \text{ Equation 6}$$

Where $\rho$ and $V$ are densities and volume fraction of constituent of the composite respectively. The subscript 1 and 2 denote the component of the composite. Mostly this density obtained is theoretical density and actual density is obtained by factoring the amount of voids present in the composite material. (Askeland, Fulay et al. 2010, Singla and Chawla 2010)

The arrangement of the reinforcement for a composite play an important role in many of the properties of the composite. The rule of mixtures tells that, for maximum properties to be obtained the volume fraction of the reinforcement should not exceed 80%, since beyond 80% the matrix will not completely surround the reinforcement which brings about poor interfacial bonding between the matrix and the reinforcement. (Askeland, Fulay et al. 2010)

### 2.5 Bamboo

Bamboo is a tall green plant belonging to the grass family of plants. It is a flowering evergreen plant and is the largest of the grass family of plants. It is woody and a fast growing plant, the growth rate depends on the nature of the local soil. Bamboo fiber/particulate contains 26% to 43 % of Cellulose and 21% to 31% Lignin (Manickavasagam, Ramnath et
Bamboo is a green plant that helps to control the carbon content in the atmosphere thereby being environmentally friendly (Hussain, Pandurangadu et al.).

There are about 1500 species of bamboo. Some varieties of bamboo species are Ci bamboo, Moso bamboo, Lv bamboo, Dan bamboo and Ma bamboo (Hussain, Pandurangadu et al.). The plant has a complex system consisting of two set similarly structured vegetative axes. One above the ground and the other below the ground (in the soil). The portion between two successive nodes is the internode. Internodes are usually hollow but not always. Bamboo is covered with sheath at the initial stage of growth but falls off as the plant culm matures. The cross section contains fibres which vary in properties. The variation in properties may be due to the nature of growth, the soil, climatic conditions and soil moisture (Sakaray, Togati et al.).

### 2.6 Properties of Bamboo

1. Bamboo fibre/particulate is hygroscopic. Absorbs moisture when changes in humidity and temperature occur in the environment.

2. They have good bending properties.

3. They have a great elastic properties (ability) and also low weight to strength ratio.

4. They are resistant to fire due to the presence of high silicate acid. It can stand at temperature of about 400°C.

5. They have low density.

6. They have a high wear resistance (Sethia and Baradiya).

In summary bamboo fibres/particulates have low abrasion, low density, high toughness, acceptable specific strength properties, good thermal properties, and enhanced energy recovery.
The advantages are low cost, renewability, biodegradability, low specific gravity, abundance, high specific strength, and non-abrasiveness (Manickavasagam, Ramnath et al.).

2.7 Applications of bamboo fibres and particulates

1. Bamboo fibres/particulates are used in reinforcement in composite materials.

2. For construction of brides in some part of the world

3. Bamboo is used for paneling.

4. Bamboo is used for making wind turbines.

5. Bamboo charcoal is used in water purifiers

6. It is used as flooring on some buses

7. bamboo mat corrugated sheets are being used in railway stations

Figure 2.7: image of corrugated bamboo roofing sheet
2.8 Extraction of bamboo fibres/particulates

2.8.1 Chemical extraction

Chemical extraction methods use alkali or acid retting, chemical retting, chemical assisted natural (CAN) and degumming to reduce or remove the lignin content of the elementary fibres. The treatment also affects the component of the bamboo microstructure including the pectin and the hemicellulose. Below are the procedures for the various methods used for extraction of bamboo fibres and particulates

2.8.1.1 Acidic/Alkali retting

Below are the step by step procedure for acidic retting method for the extraction of bamboo fibres.

- Bamboo culms without nodes which have been sun dry are cut into strips.
- The bamboo is strip are heated with 1.5N NaOH solution in a stainless steel container at 70°C for 5 hours.
- Pressing machine is to press the strips and with the help of steel nail separate fibres.
- The extracted fibres are washed with water and dried in an oven.
- The strips can also be treated with a mixture of alkali (NaOH) and acidic (trifluoroacetic acid (TFA)) solution. This helps to remove more lignin which provide good surface for the fibres to bond well with the matrix of a composite.
- This process causes less damage to the fibres (Zakikhani, Zahari et al. 2014).
2.8.1.2 Chemical retting

Researchers (Zakikhani, Zahari et al. 2014) used the Chemical Assisted Natural retting (CAN) Procedure to reduce the lignin and water content in fibres. In this process,

- Bamboo culms are cut into a thin slab in the longitudinal direction with a slicer.
- The fibres are separated manually and immersed in Zn \((\text{NO}_3)_2\) solutions with concentrations of 1%, 2% and 3% (owf) and a material to liquor ratio of 1:20.
- The fibres are immersed at 40°C at neutral pH for 116 hours and kept in a Biochemical Oxygen Demand (BOD) incubator, and then boiled in water for 1 h. These method removes more lignin compared with alkaline and acid retting, but the moisture content of the treated fibres is high.
- Another procedure is to slit bamboo culm into 2 cm chips and roast the chips for 30 min at 150°C.
- Immersed the chips in water at 60°C for 24 hours and then dry in air prior to further impurity removal by repeated rolling.
- Cook fibre bundles with 0.5% NaOH (w/v), 2% sodium silicate, 2% sodium sulphite and 2% sodium polyphosphate solutions at 100°C for 60 min at a liquor to bamboo ratio of 20:1.
- The fibres are washed with hot water and treat it with 0.04% xylanase and 0.5% diethylene triamine pentacetic acid for 60 min at 70°C and pH 6.5.
- Cook the obtained fibres again at 100°C for 60 min following the same procedure, with the exception of using 0.7% NaOH.
- Bleach in a polyethylene bag with 0.2% sodium hydroxide, 4% \(\text{H}_2\text{O}_2\), and 0.5% sodium silicate for 50 min. Keep the pH at 10.5 and the liquor ratio to be 20
Lastly, after treatment with 0.5% sulphuric acid for 10 min and emulsification for 5 days, the refined bamboo fibres are acquired. For this process the bamboo fibre had a smaller orientation angle for exterior macro fibrils, which is an important factor showing that bamboo fibre is suitable for use as fibre reinforcement in composites in comparison with ramie, flax, and cotton fibre (Zakikhani, Zahari et al. 2014).

2.8.2 Mechanical extraction

This method includes different processes such as steam explosion or heat steaming, retting, crushing, grinding and rolling in a mill. These methods have been used to extract fibre for the application of bamboo fibre in reinforced composites in various industries. The main advantage of mechanical fibre extraction over chemical processes is its better environmental characteristics. Some of the mechanical methods for extraction of fibres or particulate are described below (Zakikhani, Zahari et al. 2014).

2.8.2.1 Steam explosion method

This method has a low energy consumption used to separate the cell wall of a plant to produce pulp. It is an appropriate method for the separating of lignin from the plant surface especially for the pulp industry but the resulting fibres are rigid and dark. The method does not fully remove the lignin from the cell wall bundles. A mixing machine is used to remove the rest of the lignin after the process. The for the process is as follow;

- Cut bamboo culms into chips.

- The bamboo chips are exploded under pressure and 210°C for 5 minutes.

- The process is repeated nine times to ensure fracturing of the cell wall.

- At the end the ash is removed by washing the fibres in hot water at 90°C to 95°C with soap
Fibres are then dried in an oven at 105°C for 24 hours.

