DEVELOPMENT AND ANALYSIS OF BAMBOO/COIR FIBRE BASED COMPOSITE USING EPOXY BINDER FOR PARTICLE BOARD PRODUCTION

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APRIL 2024

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In the

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CERTIFICATION

This is to certify that this research work was caried out by Eneje Chimcheberem Shalom of the Department of Industrial Engineering, Faculty of Engineering, University of Benin, Benin City, Edo State, in accordance with the rules and regulations of University of Benin for the award of B.Eng. in Industrial Engineering.

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DEDICATION

This project is dedicated to God, my parents and to everyone who contributed to the success of this project work.

ACKNOWLEDGEMENT

I would like to express my gratitude to God for steadily providing and seeing me through every step of this work, I can’t be grateful enough for all he has done for me.

I am also deeply grateful to my supervisor, Engr. Dr. Emmanuel Ikpoza, for his invaluable guidance and constant support through every step of this process. His expertise and encouragement have been crucial in helping me complete this work.

I would also like to use this opportunity to appreciate my head of department Prof R.O Edokpia and all the lecturers who have taught me throughout my stay in this school.

I am especially grateful to my parents, Engr. Reuben and Patience Eneje and my lovely siblings for their continuous love, support and encouragement throughout my studies. Thank you for everything you have done for me; your daughter is so grateful.

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I would also like to appreciate my project group members; Kenneth, Kelvin, Kelly, Kingsley, Shaka and Gideon, thank you all so much for being part of this project.

ABSTRACT

The demand for sustainable and eco-friendly materials in the construction and furniture industries has led to a growing interest in composite materials derived from natural fibres. Bamboo and coir fibres, in particular have shown significant potential due to their renewable nature, low cost, and good mechanical and physical properties.

Fresh bamboo culms were processed and delignified using 0.1M sodium hydroxide solution. Powdered fibre was produced from the delignified and dried bamboo. Experimental composite samples were produced from the bamboo fibre combined with coir fibre and epoxy matrix. A mixture experimental design with three variables serving as mixture components was adopted in the study to plan the experiments and optimize the operating conditions (that is factor levels of the input variable) of the produced composite with respect to the predicted response parameters. Models were formulated to predict tensile stress, modulus of elasticity, thickness swelling and water absorption.

From the results obtained, the optimum percentage mixture of the composite produced were 42.2%bamboo fibre, 35% epoxy and 22.8% coir fibre. With this mix, the values of tensile stress, modulus of elasticity, thickness swelling and water absorption for the composite produced were obtained as 1.068MPa, 694.450MPa, 1.850% and 20.800% respectively. The composite possessed an overall desirable mechanical and physical properties and it is therefore recommended for deployment.

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TABLE OF ABBREVIATIONS

ANOVA	Analysis of Variance
ASTM	American Society for Testing and Materials
CCD	Central Composite Design
DIFFITS	Difference in Fits
DOE	Design of Experiment
FRP	Fiber Reinforced Polymers
MDF	Medium-Density Fibreboard
OSB	Oriental Strand Board
PRESS	Predictive Residual Sum of Squares
RCBD	Randomized Complete Block Design
RSM	Response Surface Methodology
UTM	Universal Testing Machines

CHAPTER ONE

INTRODUCTION

1.0 Background Study:

The increasing demand for wooden materials and the rise in the use of fibres have increased the importance of composite wood products. The growing popularity of wooden panels renders the market segment increasingly competitive. Composite wood products are sometimes referred to as engineered wood fibres or wood pieces that have been transformed from the original log, mixed or coated with an adhesive or special glue, then recombined to create the desired products (Donald and Kelvin, 2022). Composite products include particle boards, plywood, medium-density fibreboard (MDF), hard boards, wafer boards, etc.

Composite boards unlike conventional wood possess certain characteristics and features that give it a better advantage than wood. These features include durability, are environmental friendliness, require less maintenance, and can come in a variety of colors. Composite boards consist of two main components: Matrix and Reinforcement particles. Bamboo fibre, coir fibre, bone particles, and a lot of other particles can be used exclusively or combined with others as reinforcement particles depending on the proposed use of the composite. For this study, coir fibre and bamboo fibre will be used as the reinforcement while epoxy resin is used as the matrix.

Coir is a hard and stiff biodegradable lignocellulosic fibre that is obtained from the fibrous mesocarp of coconut fruits and makes up about 25% of the nut [Saba *et al*., 2019]. Coconut (cocos nucifera) is cultivated extensively in tropical countries such as Thailand, India, Lanka, etc. (Shandilya *et al*., 2016). The fibres also have a high elongation at break and they can also be stretched beyond the elastic limit without rupture. Coir is relatively water-resistant and resistant to saltwater and microbial deterioration and its recent research as a polymer matrix reinforcement has yielded good results (Kakou *et al*., 2015; Mohanty *et al*., 2005).

Okpala *et al*. (2021), noted that some of the "benefits of coir fibres are low level of deterioration, low thermal conductivity, insect proof, good insulator, fungi resistance, low cost, stiffness, high strength, resistance to corrosion, lightweight, less negative impact on the environment, durability, as well as ease of processing."

Bamboo is a very fast-growing plant that is renewable and simple to cultivate. It is a type of grass that grows from its roots, and when it is cut, it quickly grows back, with most species maturing in 3-5 years, it is the only type of grass that grows itself into a forest. There are over a thousand species of bamboo spread across both tropical and temperate environments, broken into two "tribes": herbaceous and woody (https://www.LewisBamboo.com/, accessed December 10, 2023).

Bamboo plants are giant, fast-growing grasses that have woody stems that have been used structurally for thousands of years in many parts of the world. Bamboo can be used as a building material for scaffolding, buildings, houses, and bridges (Kaminski *et al*, 2016). The characteristics of each vary in size, growth habits, sun tolerance, soil moisture needs, and heat/ cold temperature tolerance. Bamboo fibres are often known as natural glass fibre due to their high Strength concerning their weight derived from fibres longitudinally aligned in their body. The tensile strength of bamboo is relatively high and can reach 370 MPa. This makes bamboo an attractive alternative to steel in tensile loading applications (Talekar and Ashwini, 2017). In recent times it has the potential to be an aesthetically pleasing and low-cost alternative to more conventional materials as timber.

Since composite wood materials are preferred because of their additional features, this research tends to use bamboo fibre to produce a better alternative to conventional timber. We are using bamboo because:

i. It grows locally
ii. It's readily available.
iii. It matures quickly between 3-5 years.
iv. It is slightly more resistant to insects and fungi (due to its lower starch content).

Composites should not be regarded simply as a combination of two materials but as a combination of two distinct materials. The individual mechanical and physical properties of the materials should be tested to determine how the material combination will improve the polymer matrix in terms of mechanical and physical properties (Thodsaratpreeyakul *et al.,* 2017).

1.1 Statement of Problem:

The problem this research tends to solve is to propose bamboo and coir fibre as a close alternative to the use of conventional timber.

Timber shortage is a problem facing the civilized world, our forests aren't supplying enough wood anymore. In Nigeria today, the very rapid rate of deforestation and desertification in many parts of the country has led to log supply crisis which has led to the shortage of timber (Olorunnisola, 2022).

The present shortage of timber products cannot be salvaged in short time because it will take a long while to grow a great deal of timber and the growth and maturity of timber takes a good number of years. it takes about 10-20 years for most softwood and hardwood timber can take about 30-50 years to grow to maturity, which is the age where they have an optimum proportion of high-quality wood products (https://www.forestrycorporation.com.au/, Accessed January

20, 2024). Therefore, since it takes just about 3-5 years for bamboo plant to grow and mature (https://www.bumboo.eco/, Accessed January 20, 2024), providing bamboo composites as a viable alternative for timber will help salvage the situation of wood shortage and provide an alternative with additional desirable features.

1.2 Aim and Objectives:

This project aims to develop and analyze bamboo/coir fibre composite using epoxy as a binder for its suitability in the production of particle board.

To achieve the aim of this project, the following objectives were taken:

i. Carry out an extensive literature review
ii. Obtaining the materials needed for the experiment.
iii. Delignification of bamboo
iv. Grinding of bamboo and coir fibre into small particles
v. Use Mixture design to plan the experiment
vi. Produce experimental samples
vii. Determine the mechanical and physical properties
viii. Use RSM to analyze the experimental result
ix. Obtain an optimal composite

1.3 Scope:

This research is limited to investigating the mechanical and physical properties of a bamboo and coir fibre reinforced-epoxy composite suitable for use as a composite board. This research does not include the investigation of the levels at which the chemical elements present in the reinforcement particles contributed to the mechanical and physical properties.

1.4 Significance:

This study tends to salvage the problem of scarcity of timber by introducing bamboo and coir fibre composites with epoxy binder as an alternative that provides optimal mechanical and physical properties as a low-cost alternative to timber. It will also help in proper waste recycling of coconut husk fibre which is gotten at almost no cost.

This could lead to reduction in the amount of composite wood products that are being imported into the country.

Production of bamboo and coir fibre composites on a large scale will largely improve the economy of both an individual and the nation and promote the local content initiative of the country.

CHAPTER TWO

LITERATURE REVIEW

2.1 Composite Materials

Composite materials primarily comprise two or more constituent materials with varying physical or chemical properties, which are merged together. (www.romeorim.com, accessed February 20,2024). When combined, they generate a material exhibiting qualities distinct from their individual properties. Composites shouldn't be viewed merely as a fusion of two materials, but rather as a combination of two separate materials. The individual mechanical and physical properties of the materials should be tested to determine how the material combination will improve the polymer matrix in terms of mechanical and physical properties (Thodsaratpreeyakul *et al.*, 2017).

The two main components within a composite are the matrix (which is the bonding component) and reinforcement (which is generally fibre) (https://romeorim.com, accessed February 20, 2024). In addition to the fibre reinforcements and matrix; core materials, fillers, additives and surface finishes can also be added to a composite to provide unique performance attributes. Under ideal conditions, composites tend to have resultant properties such as: High strength/weight ratio, Impact resistant, Chemical/environmental stability. They are also corrosion resistant, are electrical insulators, are resistant to environmental degradation, and lend themselves to a variety of fabrication methods". (Manwell *et al*, 2010).

Composite wood products which are also referred to as engineered wood products, are based on wood pieces or wood fibres that have been transformed from the original log, mixed or coated with an adhesive or special glue, then recombined to create the desired product (Donald and Kelvin, 2022). Unlike paper and pulp products, the final form of composites or engineered wood products are boards or sheets.

Composite wood isn’t true lumber directly from a tree but it is partially made of wood fibres, like veneers, sawdust, or scraps. It mixes other materials and additives to provide additional properties wood alone wouldn’t have. Lumber may be treated with chemicals to improve durability, like pressure-treated pine, but it isn’t made of anything but real wood (https://www.TimberTech.com/, accessed January 21,2024) so they are quite different from composites.

When producing wood-plastic composites, wood fibres might be mixed with thermoplastic resin, or form the mixture into composite pellets that are used to create the final product. Other types of wood composites like particleboard are made by pressing layers of wood chips together with adhesive to form a final wood composite material (https://www.TimberTech.com/, accessed January 21,2024).

Additives such as UV stabilizers, colors and dyes, lubricants, and other elements are sometimes added to the composite for bonus properties like fade resistance. A finished composite product is normally formed into a solid sheet or board suitable construction purposes (https://www.TimberTech.com/accessed January 21, 2024).

Composite materials have been significant across various historical periods, aiding in the establishment of early civilizations' dwellings and paving the way for forthcoming advancements. Composites offer many benefits; the key among them are corrosion resistance, design flexibility, durability, light weight, and strength (Tri-Dung,2020). Composites have penetrated through our everyday lives such as products that are used in constructions, medical applications, oil and gas, transportation, sports, aerospace, and many more. Some applications, such as rocket ships, probably would not get off the ground without composite materials (Tri-Dung, 2020).

Composite wood products are used in various forms, from kitchen cabinets to furniture made of particleboard. Decking is a popular structure for composite materials because it tends to provide increased weather and UV resistance and overall durability. This means that bunlike traditional lumber, a composite deck a composite deck won't break into fragments or rot, and requires less regular maintenance (https://www.TimberTech.com/, accessed January 21,2024).

While some wood composites tend to look more plastic than wood, other items like plywood, which is made of cross-laminated veneer, are almost entirely made of wood and retain that authentic look and feel. As composite technology progresses, even plastic-heavy engineered materials can imitate a stunning real wood look.

Some popular wood composite products include:

i. Panel products (plywood, oriented strand board (OSB), particleboard, fibreboard, medium-density fibreboard (MDF), hardboard);
ii. Structural timber products (glued-laminated timber (glulam),
iii. laminated veneer lumber (LVL), laminated strand lumber,
iv. parallel strand lumber);
v. and wood–nonwood composites (wood fibre–thermoplastics, inorganic-bonded composites).

Composite woods are used to create several products used in homes and construction, they include: Trim, Siding, Flooring, Decking, Fences and Furniture.

2.2 History of Composite Materials

Composite materials are prevalent in nature, exemplified by wood, which comprises long cellulose fibres held together by lignin. These materials result from the combination of two or more substances with disparate properties, and they maintain their distinct identities without merging (Tri-Dung,2020). Instead, the components interact synergistically, imparting unique characteristics to the composite. Throughout history, humans have utilized composite materials across various domains.

Ancient civilizations, like the Egyptians and Mesopotamians, employed a blend of mud and straw to construct durable buildings around 1500 BC (Johnson,2018). This composite enhanced structural integrity against compression, tearing, and bending, a trend that persisted through the use of straw in pottery and boat construction. In 1200 AD, Mongols pioneered the first composite bow, utilizing a mixture of animal glue, bone, and wood wrapped with birch bark, which proved formidable in warfare and contributed to Genghis Khan's military dominance. (Tri-Dung, 2022). The exigencies of wartime need, particularly during World War II, drove the development of many composite materials, accelerating their transition from laboratory prototypes to mass production. (Johnson,2018) The emergence of composite technologies also fostered the fibre-reinforced polymers (FRP) industry, with glass fibres being extensively used for military applications by 1945. Post-war, composite materials found widespread application across industries such as aerospace, construction, and transportation, owing to their corrosion resistance and structural advantages. Notably, the introduction of the first composite commercial boat hull in 1946 and the testing of a composite automobile body in 1947 heralded a new era in transportation design, culminating in the 1953 Chevrolet Corvette. Advancements in manufacturing methods, including compression molding and filament winding, facilitated the widespread adoption of composites across industries. The marine market emerged as a significant consumer in the 1960s, while the 1970s witnessed the commercialization of carbon fibres and the maturation of the composites industry with improved resin and reinforcing fibre technologies. Infrastructure applications expanded in the late 1970s and early 1980s, with notable installations like the first all-composite pedestrian bridge in Aberfeldy, Scotland.

The development and need for composite materials also result in the fibre-reinforced polymers (FRP) industry. By 1945, more than 7 million pounds of glass fibres were used for various products, primarily for military applications. Composite materials continued to take off after the war and grew rapidly through the 1950s. The composite innovators were ambitiously trying to introduce composites into other markets such as aerospace, construction, and transportation (Ngo,2022). Soon the benefits of FRP composites, especially its corrosion resistance, became known to the public sector. Boats were one obvious product that benefited. The first composite commercial boat hull was introduced in 1946. A full automobile body was made from composite and tested in 1947 (Johnson, 2018). This led to the development of the 1953 Chevrolet Corvette. The advent of the automobile age gave rise to several new methods for moulding such as compression moulding of bulk moulding compound (BMC) and sheet moulding compound (SMC). The two techniques emerged as the dominant method of moulding for the automotive industry and other industries. During the early 1950s, significant manufacturing techniques like large-scale filament winding, pultrusion, and vacuum bag molding were pioneered. Subsequently, in the 1960s, the marine industry emerged as the principal consumer of composite materials (Johnson, 2018). It was during this period, in 1961, that the first patent for carbon fibre was granted, with commercial availability following shortly thereafter. In the 1970s, the automotive sector eclipsed the marine industry to become the primary market for composite materials—a status it maintains to this day. Towards the late 1970s and early 1980s, composites found their inaugural applications in infrastructure projects across Asia and Europe. An iconic milestone during this period occurred in the 1990s with the installation of the first all-composite pedestrian bridge in Aberfeldy, Scotland. In this period, the first FRP-reinforced concrete bridge deck was built in McKinleyville, West Virginia, and the first all-composites vehicular bridge deck was built in Russell, Kansas.

The first wood composites were produced towards the end of the 18th century, it was a form of wet-processed fibreboard and the first hardboard product was created in 1924 (Schniewind, 1989). Other composite products were later developed which include: plywood, particleboard, oriented strand board, and steam-pressed scrim lumber. A variety of household furniture when examined closely are made of composite wood materials. Composites are made from a lot of commercially important tree species. Alternative materials used for composite wood panels include bamboo, rice straw, and rubberwood (Jarusombuti *et al*, 2009). Some composites and engineered woods possess strength relative to their weight and are therefore very useful in the development of buildings and inexpensive furniture. (Donald *et al*, 2022). The particleboard industry started in the 1940's, the hardboard industry around 1950, and the flakeboard and medium density fibreboard (MDF) industries in the early 1960s (Maloney 1996). Generally, these products are produced in flat sheets and used in two-dimensional designs. It is also possible to produce these composites in three-dimensional products. Flakes and particles have been formed into pallets and packing materials using an adhesive and a rather simple mould.

Composites continue to find applications today (Johnson, 2018). Nanomaterials are incorporated into improved fibres and resins used in new composites. Nanotechnology began to be used in commercial products in the early 2000s. Bulk carbon nanotubes can be used as composite reinforcement in polymers to improve the mechanical, thermal, and electrical properties of the bulk product.

In contemporary times, the composite industry continues its dynamic evolution, with a predominant focus on renewable energy sectors. Notably, wind turbine technology stands at the forefront, constantly pushing boundaries in size and efficiency, necessitating advanced composite materials. For instance, engineers employ tailored designs to optimize composite performance, enhancing strength in specific directions by aligning fibres accordingly while prioritizing flexibility in others where strength is less critical. Additionally, engineers can fine-tune properties such as heat resistance, chemical durability, and weathering resilience by selecting appropriate matrix materials. In recent years, a growing environmental consciousness and imperative for sustainable development have spurred interest in utilizing natural fibres as replacements for synthetic counterparts in composite reinforcement (Sanjay *et al*, 2016, Ho *et al*, 2012). This chapter seeks to provide an overview of the science and technology in relation to the composite material, manufacturing process, and utilization.

