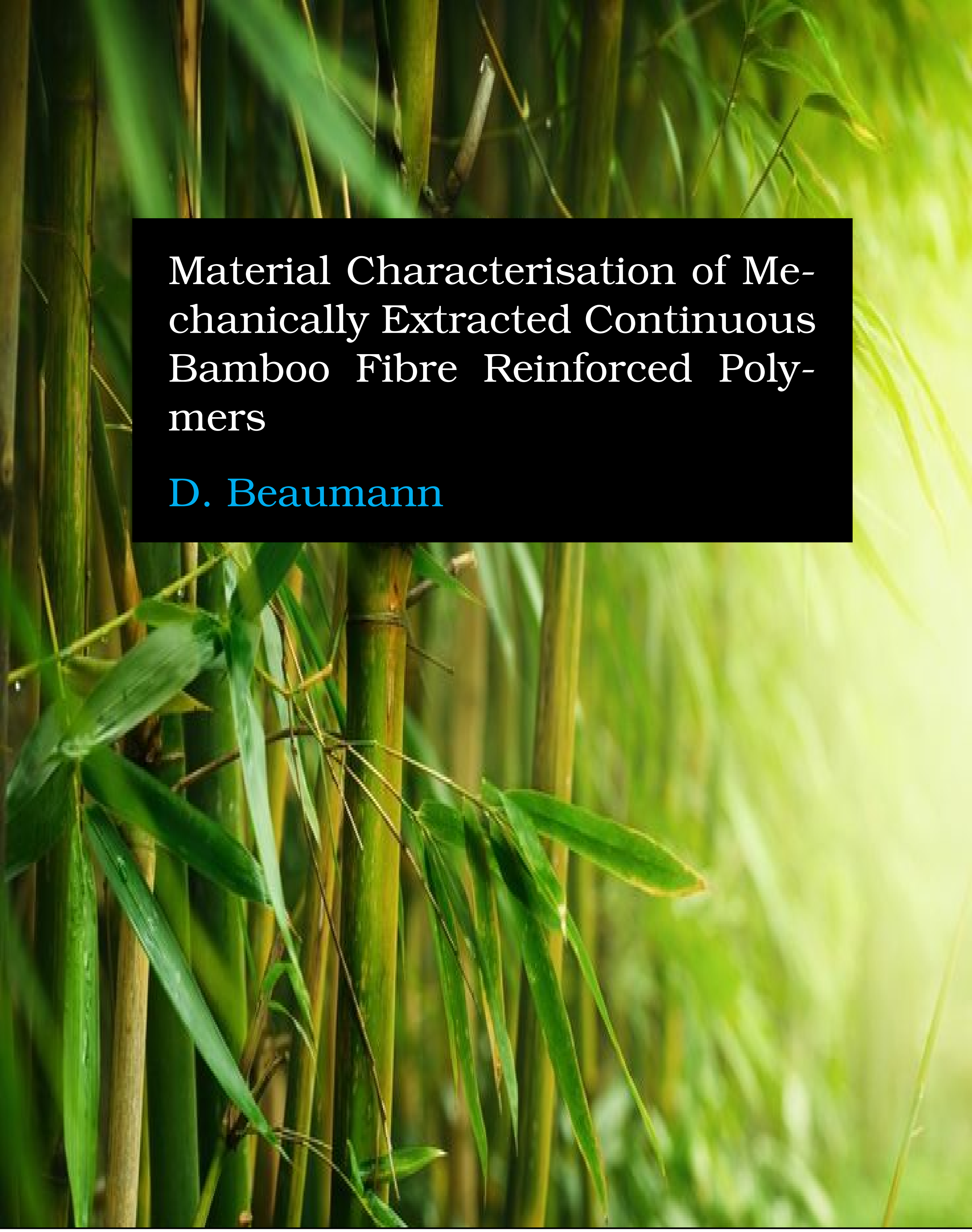

Material Characterisation of Mechanically Extracted Continuous Bamboo Fibre Reinforced Polymers

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Material Characterisation of Mechanically Extracted Continuous Bamboo Fibre Reinforced Polymers

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Abstract

The environmental impact of composite materials is a growing concern across numerous industries, prompting the need for sustainable alternatives. Bamboo fibre reinforced polymers (BFRPs) have emerged as a promising solution thanks to their high CO_2 capture leading to lower environmental footprint. A novel extraction method, developed and patented by Bambooder, aims to extract bamboo fibres through a purely mechanical industrial process while preserving their maximum performance. These fibres currently in development, necessitate comprehensive material characterisation.

In this study, BFRPs were produced using fibres provided by Bambooder, combined with polypropylene (PP) and polyamide 11 (PA11) through compression moulding, and with epoxy using resin-infusion composite production methods. The density of fibres was measured at 1.16 g/cm^3. The highest composite performance was achieved with epoxy, revealing a tensile back-calculated fibre modulus of 54.3 GPa and a strength of 509.6 MPa. These properties are higher than properties observed in current literature, having a tensile modulus and strength of approximately 36 GPa and 503 MPa respectively. Similarly, flexural back-calculated fibre properties showed a modulus of 44.6 GPa and a strength of 484.7 MPa.

Thermoplastic laminate testing demonstrated good bonding performance with PA11, attributed to the formation of hydrogen bonds at the fibre-matrix interface due to the polymer's non-polarity. In contrast, PP exhibited poor interfacial bonding. Additional fibre combing improved mechanical performance by up to 20% in tensile modulus and 9% in tensile strength, attributed to better fibre quality, improved fibre orientation, and increased fibre dispersion.

This thesis therefore validates the use of bamboo fibres for structural composite applications and highlights their potential as sustainable engineering materials, promoting the adoption of natural fibre composites such as BFRPs in various industrial sectors.

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Nomenclature

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Abbreviations

BF	Bamboo Fibre
BFRP	Bamboo Fibre Reinforced Polymer
CFRP	Carbon Fibre Reinforced Polymers
GFRP	Glass Fibre Reinforced Polymers
me-BF	mechanically extracted Bamboo Fibre
NFC	Natural Fibre Composites
PA11	Polyamide 11
PP	Polypropylene
RI	Resin Infusion
TDS	Technical Data Sheet
Tg	Glass Transition Temperature
TGA	Thermogravimetric Analysis
Tm	Melting Temperature
UD	Uni-Directional
UTM	Universal Testing Machine
Vf	Fibre Volume Fraction

Part I Background

Chapter 1

Introduction

In the quest for sustainable development and the reduction of environmental impact across industries, the composites sector faces significant challenges and opportunities. Traditional reliance on carbon fibre reinforced polymers (CFRPs) and glass fibre reinforced polymers (GFRPs) for structural composites, while beneficial for their mechanical properties and durability, poses sustainability concerns due to the energy-intensive production processes of glass fibres and the environmental footprint associated with their lifecycle [13].

In response to these challenges, there has been a concerted effort to explore sustainable alternatives to synthetic fibres. Natural fibres, such as flax, hemp, and jute, have emerged as promising candidates due to their biodegradability, lower density, and reduced energy requirements for production [14]. Among these, bamboo fibres are particularly noteworthy for their rapid growth rate, good mechanical properties, and minimal environmental impact.

Bamboo is a perennial plant that can reach maturity in just a few years, making it a highly renewable resource with abundant availability [15]. Bamboo fibres possess high specific strength, low density, and biodegradability, which makes them an attractive option for sustainable composite materials [16].

Specifically, bamboo fibres from Bambooder, a company which has pioneered a novel mechanical extraction method for producing long bamboo fibres at industrial scale, are characterized by their preserved structural integrity and mechanical performance. This novel extraction method involves cutting bamboo stems into slats and extracting fibres through a patented purely mechanical combing process, which is less energy-intensive and avoids the use of harsh chemicals [17]. This approach not only enhances the environmental friendliness of bamboo fibre production but also enables industrial-scale applications. Unlike most bamboo fibres currently used, which are short and limit their application to non-structural components, these long fibres offer a sustainable and potentially superior alternative for use in structural composite applications.

Figure 1.1: Flowchart of the full extraction process from Bamboo plant to fabric [1]

When looking at the full processing scope of bamboo fibres presented in fig 1.1, the step from bamboo strip to fibre bundle is what differentiates Bambooder from traditional extraction methods such as steam explosion or chemical extraction [18].

Therefore, this thesis aims to investigate the mechanical performance and sustainability of bamboo fibre reinforced polymers (BFRPs) produced using Bambooder's novel extraction method. The goal is to evaluate their viability as a sustainable alternative to conventional composite materials, focusing on their potential for broader applications in various industries.

The potential impact of this work can be significant. By demonstrating the feasibility and advantages of using bamboo fibres in composite materials, this research could promote the adoption of natural fibre composites and contribute to the development of more sustainable engineering materials. Thus contributing to global efforts to reduce environmental impact and move towards more eco-friendly industrial practices.

Chapter 2

Goal & Scope of research

From initial literature review and exchanging with Bambooder on the current state of research and development on their long bamboo fibres, the primary aim of this research project was set: to demonstrate the viability of mechanically extracted bamboo fibres (me-BF) as a polymer reinforcement in structural composite applications. The following research objective was formulated:

Research Objective

"Material Characterisation and processability assessment of mechanically extracted bamboo fibre reinforced polymers"

Research Question

Are Bambooder's bamboo fibres a sustainable alternative to glass fibres for use in structural composites?

Sub-Questions

In order to assess the viability of me-BF for use in structural composites, the two following sub-questions should be answered.

1. *What is the theoretical maximum tensile and flexural performance of polymers reinforced with mechanically extracted bamboo fibre without any treatment?*
   (a) *How does additional fibre processing influence composite performance?*
2. *What challenges do BFRPs face in their processing and production?*

(a) *How does processing temperature influence bonding of TP polymers during hot compression moulding of composites made from mechanically extracted bamboo fibres and corresponding mechanical properties?*

In this report the sub-sub-questions presented above will be answered by following the scope & methodology below. The individual conclusions will then be synthesized in order to draw a comprehensive conclusion to the main research question.

Scope & Methods

1. **Literature Study**
    - Conduct a thorough literature review to compare the mechanical performance and carbon footprint of bamboo composites against existing materials, particularly glass fibres.
    - Gather required knowledge through scientific reading and review of relevant literature.
2. **Composite Production**
    - Produce unidirectional (UD) composite samples using bamboo fibres with three different polymers: two thermoplastics: Polypropylene (PP) and Polyamide 11 (PA11), and a standard epoxy.
    - Employ standard production techniques such as wet lay-up, resin-infusion (RI), compression molding, and sample preparation.
3. **Material Characterization**
    - Obtain material properties of bamboo fibres provided by Bambooder, including tensile and flexural strength and modulus, elongation at break, and density.
    - Assess the tensile and flexural composite properties of each laminate through utilization of a Universal Testing Machine (UTM) and data processing, following specifications of ASTM standards.
    - Determine the fibre volume fraction (Vf) using appropriate measurement techniques.
    - Utilize microscopy to analyze and quantify fibre orientation and fibre dispersion within the composite.
    - Apply composite mechanics to estimate theoretical maximum fibre properties from experimental data.
4. **Comparison with Flax and Glass fibre Composites**
    - Compare the material characteristics and embodied energy of bamboo composites with known values for flax and glass fibre composites to quantify the potential advantages and viability of using bamboo fibre composites.

Chapter 3

Literature Review

3.1 Bamboo as Organic Fibre Reinforcement in Composite Materials

3.1.1 Overview of Natural Fibres

Natural fibres are increasingly recognized as sustainable reinforcements in composite materials due to their renewability, biodegradability, and desirable mechanical properties. These fibres offer an eco-friendly alternative to synthetic fibres like glass and carbon, aligning with the global push towards reducing environmental impacts.

Pickering et al. [14] provided a comprehensive review of natural fibre composites (NFCs), highlighting the mechanical properties and environmental benefits. Their analysis revealed that plant-based fibres, such as bamboo, possess low density and high specific strength, making them viable for structural applications. However, they also noted significant variability in mechanical properties, which can be attributed to differences in fibre type, extraction methods, and treatment processes. For example, tensile strengths for natural fibres like flax and hemp were reported to vary widely, from 200 MPa to 1500 MPa, depending on processing conditions, directly impacting composite performance.

Figure 3.1 provides a classification of various natural fibres, further emphasizing the distinct characteristics of bamboo among other natural fibres.

3.1.2 Structure and Composition of Bamboo Fibres

Bamboo fibres are distinguished by their high cellulose content and hierarchical structure, which contribute to their mechanical strength and suitability as composite reinforcements. Grosser and Liese [19] conducted a seminal histological study on bamboo, detailing the hierarchical arrangement of vascular bundles within the culm. They found that the density of these bundles increases towards the periphery, contributing to the superior mechanical strength of the outer layers.

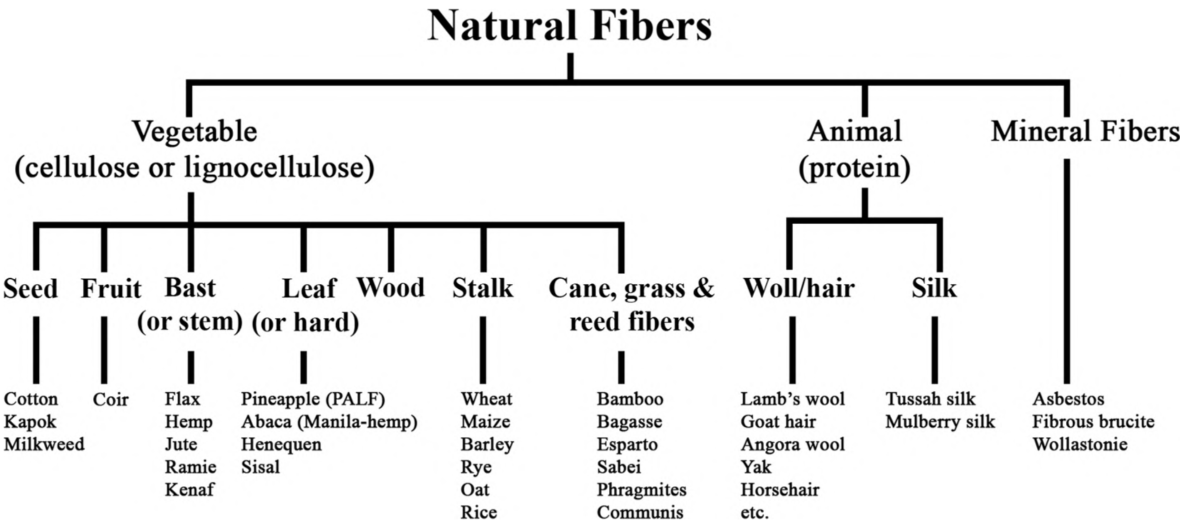


Figure 3.1: Classification of Natural fibres [2]

Liu et al. [3] further elaborated on the microstructural characteristics of bamboo fibres, noting that their low microfibrillar angle (2°-10°) enhances tensile strength and stiffness. Their study reported tensile strengths ranging from 260 MPa to 600 MPa, with an elastic modulus between 13 and 40 GPa. This makes bamboo a strong candidate for reinforcing both thermoplastic and thermoset polymer matrices. Additionally, the chemical composition of bamboo fibres, with cellulose content around 60%, supports their mechanical performance.

Divya et al. [4] expanded on this by exploring the poly-lamellate structure of bamboo fibres, which further contributes to their mechanical strength. The composition of bamboo fibres, particularly their high cellulose content (up to 73.83%) and low lignin content (around 10.15%), was shown to enhance tensile strength (up to 503 MPa) and thermal stability. These characteristics underscore bamboo's potential in sustainable and high-performance composite applications.

3.1.3 Fibre Processing Techniques

Extraction Methods

The extraction process of bamboo fibres significantly influences their properties as reinforcement in composites. Rao and Rao [20] compared mechanical and chemical extraction methods, noting that mechanical extraction, which preserves the natural structure of the fibres, resulted in higher tensile strengths (503 MPa) and moduli (35.91 GPa). However, this method also introduced variability in fibre dimensions, which could affect composite uniformity. In contrast, chemically extracted fibres, although more uniform, exhibited lower mechanical properties (tensile strength of 341 MPa and tensile modulus of 19.67 GPa) due to the removal of structural components during processing.

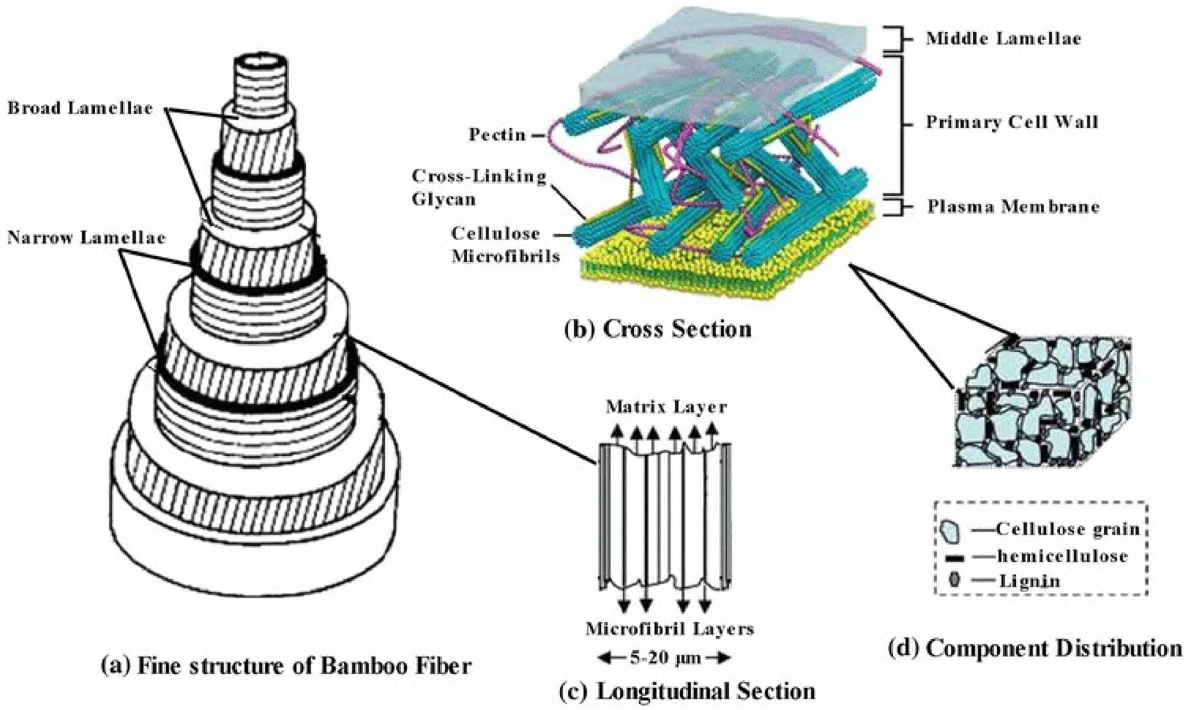


Figure 3.2: Schematic representation of the hierarchical structure of bamboo, highlighting the macro-level culms, internodes, and micro-level cellulose fibrils [3]

Fibre Treatment and Enhancement

Effective fibre treatment is essential for improving the interfacial bonding between bamboo fibres and polymer matrices. Kushwaha and Kumar [21] studied various chemical treatments, including alkali, silane, and benzoyl chloride treatments, finding that these methods significantly improved tensile strength (up to 71%) and modulus (up to 118%) of bamboo fibre composites. The treatments also reduced water absorption by up to 35%, enhancing the durability of the composites. However, they also noted that excessive chemical treatment could damage fibres, leading to reduced mechanical properties.

Nurazzi et al. [22] emphasized the importance of optimizing treatment conditions to balance fibre enhancement with structural integrity. Their review highlighted the effectiveness of silane treatment in improving compatibility between bamboo fibres and polymer matrices, particularly in thermoplastic composites.