In this method, the bamboo fibre surfaces have low shear resistance. As some lignin partly decomposed on the fibres and this is removed by ultrasonically washing the fibres and then treating them with isocyanate silane to remove those unexpended cells from steam exploded fibres. The results indicated that steam exploded bamboo (Zakikhani, Zahari et al. 2014).

2.8.2.2 Mechanical retting

Mechanical retting is the use of water to aid in the extraction as in the use of acid or alkaline in chemical retting method. The steps involved in this process is outlined below.

- Bamboo are removed and the cylindrical part of the culm is peeled to obtain strips
- Strips are kept in water for three days
- The wetted strips are beaten, scrap with sharp edge knife and comb is applied on it to separate the fibres.

The quality of fibres is affected by the scrapping process and fibres also break along their length to short pieces.

2.8.2.3 Crushing

Crushing is a mechanical method used to produce either short fibres or particulate. To produce particles, the final stage is performed for a longer time.

- Bamboo fibres are extracted bamboo into small pieces by the roller crusher.by first cutting the raw
- The small pieces of bamboo are extracted into coarse fibre by a pin roller
- The coarse fibres are boiled at 90°C for 10 hours to remove their fat and then dry in a rotary dryer and then into a dehydrator.
This process yields short fibres and may become powdered after mechanical over processing (Zakikhani, Zahari et al. 2014).

2.8.2.4 Mechanical grinding
Grinding is also another method to produce short fibres and particles. This is one of the commonest method to produce particles for reinforcement.

➢ Bamboo culms without nodes are cut into strips using a knife and soak in water for 24 hours.

➢ The drenched strips are then cut into smaller pieces with a knife.

➢ Wider strips are passed through an extruder and small chips are obtained by cutting the longer strips.

➢ Short fibres are obtained by grinding the bamboo chips with high speed blender for 30 minutes. For particulates, the blending is done for longer than 30 minutes.

➢ Fibres/particulates are separated by size using several sieves of different aperture.

➢ The particles/fibres obtained are dried in an oven at 105°C for 72 hours.

Fibres produced by this process have increased transverse length strength and tensile modulus (Zakikhani, Zahari et al. 2014).

2.8.3 Combined chemical and mechanical extraction
The compression moulding technique (CMT) and roller mill technique (RMT) are usually used after alkali and chemical treatment to extract fibres. In the CMT technique, pressurize bed of alkaline is used to treat bamboo strips between two flat platens under a load of 10 tons. In this method, the starting bed thickness and compression time are important factors to separate high quality fibres.
In the RMT technique, treat bamboo the strips and force them between two rollers, with one fixed and the other rotated.

In both methods the bamboo strips are flattened, and the combined alkaline and mechanical process enable the easy separation of strips into individual fibres.

In addition, the size of the compression mould and the diameter of the rollers are two factors that limit the ability to extract fibres with smaller strip sizes in both techniques.

In another method, only a roller is used to extract fibres. In this procedure the nodes of the bamboo culm are removed and the internodes are sliced in the longitudinal direction by the slicer to make strips. The bamboo strips are immersed in NaOH solution with concentrations of 1%, 2%, and 3% at 70°C for 10 hours. The mechanical properties of fibres immersed in 1% NaOH are higher than the properties of fibres immersed at other concentrations. Roll alkali-treated strips by a roller looser to extract fibre, and finally wash the small fibres obtained with water and dry in an oven at 105°C for 24 hours (Zakikhani, Zahari et al. 2014).

**2.9 Polyester**

Polyester resin material is a three-component material. However, the manufacturer mixes the two reactive parts. At the time of application, a catalyst is added to start the reaction. Generally polyester resins can be made by a dibasic organic acid and a dihydric alcohol. They can be classified as saturated polyester, such as polyethylene terephthalate, and Unsaturated polyester. The polyester resin is usually dissolved in monomer (styrene is the most widely used), which will copolymerize with it and contribute to the final properties of the cured resin. The addition of catalyst will cause the resin to cure. The most frequently used catalyst is methyl ethyl ketone peroxide (MEKP) 174 Polyester or benzoyl peroxide (BPO) and the amount varies from 1-2%. The catalyst will decompose in the presence of the polyester resin to form free radicals, which will attack the unsaturated groups (like C=C) to initiate
the polymerization. The processing temperature and the amount of the catalyst can control the rate of polymerization, the higher temperature or the more the catalyst, the faster the reaction.

2.10 Advantages of Polyester

Polyester resins have good chemical and physical properties which includes;

- Long lasting and durable
- Does not discolour badly
- Relatively inexpensive
- Works well on concrete

2.11 Characterization

Materials characterization when used in materials science or engineering refers to the processes in which a material’s structure and properties are being probed and measured. Without materials characterization, there will not be the understanding of engineering materials selection since the required properties of material for an application can only be determined by characterization. The scope of characterization differs; it is sometimes limited to the study of the microscopic structure and properties. It is also referred to any other material analysis performed on the material such as mechanical testing which includes flexural test and creep resistance test, thermal testing and density calculations, physical test (acoustic testing and fire resistance testing), chemical testing such as corrosion resistance testing and electrical conductive test. Depending on the properties required for an engineering application, material characterization helps to determine that, the selected material would be able to possess all the requirements (Kumar 2014).

The characterization of polyester-bamboo fibre composite roofing material is performed to determine its flexural strength, thermal conductivity, acoustic properties, corrosion resistance, fire resistance and its water absorptivity to ensure that, it meets the requirement of a good roofing material and also applicable in a given environment without any failure.
2.11.1 Thermal Conductivity Test

Thermal conductivity is an important property of a material which needs to be taken into consideration when selecting materials for building construction and other engineering applications. Thermal conductivity is a property of a material to conduct heat and directly dependent on temperature. Though several investigations (Mounika, Ramaniah et al. 2012, Mohapatra, Mishra et al. 2014) have been done on thermoplastic composite but few have explored the thermal conductivity of natural fibre reinforced composite such as wood and bamboo based (Mounika, Ramaniah et al. 2012). The thermal conductivity characterization of the bamboo fibre reinforced composites is investigated experimentally by a guarded heat flow meter method (Unitherm model 2022, ANTER Corp., Pittsburgh, PA) in accordance with ASTM E1530-99, test sample of size 50 mm in diameter and 10 mm in thickness is prepared for the test. Different fibre orientations and fibre content are used in other to investigate the thermal conductivity depending on the orientation and the fibre volume fraction (Mounika, Ramaniah et al. 2012).

Lee’s disc apparatus method is another most used thermal conductivity test performed on thin composite materials. A standard dimension for Lee’s disc apparatus method of diameter 110mm and thickness of 5mm is used. In the Lee’s setup as shown in the figure below, a nickel disc (N) is hung from a stand with the help of three strings. A heating chamber (H) with the passage of steam in and out if the chamber is created and also, a metallic disc (M) is placed on top of the heating chamber. The composite sample is then placed in between the two disc. Two holes are created in the two respective disc (Nickel disc and metallic disc) and thermometers are inserted to measure the temperature different across the sample (Mohapatra, Mishra et al. 2014). The diagram below shows the experimental setup for the test.
2.11.2 Physical Test

Physical characterisation of composite material comprises the determination of the density, fibre volume ratio and void volume ratio, coefficient of thermal expansion, sound absorption (acoustic test) and fire resistance of the composite material. Environmental friendly and comfortable materials are required for application in the manufacturing of roofing material which would have a higher tendency to absorb sound (Farid, Purniawan et al. 2017).
2.11.3 Acoustic Test

Acoustic testing or sound testing refers to the measurement of how much sound is stopped by separating walls, floors between dwellings rooms and also roofing on buildings. By creating a controlled sound at one end of the material such as floors, walls and roofing’s, by measuring the amount of sound transmitted or received at the other end, we can estimate how much sound is stopped by the structure. Sound absorption analysis on the bamboo-polyester roofing is conducted to determine its ability to absorb sound by using ASTM E1050 (Farid, Purniawan et al. 2017). A multifunction meter PCE-EM 886 is used to record the acoustic properties to determine the sound absorption of the roofing sheet. The image below shows a multifunction meter for the test.