2.3 Composition of Composite Materials

As stated earlier a composite material is made up of two basic components: The matrix and the reinforcement.

2.3.1. The Matrix: The matrix is monolithic material in which usually the reinforcement is embedded and must be uniformly distributed throughout the matrix. Materials such as aluminum, magnesium, nickel, titanium, cobalt can be used as matrix materials (Arun *et al*, 2019). The role of the matrix is to keep the reinforcement particles in place and to support them. The matrix maintains the reinforcement to create the required shape while the reinforcement increases the entire mechanical characteristics of the matrix. The matrix sets up the part geometrically, gives cohesion to the material, it is usually flexible and not very resistant and transmits efforts from one fibre to another.

2.3.1.1 Adhesives

In the context of wood composites, adhesive development is driven by adhesive cost-reduction, faster processing time, and specialized products where complex adhesive formulations are motivated. The basic chemicals most commonly used for wood adhesives and resins are formaldehyde, urea, melamine, phenol, resorcinol, and isocyanate. However, despite the apparent simplicity, in terms of families of chemicals, the formulations are highly complex mixtures of chemicals and additives. Various wood adhesives, along with their typical applications, are listed in Table 2.1. Although the requirements for cheaper raw materials and reduced press times are the same in Europe and the United States, the emphasis on environmental issues appears to be stronger in Europe. This includes the effect of adhesives on wastewater and on gas emission during panel production. Formaldehyde emission is of significant importance. It is caused by residual un-reacted formaldehyde and by slow adhesive hydrolysis under hot/humid conditions. Modern adhesives show very low formaldehyde emission rates, in compliance with the strict E1 emission class (Pizzi and Mittal, 2003).

Table2.1: Typical Choices of Structural Adhesives in Different Service Environments

Service Environment	Adhesive Type
Fully exterior	Phenol-formaldehyde
(Withstands long-term soaking and drying)	Resorcinol-formaldehyde
	Phenol-resorcinol-formaldehyde
	Emulsion polymer/isocyanate
	Melamine-formaldehyde
Limited exterior	Melamine-urea-formaldehyde
(Withstands short-term water soaking)	Isocyanate
	Epoxy
Interior	Urea-formaldehyde

(Withstands short-term high humidity)	Casein

Source: Data from USDA, 1999.

2.3.2 Reinforcements

Composite reinforcements can be in various forms including fibres, flakes, or particles. Each of one of these has its own unique properties which can be contributed to the composites, and therefore giving them individual applications. Fibres are the form that is most frequently utilized in composite applications and has the most influence on the characteristics of the composite materials. These factors include; the fibres high aspect ratio between length and diameter, which provides effective shear stress transfer between the matrix and the fibres, and the ability to process and manufacture the composites part in various shapes using different techniques (Tri-Dung, 2020). The reinforcement provides rigidity and resistance.

Natural fibre composites include coir, jute, bagasse, cotton, bamboo, hemp. Natural fibres come from plants and these fibres contain lingo cellulose in nature. Natural fibres are eco-friendly; inexpensive, lightweight, strong, renewable and biodegradable. Natural fibres can serve as reinforcements for both thermosetting and thermoplastic matrices. Thermosetting resins like epoxy, polyester, polyurethane, and phenolic are commonly utilized in composites demanding higher performance in various applications. They offer adequate mechanical properties, particularly stiffness and strength, at economically viable price points. Recent advancements in natural fibre development, including genetic engineering, present significant opportunities for enhancing materials derived from renewable resources, thereby contributing to global sustainability efforts. Natural fibre composites are increasingly appealing to industries due to their low density and environmental advantages over conventional composites. Their non-carcinogenic and biodegradable nature further adds to their appeal and underscores their growing importance in the composite materials landscape. Recent developments in natural fibres composite field and applications are summarized in presentation.

Fibre reinforced polymer composites play ascendant roles in various applications because of their high modulus and meticulous strength and reduced carbon footprint on the environment (Saw *et al*,2011). Researchers are triggered by daily growth of environmental awareness and this leads to the invention of more eco-friendly materials (Essabir *et al*, 2016). Natural fibres from coir, oil palm, sisal, bamboo, banana, rice husk, jute, kenaf etc. are environmentally friendly materials that have proved to be good reinforcement in polymeric matrices reducing the density and cost of the resultant composites (Sanjay *et al*, 2015). In historical times, natural fibres were used to produce a large variety of products ranging from roofing of houses to clothes (Rosa *et al*, 2009). However, in recent years, natural fibres have evolved as alternative to conventional glass and carbon fibres in the production of thermoplastic composites (Islam *et al*, 2015).

2.3.2.1 Bamboo fibre

Bamboo fibres have been widely used in composite industries for socio-economic empowerment of peoples. The production of bamboo fibre-based composites using different matrices(binders) has developed cost effective and eco-friendly bio composites which has a direct impact on the market values of bamboo (Talekar *et al*,2017). The sustainable future of bamboo based composite industry will enable bamboo to be used in ways other than conventional ones. The effective characterization of bamboo fibre as well as bamboo fibre-based composites should be more advance in terms of analysis and testing. Bamboo plants are giant, fast-growing grasses that have woody stems (Khalil *et al*,2012). The characteristics of each vary in size, growth habit, sun tolerance, soil moisture needs and heat/ cold temperature tolerance. Several researchers have examined bamboo as a potential source of best fibre and as a source of cellulose from pulping the bamboo (Khalil *et al*,2012). Given that bamboo is a plentiful natural resource in Asia, the Middle East, and South America, using bamboo fibres has several advantages. Because of their high strength with respect to its weight derives from fibres longitudinally aligned in its body bamboo fibres are referred to as natural glass fibre (Sanjay *et al*,2016). Bamboo has relatively high tensile strength of up to 370 MPa (Vengala *et a*, 2020). This makes bamboo an attractive alternative to steel in tensile loading application. Thus, bamboo is selected as fibres for the use of bio composite with matrix material PLA (Poly Lactic Acid). Better development of processing technologies and improvements in natural fibre treatments will facilitate the production of with optimum mechanical and physical performance but also generate high-cost advantage and greater acceptance of these materials in the market place.

2.3.2.1.1. Features of Bamboo

Bamboo (Bambusa Shreb.) is a perennial plant known to reach heights of up to 40 meters in monsoon climates. Traditionally utilized in construction, carpentry, weaving, and plaiting, bamboo also demonstrates unique properties when used in various applications. For instance, curtains crafted from bamboo fibre exhibit the ability to absorb ultraviolet radiation across different wavelengths, thereby reducing potential harm to the human body. Researchers have explored the potential of bamboo fibres in the development of eco-composites, focusing on their basic mechanical properties (Gamon *et al*, 2013). Utilizing the steam explosion technique, bamboo fibres are extracted from raw bamboo trees. Experimental findings indicate that these bamboo fibres possess adequate specific strength, comparable to conventional glass fibres (Omar *et al*, 2017). Furthermore, when incorporated into polypropylene (PP) based composites, the tensile strength and modulus experience a notable increase of approximately 15% and 30%, respectively, compared to composites utilizing mechanically extracted fibres. This enhancement is attributed to improved impregnation and a reduction in voids within the composite structure.

2.3.2.1.2. Extraction of Bamboo fibre

The bamboo fibre is obtained from bamboo tree and it is divided into two kinds of fibre according to different process flow and method: Natural original bamboo fibre and bamboo pulp fibre (namely bamboo viscose fibre or regenerated cellulose bamboo fibre). Original bamboo fibre is directly picked up from natural bamboo without any chemical additive, using physical and mechanical method (Khalil,2012). In order to differentiate from bamboo pulp fibre (bamboo viscose fibre), we call it as original bamboo fibre or pure natural bamboo fibre. But bamboo pulp (viscose) fibre belongs to regenerated cellulose fibre as chemical fibre. Broadly there are two types of processing to obtain bamboo fibres viz. mechanical processing and chemical processing. Both processes initially include splitting of bamboo strips, which is followed by either mechanical processing or chemical processing depending upon the further use of bamboo fibres. Chemical processing includes initial alkali hydrolysis (NaOH) to yield cellulose fibres. Alkali treated cellulose fibres are then passed through carbon disulphide via multi-phase bleaching. Most of the manufactures use this process as it is least time-consuming procedure to yield the bamboo fibres.

2.3.2.1.2.1 Mechanical extraction

This method can take the form of different procedures such as steam explosion or heat steaming, retting, crushing, grinding and rolling in a mill (Parnia *et al*, 2014). All of 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.

2.3.2.1.2.2 Chemical extraction: Chemical extraction procedures use alkali or acid retting, chemical retting, Chemical Assisted Natural (CAN), or degumming to reduce or remove the lignin content of the elementary fibres. This treatment also has effects on other components of the bamboo microstructure including pectin and hemicellulose. The following section reviews the chemical

2.3.2.2 Coir fibre

Coir is a hard and stiff biodegradable lignocellulosic fibre that are obtained from the fibrous mesocarp of coconut fruits and makes up about 25% of the nut (Sanjay *et al*, 2015). Coconut (cocos nucifera) is cultivated extensively in tropical countries such as Thailand, India, Lanka etc. (Naveen *et al*., 2019). Due to the high lignin content of coir fibres, they are durable, weather resistant and relatively waterproof and be chemically modified (Mir *et al*, Mittal *et al*, 2016). The fibres also have high elongation at break that is they can also be stretched beyond the elastic limit without rupture. In order to improve the overall properties of the composites, studies have reported the hybridization of coir fibre composites with other fibres such as kenaf, bamboo, rice straws and glass fibres among others (Deyholos *et al*, 2014, Abdulkareem *et al*, 2018).

The use of coconut husk-derived coir fibre-reinforced bio composites is on the rise nowadays due to the constantly increasing demand for sustainable, renewable, biodegradable, and recyclable materials (Hasan *et al*, 2021). Generally, the coconut husk and shells are disposed of as waste materials; however, they can be utilized as prominent raw materials for environment-friendly bio composite production. Coir fibres are strong and stiff, which are prerequisites for coir fibre-reinforced bio composite materials. However, as a bio-based material, the produced bio composites have various performance characteristics because of the inhomogeneous coir material characteristics. Coir materials are reinforced with different thermoplastic, thermosetting, and cement-based materials to produce bio composites. Coir fibre-reinforced composites provide superior mechanical, thermal, and physical properties, that make them outstanding materials as compared to synthetic fibre-reinforced composites.

The important properties of coconut fibre are:

i. It is a renewable resource and CO_2 neutral material.
ii. The fibre is abundant, non-toxic, biodegradable, low density and low cost.
iii. The fibre has a high degree of water retention and is rich in micronutrients.

2.3.2.2.1 Preparation/extraction of coir fibres from coconut husk

The extraction processes for fibres vary and are contingent upon the efficiency of wet processing, including bleaching and dyeing of the coir. Traditional methods for fibre production from husks are labor-intensive and time-consuming. Following nut separation, husks undergo retting techniques, typically in brackish water ponds or backwaters, for a duration of three to six months, involving anaerobic fermentation for 10–12 months (Omar *et al,* 2015). Retting softens the husks, enabling decortication, and subsequent fibre extraction through manual beating. The fibres are then hackled, washed, and dried in the shade, resulting in loosened and cleaned fibres. The residual pith, recently identified as a substitute for peat moss in horticultural production, finds a new market. Retted fibres from green husks are most suitable for dyeing and bleaching, while shorter retting periods yield coarser brown yarns, increasingly used in geotextile applications (Omar *et al,* 2015).

Mechanical processes, employing defibreing or decorticating equipment, can process husks after just five days of immersion in water tanks. Crushing the husk opens the fibres, which are then separated from woody parts and pith using revolving drums. The stronger fibres undergo washing, cleaning, drying, hackling, and combing (www.Coirstore.co.uk, accessed March 9, 2024).

Husk defibering entails two primary methods:

Wet milling: Husks are crushed between fluted rollers before soaking in retting ponds for at least 72 hours to facilitate water penetration through the exocarp. Specially designed drums then extract fibres, typically used for mature coconut husks.

Dry milling: Utilizing a down decorticator, husks are disintegrated by metal beater bars followed by sifters to separate non-fibrous matter. This method is efficient in areas lacking soaking facilities.

Environmentally friendly fibre production methods, such as those developed by the Central Coir Research Institute, employ biotechnological approaches with specific microbial enzymes to substantially reduce retting time to three to five days. Lignolytic enzymes enhance fibre surface bleaching or activation for easier dye reaction (Omar *et al*, 2015).

2.4 Bamboo Composites

Research into bamboo fibre reinforced polymeric composites as alternatives to conventional petroleum-based composites has surged in recent years (Zheng *et al*, 2022). This momentum stems from growing demand for eco-friendly materials across industries. Bamboo's renewable nature and exceptional mechanical and physical properties make it an attractive reinforcement for polymeric composites. However, these composites have yet to match the popularity of synthetic fibre reinforced ones. Consequently, manufacturers and researchers are actively exploring more sustainable composite options.

Over the past few years, significant advancements have been made in enhancing the mechanical characteristics, thermal stability, and durability of Bamboo Fibre Reinforced Composites through research and development efforts. While other natural fibres such as kenaf, flax, ramie, hemp, jute, coir, and sisal are already being utilized by sustainable manufacturers (Mahmud *et al*, 2021), bamboo fibres are gaining traction due to their lightweight nature, abundance in nature, biodegradability, and advanced functionalities. Moreover, bamboo's short life cycle and extensive growth worldwide underscore its significant potentiality. Bamboo fibres are predominantly cultivated in various Asian countries such as China, Indonesia, Myanmar, Bangladesh, Vietnam, and Thailand (Handana *et al*, 2023). Consequently, researchers are exploring advanced methods of utilizing this material, with the development of bamboo fibre reinforced bio-composites being one of them (Nirmal *et al*, 2022, Norizan *et al*). These advancements pave the way for their application in diverse fields, including transportation, aircraft, construction, and consumer products.

Bamboo fibre, derived from the cellulose of the bamboo plant, has emerged as a sustainable alternative to traditional fibres like cotton and polyester (Hasan *et al*, 2019), owing to its robust, durable, and versatile properties. The mechanical properties of natural fibre-based polymer composites are influenced by a variety of factors, including fibre volume fraction, length, aspect ratio, adhesion with the matrix, and orientation (Kahraman *et al*, 2005). To mitigate the emission of harmful materials into the ecosystem, researchers are exploring the potential of manufacturing polymeric composites using natural fibres. Numerous studies have investigated the impact of different factors on the mechanical behavior of natural fibre reinforced polymer composites. For instance, the mechanical properties of jute and kenaf fibre reinforced polypropylene composites have been examined by Schneider and Karmaker (1996), with jute-based composites demonstrating superior mechanical properties. Similarly, Thwe and Liao (2000) investigated the effects of various parameters on the mechanical properties of bamboo fibre reinforced plastics and bamboo-glass fibre reinforced plastics.

Despite extensive research on a wide range of natural fibres for polymer composites, limited attention has been given to the reinforcing potential of short bamboo fibres, despite their numerous advantages over other fibres. Additionally, the potential synergistic effects of incorporating both particulates and fibres in polymers to enhance performance have not been adequately explored. Hence, this study aims to investigate the impact of fibre and filler on the physical and mechanical properties of bamboo fibre reinforced epoxy composites.

Epoxy resins are widely utilized in advanced composites due to their excellent adhesion to various fibres, high performance at elevated temperatures, and superior mechanical and electrical properties.

2.5 Review of Past Literature on Composite and Composite Modelling

Quan, et al (2019) studied the mechanical properties of coir/bamboo hybrid composite with a thermoplastic matrix. The correlation between the tensile properties of the fibres and of the hybrid composites was analyzed to understand the hybrid effects. The failure mode and fracture morphology of the hybrid composites were also examined. The coir fibres were long coir with fibre length in the range of 200–300 mm, while the bamboo fibres had a maximum fibre length between 200 and 350 mm. The extracted coir and bamboo fibres were soaked in hot distilled water at 70 °C for 2 h, and then smoothly washed with alcohol to remove greases which may attach on the fibre surface during the fibre extraction process, rinsed with deionized water, and dried under vacuum at 90 °C. Polypropylene (PP) was used as the matrix for composites. The PP was an unmodified grade and supplied in sheet form with a melt flow rate of 5.2 g/10 min and melting temperature of 160.6 °C.

Tensile tests were performed according to the standard ASTM D3039, on composite samples of 15 mm × 200 mm × 2 mm, to which composite end-tabs were glued. A load cell of 5 kN was utilized, with a crosshead speed set at 1 mm/min. The gauge length between the two clamps was standardized at 100 mm, while an extensometer featuring a gauge length of 50 mm was employed to measure sample strain. Findings revealed that at a low bamboo fibre fraction, a positive hybrid effect was observed, leading to an increase in composite strain to failure, primarily attributed to the high strain to failure exhibited by coir fibres. Bamboo fibres contributed to enhanced stiffness and strength in the composites. The tensile behavior of coir-bamboo fibre hybrid composites in Polypropylene (PP) was explored, where coir and bamboo fibres were blended at the meso level through layer-by-layer stacking of unidirectional fibre prepregs. The study indicated that a favorable hybrid effect occurs when a low bamboo fibre fraction is combined with a higher fraction of coir fibres. Further investigation into different fibre mixing levels and variations in fibre loading could uncover additional synergistic properties for hybrid composite applications.

Examining fibre variations, it was noted that increasing fibre length from 10 mm to 20 mm and 30 mm in combination loading led to improvements in flexural strength from 5.83 MPa to 15.35 MPa, tensile strength from 1.45 MPa to 4.03 MPa, compressive strength from 4.53 MPa to 40.71 MPa, and impact strength from 14.05 to 22.58 MPa of the composites. Water absorption tests were conducted on the composites, revealing virtually identical percentage water absorption due to the constant weight of 7.5g of both fibres in the composite samples. Similarly, the density of the composite samples remained consistent owing to an equal weight of 7.5g of each fibre present in the composite. This observation aligns with the theory of increased void volume in lower-density particleboard, allowing for more water storage, contrasting with higher-density materials.

Sathish, et al (2022) studied Mechanical and thermal analysis of coir fibre reinforced jute/bamboo hybrid epoxy composites. In the current research study, nine distinct combinations of coir, jute, and bamboo reinforced epoxy composites were fabricated using a casting technique. These composites underwent mechanical tests such as flexural and impact tests, and their thermal stability was analyzed through Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC). Additionally, thermal conductivity and surface morphology were studied for hybrid composites. The hybridization of multiple fibres with the epoxy matrix resulted in improved mechanical and thermal properties compared to individual reinforcements, aligning with findings from existing literature and the present research work.