Fibre Alignment and Material Scatter

Proper alignment of bamboo fibres within the polymer matrix is crucial for maximizing composite strength and stiffness. Lotfi et al. [23] and Nurazzi et al. [22] discussed various alignment techniques, such as combing and resin transfer molding (RTM), which help achieve uniform fibre orientation. These methods were shown to significantly improve the tensile strength and Young's modulus of bamboo fibre-reinforced composites (BFRPs).

Depuydt et al. [24] investigated the issue of material scatter, revealing that variability in fibre properties, due to factors like species, harvest season, and internodal position, could lead to

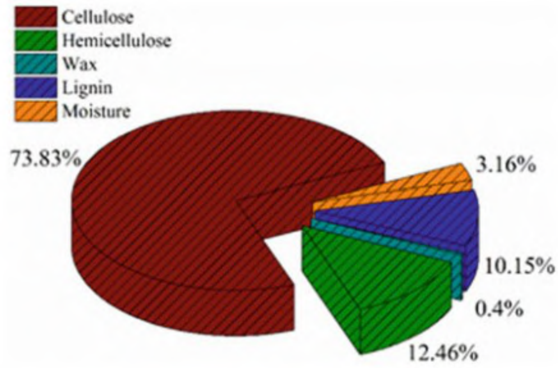


Figure 3.3: Pie chart illustrating the composition of bamboo fibres [4]

inconsistent composite performance. Their study underscored the need for rigorous quality control during fibre processing to minimize scatter and ensure reliable composite properties.

Fibre Processing and Performance

While bamboo fibres offer substantial benefits as reinforcement materials, the reviewed studies reveal several challenges. The variability in mechanical properties due to differences in extraction methods and fibre treatments poses a significant challenge for consistent composite performance. Moreover, the environmental impact of chemical extraction methods, though effective in improving fibre uniformity, cannot be overlooked, particularly in light of the sustainability goals that drive the use of natural fibres.

Further research is needed to refine processing techniques to enhance fibre properties without compromising their environmental benefits. Additionally, advancements in fibre alignment technologies and treatment optimization will be crucial for maximizing the potential of bamboo as a sustainable reinforcement in high-performance composites.

For Bambooder's mechanically extracted bamboo fibres, controlling material scatter involves optimizing the mechanical extraction process to ensure uniform fibre dimensions and properties. By standardizing the combing process and refining the extraction techniques, Bambooder can aim at producing high-quality bamboo fibres with minimal variability. Their approach is environmentally friendly and aligns with sustainable practices, but it also requires rigorous quality control to maintain consistency in fibre properties. These considerations are essential for the application of Bambooder's bamboo fibres in high-performance composites, as minimizing material scatter is critical for achieving reliable and predictable mechanical properties in the final composite materials.

3.2 Physical Properties of Bamboo fibre-Reinforced Composites (BFRPs)

Understanding the physical properties of BFRPs is essential for optimizing their use in structural applications. This section explores the key mechanical properties of bamboo fibres, their interaction with polymer matrices, and the influence of various treatments and processing methods on the overall composite performance. The analysis draws on recent studies to highlight critical factors that determine the effectiveness of bamboo fibres as reinforcements in composite materials.

3.2.1 Properties of Bamboo fibres

Mechanical Properties

The mechanical properties of bamboo fibres, including tensile strength, Young's modulus, and fracture toughness, are fundamental to their effectiveness as reinforcement materials in composites. These properties are influenced by the fibre's hierarchical structure, which includes a high cellulose content and a low microfibrillar angle.

Tensile Strength and Young's Modulus Liu et al. [3] conducted a comprehensive study on the microstructural characteristics of bamboo fibres, revealing that their low microfibrillar angle, typically ranging between 2° and 10°, plays a critical role in enhancing both tensile strength and stiffness. Their experiments reported tensile strengths of bamboo fibres ranging from 260 MPa to 600 MPa, with an elastic modulus between 13 GPa and 40 GPa. These values highlight the strong potential of bamboo fibres for reinforcing both thermoplastic and thermoset polymer matrices. The researchers attributed the variation in tensile strength to differences in the processing methods and the inherent heterogeneity within the bamboo culm.

Further insights were provided by Amada et al. [25], who focused on the variability of tensile properties across different layers of the bamboo culm. Their study indicated that the outer layer of the bamboo, characterized by a denser vascular bundle structure, exhibited significantly higher tensile strength compared to the inner layers. Amada et al. suggested that this variation is largely due to the orientation and distribution of fibres within the culm. The study also pointed out the need for standardized testing protocols to ensure consistent results across different bamboo samples, as the current variability in testing conditions and fibre processing can lead to inconsistencies in reported mechanical properties.

Fracture Toughness Fracture toughness is another critical mechanical property, particularly relevant for applications where the material is expected to absorb energy and resist crack propagation. Amada et al. [25] explored the fracture toughness of bamboo fibres across different culm layers, employing scanning electron microscopy (SEM) to observe the fracture surfaces. Their findings showed that the outer layer of the bamboo culm, which is more fibrous and contains a higher density of vascular bundles, exhibited superior fracture toughness. This was primarily due to the mechanisms of fibre pull-out and crack deflection, which contribute to higher energy absorption during fracture.

However, the study's focus on small-scale specimens may limit the generalizability of these findings to real-world applications. In large-scale structures, the variability in fibre orientation, environmental exposure, and processing conditions could significantly influence fracture behavior, suggesting the need for further research in this area.

Overall, while bamboo fibres demonstrate excellent tensile strength, Young's modulus, and fracture toughness, the variability in these properties due to factors like microfibrillar angle and fibre distribution highlights the importance of careful selection and processing of bamboo fibres to optimize their use in composite materials.

Density of Fibres

The density of bamboo fibres is a crucial factor influencing the overall properties of bamboo fibre-reinforced composites (BFRPs), particularly in terms of weight, strength, and stiffness. The density is primarily determined by the fibre's chemical composition, including the proportions of cellulose, hemicellulose, and lignin.

Khalil et al. [26] reported that the density of untreated bamboo fibres typically ranges from 1.2 to 1.5 g/cm^3, which aligns closely with other natural fibres such as flax, but is significantly lower than that of glass fibres, which generally have densities between 2.5 and 2.6 g/cm^3. This lower density contributes to the lightweight nature of bamboo composites, making them advantageous for applications where weight reduction is critical.

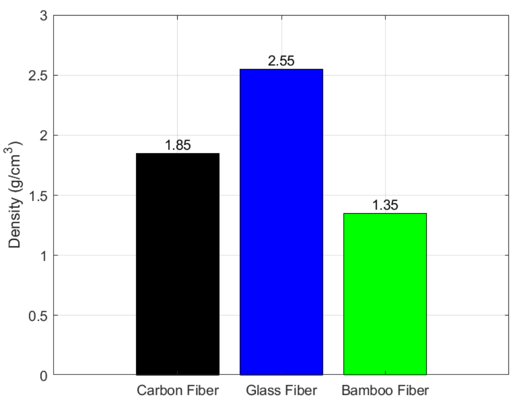


Figure 3.4: Density comparison bamboo fibres, glass fibre and carbon fibre

The impact of chemical treatments on fibre density was extensively studied by Buson et al. [27], who observed that alkali-treated bamboo fibres exhibited a decreased density due to the removal of non-cellulosic components like lignin and hemicellulose. Specifically, their study found that the density of bamboo fibres decreased from 0.49 g/cm^3 (untreated) to 0.35 g/cm^3 after alkali treatment. However, subsequent acetylation, which introduces acetyl groups to the fibre structure, resulted in a slight increase in density to 0.48 g/cm^3 due to the replacement of hydroxyl groups with bulkier acetyl groups. This study highlights how chemical treatments can alter the physical structure of bamboo fibres, thereby influencing their density and overall performance in composites.

Additionally, Huang and Young [28] noted that the density of bamboo fibres increased after alkali treatment, reaching up to 1.29 g/cm^3. This increase was attributed to the removal of amorphous materials, resulting in a more compact fibre structure that enhanced the interfacial bonding with the polymer matrix. This finding underscores the importance of understanding the effects of various treatments on fibre density, as it directly impacts the mechanical and thermal properties of the resulting composites.

Thermal Properties

The thermal properties of bamboo fibres are essential for determining their suitability in applications that involve exposure to high temperatures. The thermal stability of bamboo fibres, particularly their resistance to degradation at elevated temperatures, is a critical factor for maintaining the integrity of bamboo fibre-reinforced composites (BFRPs).

Liu et al. [3] performed a thermogravimetric analysis (TGA) to investigate the thermal degradation behavior of bamboo fibres. The study identified two primary stages of thermal degradation. The first stage, occurring between 25°C and 150°C, is associated with moisture evaporation and the loss of low-molecular-weight volatiles. The second stage, which takes place between 200°C and 400°C, corresponds to the degradation of major components such as hemicellulose, cellulose, and lignin. Notably, natural bamboo fibres exhibited a maximum degradation temperature of approximately 365.1°C.

In contrast, treated bamboo fibres often show a slightly altered thermal behavior due to the chemical modifications of their structure. For example, the study by Kumar et al. [1] observed that alkali-treated bamboo fibres had a higher onset of thermal degradation, reflecting an increase in thermal stability. This improvement is particularly relevant for composite applications that require materials to maintain their structural integrity under fluctuating temperature conditions.

However, the long-term thermal stability of bamboo fibres, particularly under cyclic heating and cooling conditions, remains underexplored. Future research should focus on evaluating how bamboo fibres behave under prolonged exposure to such conditions, as this could significantly impact their performance in thermally demanding environments.

3.2.2 Influence of fibre Treatment on Physical Properties

Physical Treatments

Physical treatments, including mechanical extraction methods and processes like steam explosion, are also employed to modify the properties of bamboo fibres. These methods typically aim to retain the natural structure of the fibres while enhancing their compatibility with polymer matrices.

Steam Explosion and Mechanical Extraction Steam explosion is a physical treatment that uses high-pressure steam to break down the lignin and hemicellulose in bamboo fibres, making them more flexible and easier to process. Gao et al. [29] examined the impact of steam explosion on the mechanical properties of bamboo fibres and found that this method significantly improved fibre flexibility and surface roughness, which in turn enhanced the interfacial bonding with polymer matrices. However, the study also noted that steam explosion could lead to a reduction in fibre strength due to the partial degradation of cellulose, which is crucial for maintaining tensile strength.

Mechanical extraction methods, such as combing and refining, are used to extract bamboo fibres without the use of chemicals. Buson et al. [27] studied the effects of mechanical extraction on the density and mechanical properties of bamboo fibres. Their findings indicated that while mechanically extracted fibres maintained a higher degree of structural integrity compared to chemically treated fibres, they also exhibited greater variability in mechanical properties. Specifically, the tensile strength of mechanically extracted bamboo fibres ranged widely, from 300 MPa to 600 MPa, depending on the extraction method and fibre preparation. This variability poses challenges for achieving consistent composite performance and highlights the need for standardized mechanical extraction techniques.

Despite the benefits of mechanical extraction, such as reduced environmental impact and preservation of natural fibre structure, the variability in fibre quality remains a significant challenge. Further research is needed to refine these extraction methods to produce more uniform fibres with consistent properties suitable for high-performance composite applications.

Chemical Treatments

fibre treatments, particularly chemical modifications, play a crucial role in enhancing the physical properties of bamboo fibres and their composites. These treatments are primarily aimed at improving interfacial bonding, reducing water absorption, and increasing thermal stability.

Alkalization Alkalization, or alkali treatment, is one of the most commonly used chemical methods to improve the properties of natural fibres, including bamboo. This treatment involves immersing the fibres in a solution of sodium hydroxide (NaOH), which removes non-cellulosic components like lignin, hemicellulose, and pectin, thereby increasing the cellulose content and enhancing the mechanical properties of the fibres.

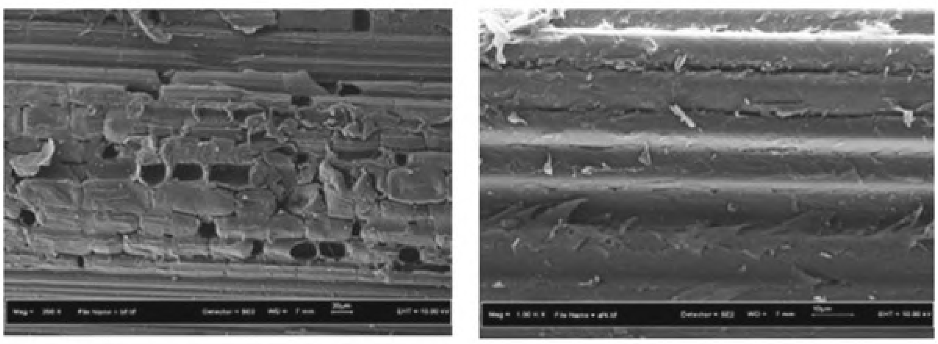


Figure 3.5: SEM Images of bamboo fibre taken before and after treatment with Alkali [5]

Huang and Young [28] investigated the effects of alkali treatment on the tensile strength, modulus, and density of bamboo fibres. Their study found that the tensile strength of bamboo fibres decreased from 717.53 MPa (untreated) to 473.05 MPa (after alkali treatment), while the Young's modulus reduced from 43.34 GPa to 33.31 GPa. Despite this reduction in tensile strength and modulus, the alkali-treated fibres exhibited improved compatibility with the polymer matrix, leading to better interfacial bonding and overall composite performance. This suggests a trade-off between fibre strength and matrix adhesion, where the removal of amorphous materials enhances bonding but at the cost of some mechanical properties.

Kushwaha and Kumar [21] expanded on these findings by studying the effects of various chemical treatments, including alkali, silane, and benzoyl chloride treatments. They observed that alkali treatment significantly improved the water resistance of bamboo fibres by reducing water absorption by up to 35%. The enhanced water resistance is crucial for applications in humid environments, where untreated fibres might swell and degrade. However, the study also noted that excessive alkali treatment could damage the fibre structure, leading to a reduction in mechanical properties. This highlights the need for careful optimization of treatment conditions to balance improved interfacial bonding with the preservation of fibre strength.

Surface Modifications In addition to alkalization, other surface modification techniques, such as benzoylation and permanganate treatment, have been employed to further enhance the properties of bamboo fibres. These treatments generally aim to improve the hydrophobicity of the fibres and enhance their bonding with hydrophobic polymer matrices.

Kushwaha and Kumar [21] reported that benzoylation, which involves treating the fibres with benzoyl chloride, significantly increased the hydrophobicity of bamboo fibres. This treatment not only reduced water absorption but also improved the interfacial bonding with polymer matrices, leading to an increase in the tensile strength and modulus of the resulting composites. Specifically, benzoylation improved tensile strength by up to 71% and modulus by up to 118% compared to untreated fibres. These enhancements are particularly beneficial for applications where moisture resistance is critical.

However, the environmental implications of such chemical treatments cannot be overlooked. Benzoylation and other similar treatments involve the use of potentially hazardous chemicals, which may pose environmental and health risks during processing and disposal. Kushwaha and Kumar's study underscores the importance of developing more sustainable treatment methods that can achieve similar improvements in fibre properties without the associated environmental drawbacks.

3.2.3 Bamboo fibre-Matrix Interactions

Interfacial Bonding

Interfacial bonding between bamboo fibres and polymer matrices is crucial for determining the overall mechanical properties and durability of bamboo fibre-reinforced composites (BFRPs). Effective bonding ensures efficient stress transfer from the matrix to the fibres, which enhances the composite's strength, stiffness, and resistance to mechanical loading.

Thermoplastic vs. Thermoset Matrices Mousavi et al. [2] conducted a comprehensive review on the interfacial properties of natural fibre-reinforced composites, emphasizing the

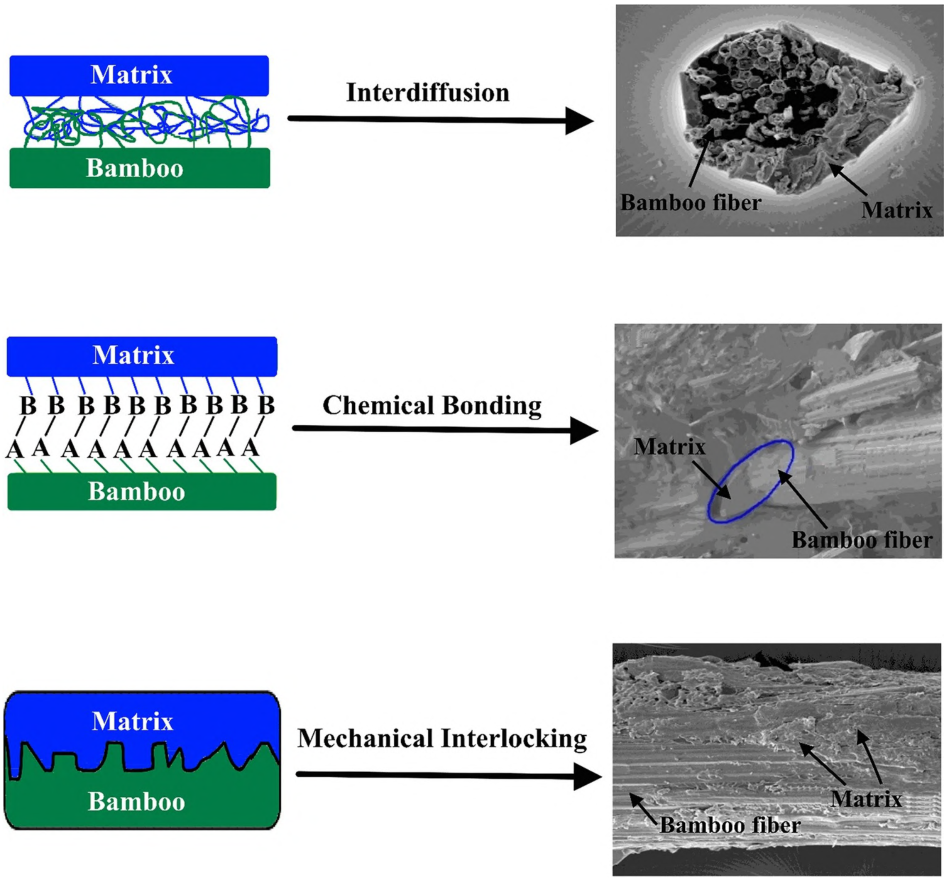


Figure 3.6: Schematic representation of interfacial bonding mechanisms in bamboo fibre composites [2]

challenges and advantages of using bamboo fibres in both thermoplastic and thermoset matrices. The study highlighted that bamboo fibres exhibit better bonding with thermoset matrices, such as epoxy and polyester, due to the chemical interactions that occur during the curing process. These interactions lead to covalent bonds that significantly enhance the interfacial strength. For example, bamboo fibre/epoxy composites showed a notable improvement in tensile strength and flexural strength compared to bamboo fibre/polypropylene (PP) composites, where bonding is primarily mechanical and often weaker.

Radzi et al. [30] further explored the influence of surface treatments on interfacial bonding in thermoplastic composites. Their study demonstrated that the application of silane coupling agents significantly improved the adhesion between bamboo fibres and PP matrices. Silane treatments create chemical bridges between the hydroxyl groups on the fibre surface and the polymer matrix, leading to enhanced mechanical properties. The treated composites exhibited a tensile strength increase from 80 MPa (untreated) to 120 MPa, illustrating the importance of chemical treatments in improving interfacial bonding in thermoplastic composites.

Woigk et al. [31], although focused on flax fibres, provided valuable insights into the challenges of achieving consistent interfacial bonding in natural fibre composites. The study discussed the variability in fibre surface properties and the difficulty of achieving uniform fibre-matrix adhesion, which can lead to inconsistent mechanical performance. These findings are directly applicable to bamboo fibres, where similar challenges in maintaining consistent interfacial properties across different batches and processing methods are often encountered.