Fig 2.11 (b): A multifunction meter PCE-EM 886

2.11.4 Fire Resistance Test

Fire resistance test of building members such as walls, columns, floors and roofing become an important characterization. It helps to determine if the condition of the building material is safe and therefore is not a threat to its neighbouring structures and the public as a whole. This is done to ensure that, in the construction of every building, the materials used meets the standard requirement of a good fire resistance material in a given society (ASTM 1999).

Fire resistance test can be classified into three; external fire exposure from flying brand from neighboring buildings to the roof, internal fire exposure from equipment and inventory to the roofing material, fire endurance testing (time temperature rating) per ASTM E119 furnace test.

The third basic type of testing is done by exposing the bottom side of the roofing material to a known temperature. The image below shows how the fire endurance testing (time temperature rating) per ASTM E119 furnace test is perform (Fricklas 1981).

Fig 2.11 (c): Fire endurance testing (time temperature rating) setup (Fricklas 1981)
2.11.5 Chemical Resistance Test

Several tests such as flexural test, water resistance test and thermal test are done to determine the failure of roofing materials. Also, chemical resistance test can be conducted to investigate the response of roofing sheets to chemical exposure such as corrosive environment. Polyester-bamboo roofing sheet needs to undergo the above said test to ensure that it is corrosion resistant. This is because, the roofing sheet would be exposed to environmental factors which can cause corrosion such as excess raining (leading to wet corrosion) and high temperatures (dry corrosion).

2.11.5.1 Corrosion Resistance Test

Corrosion resistance test on bamboo fibre reinforced polyester composite is conducted to investigate the corrosive properties. Chemicals such as glacial acetic acid, conc. nitric acid, hydrochloric acid, ammonium hydroxide, aqueous sodium carbonate and aqueous sodium hydroxide is used. The already weighed samples are dipped in above mentioned chemicals under study state conditions for 24 hours, removed, washed in distilled water and dried immediately by pressing between filter papers. The final weight of the samples after drying is weighed and the weight percent loss or gain as per ASTM D 543-87 method is recorded. The corrosion resistance test is repeated for ten sample and the average weight is recorded (Rajulu, Baksh et al. 1998).

2.11.6 Mechanical Characterization

Mechanical properties become an important tool when selecting a material for engineering application such as in the production of roofing materials. Bamboo shows better mechanical properties over other natural fibres such as sisal and banana fibre. Bamboo fibres when combined with other polymeric matrix (polyester) possesses high strength to weight ratio, high strength at elevated temperature, creep resistance and high toughness. Selection of the kind of bamboo fibres depends on the properties required after synthesizing the composite.
Long fibres are normally used in the fabrication of composite which would be used in the manufacturing of automobile roofing and roofing of building since higher flexural strength, light weight and toughness will be a requirement (Prabhu, Joel et al. 2017).

2.11.6.1 Flexural Test

Flexural strength of a material also known as the modulus of rapture, bend strength, and transverse rupture is a property of a material which is defined as the stress at which failure occurs to a material subjected to bending stress (Ashby 2005).

Research has been done to estimate the flexural strength on polyester-bamboo fibre composite. (Prabhu, Prathviraj et al. 2017), experimentally studied the flexural strength of a polyester-bamboo fibre composite. Dry bamboo fibres with three different lengths i.e. 4mm, 7mm and 10mm and a width of approximately 3mm is cut manually. A wooden mould is used in the fabrication of the composite. Three different weight fractions (10wt%, 20wt% and 30%) of the three different length (4mm, 7mm and 10mm) is used for the fabrication of the composite for the flexural test. After the bamboo reinforced polyester based polymer composite is fabricated, samples of appropriate dimensions are then prepared to carry out the flexural strength test. It is carried out using TINUS OLSEN H10KS testing machine according to ASTM standard test method for tensile properties of composite having the designation D 3039-76
The flexural test machine uses a flat specimen with rectangular cross-section of which a speed 1mm/min is applied until it fails. The testing of the composite is done by three points bend test. The effect of the fibre loading and the fibre length for each of the weight percentage is recorded (Prabhu, Joel et al. 2017).

2.11.7 Water Resistance Test

Water resistance test of a composite material is the test performed to determine how good the material will resist the penetration of water in its liquid state under pressure. Water resistance tests are normally conducted on bamboo reinforced polyester matrix material for roofing to ensure that, during raining, the bamboo fibres used as the reinforcement would be good enough not to absorb the rain and also resist the penetration of the rain into the room. Researchers have conducted test on the water absorption of bamboo fibre composite materials.

(Liu et al.) conducted several test on bamboo fibre composite which included water absorption test. The water absorption test is performed in accordance with ISO 62-2008. The bamboo-polyester composite roofing sheet is conditioned at 50°C for 3h, cooled at room
temperature for 10min and then weighed to record their dried weight. It is then immersed in distilled water at room temperature. After a scheduled times interval, the specimens are removed, wiped and weighed again immediately to determine weight increment during the immersion. It is immersed again for further measurement to be taken. The water absorption percentage (WAP) as a result of the weight gain divided by the dry weight of the specimen is recorded. The experiment is conducted on five replicate of the same specimen and the average water absorption percentage (WAP) of the roofing material is computed.

\[
Water\ Absorption = \frac{M_t - M_o}{M_o} \times 100\%
\]

Where; \(M_o\) is initial weight of sample and \(M_t\) is final weight of sample
CHAPTER THREE

MATERIALS AND METHOD

3.1 Materials

3.1.1 Matrix

The matrix used for the fabrication of the roofing sheet was polyester and was purchased from Josab Chemicals in Kumasi. A hardener (catalyst) was also added to help in the curing process. The ratio of the polyester to hardener mixture was given according to the specification of the manufacturer of the polyester and hardener.

3.1.2 Reinforcement (Bamboo)

The reinforcement (bamboo) was Bambusa vulgaris and was harvested from KNUST botanical garden, Kumasi. The targeted age of the bamboo used was between the age of 3-5 years to obtain strong bamboo fibres and particulates.

3.2 Extraction of fibres and particulates

The harvested bamboo was dried in air for five weeks to reduce the moisture content in it. The bamboo culms were then cut into pieces at the internodes and divided into strips for the mechanical grinding and chemical extraction respectively. The bamboo strips were then soaked in distilled water for 24 hours.