Among the hybrid composites, the one with the highest proportion of jute fibres reinforced with bamboo fibre exhibited maximum flexural and impact strengths of 92.521 MPa and 82.4 kJ/m2, respectively. This can be attributed to the higher modulus and energy-absorbing behavior of jute fibres, while the absence of coir fibres, which have lower modulus and strength values, contributed to this advantage. In thermal conductivity analysis, marginal variations in values were observed with different volume fractions of fibres, with the composite consisting of only coir and bamboo fibre reinforcements with the epoxy matrix exhibiting the highest thermal conductivity of 0.317 W/m-K.

Thermogravimetric analysis results revealed that all nine types of hybrid composites exhibited nearly equal thermal stability, with slight variations in degradation temperatures observed in the thermographs. Overall, the hybrid composite labeled as B2C1J7 was recommended for its superior mechanical and thermal properties, featuring 89.06 MPa of flexural strength, 78.6 kJ/m2 of impact strength, 0.233 W/m-K of thermal conductivity, and exhibiting better surface morphology.

Aireddy et al (2011) investigated coir dust reinforced epoxy matrix composites of different compositions. The abrasive wear characteristics of the composites were assessed under dry conditions utilizing a pin-on-disc apparatus against 400μm grit size abrasive paper, with a test speed set at 0.540 m/sec and normal loads ranging from 5N to 25N. Results from the experiments revealed that the abrasive wear resistance of the composite was notably affected by the concentration of coir dust, sliding distance, and applied normal load. The primary wear mechanism was associated with reinforcement attributed to the higher loading of coir dust. Notably, it was observed that abrasive wear resistance decreased with increasing normal load but increased with higher concentrations of coir dust.

Slate (1976) conducted a study on the mechanical properties of coir fibre reinforced cement sand mortar. In the study, two different design mixes were tested, featuring varying cement-to-sand ratios and fibre contents. The findings indicated that the inclusion of fibres improved the compressive and flexural strengths of the mortar compared to plain mortar. However, an increase in fibre content resulted in a decrease in mortar strength.

Reis (2006) explored the mechanical properties of epoxy polymer concrete reinforced with natural fibres, including coconut fibres. The coconut fibre reinforced polymer concrete exhibited higher fracture toughness and fracture energy compared to other fibres. Moreover, flexural strength increased by up to 25% with coconut fibre reinforcement. Additionally, the Multiquadric radial basis function (MQRBF) method was utilized for the static and dynamic analysis of coir epoxy micro-composite plates under uniformly distributed load.

Ayedh *et al*. (2021) and other researchers have been investigating the potential of manufacturing polymeric composites based on natural fibres to reduce the emission of harmful materials into the ecosystem. In their study, tribological tests were conducted on epoxy composites reinforced with bamboo fibres. The wear performance of these composites was evaluated under various operating parameters, and the worn surfaces were examined using optical microscopy. The results indicated a reduction in the specific wear rate of the composites due to the reinforcement with bamboo fibres. Scanning electron microscopy analysis revealed different wear mechanisms and damages.

Sandhyarani (2012) conducted a study to determine the physical and mechanical properties of bamboo fibre reinforced epoxy composites. Composites were fabricated using short bamboo fibre at four different fibre loadings (0 wt%, 15 wt%, 30 wt%, and 45 wt%). It was observed that certain properties increased significantly with increasing fibre loading, while properties like void fraction increased from 1.71% to 5.69% with the increase in fibre loading. To address this, silicon carbide (SiC) filler was added to the composites at four different weight percentages (0 wt%, 5 wt%, 10 wt%, and 15 wt%) while keeping the fibre loading constant (45 wt%). Significant improvements in hardness, tensile strength, flexural strength, and reduction of void fraction were observed with the addition of SiC filler, indicating the successful development of high-strength and rigid composite materials for lightweight applications.

Nandavardhan *et al.* (2024) aimed to mitigate increasing global warming by selecting bamboo as a viable reinforcement option to reduce heat transfer. Bamboo, known for its robustness, eco-friendliness, and low thermal conductivity due to its cellulose content, was further enhanced in thermal resistance through treatment with a NaOH solution. In their study, the researchers augmented the epoxy matrix with Hollow Glass Microspheres (HGM) and Kaolin fillers to enhance the insulating properties of bamboo composites. Various composite compositions were compared to ascertain the most effective thermal insulator. The reinforced composites exhibited promising results in combating heat transfer, highlighting their potential as high-performance materials in the fight against climate change. The study emphasized the impacts of these additives on thermal conductivity, thermal degradation, and mechanical attributes of the composites, noting the significant influence of HGM filler content on thermal resistance and the reinforcing effect of Kaolin fillers on strength, stiffness, and wear resistance.

Raman *et al* (2022) carried out an Investigation on Mechanical Properties of Bamboo and Coconut Fibre with Epoxy Hybrid Polymer Composite The present study focused to improve material characteristics and quality in terms of the NaOH concentration for treating the coconut and bamboo fibre to enhance the mechanical properties of natural fibre polymer-based hybrid composites. The NaOH-treated fibres were washed thoroughly using distilled water and allowed to dry for 24 hours. Composition of each specimen, bamboo (B) and coconut (C) fibre with epoxy composite(E), was prepared by hand layup process as per the American Society for Testing and Materials (ASTM) standard. The proportionality of the material was carefully fulfilled according to the previous literature reports. The weight fraction of the composite material content was set to be 30% and 70% of epoxy (E) resin and isolated fibres. Three distinct criteria were used to calculate mechanical parameters such as tensile strength, flexural strength, and material hardness. It was found that the combination of 70% E with 30% BC of hybridized composite had a maximum tensile strength of 62.42 MPa, whereas the flexural strength and hardness of the other combinations, such as 70% E with 30% C and 70% E with 30% B, were observed to be 58 MPa and 185 HRC (Hardness Rockwell C), respectively. The experimental work was designed and constructed in accordance with the American Society for Testing and Materials (ASTM) standard plate dimensions of 300 * 250 *10mm. Accordingly, in order to attain the best mechanical qualities, three alternative fibre loadings were examined. It was found that the material configuration comprised flawless orientation of the fibre was retained after the surface treatment followed by sun light exposure that was made ideal crystal structure forms.

Figure **2.1** depicts a graphical representation of varying fibre contents versus tensile strength variation for three different combinations of changed surfaced material. The true measured tensile strength was increased by increasing the ranges up to 62.42 MPa. Tensile strength significantly decreases in the order of 48.8 MPa and 18.15 MPa for bamboo epoxy and coconut epoxy alone. The descent of the tensile strength gradually slant in the order of 48.8 MPa and 18.15 MPa for bamboo epoxy and coconut epoxy alone. The addition of NaOH treatment for both bamboo and coconut fibre isolated and combined material marginally were increased correspondingly. After alkali treatment, the fibre was derived from the sun light reaction for 24 hours, and a finer fibre with excellent solid crystal was generated. During the material composition and epoxy combination were perfectly adhered with the material inspected by the testing result, the rate of tensile strength had reached 62.42 MPa for the recognized designation of the material.

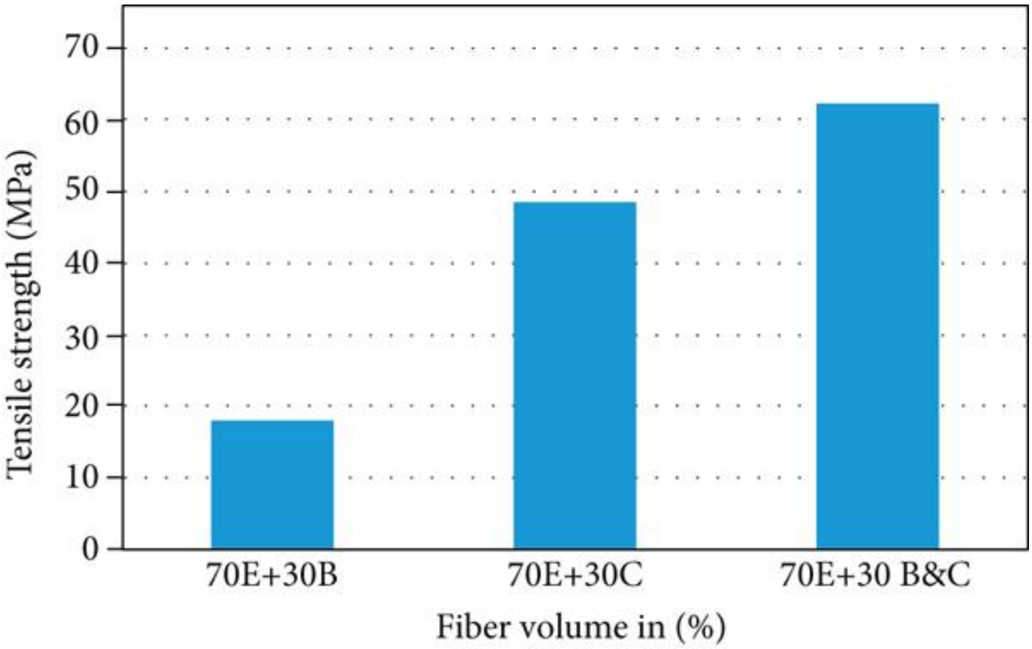


Figure 2.1: tensile strength with different fibre contents

The experimental results from studies on bamboo and coconut epoxy hybrid composites have demonstrated superior mechanical performance compared to composites without hybridization. Notably, the hybrid composite with a composition of 70% epoxy and 30% bamboo achieved a maximum tensile strength of 62.42 MPa. Similarly, combinations of 70% epoxy with 30% bamboo and 70% epoxy with 30% coconut husk fibres achieved maximum hardness and flexural strength of 185 HRC and 58 MPa, respectively.

Adelaja *et al*. (2019) conducted physical and mechanical tests on composite boards developed with sawdust, bamboo fibre, and coconut husk fibre. Different lengths of bamboo and coconut husk fibres were used in the study, ranging from 10 mm to 50 mm at a weight loading of 7.5%

for each fibre. A total of 162 samples were tested, and parameters such as percentage water absorption, density, flexural strength, compressive strength, tensile strength, and impact energy were obtained and statistically analyzed. The results showed that density and percentage water absorption did not significantly differ among the samples. However, flexural strength ranged from 5.83 MPa to 15.35 MPa, with corresponding fibre length combinations of 10:10 mm and 50:50 mm, respectively. Tensile strength ranged from 1.45 MPa to 4.03 MPa, and compressive strength ranged from 4.53 MPa to 40.7 MPa, with corresponding fibre length combinations. Impact strength varied from 14.51 J to 22.58 J, also with corresponding fibre length combinations. These findings highlight the potential of utilizing hybrid composites for various applications due to their improved mechanical properties.

2.6 Design of Experiment

Design of experiments (DOE) is indeed a powerful tool for systematically studying the relationship between multiple input variables (factors) and key output variables (responses). It allows researchers to efficiently explore various combinations of factors and determine their effects on the response variables. With respect to this experimentation that requires a variety of ratios of the individual components, the DOE plays the role of determining the effect of one factor at a time while all independent factors are held constant. The application of design of experiments (DOE) reduces errors arising from trial and error, therefore it is more efficient and all the factors can be varied and analyzed at the same time. DOE involves identifying the optimal design for an experiment. It saves time and cost and the results are usually more reliable (Montgomery, 2005).

2.6.1 Fundamental principles of Design of Experiment

2.6.1.1 Repetition

Repetition in experimental design is indeed crucial for ensuring the reliability and consistency of results. By conducting the same experiment multiple times, researchers can identify any inconsistencies or errors in the methodology and reduce the likelihood of results being due to chance. Replication, as per the Replication Principle, involves repeating the experiment more than once, applying every treatment to multiple experimental units rather than just one.

This approach helps increase the accuracy of the experiments by reducing the impact of random variability. Repetition and replication aim to enhance the precision of a study, allowing researchers to better assess the main impacts and interactions of the factors under investigation. In essence, the repetition of experiments contributes to the robustness and validity of the study's findings, ultimately improving the overall quality of scientific research. It is introduced with the objective of increasing the precision of a study—in other words, the precision with which the main impact and interactions can be accessed (www.testbook.com accessed March 3,2024).

2.6.1.2 Randomization

This principle suggests that in Design of Experiments (DOE), treatments are assigned to experimental groups in a random manner. This approach is highly regarded because it ensures that each experimental group has an equal chance of receiving any treatment. By doing so, this principle minimizes variations and biases, thereby enhancing the authenticity and credibility of experimental research. Employing a randomized sequence helps mitigate the influence of unknown or uncontrolled variables (www.testbook.com accessed March 3,2023).

2.6.1.3 Local Control

This principle aims to mitigate the influence of extraneous variables that could impact the outcome of an experiment. It involves controlling all factors except those under study. Local control is achieved through techniques such as balancing and blocking, which enhance precision and facilitate the comparison of the factors of interest. Blocking specifically helps to neutralize the effects of extraneous factors that may indirectly influence the response variables (Kapoor, 2019). In situations where randomizing a factor is impractical or costly, blocking allows for the restriction of randomization by conducting all trials with one setting of the factor first, followed by all trials with the other setting.

2.6.2 Types of experimental design

There are several types of experimental designs, some of them include: full factorial, fractional factorial, randomized complete block design (RCBD), central composite design, Box Bhenken design, saturated design and mixture design.

2.6.2.1 Full Factorial

A full factorial experimental design encompasses all potential combinations of levels for every factor involved. For a study involving k factors at 2 levels each, the total number of experiments equals 2 to the power of k. This 2^k full factorial design is particularly valuable in initial experimental phases, especially when the number of factors—be they process parameters or design variables—is no greater than 4. When factors are set at 2 levels, one assumption we operate under is that the response behaves in an approximately linear manner across the selected range of factor settings. The inaugural design in the 2^k series involves just two factors, denoted as A and B, with each factor examined at 2 levels. This configuration is termed a 2^2 full factorial design (Jiju,2023).

In a full factorial design, experimental points are generated by combining all possible levels of the factors in each complete trial or replication of the experiments. These experimental points, also known as factorial points, are positioned at the vertices of a hypercube in the n-dimensional design space, delineated by the minimum and maximum values of each factor. For instance, if there are three factors, each with four levels, employing a full factorial design necessitates conducting a total of 4^3 (64) experiments. If the experiments are replicated n times, then the total number of experiments would be n times the number conducted in a single replication (Prasanta *et al*, 2012)

2.6.2.2 Fractional factorial

A fractional factorial design is essentially a condensed version of the full factorial design, employing only a subset of the total runs. This approach is particularly advantageous when resources are constrained or when dealing with a large number of factors, as it requires fewer experimental runs compared to the full factorial design.

In a fractional factorial design, a subset of the combinations from the full factorial design is utilized. Consequently, some of the main effects and two-way interactions become confounded, meaning they cannot be isolated from the effects of other higher-order interactions. However, researchers often accept this confounding, assuming that higher-order effects are negligible. This trade-off allows for the exploration of main effects and low-order interactions while minimizing the number of experimental runs required. (www.Minitab support.com, accessed March 3, 2024).

2.6.2.3 Randomized Complete Block Design

A randomized block design (RBD) is a methodical approach to experimentation where subjects or experimental units are organized into blocks based on shared characteristics. Within each block, different treatments are randomly assigned to the individual subjects. This design enables researchers to account for variability among subjects with similar characteristics and ensures that each treatment is tested across a range of conditions. Ultimately, RBD allows for a more robust assessment of the effects of treatments while controlling for potential sources of variability within the experimental units. (study.com, accessed March 4, 2024). The Randomized Complete Block Design (RCBD) operates on the premise that the experimental units can be categorized into relatively uniform subgroups or blocks. Treatments are then randomly allocated to these units, ensuring each treatment appears an equal number of times within each block. Essentially, every block encompasses all treatments, thereby controlling for external sources of variation. During analysis, the variation among blocks is separated from the experimental error (MSE), thus minimizing this parameter and enhancing the efficacy of the test.

2.6.2.4 Central composite design

The Central Composite Design (CCD) is commonly employed in response surface methodology to construct second-order polynomials for response variables, avoiding the need for a complete full factorial design. CCD requires at least three levels of each factor to establish coefficients for quadratic terms. Within CCD, three types of points are utilized: factorial points, central points, and axial points. Factorial points are positioned at the vertices of an n-dimensional cube and are derived from a full or fractional factorial design, with factor levels coded as -1 and +1. The central point is located at the center of the design space. Axial points are symmetrically situated along the axes of the coordinate system, at a distance α from the center, representing extreme factor levels.

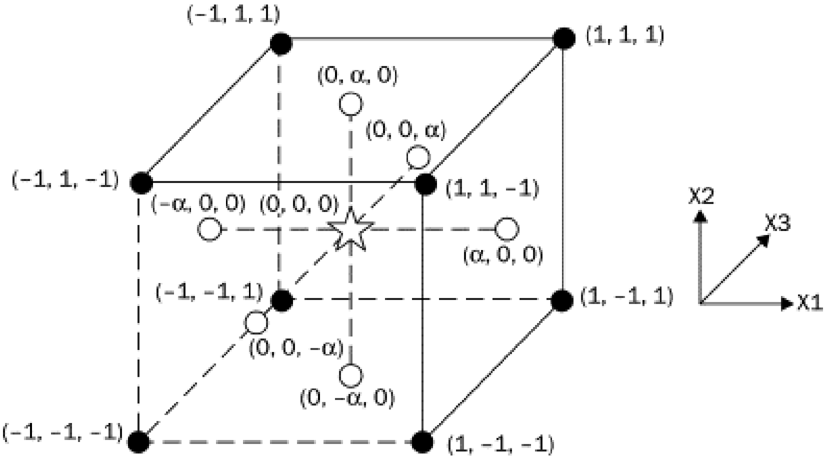


Figure 2.2: Face-centred central composite design with three factors

The rotatable central composite design (CCD) is widely utilized for modeling second-order response surfaces. A design is considered rotatable when the variance of the predicted response at any point is solely dependent on the distance of that point from the center of the design. This design ensures uniform prediction error, achieved through the proper selection of the scaling factor α. In rotatable designs, all points located at the same radial distance (r) from the center point exhibit the same magnitude of prediction error.