While surface treatments and matrix selection can significantly enhance interfacial bonding, achieving consistent bonding across different fibre batches and matrices remains a challenge. The variability in fibre properties, due to factors like species, harvest conditions, and processing techniques, can result in fluctuations in composite performance. This variability underscores the need for standardized treatment and processing methods that can ensure reliable interfacial bonding, which is critical for the development of high-performance bamboo fibre composites.

fibre Alignment and Volume Fraction

The orientation and volume fraction of bamboo fibres within the polymer matrix are key factors that influence the mechanical properties of BFRPs. Proper fibre alignment maximizes the load-bearing capacity of the fibres, while the fibre volume fraction determines the balance between reinforcement and matrix material.

Influence of fibre Alignment Kumar et al. [1] investigated the effects of fibre alignment on the tensile and flexural properties of bamboo fibre composites. Their study demonstrated that unidirectional alignment of bamboo fibres resulted in significantly higher tensile strengths compared to randomly oriented fibres. For example, the tensile strength of unidirectionally aligned bamboo fibre/epoxy composites reached up to 222.71 MPa, compared to 167.87 MPa for composites with random fibre orientation. This improvement is attributed to the more efficient stress transfer along the aligned fibres, which enhances the composite's overall mechanical performance.

However, achieving consistent fibre alignment in industrial-scale production remains a challenge. Techniques like resin transfer molding (RTM) and compression molding often result in variable fibre orientations, leading to inconsistencies in mechanical properties. Woigk et al. [31] highlighted the difficulties in maintaining uniform fibre alignment, particularly in complex-shaped components, where fibre misalignment can lead to stress concentrations and premature failure.

Optimal fibre Volume Fraction The fibre volume fraction (V_f) is another critical parameter in composite design. A higher V_f generally increases the composite's strength and stiffness, but it also poses challenges in processing and fibre dispersion. Kumar et al. [1] identified an optimal V_f of approximately 40% for bamboo fibre composites, where the tensile and flexural strengths were maximized without compromising the matrix integrity. At this optimal V_f, the composites exhibited tensile strengths of up to 200 MPa and flexural strengths of 180 MPa.

Muhammad et al. [32] explored the effects of varying V_f in hybrid composites, incorporating bamboo fibres with other natural fibres like flax. Their study found that while increasing V_f to 50% improved tensile strength by 20%, it also introduced processing challenges, such as fibre agglomeration and reduced matrix wetting. These challenges highlight the trade-offs involved in optimizing fibre volume fraction, where higher reinforcement levels can lead to manufacturing difficulties and potential defects in the final composite.

While optimizing fibre alignment and volume fraction can significantly enhance the mechanical performance of BFRPs, the variability in alignment techniques and the challenges of maintaining uniform fibre distribution in large-scale production remain significant hurdles. The scalability of these techniques for industrial applications is a critical area for future research, as inconsistencies in fibre orientation and volume fraction can lead to unpredictable composite performance.

3.2.4 Composite Fabrication and Processing Techniques

Fabrication Methods

The fabrication of bamboo fibre-reinforced composites (BFRPs) employs various techniques to integrate bamboo fibres into polymer matrices, each influencing the mechanical properties and overall performance of the composites. Two primary categories of fabrication methods are utilized depending on whether the matrix is thermoplastic or thermoset.

For thermoset composites, Resin Transfer Molding (RTM) is a widely used technique. In this process, dry bamboo fibres are placed into a mold, and a liquid resin, such as epoxy, is injected under pressure, impregnating the fibres. The resin then cures, forming a solid composite structure. Woigk et al. [31] emphasized the advantages of RTM, particularly its ability to produce composites with high fibre volume fractions and minimal void content, which are critical for achieving high mechanical strength and stiffness. However, the study also pointed out challenges related to maintaining uniform fibre distribution during the process, which can lead to variability in the composite's mechanical properties. Uneven fibre distribution can create areas of resin-rich regions or fibre-rich zones, resulting in mechanical inconsistencies within the composite.

In contrast, thermoplastic composites are often fabricated using compression molding, where a mixture of bamboo fibres and thermoplastic polymer, such as polypropylene (PP), is placed into a heated mold. The application of pressure during molding causes the polymer to melt and flow, encapsulating the fibres before cooling and solidifying. Kumar et al. [1] discussed the benefits of compression molding in achieving consistent fibre alignment, especially in components with simple geometries. However, they also highlighted the challenges of maintaining uniform fibre dispersion and avoiding fibre damage under high pressure, which can negatively impact the composite's mechanical properties.

Another fabrication method is film stacking combined with hot pressing, particularly useful for creating laminated composites with tailored mechanical properties. In this method, layers of bamboo fibre mats are alternated with polymer films, and the assembly is subjected to heat and pressure to bond the layers together. Kumar et al. [1] demonstrated that film stacking allows for precise control over the fibre content and the thickness of the composite, enabling the production of composites with specific performance characteristics. However, the process requires careful optimization of impregnation and void removal during hot pressing to ensure the composite's structural integrity.

Impact of Processing on fibre and Composite Properties

The processing conditions during the fabrication of BFRPs, including temperature, pressure, and cooling rate, play a significant role in determining the final properties of the composites. These conditions affect the fibre-matrix interaction, fibre alignment, and the overall mechanical performance of the composite.

Processing temperature is a critical factor, especially in thermoplastic composites, where the polymer must be heated to its melting point to flow and encapsulate the fibres. However, excessive temperatures can degrade the bamboo fibres, leading to a reduction in their tensile strength and modulus. Kumar et al. [1] reported that processing temperatures above 200°C could cause thermal degradation of bamboo fibres, which negatively impacts the composite's overall strength. In thermoset composites, such as those made with epoxy, the curing process must be carefully controlled to avoid overheating, which can also degrade the fibres and affect the final composite properties.

Pressure during fabrication is crucial for ensuring proper compaction of the composite and eliminating voids. In RTM and compression molding, sufficient pressure is needed to force the resin or polymer into the fibre network, ensuring thorough impregnation. Woigk et al. [31] noted that inadequate pressure could lead to incomplete matrix impregnation, resulting in voids and weak spots within the composite. Conversely, excessive pressure may cause fibre breakage or misalignment, reducing the composite's mechanical properties. Therefore, optimizing pressure levels is essential to balance effective fibre impregnation with the preservation of fibre integrity.

Cooling rate is another important processing parameter, particularly in thermoplastic composites, where the cooling process solidifies the polymer matrix. Rapid cooling can introduce residual stresses within the composite, potentially leading to warping or reduced toughness. Slow cooling, on the other hand, allows for better stress relaxation but may result in undesirable crystallization of the polymer matrix, affecting the composite's mechanical performance. Kumar et al. [1] suggested that optimizing the cooling rate is essential to minimize internal stresses while maintaining the desired mechanical properties of the composite.

In conclusion, the fabrication and processing of BFRPs require careful consideration of both the methods used and the specific processing conditions. Each method, whether for thermoplastic or thermoset matrices, presents unique challenges that must be addressed to produce high-quality composites. Achieving uniform fibre distribution, avoiding fibre damage, and optimizing processing conditions are all critical to ensuring the mechanical integrity and performance of the final product.

3.2.5 Composite Performance in Practical Applications

Mechanical Performance

The mechanical performance of bamboo fibre-reinforced composites (BFRPs) under quasi-static loading conditions, such as tensile, flexural, and impact loading, is crucial for their application in various structural and non-structural components. The ability of these composites to withstand static forces without significant deformation or failure is a key factor in their suitability for use in industries like automotive, construction, and consumer goods.

Muhammad et al. [32] investigated the tensile properties of hybrid bamboo composites, where bamboo fibres were combined with other natural fibres such as flax. Their study revealed that BFRPs exhibited tensile strengths of up to 250 MPa, depending on the fibre volume fraction and the type of matrix used. The study highlighted that the incorporation of bamboo fibres provided a significant improvement in tensile strength compared to composites reinforced solely with flax fibres. This enhancement is attributed to the high tensile modulus of bamboo fibres, which effectively transfers load within the composite.

Similarly, Amada et al. [25] explored the impact resistance of bamboo fibre composites and found that their fracture toughness made them suitable for applications requiring high energy absorption. The study employed compact tension specimens to measure the fracture toughness and observed that bamboo fibre composites exhibited values ranging from 2 to 4 MPam. The high fracture toughness was primarily due to the ability of bamboo fibres to undergo fibre pull-out and crack deflection, mechanisms that contribute to the material's resistance to crack propagation.

However, while these studies demonstrate the potential of BFRPs in applications requiring high tensile strength and impact resistance, the long-term performance under dynamic loading conditions remains less explored. Most studies have focused on quasi-static loading, leaving a gap in understanding how these composites perform under cyclic or impact loading over extended periods. This is particularly important for applications in the automotive and construction industries, where materials are subjected to repetitive stresses and must maintain their mechanical integrity over time.

Durability and Environmental Resistance

The durability and environmental resistance of BFRPs are critical for their performance in real-world applications, especially in environments exposed to moisture, temperature fluctuations, and other harsh conditions. Understanding how these composites behave under such conditions is essential for ensuring their long-term reliability and safety.

Kushwaha and Kumar [21] conducted extensive studies on the water absorption characteristics of bamboo fibre composites. Their research showed that untreated bamboo fibres tend to absorb significant amounts of water, leading to swelling, loss of mechanical properties, and potential microbial degradation. Specifically, untreated composites absorbed up to 15% of their weight in water, resulting in a 30% reduction in tensile strength after prolonged exposure. To mitigate these issues, the study explored various chemical treatments, such as alkali and silane treatments, which reduced water absorption by up to 35%. These treatments work by altering the surface chemistry of the fibres, making them more hydrophobic and enhancing the composite's resistance to moisture.

Radzi et al. [30] further examined the environmental resistance of bamboo fibre composites in different matrix systems, including both thermoplastic and thermoset matrices. Their findings indicated that composites with thermoset matrices, such as epoxy, exhibited better resistance to moisture and thermal cycling compared to those with thermoplastic matrices. The study found that after 500 hours of exposure to high humidity and temperature cycles, the tensile strength of bamboo fibre/epoxy composites decreased by less than 10%, while bamboo fibre/PP composites showed a reduction of over 20%. This difference is attributed to the stronger interfacial bonding in thermoset composites, which prevents moisture ingress and maintains mechanical integrity under environmental stress.

However, despite these improvements, the lack of comprehensive long-term durability studies under various environmental conditions remains a significant gap in the current research. Many studies focus on short-term performance, leaving uncertainties about how these composites will behave over extended periods, particularly in outdoor or harsh industrial environments. Future research should address these gaps by conducting long-term exposure tests, evaluating the effects of factors such as UV radiation, saltwater immersion, and cyclic thermal loading on the durability of BFRPs.

3.3 Environmental Impact of Bamboo Composite Materials

3.3.1 Growth and Availability

Bamboo's rapid growth and renewability are key factors contributing to its environmental sustainability as a raw material for composite production. Liese and Wiener [33] emphasized that bamboo can grow up to 91 cm per day under optimal conditions and typically reaches maturity in 3-5 years. This fast growth rate allows for frequent harvesting cycles without significant environmental degradation, making bamboo an ideal sustainable resource. Additionally, bamboo forests play a vital role in carbon sequestration, capturing substantial amounts of atmospheric carbon dioxide and storing it in both biomass and soil. This capability is crucial in reducing the overall carbon footprint and mitigating climate change.

The findings presented by Liese and Wiener are based on extensive field measurements of bamboo growth rates and carbon accumulation, providing a strong empirical foundation. However, the study primarily focused on specific bamboo species under optimal conditions, which may not represent the variability in growth rates and carbon sequestration across different environments. Further research should explore these aspects across a broader range of species and environmental conditions to enhance the generalizability of the findings.

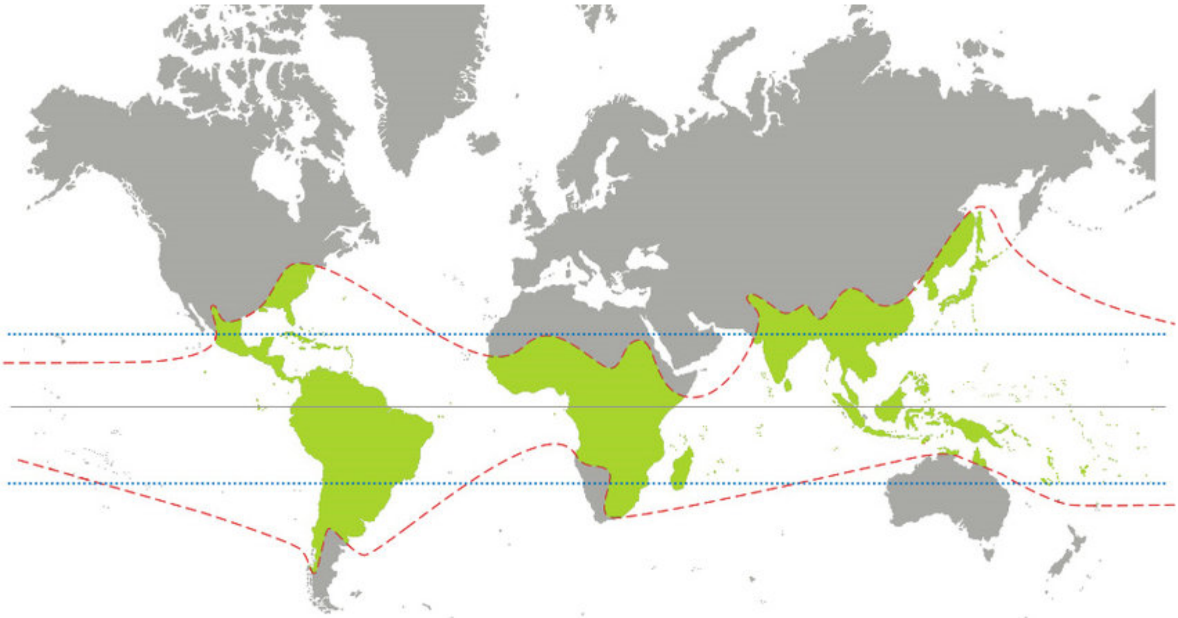


Figure 3.7: World map highlighting the geographic availability of bamboo [6]

3.3.2 Mechanical Extraction and Environmental Impact

The environmental impact of fibre extraction processes is crucial in determining the sustainability of composite materials. Mechanical extraction methods, such as those employed by Bambooder, involve cutting bamboo stems into slats and extracting fibres through a patented combing process. This method is notably less energy-intensive than traditional chemical extraction methods, which require high temperatures and significant chemical inputs.

Lotfi et al. [23] conducted a life cycle assessment (LCA) comparing the environmental impacts of mechanical and chemical extraction processes for natural fibres. The study found that mechanical extraction results in a 50% reduction in energy consumption and a 60% decrease in greenhouse gas emissions compared to chemical extraction methods. Verma et al. [34] further supported these findings by highlighting that mechanical extraction uses up to 70% less energy than chemical methods, underscoring the environmental benefits of mechanically extracted bamboo fibres.

While the LCA conducted by Lotfi et al. provides compelling evidence of the environmental benefits of mechanical extraction, the study's scope is limited by its reliance on specific assumptions about energy sources and process efficiencies. The actual environmental impact of mechanical extraction could vary depending on the energy mix and operational practices in different regions. Additionally, the environmental impact of the disposal and recycling of chemicals used in extraction methods should be explored further.

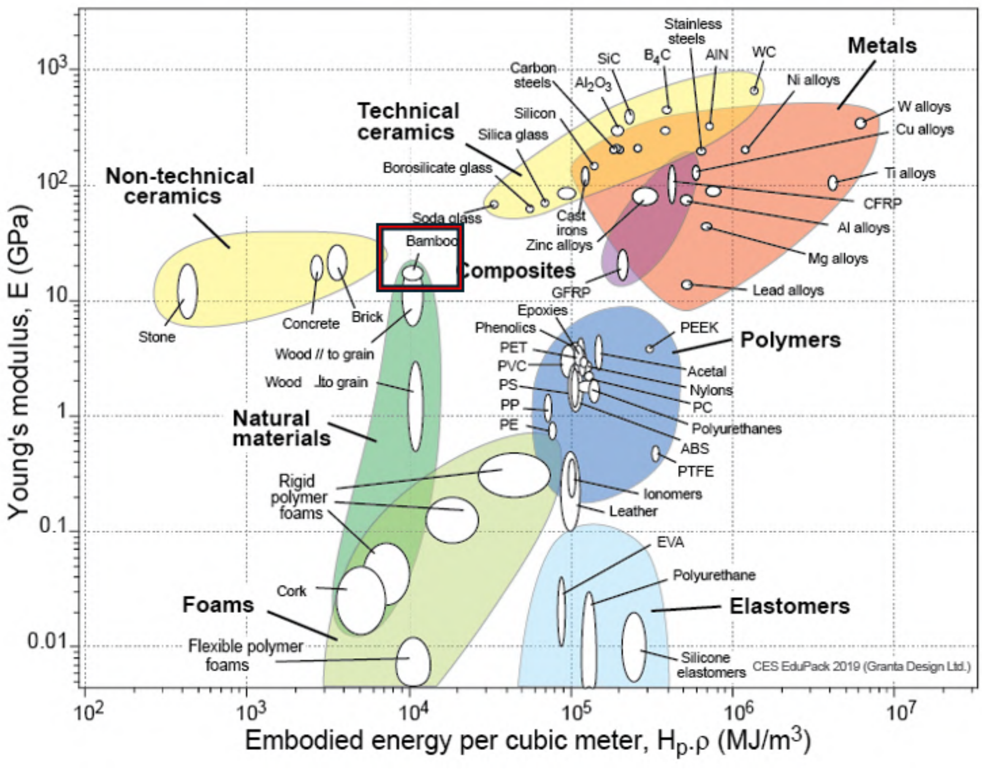


Figure 3.8: Young's modulus vs Embodied energy per cubic meter, Chart created using CES EduPack 2019, ANSYS Granta © 2020 Granta Design

The results presented in Figure 3.8 show the Young's Modulus vs Embodied energy of materials. Bamboo fibres demonstrate a favorable balance between mechanical performance and environmental impact, with a relatively high Young's Modulus and low embodied energy compared to other natural and synthetic fibres. This highlights bamboo's potential as a sustainable alternative for high-performance composite materials.

3.3.3 Comparison to Natural fibres and Glass fibres

When comparing bamboo fibre composites to other natural fibres (NFs) and glass fibres (GFs), bamboo offers several environmental advantages. Mansor et al. [35] conducted a comparative LCA to assess the CO_2 emissions associated with the production of various fibres. The study found that bamboo fibre production generates significantly lower CO_2 emissions compared to glass fibres, with the production of one kilogram of bamboo fibres emitting approximately 0.8 kg of CO_2 compared to 1.8 kg for glass fibres.

In terms of energy consumption, Joshi et al. [13] reported that producing one kilogram of bamboo fibres requires about 30 MJ of energy, which is substantially lower than the 50 MJ required for glass fibres. This lower energy requirement is attributed to the less intensive processing needed for bamboo fibres, further enhancing their environmental profile.

The LCAs conducted by Mansor et al. and Joshi et al. are valuable for their comprehensive analysis of energy consumption and CO_2 emissions. However, these studies assume standard conditions and processes, which may not fully capture the variability in environmental impacts across different production scales and locations. Additionally, the long-term environmental impact of the end-of-life disposal and potential recycling of bamboo fibre composites needs further investigation to fully understand their sustainability.