The drenched bamboo strips were then soaked in 5% mass per volume of sodium hydroxide solution for 72hrs to facilitate the extraction of the fibres. It was beaten after soaking to obtain the fibres. The fibres were pre-treated by soaking them in 3% mass per volume of sodium hydroxide solution for 24hours. The fibres were removed and washed thoroughly in distilled water, sun dried and oven dried at 105°C for 24hrs.
Bamboo particulates were extracted by mechanical grinding process. The grinding process was accomplished by the use of centre lathe machine. The grinded particulates were heated in an oven at 105°C 24hrs to remove moisture. Sieve analysis was also conducted on the particulates and a sieve size of 2mm was used to sieve the particles.
Figure 3.2 (e); Centre lathe grinding process to produce particulate

(This processes used caused less damage to the fibres and particulates also improves the interfacial bonding of the composite since lignin is soluble in acidic and alkaline solution).

3.3 Preparation of samples

3.3.1 Rule of Mixtures

Rule of mixtures was used to predict the properties and also calculate the right proportion of reinforcement to matrix to be used to acquire the desired properties since the percentage of reinforcement to use in a composite should be less or equal to 80 (≤80%).

Rule of mixtures was used to predict the properties of the roofing sheet. It was used to predict the thermal conductivity, density, elastic modulus.

The table 1 below shows the values of the properties for the constituents;

**Table 3.3: Properties of bamboo and polyester resin**

<table>
<thead>
<tr>
<th>Constituents</th>
<th>Modulus (GPa)</th>
<th>Density (g/cm³)</th>
<th>Thermal Conductivity (W/m/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyester</td>
<td>4.41</td>
<td>1.43</td>
<td>0.299</td>
</tr>
<tr>
<td>Bamboo</td>
<td>20</td>
<td>0.8</td>
<td>0.18</td>
</tr>
</tbody>
</table>
The volume fraction of the fibre can be calculated as

\[
\text{Volume fraction of fibre } V_f = \frac{\text{volume of fibre (} v_f \text{)}}{\text{total volume of composite (} V_C \text{)}} \quad \text{--- equation 1}
\]

\[
\text{Volume fraction of the matrix, } V_m = \frac{\text{volume of matrix (} v_m \text{)}}{\text{total volume of composite (} V_C \text{)}} \quad \text{--- equation 2}
\]

The rule of mixture used to predict the thermal conductivity in the longitudinal direction is given by

\[
k_{ct} = k_f V_f + k_m V_m \quad \text{--- Equation 3}
\]

\[
k_{ct} = (0.4 \times 0.18) + (0.6 \times 0.299) = 0.25 \text{ W/m/K}
\]

The rule of mixture for predicting the thermal conductivity in the lateral direction is given by

\[
k_{ct} = \frac{k_f k_m}{k_f V_f + k_m V_m} \quad \text{--- Equation 4}
\]

\[
k_{ct} = \frac{0.18 \times 0.299}{(0.4 \times 0.18) + (0.6 \times 0.299)} = 0.21 \text{ W/m/K}
\]

The rule of the mixture of fibres for the density is

\[
\rho_c = \rho_f V_f + \rho_m V_m \quad \text{--- Equation 5}
\]

\[
\rho_c = (0.8 \times 0.4) + (0.6 \times 1.43) = 1.18 \text{ g/cm}^3
\]

Rule of mixture for predicting the elastic modulus in longitudinal direction is given by

\[
E_{ct} = E_f V_f + E_m V_m \quad \text{--- Equation 6}
\]
\[ E_{cl} = (4.41 \times 0.6) + (20 \times 0.4) = 10.65 \text{GPa} \]

That for the transverse direction is given by

\[ E_{ct} = \frac{E_m E_f}{E_m V_f + E_f V_m} \]  
Equation 7

\[ E_{ct} = \frac{4.41 \times 20}{(20 \times 0.4) + (4.41 \times 0.6)} = 8.28 \text{GPa} \]

Where \( E_{cl} \) is the modulus of composite in the longitudinal direction, \( E_f \) is modulus of fibres, \( V_f \) is volume fraction of fibres, \( E_m \) is the modulus of matrix, \( V_m \) is volume fraction of matrix, \( k_{cl} \) is the thermal conductivity of composite in the longitudinal direction, \( k_{ct} \) is the thermal conductivity of composite in the transverse direction, \( k_f \) is thermal conductivity of the fibre, \( k_m \) is the thermal conductivity of the matrix, \( \rho_c \) is the density of composite, \( \rho_f \) is the density of fibre, \( \rho_m \) is the density of matrix, \( v_f \) is the volume of fibre, \( v_m \) is the volume of matrix.

3.3.2 Mould Design

Open mould was made with a wood for the fabrication of the test sample. Different mould designs were made depending on the type of test conducted. Solid edge was used to draw the pattern for the mould design. The figures below shows the various pattern for the design of the mould.
Figure 3.3.2: Pattern of (a) Lee disc sample (b) Water absorption and chemical resistance test sample (c) Acoustic test sample and (d) Flexural strength test sample.

3.3.3 Design of Roofing Sheet

The roofing sheet was corrugated (circular) shape. This shape was chosen since it eliminates stress concentration point that causes defect or easy deformation of artifacts and which also serves to provide favorable condition for crevice corrosion. Below is the design for the roofing sheet.
3.4 Fabrication of Test Samples

The samples made of particulate reinforcement were calculated and mixed using volume fractions. The fractions used were 0.1, 0.2, 0.3 and 0.4 of reinforcement. The fibre and the mixed of fibre and particulate samples were also mixed proportionally using weight fractions. The weight fractions used were 0.01, 0.02, and 0.03 of reinforcement.

The hardener to polyester ratio was mixed according to the specification of the supplier. After mixing the polyester and reinforcement, it was poured into the mold and allowed to cure within 30 minutes. The samples were removed and allowed to cure completely. The shape of the specimen was based on the shape of the mould which depended on the type of standard used for that particular test.

The image below shows the random fabrication process of the polyester-bamboo fiber/particulates roofing sheet samples for testing.
3.5 Test conducted on samples

Several tests were conducted on the raw materials used in the fabrication of the polyester-bamboo fire roofing sheet. It included moisture content analysis on the fresh bamboo particulates. The moisture content of the dried grinded bamboo particulates was also checked and compared to the moisture content in the fresh bamboo particulates to determine the moisture content lost during the drying process.

Other tests were conducted after the fabrication of the sample which included thermal conductivity test, acoustic test, chemical resistance test, water absorption test and flexural strength test.
3.5.1. Thermal Conductivity Test

Thermal conductivity test of the roofing sheet was conducted in the Physics laboratory in KNUST, Kumasi. The method that was used for the test is the Lee’s Disc experiment and the process is outlined below in accordance with ASTM D113-16;

The boiler was filled with water to nearly half and heat it to produce steam. The weight of brass disk below was taken using mass balance. Its specific heat obtained from a constant table. The diameter of the specimen was measured by a calliper, and the surface area, $A = \pi r^2$ was calculated. The thickness of the specimen was measured by screw gauge. The sample was sandwich between the lower brass disc and the upper nickel disc, suspended from the clamp stand with the two thermometers inserted.

The steam generated from the boiler was passed through the sample. The temperatures recorded in the thermometers showed a rise and finally got to it steady state. After 10 minutes, the steady temperatures were noted and recorded as $T_1$ and $T_2$. The upper nickel disc was then removed and the lower disc with the sample on top was heated with a Bunsen burner to a temperature $10^\circ$C above $T_2$ (temperature of the lower disc) and readings of temperature were taken at $\frac{1}{2}$ minute intervals till the temperature fall by $10^\circ$C below $T_2$. 


The image below shows the Lee’s disc setup for thermal conductivity test.