To achieve rotatability, the scaling factor α is computed as $\alpha = (nf)1/4$, where nf represents the number of points in the 2k factorial design. A rotatable CCD consists of 2k fractional factorial points, supplemented by 2k axial points [(± α, 0,…0),(0, ± α,...0), (0, 0,… ± α)] and nc center points (0, 0, 0, 0…,0). The number of center points, nc, can vary from three to six. With the appropriate selection of nc, the CCD can be made orthogonal or designed for uniform precision, ensuring that the variance of the response at the origin equals the variance of the response at a unit distance from the origin.

For instance, in a three-factor experimentation scenario, a total of 20 experimental runs may be considered, comprising eight factorial points (23), six axial points (2 × 3), and six center runs. The value of α, computed as $(8)1/4 = 1.682$, ensures the desired uniform precision.

2.6.2.5 Box Bhenken design

The Box-Behnken design is an independent quadratic design in that it does not contain an embedded factorial or fractional factorial design. In this design the treatment combinations are at the midpoints of edges of the process space and at the center. These designs are rotatable (or near rotatable) and require 3 levels of each factor. The designs have limited capability for orthogonal blocking compared to the central composite designs.

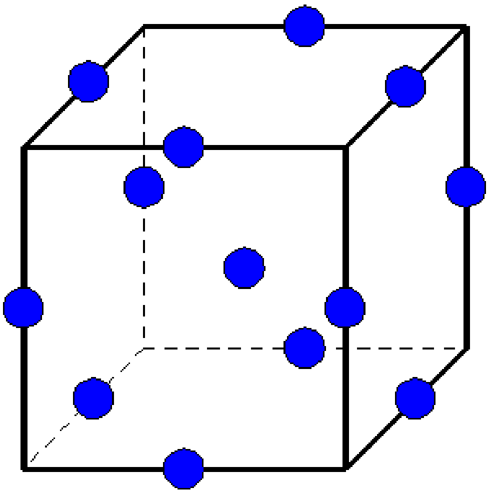


Figure 2.3: A Box-Behnken Design for Three Factors

2.6.2.6 Saturated Design

A saturated design serves as a screening experiment focused solely on examining the effects of individual factors, disregarding interactions. These experiments are also discussed in terms of resolution or confounding.

Termed as a Resolution III experiment, a saturated design confounds the main effect with the 2-way interaction. This confounding makes it challenging to discern whether the effect on the response variable stems from the main effect of a single factor or the 2-way interaction. If understanding 2-way or higher interactions is crucial, conducting a higher-resolution experiment becomes necessary (isixsigma.com, March 4,2024).

2.7 Response Surface Methodology

Response surface methodology (RSM) encompasses a set of mathematical and statistical techniques utilized for building empirical models. Through carefully designed experiments, the primary aim is to optimize a response, which represents the output variable affected by multiple independent variables, also known as input variables.

An experiment within RSM consists of a series of tests, or runs, where alterations are made in the input variables to understand the causes behind changes in the output response. RSM finds extensive applications in the industrial realm, particularly in scenarios where several input variables potentially influence a performance measure or quality characteristic of a product or process. This performance measure or quality characteristic is referred to as the response, typically measured on a continuous scale, though other types of responses like attribute responses, ranks, and sensory responses are also common. Real-world applications of RSM often involve the consideration of more than one response.

The input variables, also termed independent variables, are under the control of the engineer or scientist, at least during the course of a test or an experiment. (Raymond *et al*,2009)

RSM assumes that the response of a process is a function of a set of independent variables X1, X2, X3, …, Xk.

$Y = f(x)\beta + \varepsilon$ (2.1)

where, x = (X1, X2, X3, …., Xk),

$f(x)$, is a vector function of p elements that consists of powers and cross products of the powers of X1, X2, X3, …., Xk. β is a vector of p unknown constant coefficients called parameters while ε is a random experimental error.

2.8 Mixture Design.

Mixture designs are specialized experimental methodologies tailored to precisely understand how the response variable changes concerning the relative proportions of components. In these designs, all components are expressed in the same units of measurement, and the total sum of each experimental run remains constant. They are invaluable for maximizing informational output while minimizing the number of experimental runs needed.

Several types of mixture designs exist, including simplex (lattice and centroid) mixture designs and optimal mixture (I, A, D) designs. These designs find applications in various experimental optimization scenarios, such as pharmaceutical drug product development. The number of factors accommodated in simplex lattice, simplex centroid, and optimal designs can vary, typically ranging from 2 to 30, 3 to 8, and 2 to 24, respectively.

As high-resolution designs, mixture designs can handle higher-order mathematical models like quadratic and cubic equations to establish factor–response relationships. Moreover, they efficiently estimate the design space and provide insights into optimal solutions. This research provides comprehensive insights into the fundamentals and practical applications of mixture designs in the development and optimization of composite boards.

CHAPTER 3

MATERIALS AND METHODS

This research study was done in stages, the stages include:

The first stage is the procurement of materials, the chemical treatment of the bamboo and the preparation of the materials in the suitable state for the production of the composite.

The second stage is the production of the composite samples; the samples were produced using different configurations of the reinforcement particles (bamboo and coir fibre) and the matrix(epoxy). The different configurations used were obtained using RSM experimental design in the Design Expert software. The experimental samples were produced by pressing the mixture into the mould.

The third stage was the determination of the strength of the material through modulus of rupture, modulus of elasticity, thickness swelling and water absorption.

The last stage involves the application of the statistical analysis of the experimental results in order to obtain the optimal and suitable configuration that can be applied in the production of composite boards.

3. 1 Materials

The section highlights the materials used and the processes involved.

3.1.1 Bamboo

The first step taken for the bamboo is the procurement of the bamboo culms. Freshly harvested bamboo culms as seen in plate 3.1 were obtained from a local shop in Uselu Market Benin

Plate 3.1: Freshly harvested bamboo culms

3.1.2 Coconut husk

The first step taken for the coconut husk is the procurement of coconut husk. Dry coconut husk was obtained from a local coconut plantation in Benin city

Plate 3.2: Dry coconut husk

3.1.3 Epoxy (Resin and Hardener)

Plate 3.3: Epoxy resin and epoxy hardener

The Epoxy resin and hardener with the brand name EPOCHEM 105 Resin and EPOCHEM 205 Epoxy catalyst as shown in Plate3.3 was procured from EPOCHEM Nigeria Ltd. Located in Port-Harcourt, Rivers State Nigeria. The combination of its adhesive properties, strength, chemical resistance, versatility, and other favorable characteristics makes epoxy resin a preferred choice for a wide range of industrial, commercial, and artistic applications.

3.2 Equipment Used

This section highlights the equipment used in the course of this work. They include:

3.2.1 Wooden Mould

A wooden mould, also referred to as a wooden form or frame, serves as a structural apparatus primarily crafted from wood. Its main function is to shape and confine materials during the moulding or casting process. Wooden moulds are extensively utilized across various industries for manufacturing a wide range of items, including moulded plastics, composites, ceramics, and concrete components.

Typically, wooden moulds are constructed using either solid wood or engineered wood materials such as particleboard or plywood. The selection of wood depends on factors such as cost, dimensional stability, and durability. The construction process involves assembling individual wooden components together using screws, nails, or adhesive. Additional reinforcement, such as braces, corner supports, or ribs, may be incorporated to bolster the mould's structural integrity and prevent distortion during usage.

Wooden moulds are meticulously crafted to match the specified shape, size, and surface finish of the final product. They can be custom-made or prefabricated to meet specific requirements. The interior surfaces of wooden moulds may feature smooth, textured, or patterned finishes to impart distinctive characteristics to the moulded product. Surface treatments like sealing, varnishing, or lining with release agents are often applied to facilitate mould release and prevent adherence of moulded materials.

For the purpose of the experiment, plywood was utilized to prepare the mould, providing a suitable material choice for its strength, versatility, and cost-effectiveness.

Plate 3.4 A Wooden Mould

3.2.2 The Universal Testing Machine

A universal testing machine (UTM), alternatively referred to as a "materials testing machine," stands as a versatile and sturdy apparatus utilized for ascertaining the mechanical properties of materials. UTMs function on the premise of applying controlled forces to test specimens and gauging the resulting deformation or displacement. These machines possess the capability to impose loads in tension, compression, bending, and torsion, thereby facilitating the evaluation of materials' mechanical characteristics under diverse loading conditions.

A typical universal testing machine encompasses several key components, including a frame, load frame, actuators, load cell, grips or fixtures, displacement measurement system, and control and data collecting systems. These components work cohesively to execute the testing procedures effectively and accurately. In essence, UTMs play a pivotal role in material testing and quality assurance across a spectrum of industries, including manufacturing, construction, aerospace, automotive, and research and development.

UTMs are capable of conducting a wide range of mechanical tests to analyze various qualities of materials. These tests include: tensile testing, flexural testing, shear testing, compression testing, fatigue testing, creep testing, hardness testing.

Figure 3.1 Universal Testing Machine

(https://geoteksaintifik.com/images/post/24-04-2019_10-55-07.jpg, Accessed April 10, 2024)

3.2.3 The Hack Saw

A hack saw is a handheld cutting tool utilized primarily for cutting metal, although it can also be used on plastic and wood. It consists of a frame with a detachable blade tensioned between its ends. Hack saws are commonly found in workshops, construction sites, and for do-it-yourself (DIY) projects. They are particularly useful for cutting metal pipes, rods, bars, and other small materials. The versatility and portability of hack saws make them indispensable tools for various cutting tasks in both personal and professional settings.

Figure 3.2 Hack Saw (https://images.app.goo.gl/pDrCT825D1wLrZ2L9,Accessed April 10, 2024**)**

3.2.4 The Vernier Caliper

A vernier caliper, often simply called a caliper, is a precise measuring instrument utilized for accurately measuring both internal and external dimensions of objects. It consists of three main components: the main scale, the sliding vernier scale, and a movable jaw. The main scale is a graduated scale that is etched or printed along the caliper's fixed beam, typically marked in millimeters (mm) or inches (in), and serves for primary measurements. A vernier caliper typically features two sets of jaws: an external jaw for measuring the external dimensions of objects like the diameter of a rod or the width of a box, and an internal jaw, also known as the depth probe or depth rod, for determining internal dimensions such as the depth of a hole or the internal diameter of a pipe.

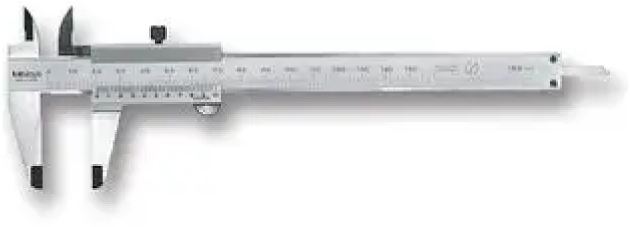


Figure3.3 Vernier Caliper

(https://ie.farnell.com/productimages/standard/en_GB/42346302.jpg, accessed April 10,2024)

3.2.5 Digital Weight Scale

A digital weight scale, also known as an electronic scale or digital weighing scale, is a device designed to accurately measure the weight of objects or substances. Unlike traditional mechanical scales that use springs or balances, digital weight scales utilize electrical sensors and a digital display for quick and precise weight readings.

The most prominent feature of a digital weight scale is its digital display, which presents weight measurements in numerical format. This display may consist of an LCD (Liquid Crystal Display) or LED (Light Emitting Diode) screen that shows the weight measurement as digits.

Digital weight scales employ a load cell, which is a transducer responsible for converting the applied weight into an electrical signal. Typically located beneath the platform or weighing surface of the scale, the load cell undergoes deformation when weight is placed on the scale, generating an electrical signal proportional to the applied force. This signal is then translated into a digital weight readout displayed on the screen.

The platform or weighing surface of a digital weight scale is where objects or substances are placed for measurement. It may feature a non-slip surface or textured pattern to enhance stability and prevent items from slipping during weighing.

Depending on the manufacturer and model, digital weight scales can operate on either batteries (such as AAA, AA, or lithium-ion batteries) or AC power adapters. Battery-powered scales offer portability and can be used in locations without access to electrical outlets, while AC-powered scales provide continuous power and are suitable for permanent installations.

Plate 3.5 Digital Weight Scale

3.2.6 The Drying Oven

A drying oven, also referred to as a drying chamber or drying cabinet, is a specialized equipment utilized for removing water, moisture, and solvents from various objects or materials. Typically constructed with an insulated chamber made from materials like stainless steel, aluminum, or mild steel, drying ovens are designed to ensure efficient heat retention and uniform temperature distribution.

The interior of a drying oven often features adjustable shelves or racks, allowing for the accommodation of samples or materials of different sizes and shapes. Seals or gaskets are integrated into the door of the drying oven to provide a tight seal, minimizing heat loss during operation and maximizing energy efficiency.

Heating elements, such as electric resistance coils or infrared lamps, are employed within the drying oven to generate heat and elevate the temperature inside the chamber. Temperature control systems, such as thermostats, temperature controllers, or programmable logic controllers (PLCs), are utilized to regulate the heating process and maintain a consistent temperature or adhere to a predefined temperature profile during the drying operation.

Safety measures are integrated into drying ovens to ensure secure operation and prevent accidents. These safety features may include overheat prevention mechanisms, door interlocks, and alarms. Overheat prevention systems are designed to automatically deactivate the heating elements if the temperature exceeds a predetermined threshold, safeguarding samples or materials from potential damage due to overheating. Door interlocks ensure that the oven cannot be opened while in operation, while alarms provide audible or visual alerts in case of any abnormalities or malfunctions.

Figure 3.4: The Drying Oven (https://images.app.goo.gl/CQxFqg4ksMoZ877H 9)

3.3 Methods

The chapter outlines the approach employed to achieve the research objectives. This chapter starts with Research Design that explains the planning and implantation of research work.

3.3.1 Research Design

The research focused on the designing, production and optimization of a bamboo fibre and coir fibre (coconut husk) reinforced matrix in an epoxy matrix. The research design used the following stages of methodology:

i. Procurement of materials
ii. Delignification of the bamboo
iii. Drying of the bamboo
iv. Grounding of some of the bamboo fibre into powder
v. Grounding of some of the coconut husk into powder
vi. Preparation of the wooden mould for the composite
vii. Design of the experiment

viii. Mixing, compounding and production of the composites
ix. Evaluation of the composite for mechanical strength
x. Validation of models produced, to determine the optimum solution.

3.3.2 Delignification of the bamboo

Delignification is a crucial process involving the extraction of lignin from plant sources, often performed through various methods. Lignin, a complex polymer present in the cell walls of plant fibres like bamboo, can negatively impact the adhesion between fibres and the matrix in composite materials. Removing lignin from bamboo fibres, therefore, becomes essential to enhance their flexibility, strength, and compatibility with the matrix material, such as epoxy or polyester resin.

By undergoing delignification, bamboo fibres experience improved quality, leading to enhanced mechanical properties of composite boards. These improvements include increased tensile strength, flexural strength, and impact resistance. To facilitate the delignification process effectively, bamboo is typically cut into smaller pieces beforehand. This reduction in size enhances surface area and promotes better penetration of the delignification solution into the fibres, thereby optimizing the overall delignification process. A delignification bath was prepared by dissolving 0.1mol of sodium hydroxide (NaOH) in distilled water. The cut bamboo fibres were submerged and left to soak in the delignification solution for a total duration of seventy-two hours (72 hours). During this time period, the delignifying agent within the bath underwent a reaction with the lignin found in the bamboo fibres. This chemical reaction caused the lignin polymer chains to break down, leading them to dissolve or disperse into the solution, while leaving the cellulose and hemicellulose components of the bamboo fibres mostly unaffected. Upon completion of the 72-hour delignification process, the delignified bamboo fibres were extracted from the solution and thoroughly washed with distilled water to eliminate any remaining chemicals or impurities. Subsequently, the delignified bamboo fibres were air-dried to remove excess moisture, followed by oven-drying at 60 degrees Celsius until the moisture content was reduced to approximately five percent.

Plate 3.6: Delignification of bamboo

Plate 3.7: Air drying of the bamboo

3.3.3 Extraction of the bamboo and coir fibre

The oven-dried bamboo and the coconut husk fibre were ground to produce a finely powdered form using a grinding machine as shown in Plate 3.8

Plate 3.8: A sample of the grounded bamboo fibre

3.4 Experimental Design

3.4.1. Mixture design

Table3.1 coded and actual levels of the factors for the composites

Factors	Unit	Symbols	Variable levels	
			Low level	High level
Bamboo fibre	%	X_1	40	45
Epoxy	%	X_2	30	35
Coir fibre	%	X_3	20	30

Table 3.2: Experimental design for the formulation of the composite

Run	Actual values of factors			Responses		
	Bamboo fibre	Epoxy	Coir fibre	Modulus of Rupture (MPa)	Thickness Swelling (%)	Water Absorption (%)
1	40.7500	30.0000	29.2500	To be determined		
2	40.7500	30.0000	29.2500			
3	45.0000	30.0000	25.0000			
4	43.3358	30.0000	26.6642			
5	41.4737	31.3498	27.1765			
6	45.0000	31.7609	23.2391			
7	42.8245	32.2000	24.9755			
8	42.8245	32.2000	24.9755			
9	42.8245	32.2000	24.9755			
10	40.0000	33.1716	26.8284			
11	40.0000	33.1716	26.8284			
12	43.7437	33.6430	22.6133			
13	45.0000	34.3257	20.6743			
14	40.0000	35.0000	25.0000			
15	41.7565	35.0000	23.2435			
16	41.7565	35.0000	23.2435			

3.5 Procedure for the Fabricating the composites

The responsive forms of the delignified bamboo fibres were measured out in weights using the digital electronic weights into a pan in batches as stated in Table 3.2. The coir fibres were measured out also in the same manner using the digital scale. The epoxy Resin and Hardener were measured out as stated in Table3.2. The Resin and Hardner were combined according to the specification of the manufacturer (Resin and hardener in the ration 2:1). Each of the sample ratios were mixed homogenously and poured into the wooden mould. The wooden mould was lined with polythene paper to ease removal from the mould. Pressure was applied on the composite and it was allowed to cure under room temperature for a period of 24 hours before extraction. The process was repeated thrice for all forms. The end result after extraction is as seen in Plate2.

Plate 3.9: Samples of the full length of extracted composite specimens

3.6 Evaluation of Bamboo composites for mechanical strength

Mechanical tests such as modulus of rupture and modulus of elasticity were carried out on the various samples. The tests were carried out in the Strength of materials lab, University of Benin

3.6.1. Modulus of Elasticity and Tensile Stress of Specimens

Tensile stress is a quantity associated with stretching or tensile forces. It is responsible for the elongation of the material along the axis of the applied load. Tensile stress is defined as:

The magnitude F of the force applied along an elastic rod divided by the cross-sectional area A of the rod in a direction that is perpendicular to the applied force.