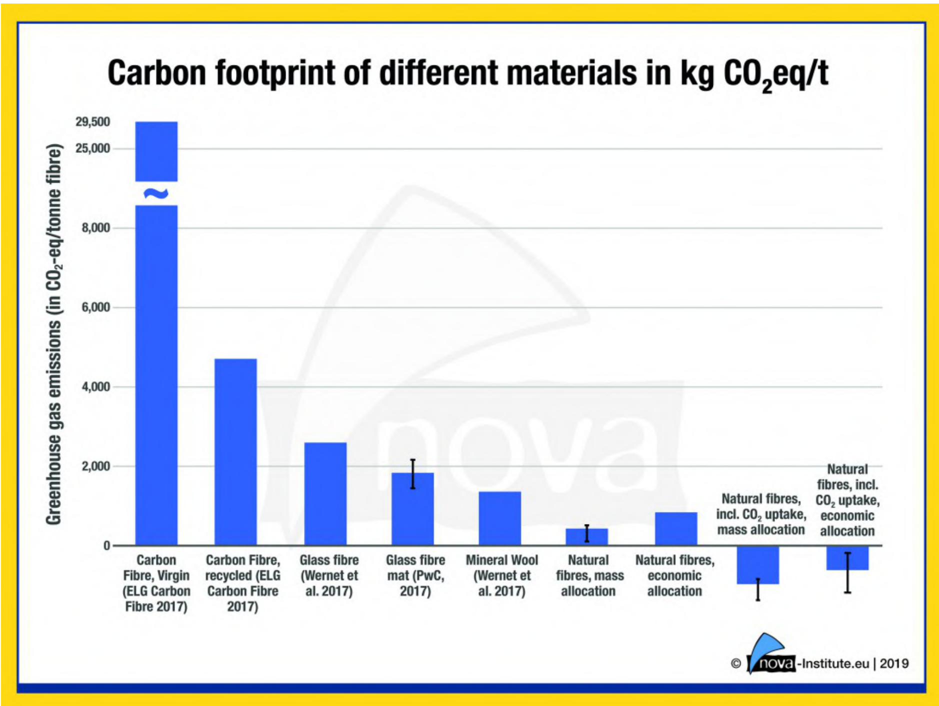


Figure 3.9: Comparison of CO_2 emissions of different materials [7]

3.3.4 Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) studies consistently demonstrate the lower environmental impact of bamboo fibre composites compared to conventional composites, particularly those reinforced with glass fibres. Subrata et al. [36] conducted an extensive LCA comparing bamboo fibre composites with traditional glass fibre composites. Their analysis revealed that bamboo composites could reduce environmental impacts by up to 60% compared to glass fibre composites. This significant reduction is attributed to bamboo's rapid growth, minimal agricultural inputs, and environmentally friendly mechanical extraction process.

The LCA methodology used by Subrata et al. involved evaluating various impact categories, such as global warming potential, acidification, and energy demand. The study found that bamboo fibre composites exhibit lower global warming potential and energy demand throughout their lifecycle, from raw material extraction to end-of-life disposal. These findings highlight the strong potential of bamboo composites to serve as a more sustainable alternative to traditional composite materials, particularly in applications where environmental impact is a critical consideration.

The LCA by Subrata et al. is comprehensive, covering multiple impact categories and providing a detailed comparison of bamboo and glass fibre composites. However, the study's conclusions are based on specific assumptions about bamboo cultivation practices and fibre processing methods, which may not be universally applicable. Additionally, the environmental impact of the transportation and distribution of bamboo fibre composites, particularly in regions far from bamboo cultivation areas, could affect the overall sustainability assessment.

3.4 Applications of Bamboo Fibre Composite Materials

Bamboo fibre composites have found applications across various industries due to their favorable mechanical properties, environmental sustainability, and versatility. This section explores the historical and current applications of bamboo fibre composites, highlighting recent advancements and future potential.

3.4.1 Previous Applications and History

Bamboo has been utilized for centuries in various applications, particularly in construction, furniture, and textiles, due to its natural strength, flexibility, and availability.

Traditional Uses in Construction and Craftsmanship

Historically, bamboo has been a vital material in building bridges, scaffolding, housing, and artisanal products. Liese and Wiener [33] provide an in-depth examination of bamboo's role in traditional construction, particularly in Asia, where it has been used extensively for building structures like bridges, houses, and scaffolding. The natural properties of bamboo, such as its high strength-to-weight ratio and flexibility, made it an ideal material for these applications long before the advent of modern construction materials.

Figure 3.10: Historical applications of bamboo in traditional construction: Bamboo hut [8]

The transition from these traditional uses to more sophisticated applications in modern composites marks a significant evolution in bamboo's role in various industries. The traditional use of whole bamboo culms in construction has gradually evolved into the use of processed bamboo fibres in composite materials, reflecting the growing recognition of bamboo's potential in advanced engineering applications.

Evolution to Modern Composites

The shift from using raw bamboo to incorporating bamboo fibres into modern composites has been driven by advancements in material science. The development of bamboo fibre-reinforced composites (BFRPCs) represents a major innovation, allowing bamboo to be used in more diverse and demanding applications. Faruk et al. [37] highlight this evolution, noting that the integration of bamboo fibres into polymers has opened new possibilities for lightweight, high-strength materials. The mechanical processing of bamboo fibres, coupled with advanced polymer matrices, has enabled the production of composites that are competitive with traditional materials like wood, steel, and even synthetic fibres in some applications.

3.4.2 Construction and Building Materials

The construction industry has seen significant interest in bamboo composites due to their mechanical properties, sustainability, and cost-effectiveness.

Load-Bearing Structures

Bamboo composites are increasingly used in structural applications, such as beams, panels, and support structures. Oliveira et al. [38] provide a detailed analysis of the mechanical properties of bamboo composites in construction, highlighting their strength, durability, and resistance to environmental degradation. Their study demonstrates that bamboo composites can be used in load-bearing structures, offering a sustainable alternative to traditional materials like steel and concrete. The use of bamboo composites in structural components not only reduces the carbon footprint of construction projects but also enhances the sustainability of buildings by using renewable materials.

Insulation and Wall Panels

Bamboo composites are also being used for thermal insulation and as wall paneling. Khalil et al. [26] discuss the thermal properties of bamboo fibre composites, emphasizing their potential for use in insulation and wall panels. The study highlights bamboo's natural thermal insulation properties, which can be enhanced through processing to create composites that provide effective insulation in buildings. These composites offer a sustainable alternative to synthetic insulation materials, with the added benefits of biodegradability and reduced environmental impact.

Sustainable Construction

The environmental benefits of bamboo composites are particularly relevant in the context of sustainable construction. The use of renewable materials like bamboo reduces the carbon footprint of construction projects and contributes to the overall sustainability of the built environment. Liese and Wiener [33] discuss the role of bamboo in sustainable construction, highlighting its rapid growth, high yield, and minimal environmental impact. Bamboo's ability to sequester carbon dioxide during its growth cycle further enhances its environmental credentials, making it an attractive option for green building projects.

3.4.3 Automotive Industry

The automotive industry has been exploring the use of bamboo composites for various components, particularly those that benefit from weight reduction and improved fuel efficiency.

Interior Components

Bamboo composites are used in automotive interior components such as dashboards, door panels, and seat backs. Faruk et al. [37] highlight the integration of bamboo fibres into thermoplastics and thermosets for automotive interiors, where their lightweight nature contributes to overall vehicle weight reduction. This reduction in weight translates into improved fuel efficiency and lower emissions, aligning with the automotive industry's goals for sustainability. Khalil et al. [26] further discuss the benefits of using bamboo composites in interior components, emphasizing their environmental advantages over traditional materials.

Figure 3.11: Use of bamboo fibre composites in automotive interior panels [9]

Structural Components

Research into using bamboo composites in load-bearing parts of vehicles is ongoing, though challenges remain, particularly regarding moisture absorption and long-term durability. Suhaily et al. [39] explore the potential for using bamboo composites in structural automotive components, noting that while bamboo offers excellent mechanical properties, further research is needed to address issues such as moisture resistance and material longevity. The study suggests that future developments in bamboo composite processing could enable their use in more demanding structural applications within the automotive sector.

Challenges and Future Prospects

Despite the promising applications of bamboo composites in the automotive industry, challenges such as moisture absorption and processing difficulties must be addressed. The ongoing research highlighted by Faruk et al. [37] and Suhaily et al. [39] suggests that improvements in surface treatments and composite processing techniques could mitigate these challenges, paving the way for broader adoption of bamboo composites in the automotive industry.

3.4.4 Packaging Industry

The packaging industry is increasingly looking to bamboo composites as a sustainable alternative to plastics, particularly for biodegradable packaging solutions.

Biodegradable Packaging

Bamboo composites are emerging as a viable option for biodegradable packaging materials, offering a balance of mechanical strength and environmental sustainability. Amjad et al. [40] discuss the mechanical properties and biodegradability of bamboo composites in packaging, highlighting their potential to replace conventional plastics. The study emphasizes that bamboo-based packaging materials are not only biodegradable but also provide sufficient mechanical strength to meet the demands of various packaging applications.

Sustainability Impact

The environmental benefits of using bamboo composites in packaging are significant, particularly in reducing plastic waste and promoting a circular economy. Faruk et al. [37] and John et al. [41] discuss the impact of bamboo composites on sustainability, noting that their use in packaging can significantly reduce the reliance on non-renewable resources and decrease the environmental impact associated with plastic waste. The biodegradability of bamboo composites ensures that they break down naturally in the environment, contributing to a reduction in long-term waste accumulation.

3.4.5 Advanced Engineering Applications

Bamboo fibre composites are being explored for advanced engineering applications, including in the aerospace, marine, and renewable energy sectors.

Aerospace Applications

The aerospace industry is investigating the use of bamboo composites for lightweight structures, particularly in non-critical structural components. John and Thomas [41] explore the potential for using natural fibre composites, including bamboo, in aerospace applications. The study highlights bamboo's high specific strength and environmental benefits, making it a promising material for interior cabin components and secondary structures where weight savings are critical.

Wind Energy

Bamboo composites are being researched for use in renewable energy, particularly in wind turbine blades. Mohanty et al. [42] discuss the potential of bamboo composites in the renewable energy sector, specifically for manufacturing wind turbine blades. The high specific strength and stiffness of bamboo composites make them suitable for reducing the weight and cost of wind turbine blades, contributing to more efficient energy production. The study suggests that with further research and development, bamboo composites could play a significant role in the renewable energy industry.

In fig. 3.12 is presented the 1.5MW Bamboo fibre composite Blade by Zhongfu Lianzhong Composites Group, China.

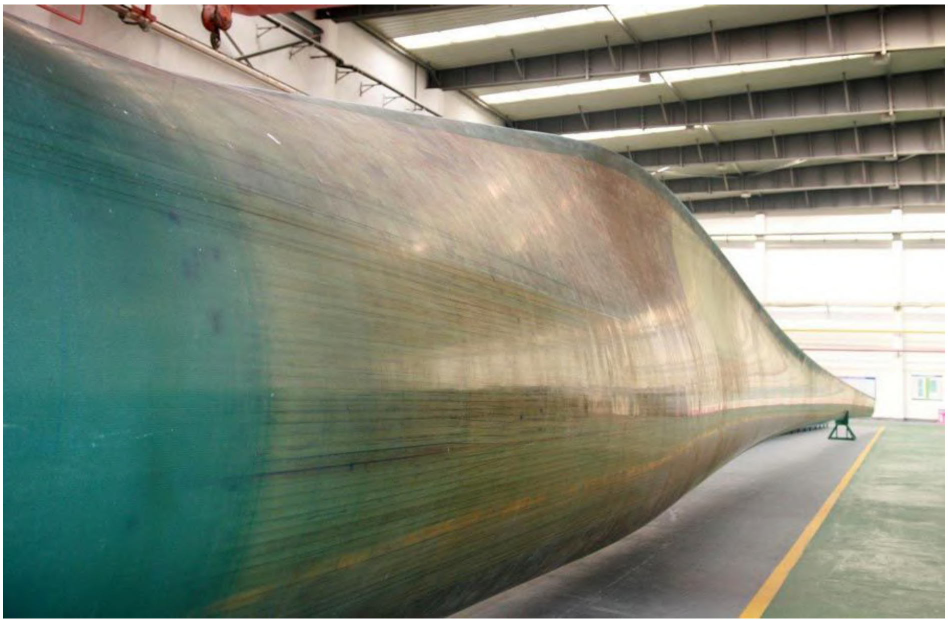


Figure 3.12: Use of bamboo fibre composites in wind turbine blades [10]

Marine and Other Specialized Uses

Bamboo composites also show potential in marine environments and other specialized engineering fields. Suhaily et al. [39] discuss the potential for using bamboo composites in marine applications, highlighting their resistance to water and environmental degradation when properly treated. The study suggests that bamboo composites could be used in boat construction, dock components, and other marine structures where lightweight, high-strength materials are required.

3.4.6 Future Trends and Developments

The future of bamboo fibre composites is promising, with ongoing research and development aimed at enhancing their properties and expanding their applications.

Material Innovations

Ongoing research into hybrid composites and nanocomposites is expected to further enhance the performance of bamboo composites. Oliveira et al. [38] discuss the development of hybrid composites that combine bamboo fibres with other natural or synthetic fibres to improve their mechanical and thermal properties. The study suggests that future innovations in material science could lead to bamboo composites that outperform traditional materials in a wider range of applications.

Expansion into New Markets

The potential for expanding bamboo composites into new markets, such as electronics or medical devices, is also being explored. Faruk et al. [37] and Amjad et al. [40] highlight the versatility of bamboo composites, noting that their unique combination of properties could open new opportunities in industries that require lightweight, strong, and sustainable materials. Future research and development efforts will likely focus on adapting bamboo composites to meet the specific requirements of these new markets.

Sustainability and Environmental Impact

The sustainability benefits of bamboo composites are expected to drive their adoption in various industries. Mohanty et al. [42] highlight the potential for bamboo composites to significantly reduce the environmental footprint of manufacturing processes due to their renewable nature and biodegradability. As industries increasingly prioritize sustainability, the demand for materials that offer both high performance and low environmental impact is likely to grow.

Future trends may also include the integration of life cycle assessment (LCA) practices into the design and production of bamboo composites, ensuring that their environmental benefits are fully realized across the entire product lifecycle. Liese and Wiener [33] and Radzi et al. [30] emphasize the importance of sustainable practices in the cultivation and processing of bamboo, which will be crucial in maintaining the environmental advantages of bamboo composites as their applications expand.

Overall, the continued development and adoption of bamboo fibre composites are likely to be driven by their exceptional mechanical properties, environmental benefits, and adaptability to a wide range of applications. As material science advances and the global focus on sustainability intensifies, bamboo composites are well-positioned to play a significant role in the future of engineering and manufacturing.

Part II Project

Chapter 4

Materials and Methods

4.1 Materials

4.1.1 Fibres

The fibres used for the all research done and composites materials produced during the project were provided by Bambooder. These fibres could be of two types: Raw loose fibres or yarn fibres. The extraction of the fibre is done through a purely mechanical process which Bambooder has developed and patented.

The newly developed mechanical extraction process is the following. The long bamboo stems are transported as a whole from the cultivation site to the manufacturing site. Upon arrival, the bamboo stems are cut according to their internodal length. Each internodal stem section is then cut in pieces which are called slats. These slats can then be placed on the automated production line. If the slats meet the dimensional requirements they are selected and can go through the combing process. The product of the combing process is the extracted fibres from each slat. These may vary in length, between 12 to 15 cm.

The fibres can then be used in their initial state, as loose fibres extracted from each slat presented in subsectionSingle fibres or in the form of a continuous yarn, presented in subsection Yarn.

Single fibres

The raw fibres used in this study were clustered in small bundles originating from the slats. These could differ slightly in terms of number of fibres, length, as well as uniformity of the fibres.

In the picture above are the loose fibres, as delivered by Bambooder. It can be observed that these are in a raw state, not in a production ready state as they are tangled and some fibres are completely loose.

Figure 4.1: Box with raw fibres from Bambooder

4.1.2 Matrix materials

In order to obtain a better and more general understanding of the bamboo fibre performance, both thermoset as well as thermoplastic polymers have been used for composite production.

Thermoset polymers

For the thermosets, two different types of epoxy were chosen. An epoxy for wet hand lay-up as well as one for resin-infusion processes. The epoxies used were Resoltech 1200 for wet hand lay-up and Epikote Resin 04908 with EpiKure 04908 curing agent for resin-infusion production.

Both these epoxies cure at room temperature and have a long pot-life thus a good choice for production with loose fibres which can be hard to handle and thus demand some time. Additionally, they have almost equivalent densities and similar mechanical properties thus making it possible to assess the impact of the production methods on the result. The main difference between these two epoxy resin systems lies in the viscosity of the mix. The viscosity of the EpiKote / EpiKure naturally being much lower to allow for flow during the vacuum-infusion process.

Thermoplastic polymers

Composite plates were made from two different thermoplastic polymers in the form of films, Polypropylene (PP) and Polyamide 11 (PA11). These two films being widely used in industry making them good reference points. Additionally, Bambooder advised to use these two films as they had them in stock since they use them for the production of their short fibre mats.

Thus, through the production and testing of composites made from these two polymers, Bambooder could also gain some insights on their current production.

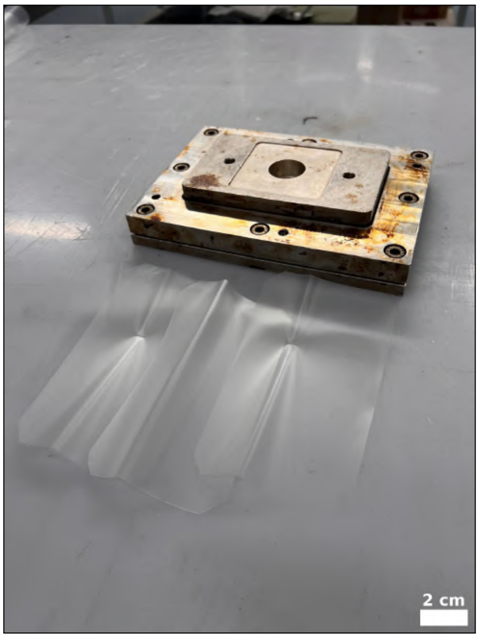


Figure 4.2: PA11 films cut to size of pressing mould

4.2 Methods

4.2.1 Composite Production

Fibre preparation

Prior to producing a composite plate using any of the composite production methods presented in the following section, special care had to be given to the fibre preparation in order to achieve uniformity in the plates. Indeed, as was presented in 4.1.1, the fibres were in a raw state with a lot of variability, thus requiring some processing before being used as reinforcements. In order to ensure proper fibre alignment as well as some uniformity through the plates made, several processing steps were taken, such as additional fibre selection, aligning, cutting and weighing.

In 4.3 can be seen the difference between a fibre bundle having a constant density, meaning an equal amount of fibres along its length (lower bundle) and a fibre bundle with only a few fibres reaching the full length of the bundle, approximately 15cm. The fibres selected for composite production were of the first type, with uniform distribution.

In most cases, the fibres received were very tangled, making it necessary to untangle them and try to obtain good fibre alignment. This was simply done by hand, spreading and rolling the fibres against one another.

Figure 4.3: Fibre selection: insufficient fibre bundle (top) and selected fibre bottom (bottom)

After having aligned the fibres, these could be cut to make the new bundles of equal size. In the case of fibres received with the wooden ends, as shown in 4.3, these were cut off after fibre alignment.

Finally, after having selected, aligned and cut a little bundle of fibres, these were weighed with the help of a little bucket placed on a high accuracy Mettler Toledo scale, shown in 4.4.

Figure 4.4: Fibre weighing on scale

Figure 4.5: Fibre combing process

The steps presented above were taken in order to manufacture composites which would be representative of the fibre properties close to the ones Bambooder would have when using their fibres in this state. However, in order to evaluate the maximum performance of their fibres, extra processing steps were taken for the production of actual "UD fibre" composites. In 4.5 is shown the alignment and combing method of the fibre bundles.