Figure 3.5.1 (a) and (b); Lee disc thermal conductivity setup

The thermal conductivity was calculated using these mathematical expressions;

\[ K = \frac{QL}{A(T_1 - T_2)} \]  \hspace{1cm} \text{Equation 8}

\[ Q = mc(\frac{\partial T}{\partial t})_{T_2} \]  \hspace{1cm} \text{Equation 9}

Where;

\( K \) = thermal conductivity of the sample (W/g/K)

\( A \) = cross-sectional area of the sample (m²)

\( L \) = thickness of the sample (m)

\( Q \) = rate of heat loss (J/s or W)

\( M \) = mass of the brass disc (g)

\( C \) = specific heat capacity of the brass (J/g/K)
3.5.2. Acoustic Test

Acoustic test was conducted on the polyester-bamboo composite sample and it was conducted in the strength of materials laboratory in KNUST, Kumasi. A rectangular box was used to house both the source of sound and the sound level meter as well as the sample to be tested. The source of sound with a frequency of 2000Hz was placed 21cm away from the sample and the sound level metre was placed 4cm from the specimen to ensure accurate readings.

Below is the setup for the acoustic test of the specimen.

![Acoustic testing setup](image)

(a) (b)

Figure 3.5.2 (a) and (b): Acoustic testing setup

Percentage of sound transmitted in air were first recorded and the percentage of sound transmitted through the samples were also recorded accordingly and it was conducted in accordance to ASTM E1050 standard.
3.5.3 Water Absorption Test

The water absorption of the roofing sheet was calculated by the formula below. The weight of the roofing sheet samples were first weighed and their masses were recorded as $M_o$. They were then immersed in distilled water for an interval of 8 hours. Samples were removed periodically from the water and their surface was wiped off, reweighed and mass recorded as $M_t$. The water absorption was calculated as;

\[
Water\ Absorption = \frac{M_t - M_o}{M_o} \times 100\% \quad \text{------------------- Equation 10}
\]

The setup below was conducted in the materials engineering laboratory in KNUST, Kumasi and it was done in accordance to ASTM D570

![Figure 3.5.3: water resistance setup](image)

3.5.4 Chemical Resistance Test

Hydrochloric acid solution of 1.5N concentration was used for the chemical resistance test of the sample. The test samples were weighed and dipped in the hydrochloric acid solution for
24 hours, removed, washed thoroughly in a distilled water and dried immediately in the oven at 105°C for 30mins. The final weight of the samples and their percentage weight loss were determined by the formula below.

\[
\% \text{weight loss} = \frac{M_0 - M_t}{M_t} \times 100\% \quad \text{-----------------------------------Equation 11}
\]

Where;

\(M_0\) = initial mass of the sample.

\(M_t\) = final mass of the sample.

The chemical resistance test was performed in accordance to ASTM D543-87. The image below shows the chemical resistance setup of the samples.

Figure 3.5.4: chemical resistance test

3.5.5. Flexural Test

Flexural test of the roofing was performed using 3-point bending machine (SM1004 BEAM APPARATUS) according to ASTM D3039 procedure in the strength of materials laboratory in KNUST, Kumasi. The specimens was tested by loading the holder in the ranges of 5lb. the total load that was applied was 35lb. Three replicate specimens were tested and the results
presented as an average of tested specimens. The flexural tests were conducted at a standard laboratory atmosphere, 27±2 °C and 65% relative humidity (RH 65%). The equation that was used for the calculation of the flexural strength is given as;

\[
\sigma = \frac{3FL}{2bd^2}
\]

---

Equation 11

Where F is the load at fracture, L is the length of the support span, b is the width and d is the thickness, \( \sigma \) is flexural or bend strength.

Figure 3.5.5 (a) and (b): flexural strength test set up
CHAPTER FOUR

RESULTS AND DISCUSSIONS

This chapter focuses on the result obtained from the various types of experiments as said and described in the previous chapter. Different weight fractions of fibre, particulates and mixed (fibre and particulates) were used to fabricate the polyester bamboo composite roofing sheet sample. Several tests were conducted such as thermal conductivity test, acoustic test, water absorption test, chemical test and flexural test. The results of these tests are discussed below.

4.1. Thermal Conductivity

Thermal conductivity of bamboo – polyester samples were tested using the Lee disc experiment. The samples were made of 0% reinforcement and up to 3% weight fraction and 40% volume fraction of fibre, fibre and particulates and particulate respectively.

![Thermal Conductivity Graph](image)

Figure 4.1 (a): Thermal conductivity verses weight fraction (fibre and mix)
The thermal conductivity of the polyester reinforced with bamboo fibres increased from 0.9102W/m.K to 1.7528W/m.K as the volume fraction of the fibre decreased.

The behaviour of varying the reinforcement content is explained using the data obtained from the test.

Figure 4.1 (b): Thermal conductivity versus volume fraction (particulates)

From the test, increasing the reinforcement (particulates and mix) content also decreases the thermal conductivity. On the other hand, increasing the reinforcement decreases the rate of heat loss. That is the samples takes a longer time to cool. Comparing the mixed reinforcement to the fibre reinforcement, it was observed that the mixed reinforcement conducted less than that of the fibre reinforced samples or composite. The conductivity of both reinforcement types tends to decrease sharply at 3%wt of reinforcement.
4.2. Acoustic Test

The sound test was conducted using sound level meter. The results obtained show that increasing the reinforcement content increases the percentage of sound that passes through the specimen. The lowest of percentage transmission was obtained from 10% particulate reinforcement with a value of 56% and the highest from 3wt% fibre with a value of 70.7% sound transmission.

Figure 4.2 (a): A graph of noise reduction coefficient (NRC) versus volume fraction (particulates)
4.3. Chemical Test

The chemical test was conducted on specimen with no reinforcement that is 0% reinforcement and the samples with various reinforcement content. From the results obtained, the samples with no reinforcement had the lowest mass loss. That is increasing the reinforcement content increases the loss of mass from the sample. The mass loss was high in samples reinforced with bamboo particles than the once reinforced with a mixture of fibre and particulate and fibre itself. The degradation was low in fibre reinforced composite.
Figure 4.3 (a): A graph of % Mass reduction versus weight fraction (fibre and mix)

Figure 4.3 (b): A graph of % Mass reduction versus volume fraction particulates
4.4. Flexural Test

The flexural test was conducted using a three-point bending test machine (SM1004 BEAM APPARATUS). The samples with least reinforcement deflected most. Increasing the reinforcement content decreased the bending property and it was much appreciated in sample reinforced with particles. The bamboo particles tend to make the samples stiffer. The sample with fibre reinforcement gave the good bending strength.

![Figure 4.4 (a): A graph of deflection versus load (mix)](image-url)
Figure 4.4 (b): A graph of deflection versus load (fibre)

Figure 4.4 (c): A graph of deflection versus load (particulate)
4.5 Water absorption test
The water absorption test was conducted to determine the increase in mass of the sample after immersion in water periodically. It was observed that, the percentage of water absorbed by the sample increased as the percentage of reinforcement was increased. There was a significant increase in mass at 0.4 volume fraction of the particulates from 2.0575% to 9.3668% since bamboo is hydrophilic in nature. The graph below shows the percentage increase in mass versus weight fraction for the fibre and mix reinforcement.