Elastic modulus: It is the stiffness of the material and also known as the modulus of elasticity. It is defined as the ratio of stress and strain when the deformation is completely elastic. To measure elastic modulus, the stress-strain curve is used.

Tensile stress = $\frac{stress}{strain}$

3.6.2. Water Absorption Test on Samples

Each experimental sample's weight was measured and then these samples were immersed in water at room temperature over a duration of 24 hours. After that time had elapsed, these samples were extracted from water and re-weighed. Water absorption percentage was determined by

$$Water\ Absorption\ = \frac{Final\ Weight - Original\ Weight}{Original\ Weight} \times 100$$

3.1.6.3 Thickness Swelling Test

Initial thickness of samples was measured, and then the samples were immersed in water over 24 hours. After the span of 24 hours, the samples were extracted and the thickness of immersed samples was measured to ascertain thickness swelling. The thickness swelling percentage was determined by

$$Thickness\ Swelling\ = \frac{Final\ thickness - Original\ thickness}{Original\ thickness} \times 100$$

CHAPTER 4

RESULTS AND DISCUSSION

In this study, a mixture experimental design with three variables which are the mixture components was used to plan the experiments for the production of the composite board sample. Sixteen (16) experimental runs were carried out for powdered bamboo fibre, powdered coir fibre and epoxy. The results are shown in the tables below:

Table 4.1: Summary of the experimental results for the composites

Run	Actual values of factors			Responses			
	Bamboo fibre	Epoxy	Coir fibre	Tensile Stress (MPa)	Modulus Of Elasticity (MPa)	Thickness Swelling (%)	Water Absorption (%)
1	45.000	31.761	23.240	0.802	562.480	4.900	54.050
2	40.000	35.000	25.000	1.053	700.080	3.100	20.800
3	43.744	33.643	22.613	0.982	690.980	3.700	29.600
4	42.825	32.200	24.976	0.740	480.500	4.650	33.640
5	45.000	34.326	20.674	0.930	582.650	3.570	26.000
6	40.000	33.172	26.828	0.970	682.900	3.720	31.200
7	42.825	32.200	24.976	0.746	503.610	4.620	33.640
8	40.750	30.000	29.250	0.737	368.600	7.090	59.600
9	40.750	30.000	29.250	0.737	367.800	7.050	59.140
10	40.000	33.172	26.828	0.970	682.980	3.720	31.200
11	45.000	30.000	25.000	0.741	483.610	6.760	61.600
12	41.474	31.350	27.177	0.785	541.460	5.300	51.500
13	42.825	32.200	24.976	0.748	507.130	4.600	33.640
14	43.336	30.000	26.664	0.739	394.870	6.480	29.600
15	41.757	35.000	23.244	1.059	695.780	3.300	24.300
16	41.757	35.000	23.244	1.059	695.840	3.300	24.600

4.1 Response surface Modelling (RSM)

4.1.1 Determination of Most Appropriate Model

The software (Design Expert) provided different statistical model which were used for the suitable modelling of the responses (Tensile stress, modulus of elasticity, thickness swelling and water absorption). These models include cubic, linear, quadratic, special cubic, quartic and special quartic and their suitability assessed on the basis of their coefficient of determination (R^2), p value etc. The result of the analysis shows the summary of model fit for all four (4) responses for the composite samples as shown in Table 4.6

Table 4.2: Summary of model fit results

Tensile stress						
Source	Standard Deviation	R^2	Adjusted R^2	Predicted R^2	PRESS	Remark
Linear	**0.0573**	**0.8412**	**0.8168**	**0.7903**	**0.0563**	**Suggested**
Quadratic	0.0489	0.9109	0.8664	0.7245	0.0739	
Special Cubic	0.0515	0.9109	0.8515	-0.2160	0.3263	
Cubic	0.0297	0.9803	0.9508	-5.1814	1.6600	
Special Quartic	**0.0268**	**0.9812**	**0.9597**	**-0.6369**	**0.4392**	**Suggested**
Quartic	0.0026	0.9999	0.9996		*	Aliased
Modulus of Elasticity						
Source	**Std. Dev.**	**R^2**	**Adjusted R^2**	**Predicted R^2**	**PRESS**	Remark
Linear	**58.9500**	**0.7981**	**0.7670**	**0.6720**	**73387.2500**	**Suggested**
Quadratic	49.3100	0.8913	0.8369	0.6541	77384.5500	
Special Cubic	51.6300	0.8928	0.8213	-0.1051	2.4720E+05	
Cubic	41.6600	0.9535	0.8836	-13.1286	3.1610E+06	
Special Quartic	**37.8900**	**0.9551**	**0.9037**	**-3.7035**	**1.0520E+06**	**Suggested**
Quartic	9.1500	0.9981	0.9944		*	Aliased
Thickness Swelling						
Source	Standard Deviation	R^2	Adjusted R^2	Predicted R^2	PRESS	Remark

Linear	0.3957	0.9315	0.9209	0.8915	3.2200	
Quadratic	0.1294	0.9944	0.9915	0.9815	0.5497	
Special Cubic	0.0944	0.9973	0.9955	0.9659	1.0100	
Cubic	**0.0217**	**0.9999**	**0.9998**	**0.9917**	**0.2472**	**Suggested**
Special Quartic	0.0647	0.9990	0.9979	0.9765	0.6977	
Quartic	0.0203	0.9999	0.9998		*	Aliased
Water Absorption						
Source	Standard Deviation	R^2	Adjusted R^2	Predicted R^2	PRESS	Remark
Linear	**8.83**	**0.6628**	**0.6110**	**0.4801**	**1563.23**	**Suggested**
Quadratic	9.0300	0.7286	0.5929	-0.0335	3107.7300	
Special Cubic	5.8800	0.8964	0.8273	0.4687	1597.5900	
Cubic	3.6000	0.9741	0.9354	-7.1577	24530.4400	
Special Quartic	**4.0400**	**0.9621**	**0.9187**	**-3.4549**	**13396.1500**	**Suggested**
Quartic	0.1737	0.9999	0.9998		*	Aliased

Table 4.3: Lack of Fit test results

Tensile stress						
Source	**Sum of Squares**	**df**	**Mean Square**	**F-value**	**p-value**	Remark
Linear	**0.0426**	**8**	**0.0053**	**767.6000**	**< 0.0001**	**Suggested**
Quadratic	0.0239	5	0.0048	688.6300	< 0.0001	
Special Cubic	0.0239	4	0.0060	860.7600	< 0.0001	
Cubic	0.0052	1	0.0052	756.6100	< 0.0001	
Special Quartic	**0.0050**	**2**	**0.0025**	**361.3700**	**< 0.0001**	**Suggested**
Quartic	0.0000	0				Aliased
Pure Error	0.0000	5	6.933E-06			
Modulus of Elasticity						
Source	**Sum of Squares**	**df**	**Mean Square**	**F-value**	**p-value**	Remark
Linear	**44754.7300**	**8**	**5594.3400**	**66.7800**	**0.0001**	**Suggested**
Quadratic	23899.9900	5	4780.0000	57.0600	0.0002	
Special Cubic	23572.3500	4	5893.0900	70.3500	0.0001	
Cubic	9994.0600	1	9994.0600	119.3000	0.0001	

Special Quartic	**9632.2000**	**2**	**4816.1000**	**57.4900**	**0.0004**	**Suggested**
Quartic	0.0000	0				Aliased
Pure Error	418.8600	5	83.77			
Thickness Swelling						
Source	**Sum of Squares**	**df**	**Mean Square**	**F-value**	**p-value**	Remark
Linear	2.0300	8	0.2542	615.0600	< 0.0001	
Quadratic	0.1655	5	0.0331	80.0600	< 0.0001	
Special Cubic	0.0782	4	0.0196	47.3000	0.0004	
Cubic	**0.0008**	**1**	**0.0008**	**1.8500**	**0.2321**	**Suggested**
Special Quartic	0.0273	2	0.0136	32.9700	0.0013	
Quartic	0.0000	0				Aliased
Pure Error	0.0021	5	0.0004			
Water Absorption						
Source	**Sum of Squares**	**df**	**Mean Square**	**F-value**	**p-value**	Remark
Linear	**1013.7000**	**8**	**126.7100**	**4201.3200**	**< 0.0001**	**Suggested**
Quadratic	815.9000	5	163.1800	5410.5000	< 0.0001	
Special Cubic	311.4100	4	77.8500	2581.3400	< 0.0001	
Cubic	77.5800	1	77.5800	2572.3800	< 0.0001	
Special Quartic	**113.9200**	**2**	**56.9600**	**1888.5600**	**< 0.0001**	**Suggested**
Quartic	0.0000	0				Aliased
Pure Error	0.1508	5	0.0302			

Table 4.6 and 4.7 shows the model summary of fit and lack of fit for the models representing tensile stress, modulus of elasticity, thickness swelling and water absorption. The special cubic model was selected for the Tensile Stress, while the linear model was selected for modulus of elasticity, thickness swelling and water absorption. This selection was based on the fact that they displayed the highest R2 value and the lowest standard deviation and the lowest PRESS when compared to other models as shown in table 4.7.

4.1.2 Analysis of Statistical Models

Statistical analysis of the chosen models was done by fitting the models to the experimental data as obtained from the mixture experimental design. The quadratic model was fitted for the Tensile Stress, the cubic model fitted for the modulus of elasticity, the linear model for thickness swelling and the special quartic model for water absorption. The process of fitting the appropriate models to their respective experimental data was achieved through multiple regression analysis which culminated in the estimation of the unknown model parameters. Substitution of the estimated model parameters into the respective models resulted in the final models for predicting Tensile Stress, modulus or elasticity, thickness swelling and water absorption for the composite. The final model equations representing these responses in terms of the input factors, bamboo fibre level(X_1), epoxy level (X_2) and Coir fibre level (X_3) are presented thus.

$$\text{Thickness swelling} = 748.8\,X_1 + -1279.34\,X_2 - 203.4X_3 + 9.64X_1X_2 - 5.4X_1X_3 + 17.74X_2X_3 - 0.007X_1X_2X_3 + 0.308\,X_1X_2(X_1-X_2) - 0.21\,X_1X_3(X_1-X_3) - 0.216\,X_2X_3(X_2-X_3) \qquad \textbf{(4.1)}$$

NB: Water absorption, tensile stress and modulus of rupture doesn't have an equation because the selected model is not hierarchical

Equation 4.1 was used to predict thickness swelling for the composite. Tables 4.8 to 4.11 shows the experimental and model predicted results for tensile stress, modulus or elasticity, thickness swelling and water absorption for the composite. For all the results and responses obtained under investigation, it was observed that the model predicted values were similar to the experimental results indicating the validity of the statistical models developed to predict the responses

Table 4.4: Experimental and RSM Predicted values for tensile stress

Run Order	Actual Value of Factors			Response (MPa)	
	Bamboo (%)	Epoxy (%)	Coir (%)	Actual Value	Predicted Value
1	45.000	31.761	23.239	0.8020	0.7897
2	40.000	35.000	25.000	1.0500	1.0500
3	43.744	33.643	22.613	0.9820	0.9648
4	42.825	32.200	24.976	0.7400	0.7635
5	45.000	34.326	20.674	0.9300	0.9356
6	40.000	33.172	26.828	0.9700	0.9762
7	42.825	32.200	24.976	0.7460	0.7635
8	40.750	30.000	29.250	0.7370	0.7445
9	40.750	30.000	29.250	0.7370	0.7445
10	40.000	33.172	26.828	0.9700	0.9762
11	45.000	30.000	25.000	0.7410	0.7448
12	41.474	31.350	27.177	0.7850	0.7280
13	42.825	32.200	24.976	0.7480	0.7635
14	43.336	30.000	26.664	0.7390	0.7377
15	41.757	35.000	23.244	1.06	1.06
16	41.757	35.000	23.244	1.06	1.06

Table 4.5: Experimental and RSM Predicted values for modulus of elasticity

Run Order	Actual Value of Factors			Response (MPa)	
	Bamboo (%)	Epoxy (%)	Coir (%)	Actual Value	Predicted Value
1	45.000	31.761	23.239	562.480	556.180
2	40.000	35.000	25.000	700.080	689.600
3	43.744	33.643	22.613	690.980	655.440
4	42.825	32.200	24.976	480.500	521.120
5	45.000	34.326	20.674	582.650	591.240
6	40.000	33.172	26.828	682.900	693.550

7	42.825	32.200	24.976	503.610	521.120
8	40.750	30.000	29.250	368.600	377.060
9	40.750	30.000	29.250	367.800	377.060
10	40.000	33.172	26.828	682.980	693.550
11	45.000	30.000	25.000	483.610	481.280
12	41.474	31.350	27.177	541.460	464.180
13	42.825	32.200	24.976	507.130	521.120
14	43.336	30.000	26.664	394.870	400.310
15	41.757	35.000	23.244	695.780	699.220
16	41.757	35.000	23.244	695.840	699.220

Table 4.6: Experimental and RSM Predicted values for thickness swelling

Run Order	**Actual Value of Factors**			**Response (MPa)**	
	Bamboo (%)	**Epoxy (%)**	**Coir (%)**	**Actual Value**	**Predicted Value**
1	45.000	31.761	23.239	4.900	4.900
2	40.000	35.000	25.000	3.100	3.100
3	43.744	33.643	22.613	3.700	3.720
4	42.825	32.200	24.976	4.650	4.620
5	45.000	34.326	20.674	3.570	3.570
6	40.000	33.172	26.828	3.720	3.720
7	42.825	32.200	24.976	4.620	4.620
8	40.750	30.000	29.250	7.090	7.070
9	40.750	30.000	29.250	7.050	7.070
10	40.000	33.172	26.828	3.720	3.720
11	45.000	30.000	25.000	6.760	6.760
12	41.474	31.350	27.177	5.300	5.320
13	42.825	32.200	24.976	4.600	4.620
14	43.336	30.000	26.664	6.480	6.480
15	41.757	35.000	23.244	3.300	3.300
16	41.757	35.000	23.244	3.300	3.300

Table 4.7: Experimental and RSM Predicted values for water absorption

Run Order	**Actual Value of Factors**			**Response (MPa)**	
	Bamboo (%)	**Epoxy (%)**	**Coir** (%)	**Actual Value**	**Predicted Value**
1	45.000	31.761	23.239	54.050	53.940
2	40.000	35.000	25.000	20.800	19.390
3	43.744	33.643	22.613	29.600	25.190
4	42.825	32.200	24.976	33.640	36.100
5	45.000	34.326	20.674	26.000	26.960
6	40.000	33.172	26.828	31.200	32.440
7	42.825	32.200	24.976	33.640	36.100
8	40.750	30.000	29.250	59.600	60.240
9	40.750	30.000	29.250	59.140	60.240
10	40.000	33.172	26.828	31.200	32.440
11	45.000	30.000	25.000	61.600	60.950
12	41.474	31.350	27.177	51.500	43.330
13	42.825	32.200	24.976	33.640	36.100
14	43.336	30.000	26.664	29.600	30.560
15	41.757	35.000	23.244	24.300	25.050
16	41.757	35.000	23.244	24.600	25.050

4.1.3 Analysis of Variance of Models

Table 4.8: ANOVA results for model representing tensile stress

Source	**Sum of Squares**	**Df**	**Mean Square**	**F-value**	**p-value**
Model	0.2633	8	0.0329	45.6600	< 0.0001
(1)Linear Mixture	0.2257	2	0.1129	156.5800	< 0.0001
AB	0.0001	1	0.0001	0.2048	0.6646
AC	0.0000	1	0.0000	0.0612	0.8117

BC	0.0014	1	0.0014	1.8700	0.2133
A^2BC	0.0002	1	0.0002	0.2649	0.6226
AB^2C	0.0091	1	0.0091	12.6200	0.0093
ABC^2	0.0109	1	0.0109	15.1800	0.0059
Residual	0.0050	7	0.0007		
Lack of Fit	0.0050	2	0.0025	361.3700	< 0.0001
Pure Error	0.0000	5	6.933E-06		
Cor Total	0.2683	15			

Table 4.9: ANOVA results for cubic model representing modulus of elasticity

Source	**Sum of Squares**	**Df**	**Mean Square**	**F-value**	**p-value**
Model	2.1370E+05	8	26707.3400	18.6000	0.0005
(1)Linear Mixture	1.7850E+05	2	89268.1100	62.1700	< 0.0001
AB	93.2900	1	93.2900	0.0650	0.8061
AC	1454.8700	1	1454.8700	1.0100	0.3476
BC	12998.7800	1	12998.7800	9.0500	0.0197
A^2BC	224.9900	1	224.9900	0.1567	0.7040
AB^2C	11217.0400	1	11217.0400	7.8100	0.0267
ABC^2	3830.0600	1	3830.0600	2.6700	0.1464
Residual	10051.0700	7	1435.8700		
Lack of Fit	9632.2000	2	4816.1000	5.7490	0.0004
Pure Error	418.8600	5	83.7700		
Cor Total	2.237E+05	15			

Table 4.10: ANOVA results for linear model representing thickness swelling

Source	**Sum of Squares**	**Df**	**Mean Square**	**F-value**	**p-value**
Model	27.3600	2	13.6800	88.9100	< 0.0001
(1)Linear Mixture	27.3600	2	13.6800	88.9100	< 0.0001
Residual	2.0000	13	0.1539		
Lack of Fit	2.0000	8	0.2500		
Pure Error	0.0000	5	0.0000		
Cor Total	29.6300	15			

Table 4.11: ANOVA results for special quartic model representing water absorption

Source	**Sum of Squares**	**Df**	**Mean Square**	**F-value**	**p-value**
Model	2892.98.0000	8	361.6200	22.1900	0.0003
(1)Linear Mixture	1993.2000	2	996.6000	61.1600	< 0.0001
AB	672.3900	1	672.3900	41.2600	0.0004
AC	817.7800	1	817.7800	50.1800	0.0002
BC	135.2900	1	135.2900	8.3000	0.0236
A^2BC	37.0600	1	37.0600	2.2700	0.1753
AB^2C	162.0900	1	162.0900	9.9500	0.0161
ABC^2	343.9100	1	343.9100	21.1000	0.0025
Residual	114.0700	7	16.3000		
Lack of Fit	113.9200	2	56.9600	1.8886	< 0.0001
Pure Error	0.1508	5	0.0302		
Cor Total	3007.0500	15			

The fit for models for predicting the responses was further examined using the goodness of fit parameters such as adequate precision which include coefficient of determination(R^2), adjusted coefficient of determination (Adjusted R^2), mean standard deviation, coefficient of variation and adequate precision and the results are as shown in table 4.16. The R^2 values for all models considered are above 0.93. The R^2 value is used to access the level of fit between the model and experimental results. The high R^2 values shows a very good fit between the model and experimental results. The agreement between the $R^2$and the adjusted R^2 shows a very good fit for the models. The values of the standard deviation is very small when compared to the values of the mean which further indicates that the models for predicting the responses have a very good fit.