Compression Moulding

Compression moulding is a commonly used manufacturing process, especially for the production of composites made from thermoplastic polymers. It implies putting a controlled amount of fibre and matrix material in a closed mould on which a force can be applied. A pressing cycle of given temperature and pressure is then applied to the mould. In Fig. 4.6 can be seen the mould used for compression moulding.

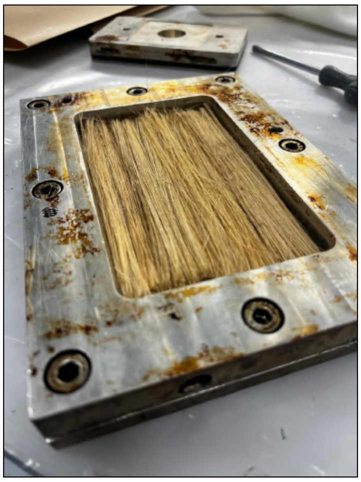


Figure 4.6: Pressing mould with aligned raw fibres

The quantity of material placed in the mould, polymer as well as fibre, was weighed in order to produce composites at 45% fibre volume fraction (vf). The composite plates were then produced using the following methodology. All parts of the mould were first cleaned and then released. Next, the pre-cut film of thermoplastic, either PP or PA11, was stacked with bundles of fibres placed in between every couple layers. The stacking sequence varied depending on the material used and the desired thickness of the laminates, produced for either tensile or flexural testing. Once all material was placed in the mould, it could be closed and set in the press. The structure of the pressing cycle applied was same for both PP and PA11 composites produced, with the exception of the maximum temperature which was the only parameter modified.

Plates produced using this process were of good and consistent quality. Indeed, thanks to the controlled amount of resin and fibres as well as the controlled processing parameters, all laminates produced had similar thicknesses.

For both PP and PA11, composite plates were produced at temperatures ranging through the full processing range of the polymer. These are presented in 4.1 below. The limitations of this range are defined on the lower end by the melting temperature (Tm) of the polymers and on the higher end by the fibre burning.

Five samples could be obtained from the production of one plate. Thus, two plates for each were made in order to have 10 samples per temperature value, ensuring enough statistical significance of results. For PA11, the lowest temperature value (185°C) did not provide enough heat for the polymer to fully reach its melting temperature (Tm) and flow. Most fibres were not impregnated, thus no data was obtained for these laminates. Also, past 215°C

Figure 4.7: Composite plates produced by compression moulding

Material	Temperature (°C)				
PP	170	180	190	200	210
PA11	185	195	205	215	225

Table 4.1: Processing temperatures used for PP and PA11 laminates

the laminates were almost fully burnt and would fall in pieces. Laminates pressed at 225°C are thus also out of the processing temperature range.

Resin Infusion

Vacuum-assisted resin infusion is a common thermoset composite production method. It consists of placing the dry reinforcement materials, here bamboo fibres, in a mould or plate, setting it under vacuum and allowing resin to flow through the compressed material. It allows good control over the lay-up of fibres prior to infusion, as well as over the fibre volume fraction.

The following method was followed for production of epoxy composite plates. First, the aluminium plates were cleaned and released. Processed fibres were then placed on the base plate between two strips of tacky tape. These enable to direct the flow of resin through the fibres and not have resin escape to other areas of the bottom plate. Before vacuum bagging, a backing plate was placed on top of the fibres. This specification is necessary to obtain a flat and smooth surface on both sides of samples. Indeed due to the use of loose fibres, if no backing plate was used the vacuum bag would take the shape of the fibres and have a very uneven surface.

After vacuum bagging and reaching the required vacuum-level, the pump was turned off to perform drop tests. If the pressure would stay stable or increase at a very slow rate then the vacuum bag was of good quality and the epoxy could be mixed. The mix was placed in a vacuum chamber to be degassed. Once degassing was completed, the infusion could be started. The infusions were performed at a pressure of 50 mbar and then left to consolidate at 450 mbar for 24 hours.

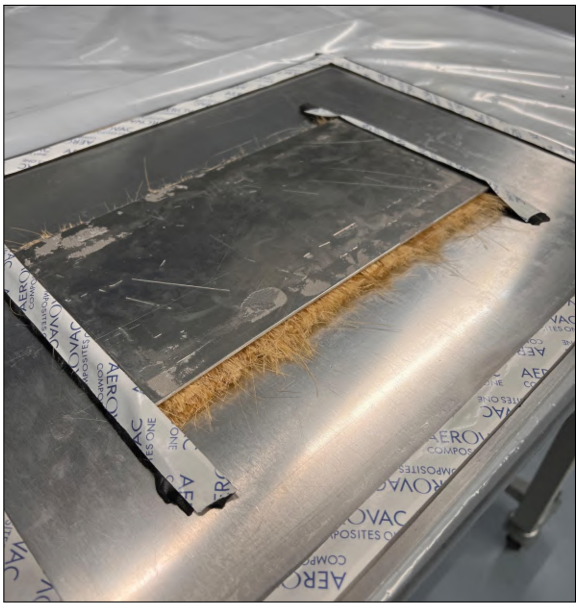


Figure 4.8: Backing plate on fibres before Vacuum-Infusion

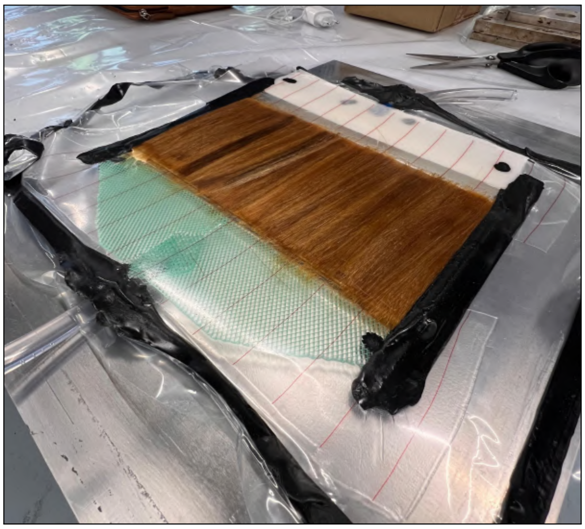


Figure 4.9: Laminate upon demoulding after Vacuum-Infusion

Wet lay-up

Wet lay-up is a very simple thermoset composite production method. Indeed, it consists in direct impregnation of dry fibres with liquid resin. After impregnation can the fibres and resin then be placed under pressure with the assistance of vacuum or placed in a press. The main advantage of wet lay-up is the simplicity and rapidity of the process, however allowing for less control than resin infusion.

In the initial phase of the project two plates were produced with wet lay-up. The void content of one of them being very high, and the other having partly dry areas, led to a search for production methods which would yield higher quality and more consistent results.

In order to compare the mechanical performance from different composite plates produced, repeatability of the process and result is necessary. Therefore it was opted for production of plates using resin infusion.

4.2.2 Sample preparation

Cutting

All composite plates made were cut into samples of the desired dimensions using a powered diamond blade cutting machine. A picture of this machine is shown in Figure 4.10. This machine uses water mixed with a bit of anti-corrosive oil as lubricant. Using water for cutting natural fibre composites is known to impact negatively its mechanical properties due to the poor hygrothermal properties, however necessary when using this machine. Indeed, dry cuts without using any lubricant were attempted however the blade would due to too much friction start bending and vibrating significantly. Therefore, all composites were cut

Figure 4.10: SECOTOM Diamond saw cutting machine [Source: Struers [11]]

using water as lubricant. Even though this may negative impact the results observed, it does not affect comparison of results.

After cutting samples, these often had rough edges, thus some sanding was done to obtain nice and smooth edges allowing for more precise measuring.

Measuring

Measuring of samples is not a task to be looked over. Indeed, since all results are strongly dependant on samples dimensions, this had to be performed precisely. In order to do so, the thickness of all samples was measured at five separate locations along the length. The width was measured at three different locations. All measurements were made with a digital caliper.

Weighing

Weighing of all samples was performed in order to estimate the fibre volume fraction of laminate produced, and assess variation between samples from the same plates. All mass measurements were performed with the help of a high precision Mettler Toledo scale which can be seen in 4.4.

4.2.3 Mechanical testing

Mechanical characterisation of composite materials can be performed through numerous sorts of mechanical testing including tensile, flexural, compressive, shear testing, and more. For most composite design projects, the first properties looked at are often tensile and flexural modulus as well as tensile and flexural stress. Thus, due to time restrictions imposed by the thesis duration, it was decided to perform only tensile and flexural tests and obtain from both modulus and strength.

Tensile testing

Tensile testing was performed according to standard ASTM D3039 *Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials*. This standard was chosen as it is the most recognized in the European composite material industry.

Even though the distribution of fibre could not be fully controlled as explained in 4.2.1, the samples tested are assumed to be balanced and symmetric. Also, as explained in 4.2.2, the samples not having perfectly constant dimensions, average dimensions were used.

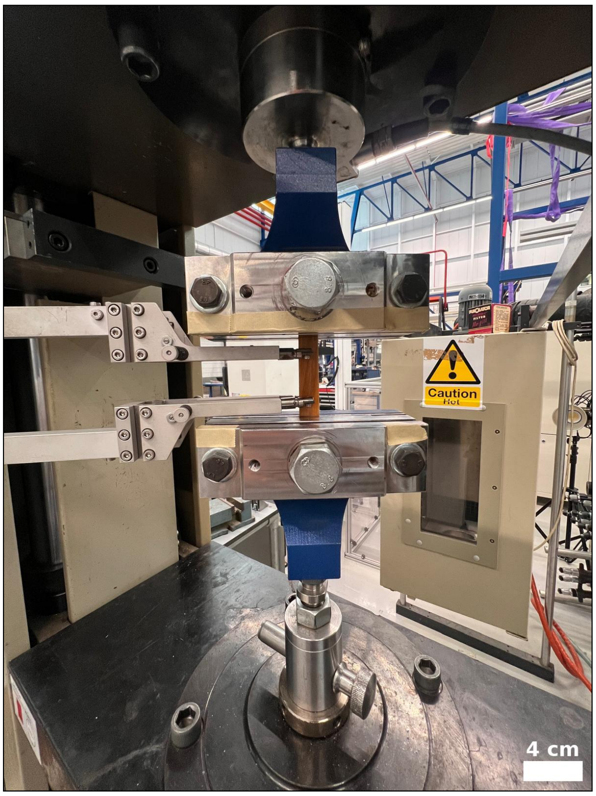


Figure 4.11: Tensile testing set-up on UTM

The testing was performed on a 20kN Univerval Testing Machine (Zwick) using a 20kN loadcell and aw well as an extensometer that clamped directly on the samples. The use of an extensometer provides the most accurate data as it eliminates any compliance that could be in the machine. Thus from the data exported, the extensometer data was used for the strain calculations.

The samples being shorter than desired due to the limitation in fibre length, the standard could not be followed as recommended. Indeed with samples of approximately 140mm long, the grip-to-grip gauge length was set to 65mm. This would ensure that the clamping area was enough to prevent any slipping.

Testing conditions, such as speed, was set to 1mm/s as defined per the ASTM standard. Temperature and relative humidity (RH) were also noted. These were approximately 20°C and 38% RH.

To obtain the ultimate tensile strength of the composites tested the following formula was used:

$$F^u = Pmax/A$$

Where Pmax is the maximum force in N reached before failure and A the cross-sectional area of the sample in mm^2.

The modulus of elasticity was obtained according to the following formula:

$$E^{chord} = \Delta\sigma/\Delta\epsilon$$

Where $\Delta\sigma$ is the stress delta and $\Delta\epsilon$ is the strain delta between two strain points, chosen to be 0.001 and 0.003 strain according to the method given in [REF: ASTM stand].

Flexural testing

Flexural testing was performed according to standard ASTM D7264 *Standard Test Method for Flexural Properties of Polymer Matrix Composite Materials*.

Same assumptions applied to the samples than for tensile testing (4.2.3).

The testing was again performed on a 20kN universal testing machine (Zwick), using a 1kN loadcell. As can be seen from 4.12, the four point bending (4PB) set-up was chosen, over the more common three point bending (3PB) set-up. The reason for this choice is the more natural infliction of strain on the sample, which has a distributed stress between the two contact points instead of a singular contact point load. This option thus leads to more representative failure modes of the laminates.

However, special attention should be paid when calculating the stress and strain ast these differ for the 3PB and 4PB set-up. The follwing formulas were used, specified in the ASTM standard:

Figure 4.12: Flexural testing: 4PB set-up [Zoom 0.5X]

$$\sigma = \frac{3PL}{4bh^2}$$

where:

- σ = stress at the outer surface in the load span region, MPa
- P = applied force, N
- L = support span, mm
- b = width of beam, mm
- h = thickness of beam, mm

$$\epsilon = \frac{4.36\delta h}{L^2}$$

where:

- δ = mid-span deflection [mm]
- ϵ = maximum strain at the outer surface [mm/mm]
- L = support span [mm]
- h = thickness of beam [mm]

The mid-span deflection δ is defined assuming beam theory, to be $\delta = \frac{3}{2}\delta^{nominal}$ where $\delta^{nominal}$ is the nominal deflection measured by the UTM, at the load points.

Due to the limitation in length of fibres, and thus samples, the recommended span length of 128mm could not be used. The span length was thus set to 112mm. This results in a 3.5mm thickness according to the 32:1 span to thickness ratio specified. This value was aimed for all flexural samples produced, however challenging for the epoxy resin-infused plates due to the nature of fibres and varying distribution.

Testing conditions, such as speed, was set to 1mm/s as defined per ASTM standard. Temperature and relative humidity (RH) were also noted. These were around 20°C and 38% RH.

Data processing

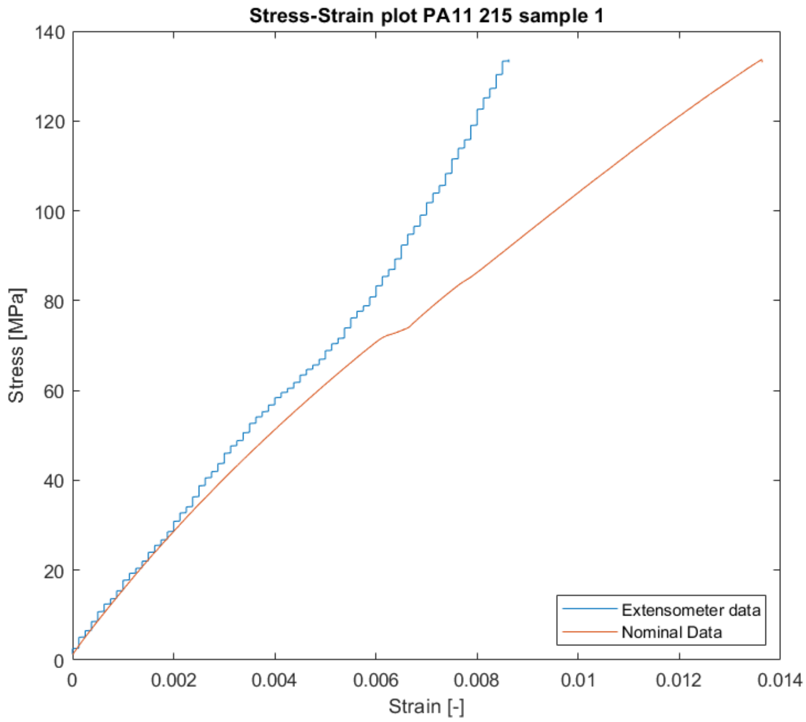


Figure 4.13: Stress-Strain plot from testing data

For both tensile and flexural tests performed, some data processing was required in order to extract the desired values for strength and Modulus. The strength was rapidly determined using the measured average cross-sectional area and formulas given in the ASTM standards. The tensile and flexural modulus were taken in between strain points 0.001 and 0.003, as specified by the standards.

However, additional data processing was also done for the tensile modulus. Indeed, contrarily to the expected behaviour of a sample being tested under tension, the modulus of the samples increased past a certain stress / strain threshold, being approximately 0.005 strain. Possible explanations for this phenomena will be investigated in 6.1.1.

In order to search and obtain the value of the Modulus measured in each sample after its increase, a code searching for the maximum slope on the stress-strain curve of each sample was created. To make sure that this information would still be representative of the material behavior, and not of a possible very local peak in the curve, the strain delta of 0.002, same than used in the standard, was kept. The code would then search for the maximum slope between two strain points of 0.002 apart, over the entire range of the curve.

Both the modulus value as defined in the ASTM standard, and the maximum value were thus extracted and considered for analysis.

Back-Calculation of Fibre properties

The fibre Modulus was back-calculated from the composite properties obtained using the Rule of Mixtures (ROM). This rule assumes that the composite properties are equal to the sum of the matrix and fibre properties relative to their volume fraction. For this calculation the polymer matrix properties were taken as given in the material technical datasheet (TDS) and by polymer testing data provided by Bambooder.

The ROM for composite Modulus is the following:

$$E_{Composite} = E_{Fibre} \cdot V_{Fibre} + E_{Matrix} \cdot V_{Matrix}$$

The formula used for calculation of the fibre Modulus is thus the following.

$$E_{Fibre} = \frac{E_{Composite} - E_{Matrix} \cdot V_{Matrix}}{V_{Fibre}}$$

The limitation of using the ROM is that it assumes linear composite properties for all volume fractions used. Although this is known to not be true, for the fibre volume fractions of composites tested, between 30 to 50% V_F, this rule can be applied to obtain good estimates.

In contrast to the fibre Modulus, back-calculating the fibre strength is less straight-forward. Indeed, the ROM does not stand for strength as it is non-linear.

Stress in composite:

$$\sigma_{Composite} = \sigma_{Fibre} + \sigma_{Matrix}$$

Since we know that $\sigma = E \cdot \epsilon$ where E is Modulus and ϵ is strain.

The stress in composite can be expressed as :

$$\sigma_{Composite} = E_{Fibre} \cdot \epsilon + E_{Matrix} \cdot \epsilon$$

Furthemore, the strength of the composite being determined by its maximum stress value, its corresponding strain value was saved in order to determine fibre strength. Indeed, the fibre strength can be expressed by:

$$\sigma_{fibre} = \frac{\sigma_{composite} - \sigma_{matrix} \cdot (1 - V_f)}{V_f}$$

Where $\sigma_{composite}$ is the ultimate stress measured and $\sigma_{matrix} = E_{Matrix} \cdot \epsilon^{maxstress}$, the stress in the matrix when failure is observed, assuming elastic deformation of the matrix.

Huang et al. [43] use the same equation and method in the determination of fibre strength, derived from the Principles of Composite Material Mechanics book by Ronald F. Gibson [44].

The back-calculated flexural modulus and strength of fibres were determined according to the same calculation method.

4.2.4 Material Analysis

In order to get a deeper understanding of results, some research on the fibres as well as composites produced was performed through fibre density measurement, microscopy, image analysis and tomography.

Fibre Density Measurement

The fibre density is an essential property in determining its mechanical properties, such as modulus or strength. Indeed, the fibre volume ratio (Vf) of composites is dependant on the density of the materials. Therefore, density of fibres was the first property measured before starting with composite production. Information on the fibre density measurement method and results can be found in Appendix A A.

Determination of Fibre Volume (Vf)

The fibre volume of each laminate produced was determined by precisely weighing the mass of fibre and polymer material prior to composite production. In the case of epoxy laminates produced by resin-infusion, only the fibre mass was initially measured. The produced laminates were then precisely weighed. Any mass loss occurring during compression moulding was thus taken into account and assumed to come from fibre mass loss. This assumption decreases the Vf.

To get even more precise data, the idea of weighing all samples to estimate the deviation in Vf within samples was considered. However, due to the dimensional error already present in the measurements of sample volume, as well as the density of fibres being very close to the density of thermoplastic polymers used, or nearly equal in the case of the epoxy used, made the mass of individual samples irrelevant data in determining the Vf.