Figure 4.5 (a): A graph of % increase in mass versus weight fraction (mix and fibre)
Figure 4.5 (b): A graph of % increase in mass versus volume fraction (fibres)
CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The bamboo reinforcement improved the thermal property of the composite. Increasing the reinforcement reduces the sound absorptivity of the composite. On the other hand, increasing the reinforcement decreases the mass of the composite or the chemical reactivity increases with increasing the reinforcement content.

Another observation made was that, the bending property of the composite decreased with increasing reinforcement while the water absorptivity increases.

All properties either increasing or decreasing undergo massive changes after 3wt% and 40% volume fraction for fibres and particulate reinforcement respectively.

5.2 Recommendation

The main objective of this research was to determine the Thermal conductivity and Acoustic property of alternative roofing material made of polyester- bamboo reinforced composite. Though the thermal conductivity test proved that increasing the fibre and particulate content reduces the thermal conductivity and on the other hand increasing the fibre and particulate content increases the amount of sound that travels in the samples, there was a few lapses in the other tests performed. However, from the results of the various tests performed, the following recommendation is being made

- Epoxy resin can be used in further research as the matrix because it has better flexural property than the polyester resin
• Vacuum moulding can alternatively be used to prevent trapping of air during fabrication hence minimising porosity.

• Acoustic test can be performed under controlled environment to get accurate readings.

• Better extraction process of the bamboo can be performed to avoid beating of the bamboo, this will affect the strength of the fibre.
REFERENCES


Sakaray, H., et al. "Investigation on properties of bamboo as reinforcing material in concrete."

Sethia, A. and V. Baradiya "Experimental Investigation on Behavior of Bamboo Reinforced Concrete Member."


APPENDIX A

MOISTURE CONTENT ANALYSIS

Dry bamboo particulates

Mass of empty can = 33.104g  Mass of sample = 5.000g

Mass of sample + can = 5.000 + 33.104 = 38.104g

Table 2.0: moisture content analysis on dried bamboo particulates

<table>
<thead>
<tr>
<th>TIME</th>
<th>WEIGHT (g)</th>
<th>MOISTURE CONTENT (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2:50pm-3:50pm</td>
<td>37.845</td>
<td>(\frac{38.104 - 37.845}{5} \times 100 = 5.180)</td>
</tr>
<tr>
<td>3:50pm-4:50pm</td>
<td>37.854</td>
<td>(\frac{37.854 - 37.845}{5} \times 100 = 0.60)</td>
</tr>
<tr>
<td>4:50pm- 5:20pm</td>
<td>37.824</td>
<td>(\frac{37.854 - 37.824}{5} \times 100 = 0.18)</td>
</tr>
<tr>
<td>5:20pm-5:50pm</td>
<td>37.824</td>
<td>(\frac{37.824 - 37.824}{5} \times 100 = 0)</td>
</tr>
</tbody>
</table>

Moisture content = \(\frac{\text{initial Mass of sample} - \text{final Mass of sample}}{\text{Mass of sample}} \times 100\)

\(\frac{38.104 - 37.825}{5.00} = 5.58\%\)

For fresh wet bamboo particulates

Mass of empty can = 35.286g

Mass of sample + can = 5.000 + 35.286 = 40.286g

Mass of sample = 5.000g
Table 3.0; moisture content analysis on fresh wet bamboo particulates

<table>
<thead>
<tr>
<th>TIME</th>
<th>WEIGHT (g)</th>
<th>MOISTURE CONTENT (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2:50pm-3:50pm</td>
<td>38.792</td>
<td>( \frac{40.286 - 38.792}{5} \times 100 = 29.880 )</td>
</tr>
<tr>
<td>3:50pm-4:20pm</td>
<td>38.418</td>
<td>( \frac{38.792 - 38.418}{5} \times 100 = 7.480 )</td>
</tr>
<tr>
<td>4:20pm - 4:50pm</td>
<td>38.373</td>
<td>( \frac{38.418 - 38.373}{5} \times 100 = 0.900 )</td>
</tr>
<tr>
<td>4:50pm- 5:20pm</td>
<td>38.373</td>
<td>( \frac{38.373 - 38.373}{5} \times 100 = 0.00 )</td>
</tr>
</tbody>
</table>

Moisture content = \( \frac{40.286 - 38.373}{5} \times 100 = 38.260\% \)

Average diameter of bamboo fibres (mm) = \( \frac{0.17 + 0.18 + 0.04}{3} = 0.13\text{mm} \)
APPENDIX B

Modulus of short random oriented bamboo fibres

Halpin-Tsai equations

\[
\frac{E_l}{E_m} = \frac{1 + (\frac{2l}{d}) \eta_L V_f}{1 - \eta_L V_f} \quad \frac{E_T}{E_m} = \frac{1 + 2\eta_T V_f}{1 - \eta_T V_f}
\]

Where

\[
\eta_L = \frac{\left(\frac{E_f}{E_m}\right)^{-1}}{\left(\frac{E_f}{E_m}\right)^{+2} + \frac{l}{d}} \quad \eta_T = \frac{\left(\frac{E_f}{E_m}\right)^{-1}}{\left(\frac{E_f}{E_m}\right)^{+2}}
\]

\[E_{random} = \frac{3}{8}E_L + \frac{5}{8}E_T\]

For length L=60mm, diameter d=0.13, \(E_m = 3.08\text{Gpa}\), \(E_f = 20\text{Gpa}\);

- For volume fraction of fibre to be 0.1

\[
\eta_L = \frac{(\frac{20}{3.08})^{-1}}{(\frac{20}{3.08})^{+2} + \frac{60}{3.08}} = 5.9097 \times 10^{-3} \quad \eta_T = \frac{(\frac{20}{3.08})^{-1}}{(\frac{20}{3.08})^{+2}} = 0.6468
\]

\[
\frac{E_L}{E_m} = \frac{1 + \left(\frac{2 \times 60}{0.13}\right) \times 5.9097 \times 10^{-3} \times 0.1}{1 - 5.9097 \times 10^{-3} \times 0.1} = 1.5464.
\]

\[E_L = 1.5464 \times 3.08 = 4.7630\text{Gpa}\]

\[
\frac{E_T}{E_m} = \frac{1 + 2 \times 0.6468 \times 0.1}{1 - (0.1 \times 0.6468)} = 1.2075
\]

\[E_T = 1.2075 \times 3.08 = 3.7190\text{Gpa}\]
• For volume fraction of fibre to be 0.2

\[
\frac{E_l}{E_m} = \frac{1 + \left(\frac{2 \times 60}{0.13}\right) \times 5.9097 \times 10^{-3} \times 0.2}{1 - 5.9097 \times 10^{-3} \times 0.2} = 2.093496.
\]

\[E_l = 2.093496 \times 3.08 = 6.4480\text{Gpa}\]

\[
\frac{E_T}{E_m} = \frac{1 + 2 \times 0.6468 \times 0.2}{1 - (0.2 \times 0.6468)} = 1.4457
\]

\[E_T = 1.4457 \times 3.08 = 4.45288\text{Gpa}\]

• For volume fraction of fibre to be 0.3

\[
\frac{E_l}{E_m} = \frac{1 + \left(\frac{2 \times 60}{0.13}\right) \times 5.9097 \times 10^{-3} \times 0.3}{1 - 5.9097 \times 10^{-3} \times 0.3} = 2.6412
\]

\[E_l = 2.6412 \times 3.08 = 8.1349\text{Gpa}\]

\[
\frac{E_T}{E_m} = \frac{1 + 2 \times 0.6468 \times 0.3}{1 - (0.3 \times 0.6468)} = 1.7223
\]

\[E_T = 1.7223 \times 3.08 = 5.30459\text{Gpa}\]