Table 4.12: Goodness of fit for response models

Parameter	**Tensile Stress**	**Modulus of elasticity**	**Thickness Swelling**	**Water Absorption**
R^2	0.9812	0.9550	0.9990	0.9620
Adjusted R^2	0.9597	0.9040	0.9990	0.9190
Mean	0.8620	558.8000	4.7400	37.7000
Standard Dev	0.0027	37.8900	0.0220	4.0400
CV	3.1100	6.7800	0.4580	10.6400
Adeq. Precision	16.3980	11.3360	230.8370	13.7270

4.1.4. Model Diagnostics

Diagnosis of the models developed to predict the responses for the composites was also carried out to assess their accuracy and indeed adequacy for the intended purpose. The diagnostic tools used to achieve this included the normal probability plot, plot of cook’s distance versus experimental run, plot of difference in fits (DIFFITS) versus experimental run order and plot of residual versus experimental run.

Figures 4.1 to 4.4 show the normal probability plots for the models representing the Tensile Stress, modulus of elasticity, thickness swelling and water absorption for the composite samples.

The normal probability plot is used to evaluate whether or not a dataset is approximately normally distributed (Chambers et al, 1983). A look at results obtained in Figure 4.1 to 4.4 shows that the residuals of the models representing tensile stress and thickness swelling follow a normal distribution based on the fact that the points are clustered around the straight-line distribution. While the models representing modulus of elasticity and water absorption do not follow a normal distribution.

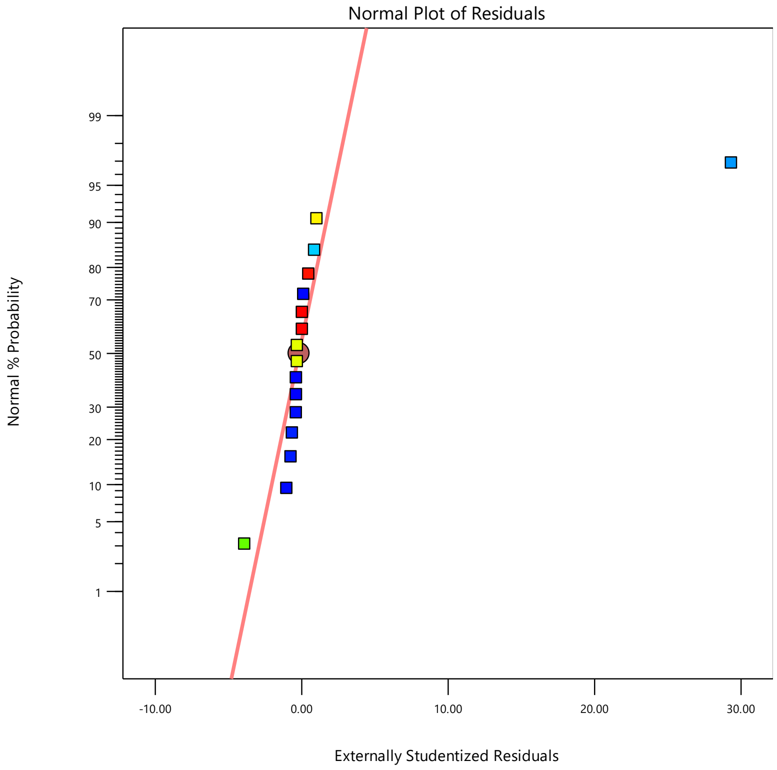


Figure4.1: Normal Probability for model representing tensile stress

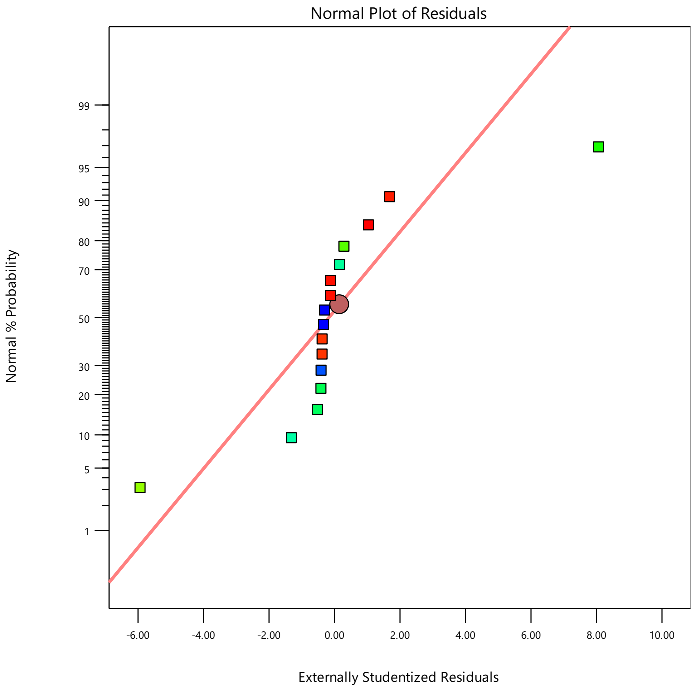


Figure 4.2: Normal Probability for model representing modulus of elasticity

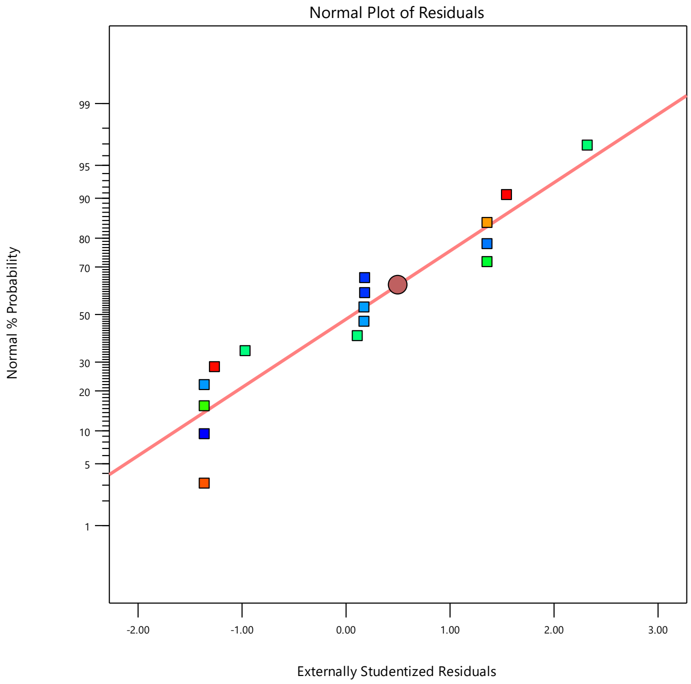


Figure 4.3: Normal Probability for model representing thickness swelling

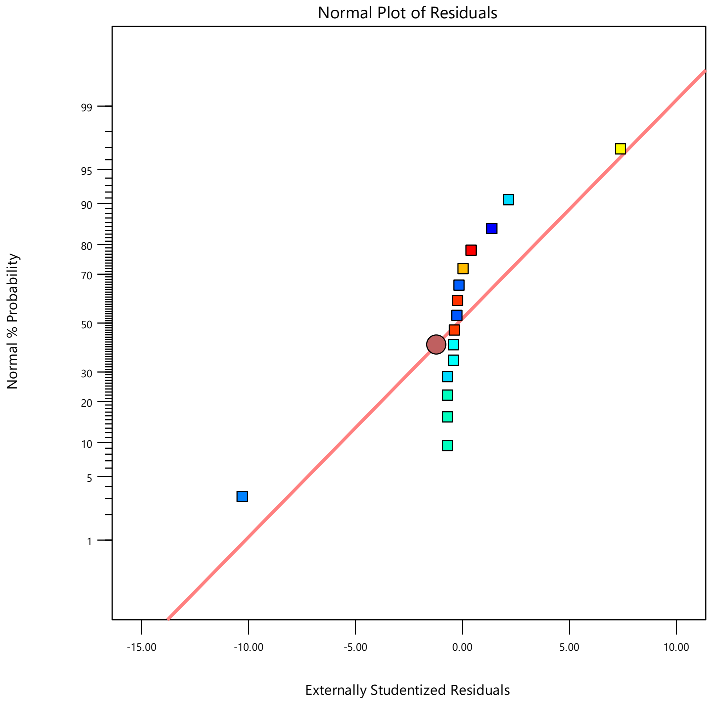


Figure 4.4: Normal Probability for model representing water absorption

Figures 4.5 to 4.8 shows the plots of Cook's distance versus the experimental run order for the models representing the Tensile Stress, modulus of elasticity, thickness swelling and water absorption for the composite samples. The plot of Cook's distance is used to determine the presence of outliers. Large values of Cook's distance signify high leverage and large studentized residuals which implies the presence of outliers. A look at the results in Figure 4.5 to 4.8shows that the values for Tensile Stress, modulus of elasticity and water absorption do not fall within limit therefore indicating that the design contains outliers, whereas the result for thickness swelling(Figure4.17) shows that the values fall within limit showing that the design doesn't contain possible outliers.

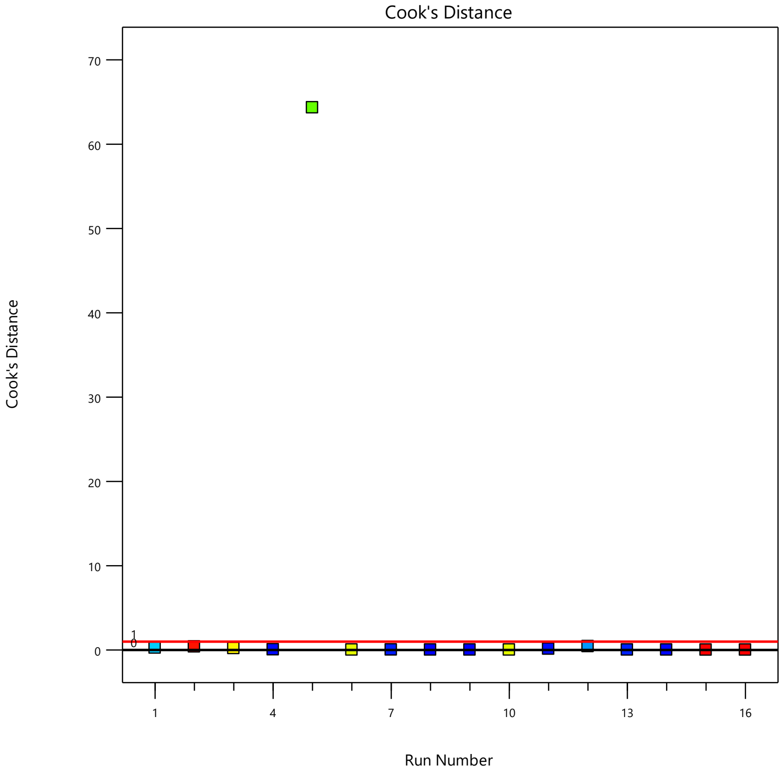


Figure 4.5: Plot of cook’s distance versus experimental run order for model representing tensile stress

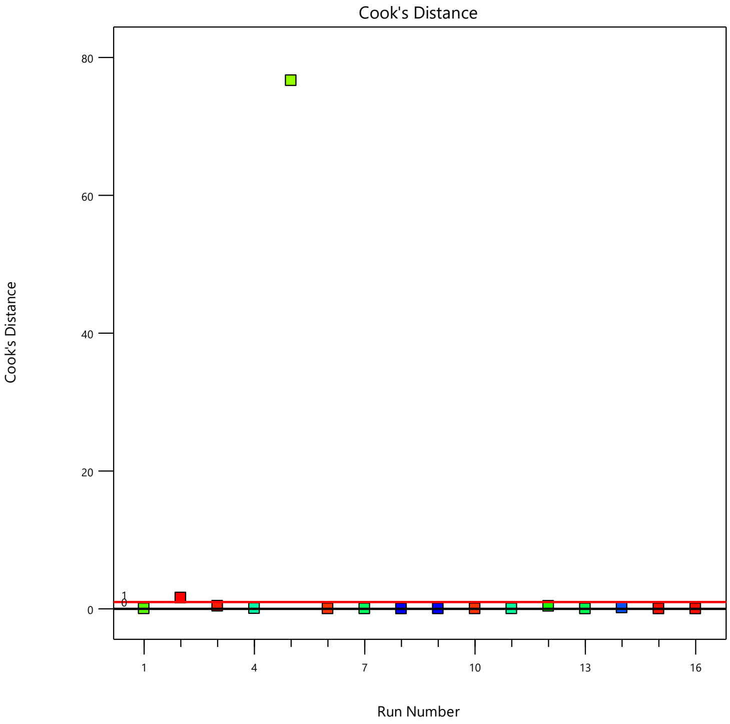


Figure 4.6: Cook’s Distance for model representing Modulus of elasticity

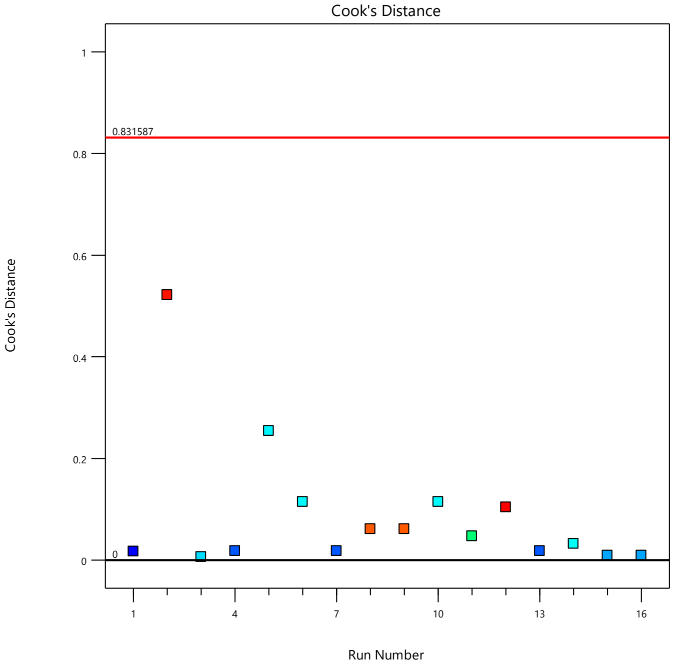


Figure 4.7: Cook’s Distance for model representing thickness swelling

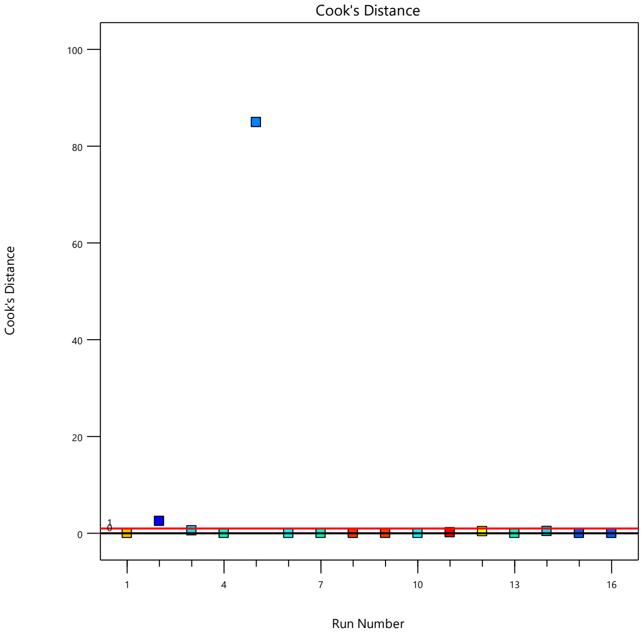


Figure 4.8: Cook’s Distance for model representing water absorption

Figures 4.9 to 4.12 show the plots of the externally studentized residuals versus experimental runs for the models representing the tensile Stress, modulus of elasticity, thickness swelling and water absorption for the composite samples. The plot of externally studentized residuals versus experimental runs checks for lurking variables that may have influenced the response during the experiment. Generally, if there are no hidden variables lurking in the background that could influence the results, then the plot of residuals versus experimental run order will display a random scatter. The results in Figure 4.9 to 4.12 show a random scatter therefore there are no hidden variables lurking in the background.