Microscopy and Image Analysis

To obtain good quality images from analysing the samples with microscopy, sample preparation was required. This included the following steps:

1. Cutting Pieces of the selected samples were cut to size using the diamond saw cutting machine previously mentioned in Figure 4.10. The pieces were then placed in a holder as shown in Figure 4.14

2. Embedding The clamped sample pieces were then placed in a mould. The mould was then filled with an fast curing epoxy resin system, Technovit 4071, to fully embed the samples. After curing and demoulding, the samples were then ready for grinding and polishing.

3. Polishing

The embedded samples shown in 4.16 were grinded to get rid of any excess resin preventing the cross-section of samples from being exposed, and then polished according to the polishing sequence described in 4.15. Polishing was done with the Struers Tegramin-20, a force-controlled semi-automatic polishing machine.

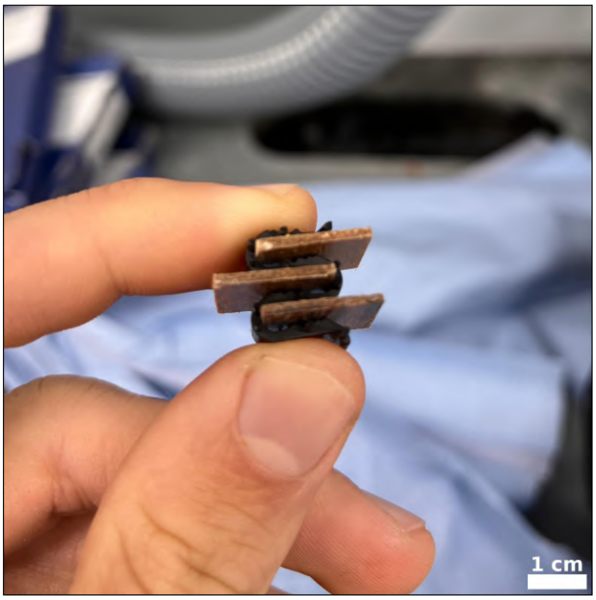


Figure 4.14: Cut samples pieces clamped in holder

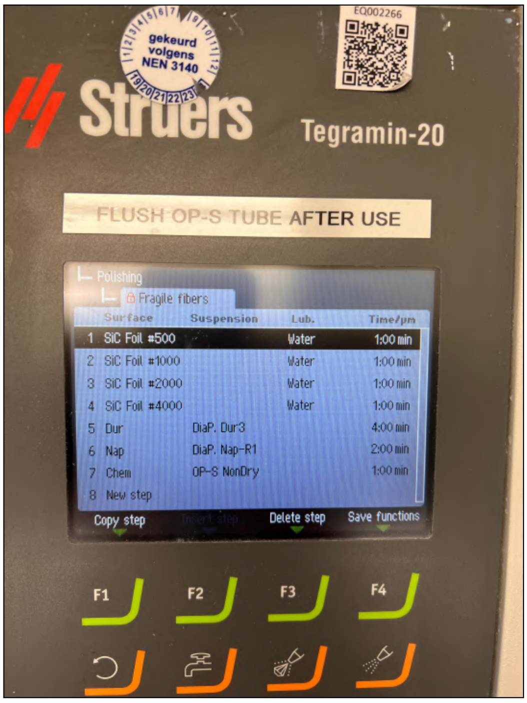


Figure 4.15: Polishing sequence

Figure 4.16: Polished samples

Microscopy observation was performed using a Keyence Laser Confocal Microscope. Observation could be done from 2.5X until 50X zoom, and with several lighting modes: ring, coaxial or laser.

Tomography (LIST)

In section 4.2.1 was explained why having full control and reproducible production was a challenge. In order to understand more about the quality and physical properties of the laminates produced, these were analysed using tomography image techniques. This imaging was performed by researchers at Luxemburg Institute of Science and Technology (LIST) to which several samples were sent.

Tomography, also known as CT-scan, is a method that uses X-rays to create cross-sectional images (slices) of an object, which can be reconstructed into a 3D representation. Such a representation is visible in Figure 4.17.

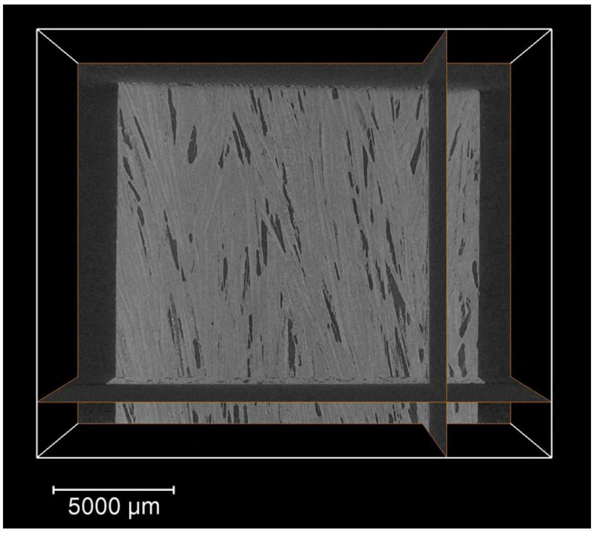


Figure 4.17: CT scan observation

CT-scan is a non-destructive inspection technique commonly used to analyse the quality of composite materials through their void and porosity content, delaminations, fibre alignment and distribution. It can also be used for damage assessment and failure analysis. For the bamboo fibre reinforced polymer composite laminates produced in this research, CT-scans were performed with the objective of obtaining precise fibre volume fractions and quantifying the angular fibre misalignment, as well as the percentage of fibres within a given angular range.

In addition to the CT-scans performed, which can only be performed on a small area per scan (11.8mm x 10.8mm), surface analysis was performed using optical microscope and image analysis techniques. Indeed, after recording and stitching of images obtained by binocular microscope, FFT (Fast Fourier Transform) was used with ImageJ to analyse the surface properties of the samples and identify patterns.

In image processing, FFT can be used to analyze the frequency content of an image for surface texture analysis, pattern recognition or simply filtering. For fibre composites, pattern recognition can be used as a method to identify and quantify the fibre orientation on the sample surface. This analysis was also performed in order to obtain more information and correlate to the results obtained from the CT-scans.

Figure 4.18: Sample image processed with ImageJ

4.2.5 Young's Modulus calculation in function of fibre orientation

After acquiring data, presented previously in Figure 4.2.4, on the mean fibre orientation of the epoxy samples produced, the Young's Modulus of the composite laminate could then be estimated for all fibre angles.

This was done using the Classical Laminate Theory (CLT) and the tensor transformations used to calculate the modulus in rotated planes. All calculations and formulas used in this section were taken from the book of composite structural mechanics by C. Kassapoglou [45].

The stiffness in the coordinate system of a ply rotated by an angle θ is given by:

$$Q_{11}(\theta) = m^4 Q_{xx} + n^4 Q_{yy} + 2m^2n^2 Q_{xy} + 4m^2n^2 Q_{ss}$$

Where:

$$Q_{xx} = \frac{E_L}{1 - \nu_{LT}\nu_{TL}} \tag{4.1}$$

$$Q_{yy} = \frac{E_T}{1 - \nu_{LT}\nu_{TL}} \tag{4.2}$$

$$Q_{xy} = \frac{\nu_{LT}E_T}{1 - \nu_{LT}\nu_{TL}} = \frac{\nu_{TL}E_L}{1 - \nu_{LT}\nu_{TL}} \tag{4.3}$$

$$m = \cos\theta \quad \text{and} \quad n = \sin\theta \tag{4.4}$$

Re-arranging the above formula for E_L (E1), the stiffness in the longitudinal direction along fibres, gives us the following formula:

$$E_1 = \frac{E_{\text{composite\_norm}} - 4G_{12}\sin^2(\theta_o)\cos^2(\theta_o) - \frac{E_2\sin^4(\theta_o)}{1-\nu_{12}\nu_{21}}}{\frac{\cos^4(\theta_o)}{1-\nu_{12}\nu_{21}} + \frac{2\nu_{21}\sin^2(\theta_o)\cos^2(\theta_o)}{1-\nu_{12}\nu_{21}}}$$

where:

- $E_{\text{c\_norm}}$: Represents the normalized modulus of the composite at angle θ_o.
- θ_o: The fibre angle of the original laminate in degrees.
- ν_{12}: Poisson's ratio (ROM of assumed fibre and matrix poisson ratio).
- ν_{21}: Transverse Poisson's ratio (calculated from poisson ratio and E2/E1 ratio).
- G_{12}: Shear modulus (estimated using Halpin-Tsai model).
- E_2: Transverse modulus (estimated using Halpin-Tsai model).

In order to calculate the Modulus in the longitudinal direction, the unknown parameters had to be estimated. These parameters are the transverse modulus E2, the longitudinal shear modulus G12, and the poisson ratio.

E2 and G12 were approximated using the Halpin-Tsai equations, as defined in the review by Halpin and Kardos [46] and presented below.

$$E_2 = E_m \cdot \frac{1 - \eta_E \cdot V_f}{1 + \eta_E \cdot \xi_E \cdot V_f}$$

$$G_{12} = G_m \cdot \frac{1 - \eta_G \cdot V_f}{1 + \eta_G \cdot \xi_G \cdot V_f}$$

with $\xi_E = 2$ for E2 and $\xi_G = 1$ for G12.

The poisson ratio for the fibre and epoxy was assumed to be 0.28 and 0.35 respectively. The composite poisson ratio was then calculated using the ROM formula $\nu_{12} = \nu_{fibre} V_f + \nu_{matrix}(1 - V_f)$.

The transverse poisson ratio was then calculated with: $\nu_{21} = \nu_{12} \frac{E2}{E1}$

Finally, once all necessary parameters and E1 was calculated, the ABD matrix could be calculated for all fibre angles and the Young's Modulus in function of fibre orientation plotted. Also, the fibre tensile modulus was back-calculated from the longitudinal modulus to obtain a theoretical value.

Chapter 5

Results and Discussion: Bamboo fibre-thermoplastic laminates

Part I: Mechanical performance

5.1 Tensile properties

5.1.1 Results

All composite properties presented are normalized to 50% V_f. The variations in V_f are assumed to have a negligible impact on the overall normalized performance since all within a close range for each polymer used. Indeed, 45% to 50% V_f for PP laminates, 35% to 45% V_f for PA11 laminates and 34% to 36% V_f for epoxy laminates. Results for epoxy laminates are also represented in Figure 5.1 and Figure 5.2 below for reference.

For all laminates tested, two modulus values were extracted, the first according to ASTM standard referred to as standard modulus and the maximum modulus value measured on the stress-strain curve, according to the methodology explained in Figure 4.2.3.

The epoxy samples tested exhibited a mean standard modulus and strength of 11.92 GPa and 277.47 MPa respectively, with corresponding standard deviations (S.Ds) of 1.19 GPa (10.0%) and 15.57 MPa (5.6%). The mean maximum modulus is equal to 23.86 GPa with a S.D of 2.51 GPa (10.5%).

The mean standard modulus and strength of PP samples is 10.68 GPa and 183.0 MPa respectively, with corresponding S.Ds of 0.94 GPa (8.8%) and 18.13 MPa (9.9%). The mean maximum modulus is equal to 20.32 GPa with a S.D of 1.22 GPa (6.0%).

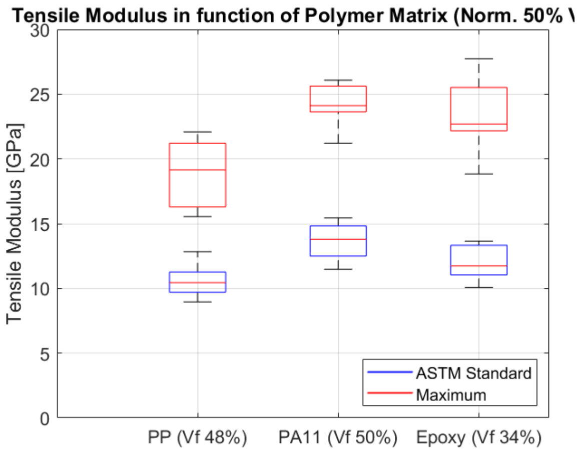


Figure 5.1: Modulus of Bamboo Fibre laminates in function of polymer matrix used

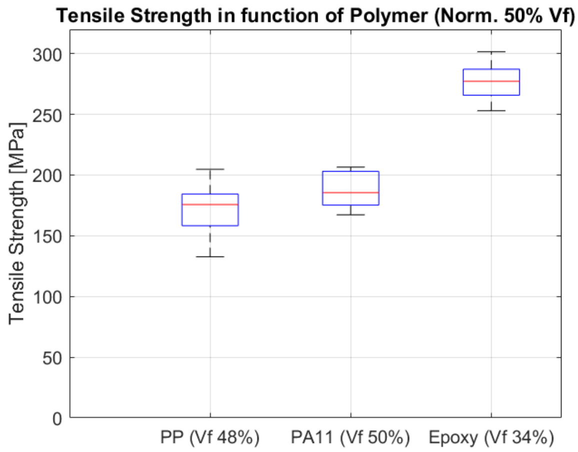


Figure 5.2: Strength of Bamboo Fibre laminates in function of polymer matrix used

The PA11 laminate has a mean standard modulus and strength of 13.62 GPa and 187.0 MPa respectively, with corresponding S.Ds of 1.41 GPa (10.3%) and 14.0 MPa (7.5%). The mean maximum modulus equals 24.09 GPa and has an S.D of 1.67 GPa (6.9%).

These results are expected results for average bamboo fibre when considering the ASTM standard values. The strength of PP and PA11 however is quite poor. It was also expected that the strength with epoxy would be much greater than with TP polymers.

The higher tensile modulus of PA11 than Epoxy, which is an unexpected result, can possibly be due to the fact that PA11 laminates were manufactured later in the project than the Epoxy one, which means that some improvements in manufacturing methods, namely the fibre preparation, over the project timeline might affect positively the laminates produced later.

5.1.2 Failure analysis

The failure mechanisms of each sample tested, including the epoxy samples used for comparison, were analysed and are presented below.

Epoxy

Epoxy samples showed to have a quite brittle failure, with a net fibre and matrix failure perpendicular to loading direction, observable in Figure 5.3 below.

Figure 5.3 displays an acceptable failure of the sample according to the standard, in the grip-to-grip region. However, several samples broke in the clamp region, observable for samples 1 and 2 in Figure 5.4. The first tests performed were more prone to failure in the clamp due to the trial and error process to find the optimal clamping force. Indeed, a too low clamping force leads to slipping of the sample, which in turn can lead to damage and failure within

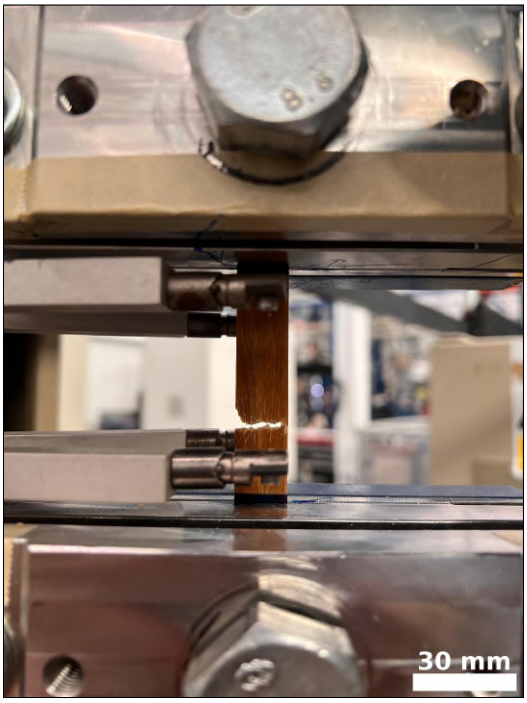


Figure 5.3: Failure of epoxy sample in UTM

Figure 5.4: Failure of epoxy samples 1 to 5

the clamp, and a too high clamping force can cause crushing and damaging of the sample. However, the failure strength of these samples generally showed to be in the same range than samples failing in the clamp-to-clamp region, thus their values were considered for the results presented in the previous sections.

PP

PP samples displayed a more complex failure mechanism. Indeed some fibre-matrix debonding leading to fibre pull-out was observed. As can be seen in Figure 5.5 this resulted on a macroscopic level in a failure where the samples would not break in two separate pieces but instead crack and slide open.

Furthermore, a gradual change in failure mode was observed with increasing processing temperature. Indeed, laminates processed at higher temperatures exhibited more brittle failures. Yet not comparable to failure of epoxy samples.

In Figure 5.7 and 5.8 can be compared the failures of a PP 170 sample and PP 210 sample. Although it is not fully ruptured like epoxy samples, the crack observed in Figure 5.8 is deeper, exhibiting more fibre failure and less fibre pull-out.

PA11

Similarly to epoxy samples, as can be observed in Figure 5.9, PA11 samples displayed a more brittle failure, with the samples fully rupturing in two separate pieces.

Figure 5.5: Failure of PP UD sample

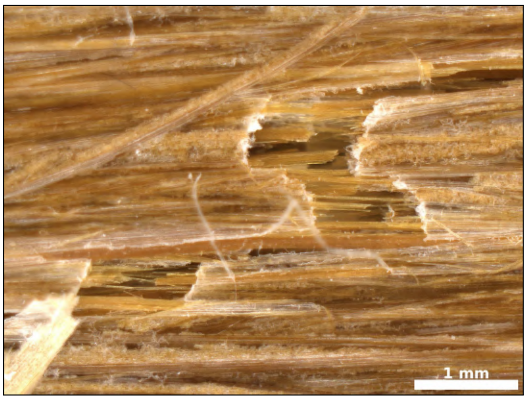


Figure 5.6: Failure of PP 180 sample 1 [5X zoom]

Figure 5.7: Failure of PP 170 sample

Figure 5.8: Failure of PP 210 sample

5.2 Flexural performance

5.2.1 Results

The flexural modulus of bamboo-epoxy performing only slightly better than the one of bamboo-PP samples is surprising, given the poor performance of PP samples observed in tensile testing. Oppositely, the flexural strength of bamboo-PP samples being so low is surprising, however logical when looking at the failure mode, presented in the following section.

The flexural properties are in the same order of magnitude than the tensile properties. The flexural modulus for both PP and epoxy is notably higher than the standard tensile mod-

Figure 5.9: Failure of PA11 195 samples

Figure 5.10: Failure of PA11 205 sample

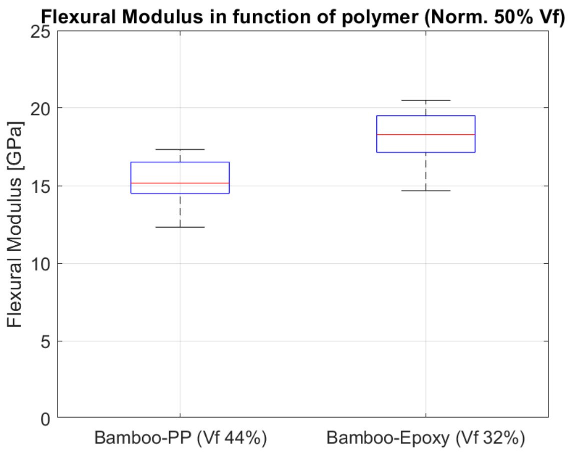


Figure 5.11: Flexural Modulus in function of polymer matrix

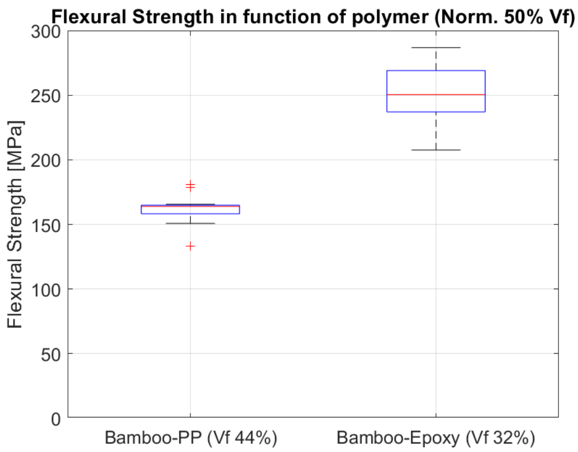


Figure 5.12: Flexural Strength in function of polymer matrix

ulus, but however not higher than the maximum tensile modulus. The flexural modulus of composite laminates normally being close to the tensile one, shows that the standard tensile modulus measured is lower than should be and does not represent well the optimal fibre properties. Additionally, the flexural strength corresponds to the lower end of the tensile strength measured.