• For volume fraction of fibre to be 0.4

\[
\frac{E_l}{E_m} = \frac{1 + \left(\frac{2 \times 60}{0.13}\right) \times 5.9097 \times 10^{-3} \times 0.4}{1 - 5.9097 \times 10^{-3} \times 0.4} = 3.18958
\]

\[E_l = 3.18958 \times 3.08 = 9.8239\text{Gpa}\]

\[
\frac{E_T}{E_m} = \frac{1 + 2 \times 0.6468 \times 0.4}{1 - (0.4 \times 0.6468)} = 2.04705
\]

\[E_T = 2.04705 \times 3.08 = 6.3049\text{Gpa}\]
For volume fraction of fibre to be 0.5

\[
\frac{E_l}{E_m} = \frac{1 + \left(\frac{2 \times 60}{0.13}\right) \times 5.9097 \times 10^{-3} \times 0.5}{1 - 5.9097 \times 10^{-3} \times 0.5} = 3.7386
\]

\[E_l = 3.18958 \times 3.08 = 11.5149 \text{Gpa}\]

\[
\frac{E_T}{E_m} = \frac{1 + 2 \times 0.6468 \times 0.5}{1 - (0.5 \times 0.6468)} = 2.4339
\]

\[E_T = 2.04705 \times 3.08 = 7.4965 \text{Gpa}\]

\[E_{\text{random}} = \frac{3}{8} E_l + \frac{5}{8} E_T\]

Table 4.0; modulus of short random oriented bamboo fibres

<table>
<thead>
<tr>
<th>(V_f)</th>
<th>(E_l) (Gpa)</th>
<th>(E_T) (Gpa)</th>
<th>(E_{\text{random}}) (Gpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>4.7630</td>
<td>3.7190</td>
<td>4.1105</td>
</tr>
<tr>
<td>0.2</td>
<td>6.4480</td>
<td>4.45288</td>
<td>5.2011</td>
</tr>
<tr>
<td>0.3</td>
<td>8.1349</td>
<td>5.30459</td>
<td>6.3660</td>
</tr>
<tr>
<td>0.4</td>
<td>9.8239</td>
<td>6.3049</td>
<td>7.6245</td>
</tr>
<tr>
<td>0.5</td>
<td>11.5149</td>
<td>7.4965</td>
<td>9.0034</td>
</tr>
</tbody>
</table>
## APPENDIX C

### TABLE OF WATER ABSORPTIVITY TEST RESULT

<table>
<thead>
<tr>
<th>SAMPLES</th>
<th>PARTICULATE REINFORCEMENT</th>
<th>FIBER REINFORCEMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1V_f</td>
<td>AVG.(%)</td>
</tr>
<tr>
<td>A</td>
<td>0.4097</td>
<td>0.7169</td>
</tr>
<tr>
<td>B</td>
<td>0.2937</td>
<td>0.6363</td>
</tr>
<tr>
<td>C</td>
<td>0.6626</td>
<td>1.1596</td>
</tr>
</tbody>
</table>

| Total average (absorption %) | 0.8173 | 0.9152 | 2.0575 | 9.3668 |

<table>
<thead>
<tr>
<th>SAMPLES</th>
<th>1 Wt.%</th>
<th>Average (%)</th>
<th>2Wt.%</th>
<th>Average (%)</th>
<th>3Wt.%</th>
<th>Average (%)</th>
<th>AVG</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.2649</td>
<td>1.1920</td>
<td>1.9868</td>
<td>1.1479</td>
<td>0.1632</td>
<td>0.7751</td>
<td>2.4072</td>
</tr>
<tr>
<td>B</td>
<td>0.2445</td>
<td>0.7742</td>
<td>1.8745</td>
<td>0.9644</td>
<td>0.1307</td>
<td>0.9150</td>
<td>1.6558</td>
</tr>
<tr>
<td>C</td>
<td>0.2586</td>
<td>0.8621</td>
<td>1.6379</td>
<td>0.9195</td>
<td>0.2617</td>
<td>1.1774</td>
<td>2.4422</td>
</tr>
</tbody>
</table>

<p>| Total average (absorption %) | 1.0106 | 1.1032 | 1.2392 |</p>
<table>
<thead>
<tr>
<th>SAMPLES</th>
<th>1 Wt.%</th>
<th>Average (%)</th>
<th>2Wt.%</th>
<th>Average (%)</th>
<th>3Wt.%</th>
<th>AVG</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.1649</td>
<td>0.5773</td>
<td>0.7422</td>
<td>0.4948</td>
<td>0.1693</td>
<td>0.5925</td>
</tr>
<tr>
<td>B</td>
<td>0.1989</td>
<td>0.4775</td>
<td>0.6765</td>
<td>0.4510</td>
<td>0.2076</td>
<td>0.5814</td>
</tr>
<tr>
<td>C</td>
<td>0.2395</td>
<td>0.8142</td>
<td>1.1973</td>
<td>0.7503</td>
<td>0.2578</td>
<td>0.9025</td>
</tr>
<tr>
<td>Total average (absorption %)</td>
<td>0.5654</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

FIBER/PARTICULATE REINFORCEMENT
## APPENDIX D

### CHEMICAL RESISTANCE TEST RESULTS

#### PARTICULATE REINFORCEMENT

<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>Percentage mass reduction</th>
<th>0 (V_f)</th>
<th>0.1(V_f)</th>
<th>0.2(V_f)</th>
<th>0.3(V_f)</th>
<th>0.4(V_f)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
<td>0.0998</td>
<td>0.1054</td>
<td>0.1085</td>
<td>0.3829</td>
<td>1.6129</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td>0.1032</td>
<td>0.0561</td>
<td>0.1819</td>
<td>0.3029</td>
<td>1.3800</td>
</tr>
<tr>
<td>C</td>
<td></td>
<td>0.0835</td>
<td>0.2719</td>
<td>0.2596</td>
<td>0.3744</td>
<td>2.4686</td>
</tr>
<tr>
<td><strong>Average mass reduction (%)</strong></td>
<td></td>
<td><strong>0.0955</strong></td>
<td><strong>0.1445</strong></td>
<td><strong>0.1833</strong></td>
<td><strong>0.2286</strong></td>
<td><strong>1.8205</strong></td>
</tr>
</tbody>
</table>

#### FIBER REINFORCEMENT

<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>0 Wt.%</th>
<th>1 Wt.%</th>
<th>2 Wt.%</th>
<th>3 Wt.%</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.0998</td>
<td>0.1733</td>
<td>0.1176</td>
<td>0.2363</td>
</tr>
<tr>
<td>B</td>
<td>0.1032</td>
<td>0.1601</td>
<td>0.1493</td>
<td>0.2832</td>
</tr>
<tr>
<td>SAMPLE</td>
<td>PARTICULATE/FIBRE REINFORCEMENT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>-------------------------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0 Wt.%</td>
<td>1 Wt.%</td>
<td>2 Wt.%</td>
<td>3 Wt.%</td>
</tr>
<tr>
<td>A</td>
<td>0.0998</td>
<td>0.1553</td>
<td>0.1522</td>
<td>0.1512</td>
</tr>
<tr>
<td>B</td>
<td>0.1032</td>
<td>0.1633</td>
<td>0.1596</td>
<td>0.1614</td>
</tr>
<tr>
<td>C</td>
<td>0.0835</td>
<td>0.1664</td>
<td>0.1755</td>
<td>0.2452</td>
</tr>
<tr>
<td>Average mass reduction (%)</td>
<td>0.0955</td>
<td>0.1603</td>
<td>0.1624</td>
<td>0.1859</td>
</tr>
</tbody>
</table>
### APPENDIX E