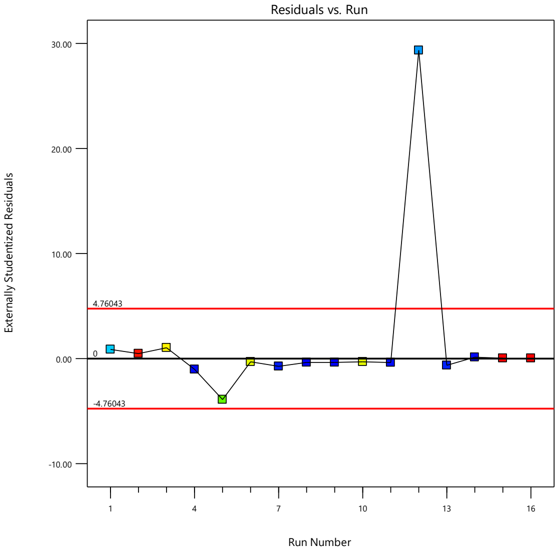


Figure 4.9: Plot of residual versus experimental run for model representing tensile stress

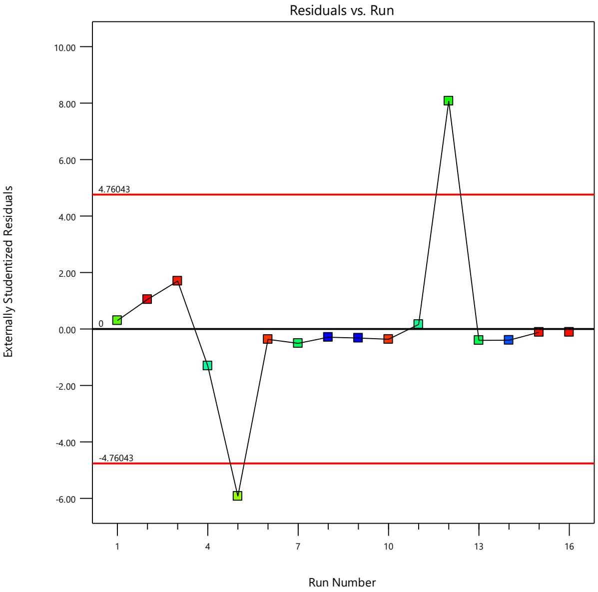


Figure 4.10: Plot of residual versus experimental run for model representing modulus of elasticity

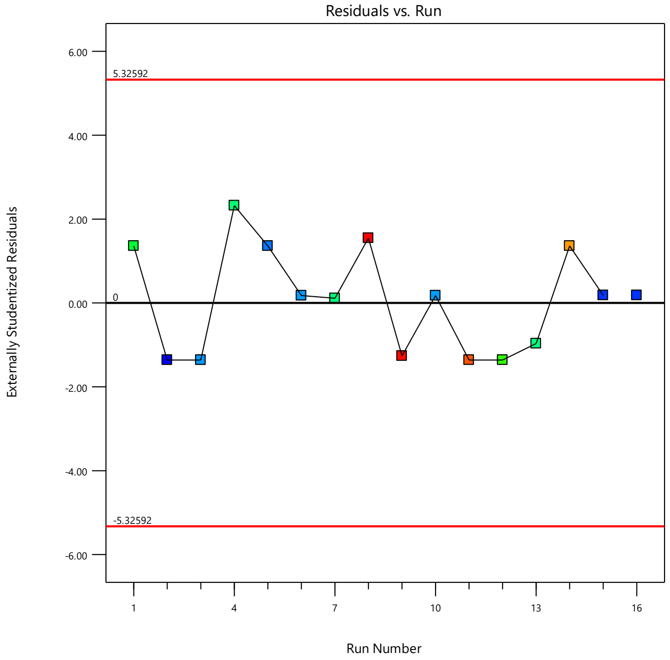


Figure 4.11: Plot of residual versus experimental run for model representing Thickness swelling

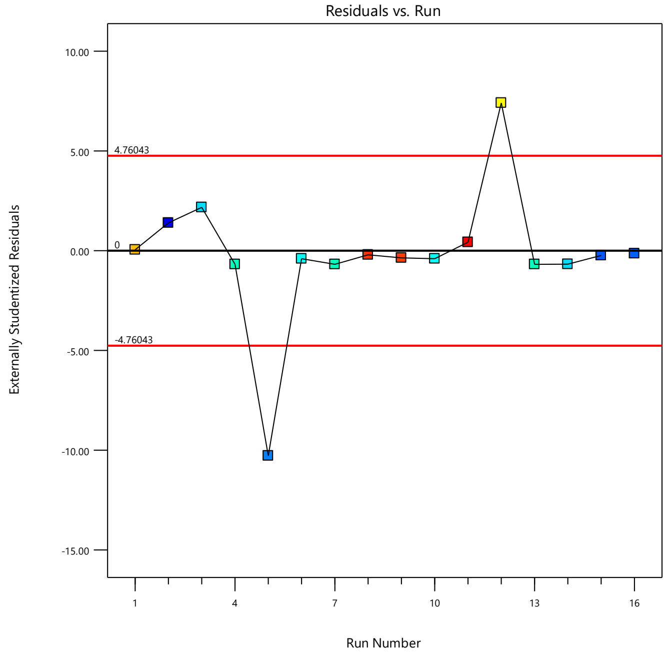


Figure 4.12: Plot of residual versus experimental run order for model representing water absorption

Figures 4.13 to 4.16 shows the plots of DIFFITS versus the experimental run order for the models representing Tensile Stress, modulus of elasticity, thickness swelling and water absorption for the composites. The difference in fits is seen as a measure of the change in the value of the predicted response with respect to two fits to the data, one with and without the ith response. The DIFFTS tells whether a particular experimental observation will influence the prediction model. If there are no statistical outliers or extreme experimental results in the design the DIFFITS is within limit. A statistical outlier is a value in a dataset that significantly differs from other observations. The presence of a statistical outlier results in the DIFFITS being outside the limits. A look at the results shown in Figures4.13 to 4.16 shows that the DIFFITS for Tensile Stress, thickness swelling and water were not within limits whereas modulus of elasticity was within limit.

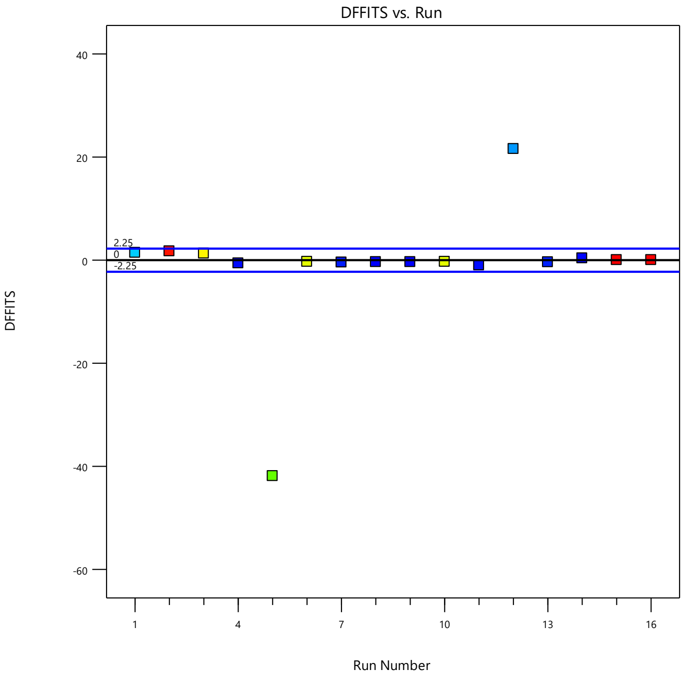


Figure 4.13: Plot of DIFFITS versus experimental run order for model representing tensile test

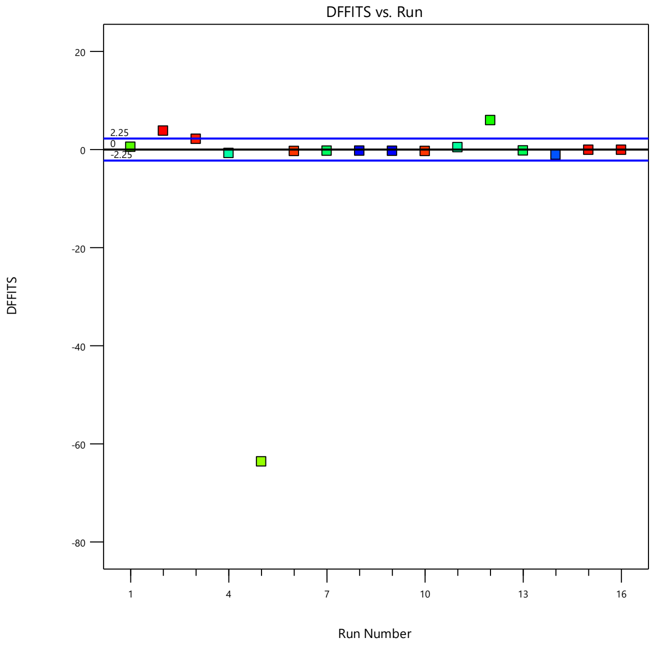


Figure 4.14: Plot of DIFFITS versus experimental run order for model representing modulus of elasticity

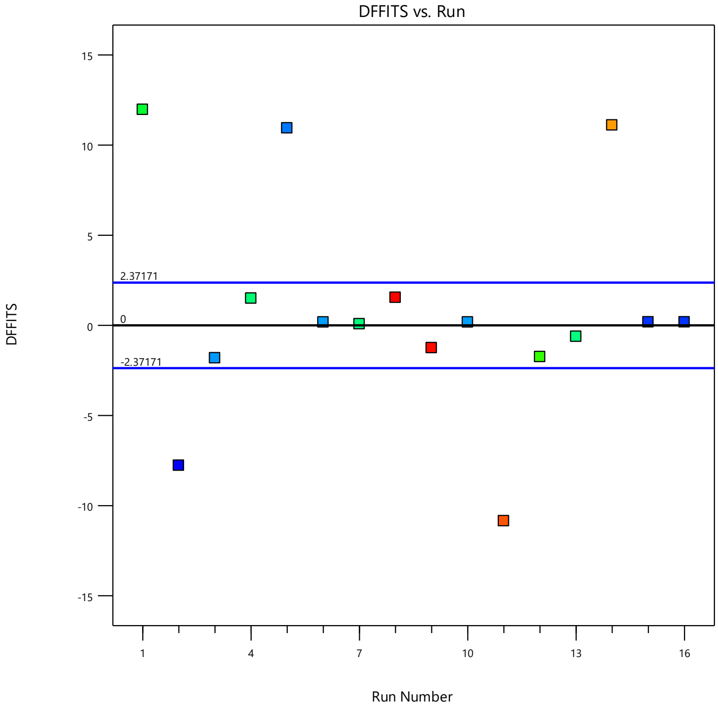


Figure 4.15: Plot of DIFFITS versus experimental run order for model representing thickness swelling

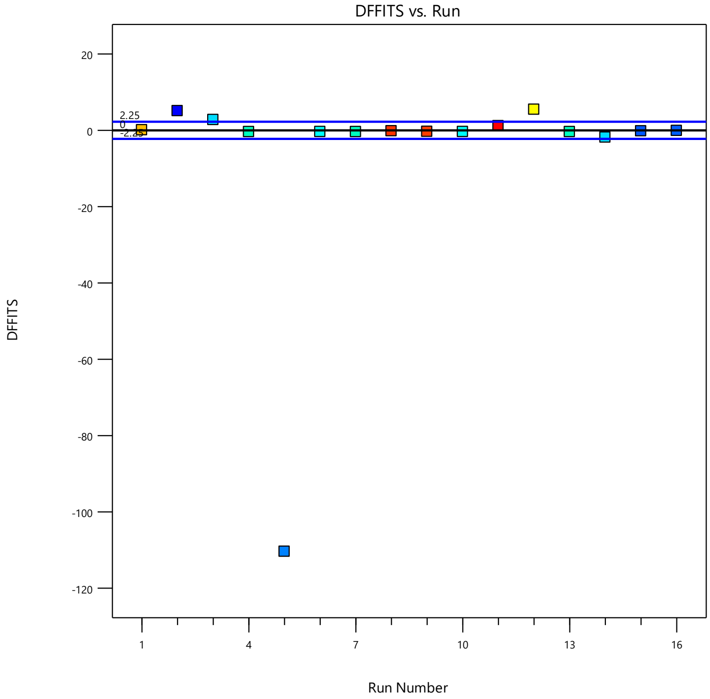


Figure 4.16: Plot of DIFFITS versus experimental run order for model representing water absorption

4.1.5 Validation of Response Model

4.1.5.1. 3D Response Surface Plot showing Effect of Input Factors on Responses

Three-dimensional (3D) response surface plots were generated from the statistical models to evaluate the effect the effect of the input factors (level of bamboo fibre, epoxy and coir fibre) on the respective responses (tensile stress, modulus of elasticity, thickness swelling and water absorption) for the composite produced. The response surface plots were generated by varying two variables within the experimental range and while one is kept constant at its center point value. The contour plot shows the simultaneous effect of two factors on a chosen response.

i. Effect of input factors on all tests (Contour and Surface Plots)

Figure 4.17 shows the 3D response surface showing the effect of the amount of bamboo fibre, epoxy and coir fibre on the tensile stress for the composite produced while Figure 4.18 shows the corresponding contour plot. The results show that increasing the amount of bamboo leads to an increase in the tensile stress. The results also show that an increase in the amount of coir fibre led to an increase in the tensile stress. The same trend is also applicable for epoxy resin

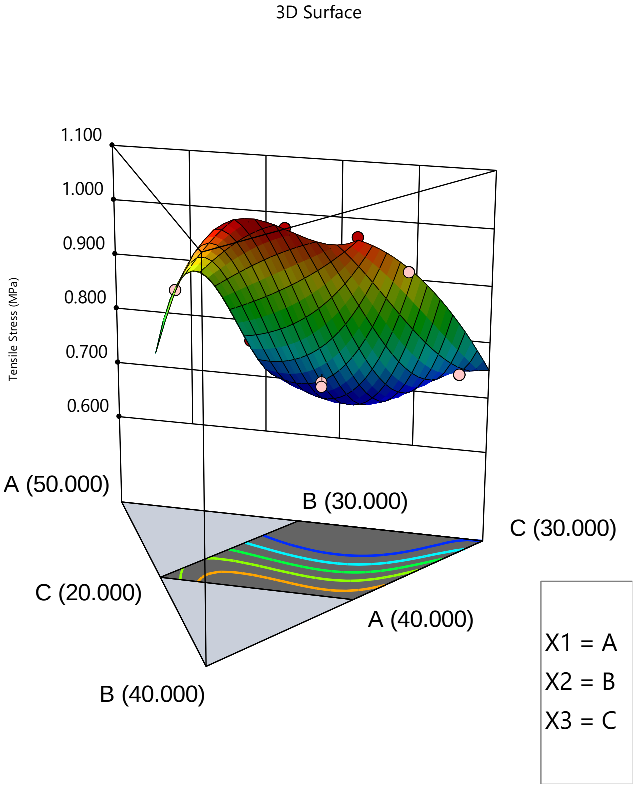


Figure 4.17 Response Surface plot showing the effect of bamboo fibre, Coir fibre and epoxy on Tensile stress of the Composite

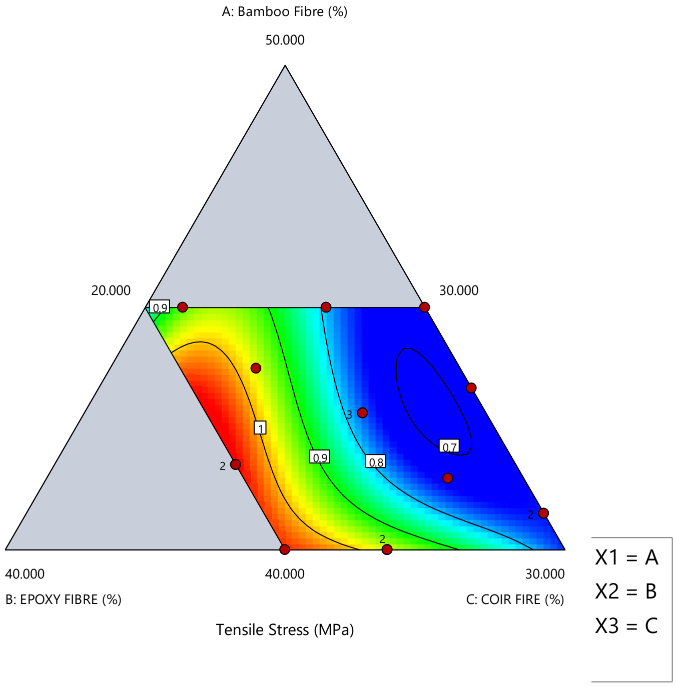


Figure 4.18 Contour plot showing the effect of bamboo fibre, Coir fibre and epoxy on Tensile stress of the Composite

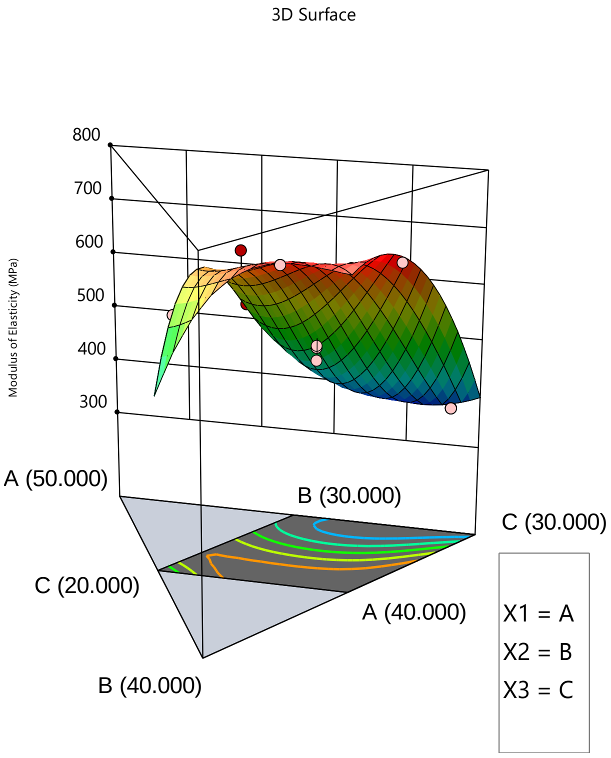


Figure 4.19 Response Surface plot showing the effect of bamboo fibre, Coir fibre and epoxy on modulus of elasticity of the Composite

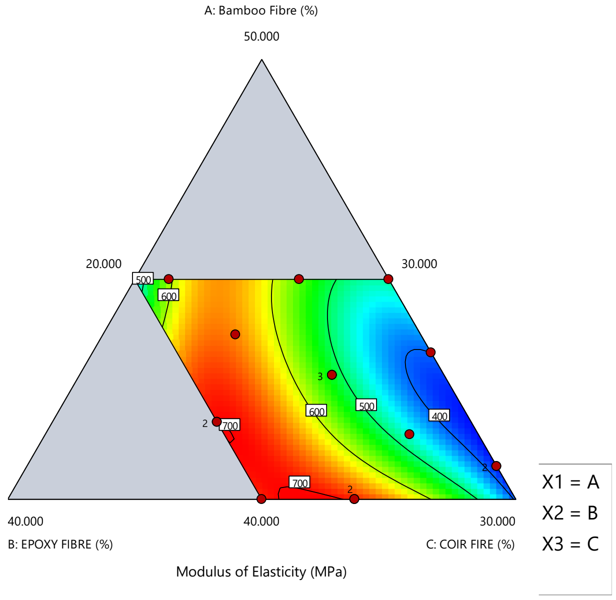


Figure 4.20 Contour plot showing the effect of bamboo fibre, Coir fibre and epoxy on modulus of elasticity of the Composite