5.2.2 Failure analysis

Epoxy and PP laminates exhibited significantly different deformation and failure mechanisms. The difference in behaviour can be observed from the stress-strain curves displayed in fig. 5.13 and 5.14 below.

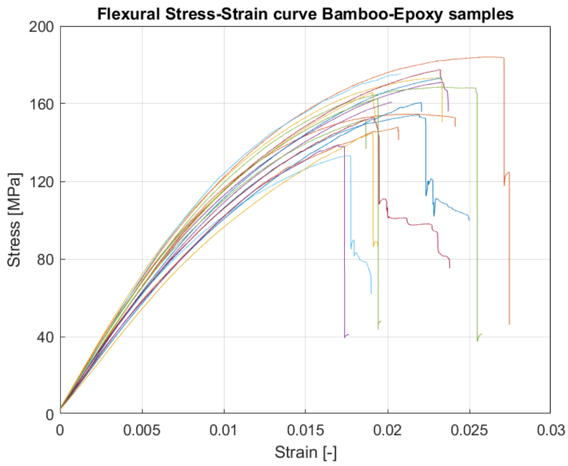


Figure 5.13: Bamboo-Epoxy Flexural Stress-Strain curve

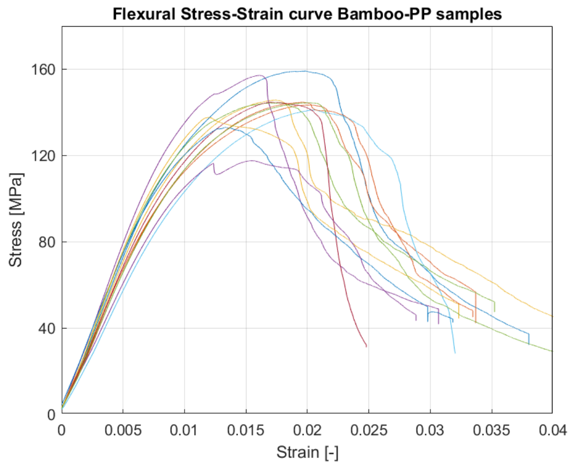


Figure 5.14: Bamboo-PP Flexural Stress-Strain curve

The stress-strain curve of epoxy samples exhibits an abrupt drop at maximum stress, meaning catastrophic failure occurs where all structural integrity is lost. On the other hand, PP samples exhibit a more progressive drop in stress, demonstrating the much greater ductility of the laminate and progressive failure mechanism.

Epoxy

Figures 5.15 and 5.16 display the failure modes of epoxy samples when submitted to flexural loading. These failed either due to tensile fibre fracture or shear failure at the mid-plane of the sample.

PP

The PP samples failed in a much different mode than the epoxy samples. Indeed, oppositely to the epoxy sample, they failed under compression due to buckling. Two different types of failures were observed. Single point buckling of the sample at or close to it's middle point (5.17 and 5.18) and dual point buckling of the sample under each loading point (5.19 and 5.20).

5.3 Interpretation of results

The main hypothesis explaining the better performance of PA11 than PP is that PA11 bonds significantly better thanks to formation of hydrogen bonds at the fibre-matrix interface.

Figure 5.15: Tensile fibre fracture epoxy flexural sample [3X Zoom]

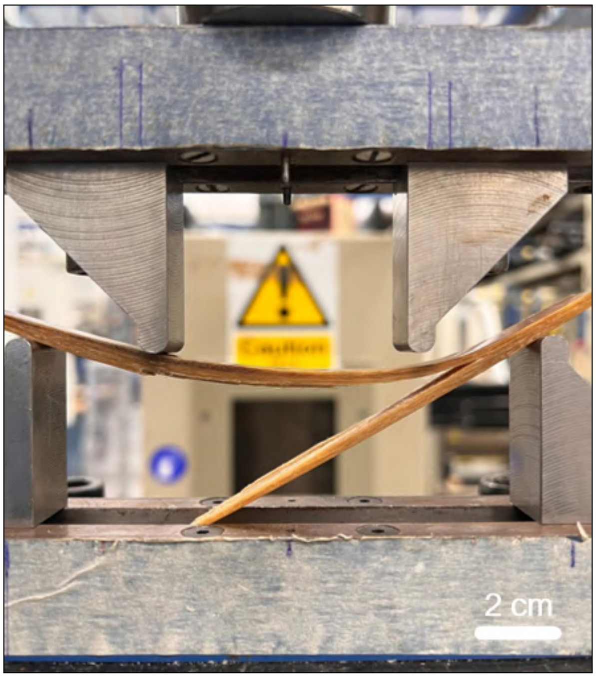


Figure 5.16: Shear failure epoxy flexural sample

Research over the polymer properties and their interactions with the fibre was then done to determine if this hypothesis is true.

5.3.1 Polymer properties

Aside from the intrinsic differences in mechanical properties between PP and PA11, which were taken into account in the calculations of results, this analysis will focus on the less familiar properties that can affect the bonding of the polymer to the fibres. All these properties are summarized in Table 5.1 below.

	PP	**PA11**
Tm (°C)	166	185
Thermal stability	Medium	High
MFI (g/10min)	8	8-12
Crystallinity (%)	50-70	30-50
Polarity	No	Yes
Hydro-	-phobic	-philic
Hygroscopic	No	Yes

Table 5.1: Detailed properties of Polymers

Figure 5.17: Middle Buckling PP flexural sample

Figure 5.18: Middle Buckling PP flexural sample [3X Zoom]

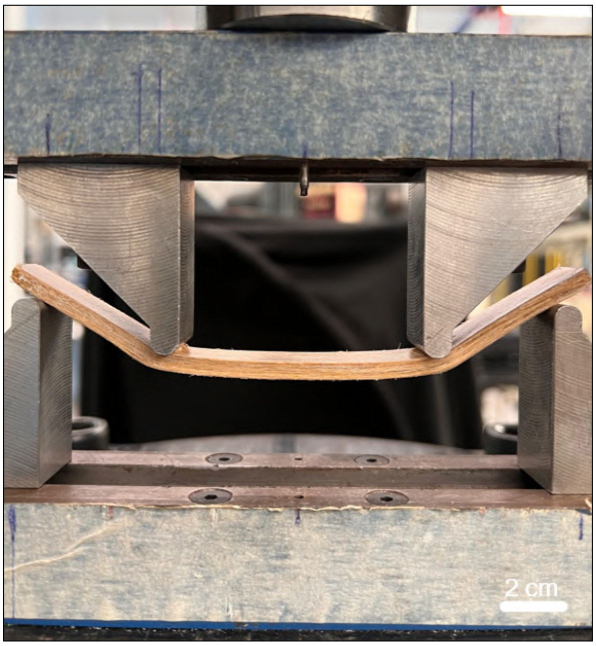


Figure 5.19: Dual Buckling PP flexural sample

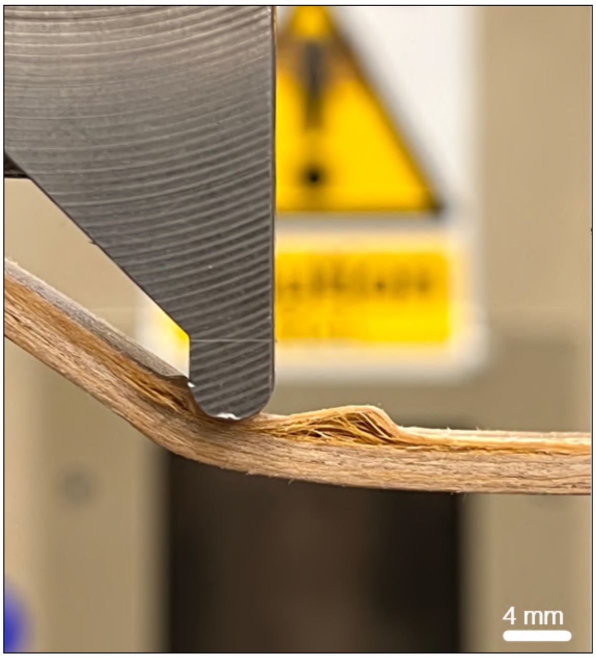


Figure 5.20: Buckling PP flexural sample under loading point [3X Zoom]

First, it is important to mention that the melting temperature being higher for PA11 than PP, influences the processing temperature range used for production of composite laminates which in turn creates differences in fibre as well as interfacial properties. These interactions will be investigated in the following sections.

The thermal stability of PA11 is greater than the one of PP. Indeed, PA11, thanks to its polar nature can withstand higher temperatures without significant degradation [47]. It can thus be assumed that the mechanical properties of the PA11 stay constant over the temperature processing range used, and that no polymer mass loss occurred. On the other hand, due to the lower thermal stability of PP, some degradation in mechanical properties should be considered for the PP samples produced at temperatures much over its Tm. However, the thermal degradation temperature of PP being around 350°C [48] [49], it is safe to assume no polymer mass loss during production.

The melt flow index (MFI) of both polymers being almost equal, should not be responsible for differences in performance. The MFI values were obtained from the TDS of each material polymer.

Furthermore, submitting the polymers to temperatures above their Tm and slowly cooling down generally increases their crystallinity [50]. Increased crystallinity of polymers generally increases their tensile strength and stiffness but comes with the price of increased brittleness. [51]

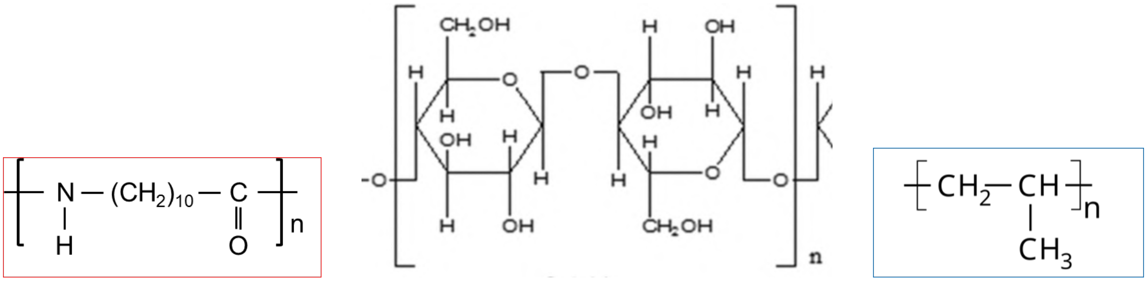
Finally, PP is non-polar, hydrophobic and non-hygroscopic whereas PA11 is polar, moderately hydrophilic and hygroscopic. [47] These properties improve the chemical resistance of PP versus PA11 due to possible hydrolysis of PA11.

5.3.2 Interfacial properties

Due to the differences in polymer properties previously presented in Table 5.1 the bonding mechanisms at the fibre-matrix interface can differ. Indeed, the core difference in bonding of PP and PA11 to bamboo fibre comes from the polymer polarity and its hygroscopic properties. The hydrophobic nature of PP in contrast with the hydrophilic nature of the fibres creates a lack of chemical bonding at the fibre-matrix interface. On the other hand, the PA11 is prone to the formation of hydrogen bonds with the fibre. The polar nature of PA11 due to its amide groups, makes it possible for hydrogen bonds to form with the hydroxyl groups present at the fibre surface. [52]

Furthermore, since the hydroxyl groups are mostly available in the cellulose and hemicellulose of the fibres, increasing temperature causing melting of the lignin and softening of the hemicellulose and cellulose can make it easier for hydrogen bonds to form. Indeed, the hydroxyl groups in the fibre then become more available to the amide groups present at the fibre-matrix interface. [53]

Additionally, the better wetting properties of PA11 can also lead to enhanced mechanical interlocking, in contradiction with PP which has poor wetting properties due to its low surface energy. [31]



(a) PA11 **(b)** Cellulose (Fibre) **(c)** PP

Figure 5.21: Molecular Microstructure of Fibre Cellulose and polymer matrices

Polypropylene (PP) and Polyamide 11 (PA11) have significantly different bonding behaviors with cellulose (5.21b) due to their distinct microstructures and molecular interactions.

PP (5.21c) is a non-polar, semi-crystalline polymer primarily composed of carbon and hydrogen atoms with a methyl group (-CH3) attached to its backbone. This lack of polar functional groups results in weak intermolecular interactions, such as van der Waals forces, making it difficult for PP to bond effectively with cellulose, which is rich in hydroxyl (OH) groups.

In contrast, PA11 (5.21a has a semi-crystalline structure with repeating amide groups (-CONH-) along its backbone, which introduce polarity and the capability for hydrogen bonding. The presence of these polar amide groups allows PA11 to form strong hydrogen bonds with the hydroxyl groups in cellulose. These hydrogen bonds significantly enhance the adhesion between PA11 and cellulose, leading to better compatibility and bonding.

In order to conclude that PA11 bonds better to bamboo fibres than PP does, recent literature which states that a dense network of static hydrogen bonds can be formed between PA11 and bamboo fibres [54] was found. Additionally, this hypothesis was attempted to be self-validated through FTIR analysis. Due to uncertainty in the interpretation of results, the latter were not considered for the analysis and placed in Appendix **??**.

5.3.3 Fibre-Matrix Bonding Efficiency

From the polymer, fibre and interfacial properties correlated to the composite properties found in results, the fibre-matrix bonding can be estimated. Bonding efficiency is considered by introducing a k bonding efficiency factor, similarly to how to how it was done in the work of Woigk et al. [31]. The k efficiency factor is the percentage of the measured property in comparison to the theoretical maximum, to quantitatively describe impregnation and interface efficiency. In the case of our study, the theoretical maximum was taken to be the maximum modulus achieved with epoxy, and compared to the measured modulus of PP and PA11 samples.

The k efficiency factor applies to the RoM formula when determining the modulus of a composite. It does not apply to the strength determination formula because of the more complex and non-linear mechanisms involved with composite failure.

$$E_{composite\_real} = k[V_{fibre} * E_{fibre} + (1 - V_{fibre}) * E_{matrix}] \tag{5.1}$$

Where

$$k = \frac{E_{composite\_real\_Normalized}}{E_{composite\_theoretical}}$$

With E_{fibre} being the back-calculated fibre modulus obtained from the epoxy samples tested. A 100% bonding efficiency is thus assumed for the epoxy laminates. This will serve as reference to estimate the bonding efficiency of PP and PA11 laminates.

The k bonding efficiency factor was then estimated for the following assumption case: No fibre degradation, No polymer degradation - Constant fibre Modulus - Constant polymer Modulus

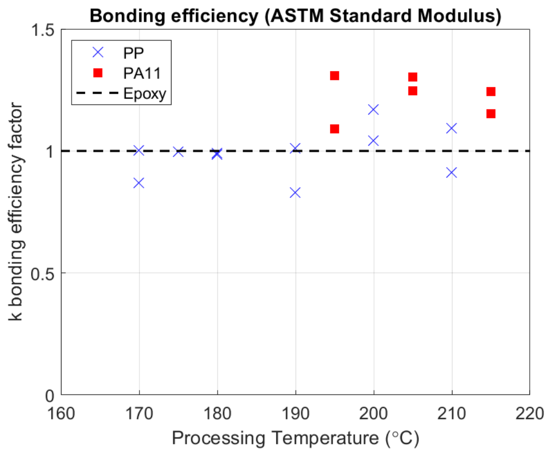


Figure 5.22: Fibre-Matrix bonding efficiency in function of processing Temperature (ASTM Standard Modulus)

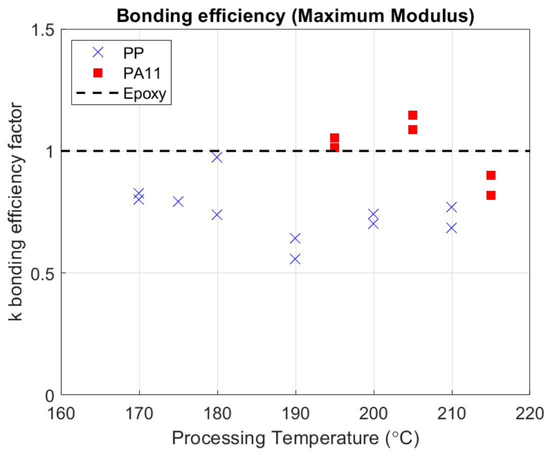


Figure 5.23: Fibre-Matrix bonding efficiency in function of processing Temperature (Maximum Modulus)

In figures 5.22 and 5.23 is presented the k efficiency factor for PP and PA11 laminates in function of their processing temperature using both the ASTM standard modulus and the maximum modulus measured.

The results obtained for the ASTM Standard Modulus are unreliable. Indeed, not only does the k efficiency factor of PP, on average over the temperature processing range, equal the one of epoxy, but the bonding efficiency values found for PA11 laminates have a lot of scatter and are surprisingly high. After having observed the lower performance of Bamboo-PP laminates and their failure due to poor fibre-matrix adhesion, any calculation stating that PP bonds equally well to Bamboo than epoxy does is illogical results which can be discarded. Additionally, covalent bonds which form between epoxy matrix and fibre being the strongest in polymers, results displaying a 50 or even up to 80 % increase in bonding efficiency for a thermoplast is highly debatable. However, the possibility of a thermoplastic polymer bonding better to bamboo fibre than a thermosetting polymer is considered. The data thus obtained and presented in 5.22 is considered irrelevant and disregarded for further analysis.

Fortunately, the results observable in fig. 5.23 are coherent with previous observations made. Indeed, PP laminates overall show a significantly lower bonding efficiency than epoxy, which is expected after observing the poor fibre-matrix adhesion upon failure. Also, PA11 again performed better than epoxy but this time within an acceptable range, with a 10 to 30 %

stronger bonding. The bonding mechanisms of PA11 to Bamboo fibre, investigated in 5.3.2, make this a plausible result.

Although the results and values obtained for the k bonding efficiency are debatable, since it is physically impossible that a thermoplastic polymer forms stronger bonds than covalent bonds which are present with epoxy, the results correspond to the tensile modulus values shown in Figure 5.1. Additionally, the results observed for the k factor puts forward that the use of maximum modulus values and their relation for laminates with different polymer matrices shows more coherence than the ASTM standard modulus values obtained.

Part II: Influence of Processing Temperature during Compression Moulding of Bamboo Fibre-Thermoplastic laminates

How does the processing temperature influence bonding of TP polymers to mechanically extracted Bamboo fibres and corresponding mechanical properties?