#### ACOUSTIC TEST RESULTS

<table>
<thead>
<tr>
<th>Weight percent</th>
<th>0%</th>
<th>1%</th>
<th>2%</th>
<th>3%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise reduction coefficient (NRC)</td>
<td>0.2123</td>
<td>0.2447</td>
<td>0.7734</td>
<td>0.8258</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Weight percent</th>
<th>0%</th>
<th>1%</th>
<th>2%</th>
<th>3%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise reduction coefficient (NRC)</td>
<td>0.2123</td>
<td>0.6015</td>
<td>0.6869</td>
<td>0.7146</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Volume fraction</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise reduction coefficient (NRC)</td>
<td>0.2123</td>
<td>0.2660</td>
<td>0.3185</td>
<td>0.3560</td>
<td>0.3590</td>
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</tbody>
</table>
## FLEXUAL TEST RESULTS

### Particulate reinforcement

<table>
<thead>
<tr>
<th>Load (lb)</th>
<th>Deflection of 0% $V_f$ (mm)</th>
<th>Deflections of 10% $V_f$ (mm)</th>
<th>Deflections of 20% $V_f$ (mm)</th>
<th>Deflections of 30% $V_f$ (mm)</th>
<th>Deflections of 40% $V_f$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>-1.66</td>
<td>-1.52</td>
<td>-0.81</td>
<td>-0.40</td>
<td>-0.32</td>
</tr>
<tr>
<td>10</td>
<td>-3.94</td>
<td>-3.82</td>
<td>-1.33</td>
<td>-0.78</td>
<td>-2.00</td>
</tr>
<tr>
<td>15</td>
<td>-7.03</td>
<td>-6.16</td>
<td>-1.89</td>
<td>-1.09</td>
<td>-3.98</td>
</tr>
<tr>
<td>20</td>
<td>-8.87</td>
<td>-8.25</td>
<td>-2.43</td>
<td>-1.44</td>
<td>-6.42</td>
</tr>
<tr>
<td>25</td>
<td>-11.56</td>
<td>-10.88</td>
<td>-2.96</td>
<td>-1.81</td>
<td>-</td>
</tr>
<tr>
<td>30</td>
<td>-15.44</td>
<td>-13.35</td>
<td>-3.80</td>
<td>-2.19</td>
<td>-</td>
</tr>
<tr>
<td>35</td>
<td>-18.58</td>
<td>-16.00</td>
<td>-5.21</td>
<td>-2.54</td>
<td>-</td>
</tr>
</tbody>
</table>

### Fibre reinforcement

<table>
<thead>
<tr>
<th>Load (lb)</th>
<th>Deflection of 0wt% (mm)</th>
<th>Deflections of 1wt% (mm)</th>
<th>Deflections of 2wt% (mm)</th>
<th>Deflections of 3wt% (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>-1.66</td>
<td>-1.11</td>
<td>-0.54</td>
<td>-0.24</td>
</tr>
<tr>
<td>10</td>
<td>-3.94</td>
<td>-2.16</td>
<td>-1.11</td>
<td>-0.54</td>
</tr>
<tr>
<td>15</td>
<td>-7.03</td>
<td>-3.40</td>
<td>-1.58</td>
<td>-0.90</td>
</tr>
<tr>
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<td>-8.87</td>
<td>-4.81</td>
<td>-2.18</td>
<td>-1.24</td>
</tr>
<tr>
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<td>-11.56</td>
<td>-5.55</td>
<td>-2.68</td>
<td>-1.57</td>
</tr>
<tr>
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<td>-15.44</td>
<td>-5.55</td>
<td>-3.23</td>
<td>-1.91</td>
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<tr>
<td>35</td>
<td>-18.58</td>
<td>-5.55</td>
<td>-03.80</td>
<td>-2.38</td>
</tr>
<tr>
<td>Load (lb)</td>
<td>Deflection of 0wt% (mm)</td>
<td>Deflections of 1wt% (mm)</td>
<td>Deflections of 2wt% (mm)</td>
<td>Deflections of 3wt% (mm)</td>
</tr>
<tr>
<td>----------</td>
<td>------------------------</td>
<td>--------------------------</td>
<td>--------------------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>5</td>
<td>-1.66</td>
<td>-0.61</td>
<td>-0.40</td>
<td>-0.35</td>
</tr>
<tr>
<td>10</td>
<td>-3.94</td>
<td>-1.24</td>
<td>-0.76</td>
<td>-0.70</td>
</tr>
<tr>
<td>15</td>
<td>-7.03</td>
<td>-1.82</td>
<td>-1.17</td>
<td>-1.12</td>
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<tr>
<td>20</td>
<td>-8.87</td>
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<td>-1.45</td>
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<td>-1.81</td>
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<tr>
<td>30</td>
<td>-15.44</td>
<td>-3.64</td>
<td>-2.51</td>
<td>-2.22</td>
</tr>
<tr>
<td>35</td>
<td>-18.58</td>
<td>-4.06</td>
<td>-3.01</td>
<td>-2.61</td>
</tr>
</tbody>
</table>
## APPENDIX G
### THERMAL CONDUCTIVITY TEST

#### PARTICULATE REINFORCEMENT

<table>
<thead>
<tr>
<th>Volume fraction</th>
<th>Rate of heat loss (Watt)</th>
<th>Thermal conductivity (W/m.K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>106.6112</td>
<td>1.7528</td>
</tr>
<tr>
<td>10%</td>
<td>102.1118</td>
<td>1.5801</td>
</tr>
<tr>
<td>20%</td>
<td>94.4534</td>
<td>1.5059</td>
</tr>
<tr>
<td>30%</td>
<td>78.7112</td>
<td>1.2549</td>
</tr>
<tr>
<td>40%</td>
<td>72.6565</td>
<td>1.1243</td>
</tr>
</tbody>
</table>

#### FIBRE REINFORCEMENT

<table>
<thead>
<tr>
<th>Weight fraction</th>
<th>Rate of heat loss (Watt)</th>
<th>Thermal conductivity (W/m.K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>106.6112</td>
<td>1.7528</td>
</tr>
<tr>
<td>1wt%</td>
<td>99.4246</td>
<td>1.4137</td>
</tr>
<tr>
<td>2wt%</td>
<td>82.1334</td>
<td>1.0803</td>
</tr>
<tr>
<td>3wt%</td>
<td>72.6565</td>
<td>0.9102</td>
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</tbody>
</table>

#### PARTICULATE/FIBRE REINFORCEMENT

<table>
<thead>
<tr>
<th>Weight fraction</th>
<th>Rate of heat loss (Watt)</th>
<th>Thermal conductivity (W/m.K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>106.6112</td>
<td>1.7528</td>
</tr>
<tr>
<td>1wt%</td>
<td>89.9557</td>
<td>1.1832</td>
</tr>
<tr>
<td>2wt%</td>
<td>75.5627</td>
<td>0.9466</td>
</tr>
<tr>
<td>3wt%</td>
<td>65.1403</td>
<td>0.7451</td>
</tr>
</tbody>
</table>