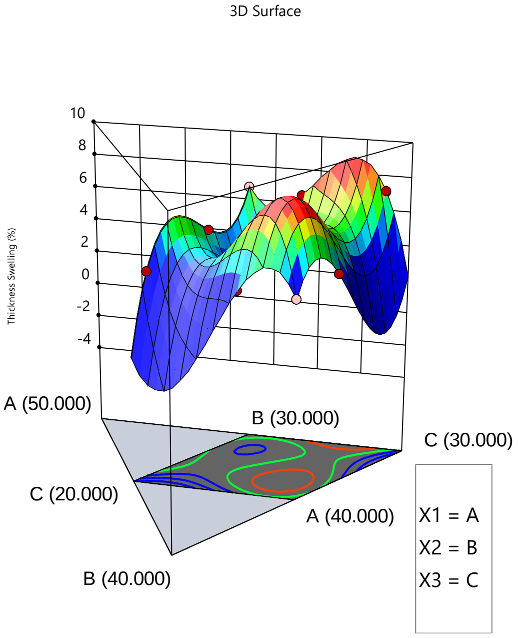


Figure 4.21 Response Surface plot showing the effect of bamboo fibre, Coir fibre and epoxy on thickness swelling of the Composite

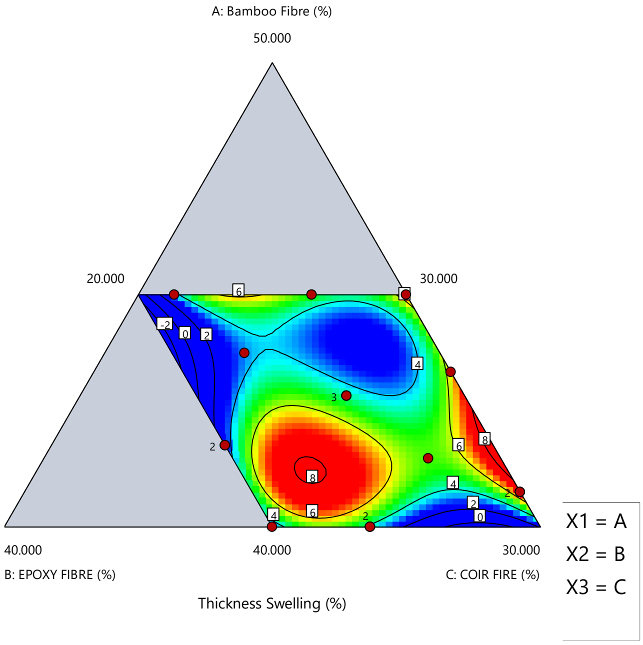


Figure 4.22 Contour plot showing the effect of bamboo fibre, Coir fibre and epoxy on Tensile stress of the Composite

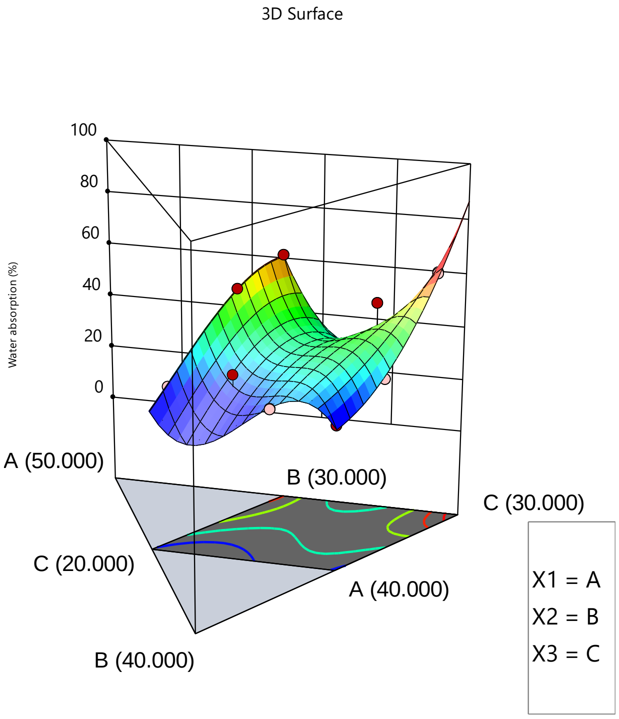


Figure 4.23 Response Surface plot showing the effect of bamboo fibre, Coir fibre and epoxy on Water Absorption of the Composite

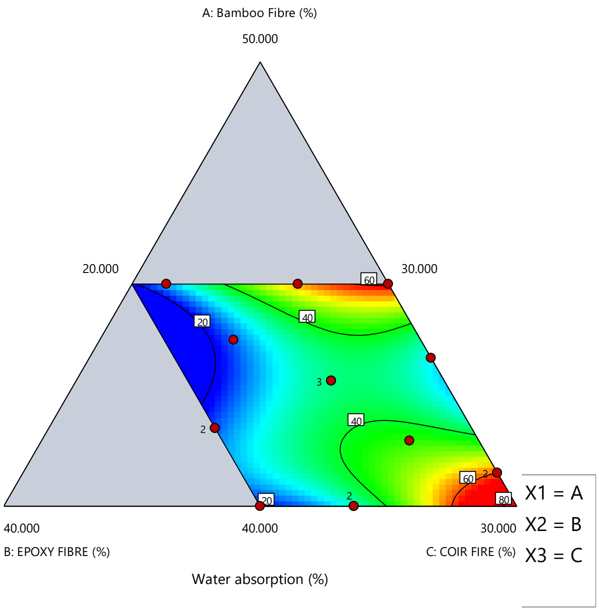


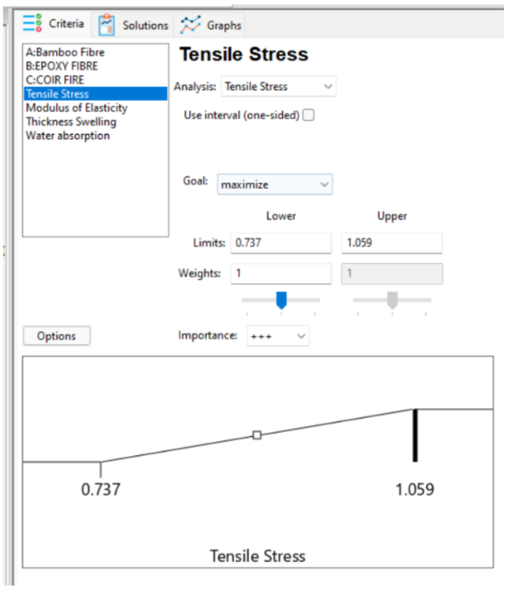
Figure 4.24 Contour plot showing the effect of bamboo fibre, Coir fibre and epoxy on Water absorption of the Composite

4.1.6. Optimization of Input Factors and Responses

The responses and the corresponding input factors were optimized using numerical optimization. To achieve this the input fetors were fixed in range as shown in the table of constraints for numerical optimization (Table 4.12). Tensile Stress and modulus of elasticity were maximized for better productivity, Thickness swelling and water absorption were minimized, since the final composite is supposed to have maximum value for tensile Stress and modulus of elasticity, alongside minimum thickness swelling and water absorption. The optimization steps are summarized in Figures 4.17 to 4.20. At the end of the evaluation the model graphs and solutions were suggested by the numerical optimization package, the one with the highest desirability value was chosen as the optimum conditions.

Table 4.13: Table of constraints for numerical optimization

Variables	Symbols	Goal	Lower limit	Upper Limit	Lower weight	Upper weight	Importance
Input variables/factors							
A: Bamboo Fibre	X_1	is in range	40.00	45.00	1	1	3
B: Epoxy	X_2	is in range	30.00	35.00	1	1	3
C: Coir Fibre	X_3	is in range	20.00	30.00	1	1	3
Output variables/responses							
Tensile Stress	Y_1	none	0.74	1.06	1	1	3
Modulus of Elasticity	Y_2	none	367.80	700.08	1	1	3
Thickness Swelling	Y_3	none	3.10	7.09	1	1	3
Water absorption	Y_4	none	20.80	61.60	1	1	3



Tensile Stress

Analysis: Tensile Stress

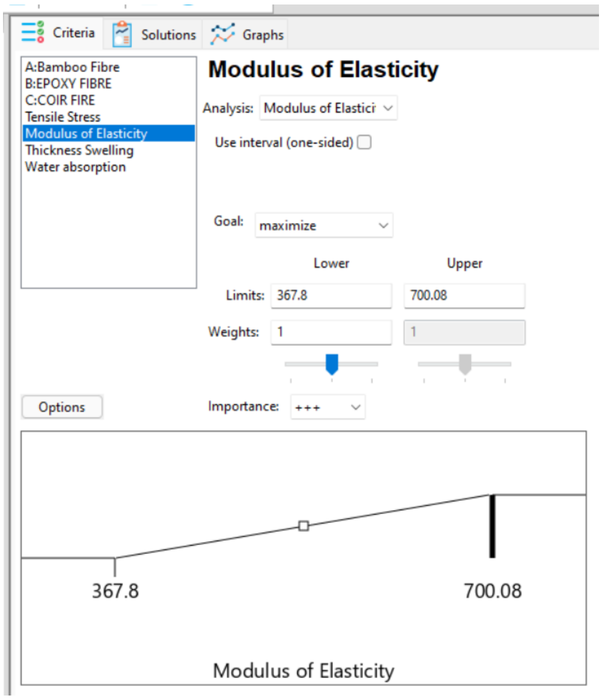
Use interval (one-sided) ☐

Goal: maximize

	Lower	Upper
Limits:	0.737	1.059
Weights:	1	1

Importance: +++

Figure 4.25: Optimization step for Tensile Stress



Modulus of Elasticity

Analysis: Modulus of Elastici

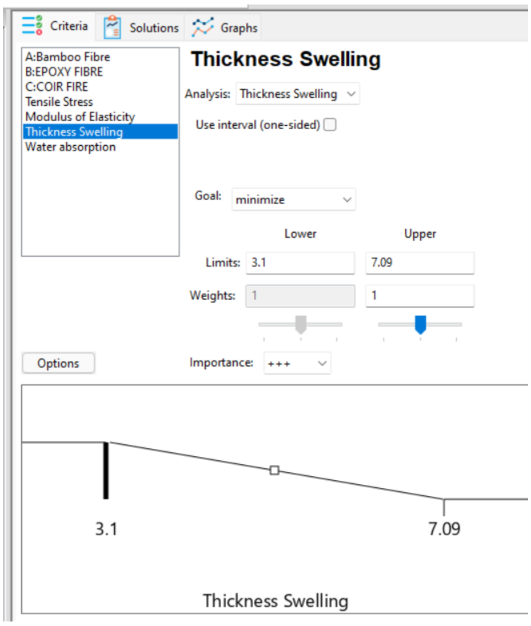
Use interval (one-sided) ☐

Goal: maximize

	Lower	Upper
Limits:	367.8	700.08
Weights:	1	1

Importance: +++

Figure 4.26: Optimization step for modulus of elasticity



Thickness Swelling

Analysis: Thickness Swelling

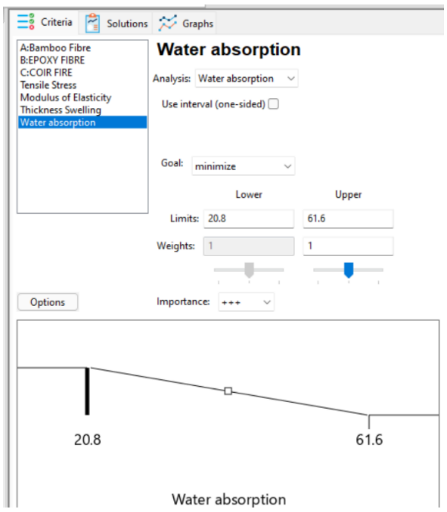
Use interval (one-sided) ☐

Goal: minimize

	Lower	Upper
Limits:	3.1	7.09
Weights:	1	1

Importance: +++

Figure 4.27: Optimization step for thickness swelling



A:Bamboo Fibre
B:EPOXY FIBRE
C:COIR FIRE
Tensile Stress
Modulus of Elasticity
Thickness Swelling
Water absorption

Water absorption

Analysis: Water absorption

Use interval (one-sided) ☐

Goal: minimize

	Lower	Upper
Limits:	20.8	61.6
Weights:	1	1

Importance: +++

Figure 4.28: Optimization step for water absorption

The optimization results are shown in Figure 4.21 and Table 4.13. This optimal point was chosen with the highest desirability of 0.902. The optimum values for Tensile Stress, modulus of elasticity, thickness swelling and water absorption were obtained as 18.97MPa, 1086.97MPa, 2.871% and 20.8% respectively. The corresponding values for the bamboo fibre, epoxy and coir fibre were 443.8%, 34.2% and 22.0% respectively

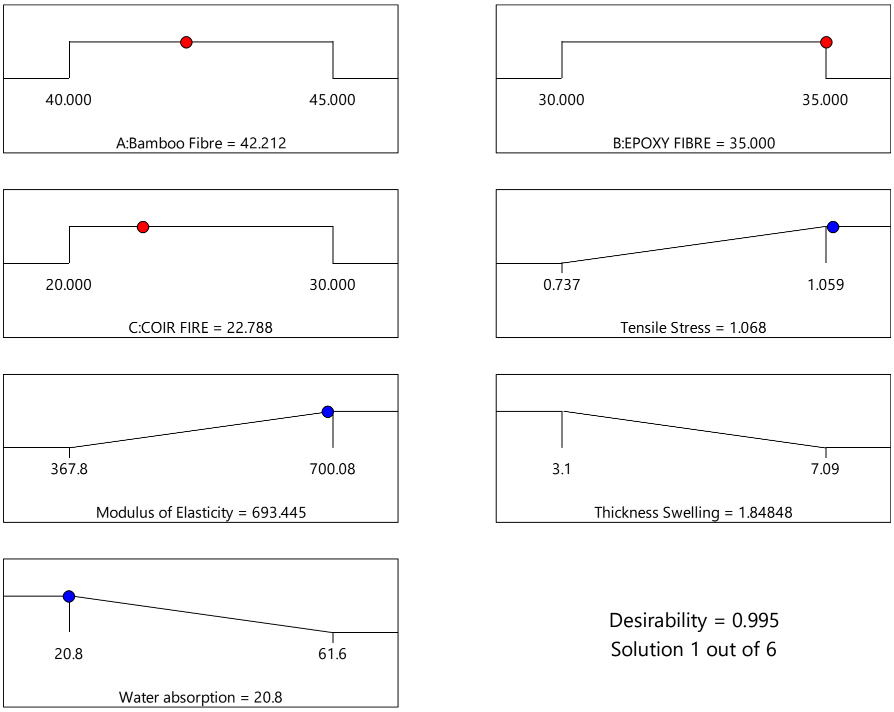


Figure 4.29: Solution to the optimization problem

Table 4.14: Optimization results

Variable	Value
Bamboo	42.2000%
Epoxy	35.0000%
Coir fibre	22.8000%
Tensile Stress	1.0680MPa
Maximum modulus of elasticity	693.4500MPa
Minimum Thickness swelling	1.8500%
Minimum water absorption	20.8000%
Desirability	0.9950

CHAPTER 5

CONCLUSION, RECOMMENDATION

5.1 Conclusion

This paper presents a report on the potential use of bamboo fibre and coir fibre for the production of composite materials used for furniture production using epoxy as the binder. The following conclusions can be drawn, that:

1. The delignification process using sodium hydroxide effectively removes lignin from bamboo fibres, leading to improved compatibility and bonding with the binding agent
2. The addition of epoxy as a binding agent enhances the cohesion and structural integrity of the bamboo composite boards, resulting in increased mechanical strength and durability.
3. Tensile testing and evaluation of the composite boards reveal their mechanical properties, including tensile strength, elongation at break, and Young's modulus providing insights into their structural performance under tensile loading.
4. After evaluating the model graphs and the solutions suggested by the numerical optimization package, the optimum conditions were chosen as the one with the highest desirability value. The optimum point was chosen with the highest desirability of 0.995 showing the adequacy of model. The optimum values for tensile stress, modulus of elasticity, thickness swelling and water absorption for the composite composed were obtained as: 1.068MPa, 693.450MPa, 1.850% and 20.8% respectively. The corresponding optimal values for bamboo, coir fibre and epoxy are given as:42.2%, 22.8% and 35% respectively.
5. ANOVA results shows that the model terms were significant indicating that changes in the levels of bamboo, epoxy and coir fibre will have a significant influence on the

physical and mechanical properties of the composite boards produced by the bamboo fibres. An increase in the epoxy percentage resulted to an increase in the mechanical and physical properties of the composite produced.

6. The results of our experiments show that composite boards produced using bamboo and coir fibre and epoxy as the matrix is very suitable for light weight applications for instance in furniture production.

Finally, it’s worth noting that the ASTM D1037-12 (2020) standard were used to compare the experimental results.

The values of the modulus of elasticity of the developed particle boards obtained were within the range of 1295-2782MPa. For tensile strength, the values obtained were within the range of 10-48MPa. As for water absorption, the values obtained were within the range 14.52-29.04%, while the values recorded for thickness swelling ranged from 2.76-35.05.

While the ASTM standard does not specify exact numerical values for these properties, it outlines testing methods and acceptance criteria that can be used to assess the performance of materials and compare experimental results. The acceptance criteria for modulus of elasticity values can range from around 1,000 MPa to 10,000 MPa or higher, depending on factors such as material density, resin content, and manufacturing process. For tensile strength, values can range from approximately 10 MPa to 50 MPa or higher, depending on factors such as adhesive type, panel density, and fiber orientation. For water absorption, acceptable values may range from 5% to 15% or lower. For thickness swelling, values can range from approximately 5% to 15% or lower.

Based on comparison of experimental results with these ranges, we can conclude that the bamboo/coir fibre composite with epoxy as binder satisfied the ASTM standard for modulus of elasticity and tensile strength and thickness swelling. However, for water absorption some experimental runs exceeded the acceptable range.

In summary, the performance characteristics of these composites are enhanced as the epoxy content by weight is increased.

5.2 Recommendations

From the results obtained in this research study, the following recommendations are made:

i. That the physical and mechanical properties of more bamboo fibre configurations be further investigated for its suitability in production of composite boards.
ii. That the empirical study should be carried out to establish the levels at which the different chemical elements present in the fabricated specimen contributed to the improved mechanical properties of the matrix as obtained as the optimized result.
iii. Conduct long-term durability testing and accelerated aging studies to assess the resistance of the composite boards to environmental factors such as moisture, temperature and UV exposure
iv. Investigate the effect of post-processing treatments, such as heat curing or surface modification on the properties of the bamboo composite boards to further enhance their performance and durability.

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