5.4 Tensile composite properties in function of processing temperature

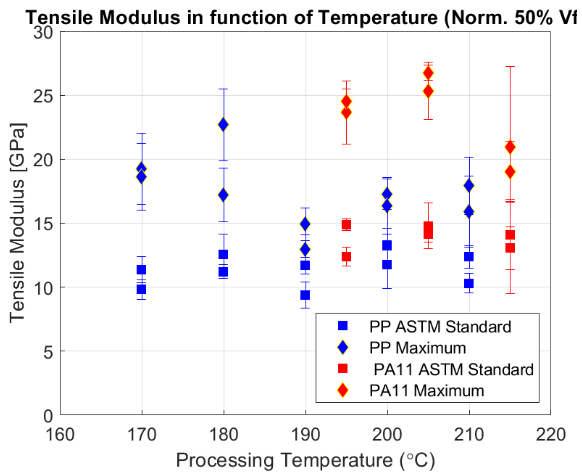


Figure 5.24: Tensile Modulus in function of processing temperature

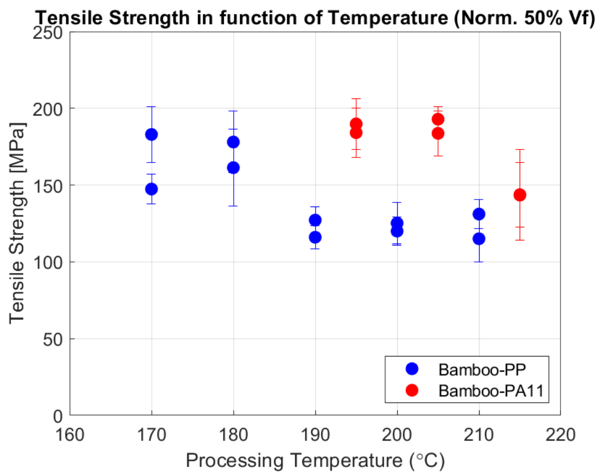


Figure 5.25: Tensile Strength in function of processing temperature

From fig. 5.24 and 5.25 can be observed that the modulus stays approximately constant over the processing temperature range for both the PP and PA11. The same is observed for the strength of PA11 laminates which stays constant at approximately 210 MPa. The strength of PP laminates however exhibits a significant drop of 33% for laminates processed at 190°C and above. Despite this sudden drop, the strength then keeps a constant performance even with increasing temperatures. Moreover, these figures display the significantly greater performance of PA11 over PP.

		PP				
Processing Temp (deg)		170	180	190	200	210
Modulus (GPa)	- ASTM	10.6 ± 1.17	11.2 ± 1.11	10.4 ± 1.3	12.5 ± 1.7	11.3 ± 1.3
	- MAX	18.9 ± 2.6	19.9 ± 3.7	13.9 ± 1.5	16.8 ± 1.7	16.9 ± 2.6
Strength (MPa)		165.2 ± 23.2	169.7 ± 22.0	121.6 ± 9.6	122.6 ± 11.1	123.1 ± 16.6
Elongation @break (%)						

Table 5.2: Tensile Properties - PP

		PA11		
Processing Temp (deg)		195	205	215
Modulus (GPa)	- ASTM	13.6 ± 1.4	14.5 ± 1.7	13.6 ± 2.2
	- MAX	24.1 ± 1.7	26.1 ± 1.6	20.0 ± 3.6
Strength (MPa)		187.0 ± 14.0	188.3 ± 10.9	143.6 ± 18.1
Elongation @break (%)				

Table 5.3: Tensile Properties - PA11

5.4.1 Bamboo-PP Performance

First, the significant drop in strength of the PP laminates processed above 190°C can be explained by a drop in fibre strength. Indeed, due to the PP having poor bonding with the fibre, the expected increase in bonding due to the better fibre wettability, achieved through the lower viscosity when processing at higher temperatures, is thus negligible. The change in properties observed are thus mostly driven by direct changes to fibre properties. In consequence, the drop in strength happening at a lower temperature than the drop in modulus can be associated to the lignin being the first fibre component to start degrading, from temperatures around 180°C. Indeed, the lignin, acting as the main binding agent in the fibre is thus more responsible for the strength than the modulus. The impact on the composite strength thus becomes ever more significant with poor matrix adhesion [3].

Additionally, the TGA (Fig. 5.26 below) showed that the rest of the fibre starts degrading at temperatures above 200°C, in-line with the drop in modulus observed only for PP laminates produced at 210°C.

In consequence, increasing the processing temperature will negatively impact the strength of PP composites before impacting its Modulus.

5.4.2 Bamboo-PA11 Performance

When looking at the tensile results for PA11, it is surprising to see that the Modulus of the fibre does not drop. Indeed, although a noticeable fibre degradation is observed past 200°C, the modulus steadily increases up to 215°C. This increase can be attributed to some fibre fusion occurring, which counteracts the drop in performance expected due to thermal degradation. The increased internal cohesion achieved though fibre fusion has a greater impact on the modulus than the strength because of more complex failure mechanisms of the composite affecting its strength. In consequence, the strength of PA11 composites showed a slight decrease between PA11 195 and PA 215 laminates, however minimal in comparison to the mass loss from fibre burning.

Furthermore, the increase in modulus and minimal decrease in strength observed can be correlated to a better fibre-matrix bonding efficiency occurring in relation to increasing temperature. Indeed, at higher temperatures a greater bonding efficiency can be achieved through the increase of hydrogen bonds at the fibre-matrix interface, as explained in 5.3.2, which result in a better distributed load through the laminate in turn enabling greater stiffness and strength.

5.5 Fibre properties

5.5.1 Fibre Thermo-Gravimetric Analysis

Thermo-Gravimetric Analysis (TGA) is an analytical technique used to measure the amount and rate of weight change in a material as a function of temperature or time under a controlled atmosphere. This analysis was performed by Bambooder for their bamboo fibre with the results shared and presented in 5.26. In this graph, the weight loss in percentage of initial mass is shown for three different fibre types (coloured lines), as well as for the lignin content.

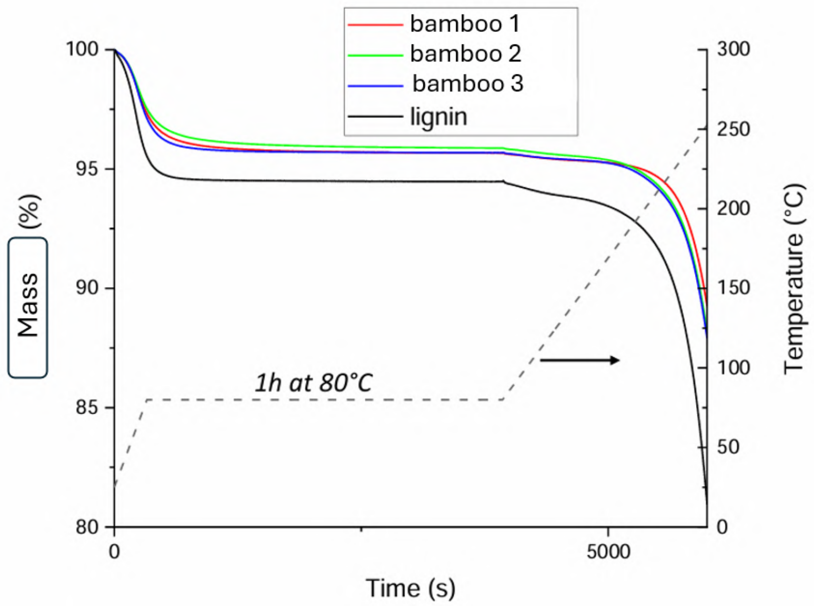


Figure 5.26: TGA of Bambooder fibres

The TGA reveals that the lignin starts degrading much faster than the rest of the fibre, with a 5% weight loss already at 80°C and an exponential drop measured from 200°C onward. The rest of the fibre, namely the cellulose and hemi-cellulose, start to burn at slightly more elevated temperature, with a significant drop in weight from 225°C onward. Additionally, the approximately 4 % initial drop in fibre mass can be correlated to the moisture present in the fibre.

5.5.2 Fibre morphology: Microscopy

Temperature influence on PP laminates

Close comparison of Figure 5.27 and 5.28 reveals a difference in the bundles of technical fibres observed. Indeed, it seems that with more elevated temperature the fibres have started to get closer to each other as it can be observed that the fibre cell walls within a bundle become less visible.

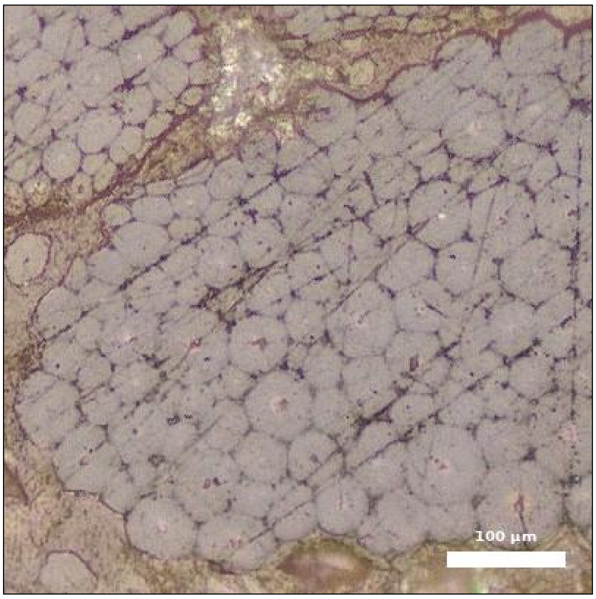


Figure 5.27: Zoom on Cross-section of PP 170 [20X Zoom + Image Zoom]

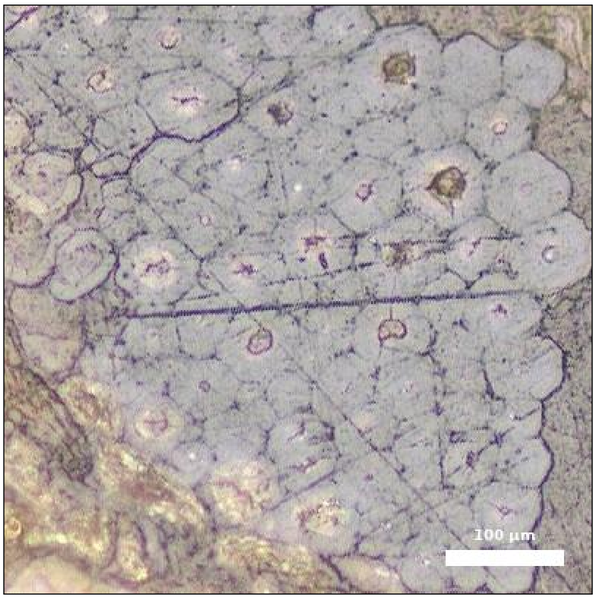


Figure 5.28: Zoom Cross-section of PP 210 [20X Zoom + Image Zoom]

Temperature influence on PA11 laminates

Similarly to the PP laminates, the fibres began to be closer to each other when subjected to increased temperature. When comparing 5.29 and 5.30 this seems even more visible than for the PP samples. This may be due to the processing temperature being the highest for the PA11 215 laminate where merging of individual fibres in the bundles is the most visible.

This physical phenomena can be explained by looking at the thermal properties of the main components of the fibre: Cellulose, hemicellulose and lignin. The cellulose only starts degrading at temperatures around 240°C however it starts softening before reaching these temperatures. The softening of the cellulose allows it to deform and create more contact points between fibres. Similarly to the cellulose, the hemicellulose contributes to this phenomenon through its softening at lower temperatures, as it starts degrading around 200°C. The lignin, key component for fibre surface, is known to be the main binding agent in the fibre. Indeed,

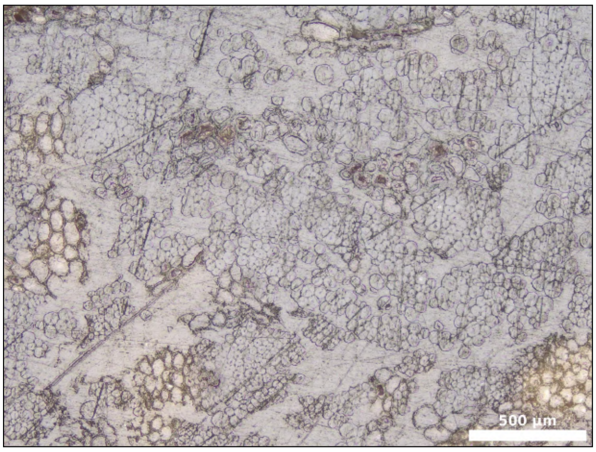


Figure 5.29: Cross-section of PA11 195 [20X Zoom]

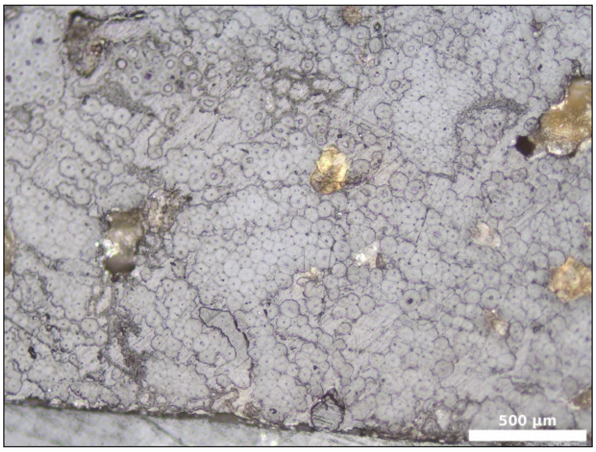


Figure 5.30: Cross-section of PA11 215 [20X Zoom]

lignin being amorphous can act as a binding agent between fibres, as it can soften and re-solidify. [52] Additionally, its degradation at lower temperatures around 170°C, as observed in the TGA Fig. **??** above, thus allows the fibres to better bind together without significant thermal degradation.

5.6 Interfacial bonding

For the Bamboo-PA11 laminates, an increase in hydrogen bonding was expected with increasing temperature due to the greater amount of fibre hydroxyl groups becoming available as the lignin starts melting and hemicellulose and cellulose start softening. [3] However, the mechanical properties significantly dropped for the laminate produced at 215 deg. In addition to the fibre and polymer degradation, a plausible explanation for this result is the increase in hydrolysis of the PA11, explained in next section 5.7.1. Hydrolysis in PA11 causes the scission of amide bonds which breaks down the polymer chains and therefore reduces the number of available amide groups [55]. In consequence, fewer amide groups are available to form hydrogen bonds with the hydroxyl groups on bamboo fibres, even though more hydroxyl groups were theoretically made available with increasing temperature.

5.6.1 Failure Analysis

The failure mechanisms observed for PP and PA11 composites in function of temperature can also be representative of the fibre-matrix bonding properties.

Observation of the failure modes of PP and PA11 samples showed that increasing temperature led to a more brittle failure. Indeed, PP samples processed at 210°C (Fig. 5.8) featured more fibre rupture and less fibre slippage and pull-out than the PP 170°C samples (Fig. 5.7). The failure thus starting to resemble more the one of epoxy samples, which are known to have good fibre-matrix bonding thanks to their covalent bonds. This improvement in bonding was however not sufficient to counteract the thermal degradation of the composite.

The PA11 samples featured a failure mode similar to the one of epoxy for all samples in the temperature processing range, much more brittle. Indeed, the samples fail due to fibre rupture. This therefore shows the good bonding of PA11 with the fibres for all laminates produced. However, no difference in failure was observed between the PA11 215°C and PA11 195°C thus not providing any information on any difference in bonding in function of temperature.

It can thus be concluded that for the PP laminates produced, higher processing temperature led to a greater fibre-matrix bonding efficiency which however came at the price of overall degraded properties of the composite due to thermal degradation of its components. Moreover, fibre slippage of the PP samples highlights the poor adhesion between fibre and matrix, whereas fibre breakage failure of PA11 shows that the load was successfully distributed through the matrix to the fibres, which can sustain higher stresses. Thus confirming the better fibre-matrix adhesion obtained with PA11 and justifying the significantly higher strength of samples in comparison to PP samples.

5.7 Mass Loss and Fibre Volume Fraction

5.7.1 Composite Mass Loss

In Fig. 5.31 is presented the mass loss measured for each laminate produced, in function of processing temperature. This data was obtained by subtracting the mass of the laminate measured after production to its initial material mass.

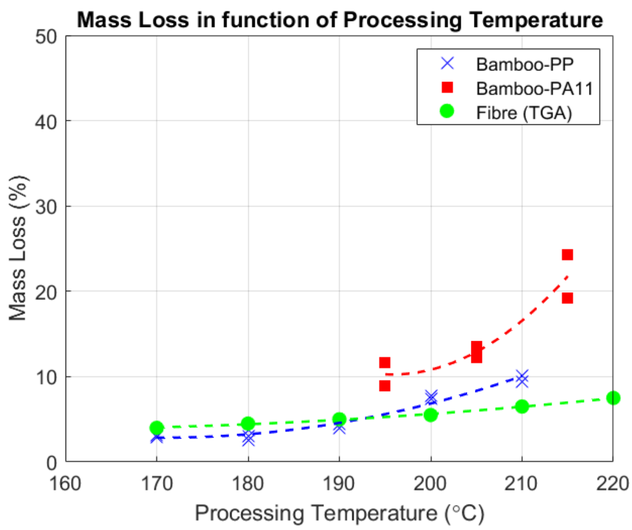


Figure 5.31: Mass loss in function of processing Temperature

Firstly, the results visible in fig. 5.31 show the minimal mass loss of laminates produced under 180 deg C. Indeed, the 3 % mass loss, corresponding to an approximately 5 % mass loss when assuming fibre degradation only, matches the results found for the fibre TGA. Thus confirming that other than moisture escaping, no degradation is observed under 180°C. Additionally, the mass loss starts to increase significantly past 200°C, in line with the exponential loss observed in the fibre TGA past this temperature point.

When comparing the TGA results to the mass loss during composite production presented in Fig. 5.31, it is important to distinguish the differences in heating cycles. Indeed, the TGA was performed with an initial hold at 80°C for one hour followed by a linear temperature increase until no fibre mass would remain, whereas the pressing cycle featured a linear increase of 10 deg C / min directly up to maximum temperature followed by a hold period of 40min. This implies that although the weight loss is only of approximately 5% at 200°C for the TGA, holding this critical temperature for a prolonged period of time can result in a greater weight loss. This difference in heating cycle can explain the greater fibre mass loss, of approximately 13% for Bamboo-PP laminates when processed at 200 and assuming fibre mass loss only.

Initially, based on literature presented in subsection 5.3.1 the assumption was made that no direct mass loss is observed for the polymers for the temperature processing range used. Therefore assuming that all mass loss came from fibre degradation. However, this assumption is debatable due to two main arguments:

The first being that some percentage of mass lost by resin flowing and being trimmed off the laminate edges before weighing. Unfortunately, the mass of polymer trimmed off was not measured, making the polymer mass loss due to resin escaping not quantifiable with the current data.

The second argument is the significant difference in mass loss observed between laminates produced with PP or PA11, which reveals that the mass loss is not only dependant on the fibre. This difference in mass loss is an interesting phenomena to be investigated. There can be several reasons to explain this difference, investigated below.

Although the thermal stability of PA11 is known to be greater than of PP, its hygroscopic properties make it prone to hydrolytic degradation, especially if exposed to moisture at elevated temperatures [47]. The fibres containing a certain amount of moisture, observed from the TGA to be around 4%, due to their raw, untreated and non-dried nature, makes this phenomena a valid hypothesis for the greater mass loss of PA11 laminates in comparison to PP laminates. Lods et al. [54] confirmed the decrease in polymer degradation temperature upon processing of Bamboo-PA11 laminates. Additionally, Bahrami et al. [55] explain that when hygroscopic polymers such as PA11 are exposed to moisture at high temperatures, the amide bonds in PA11 react with the water molecules, leading to chain scission and reduction in molecular weight. Therefore, for the PA11 laminates produced a percentage of the mass loss can be considered polymer loss.

Conversely, the hydrolyctic degradation may exacerbate the fibre degradation, adding to the explanation of increased mass loss when processing Bamboo-PA11 laminates. [56]

To conclude, for the PP laminates, when neglecting possible polymer mass trimmed off after production, the mass loss can be associated solely to fibre degradation. For the PA11 laminates however, the mass loss can be associated to fibre mass loss as well as early polymer degradation induced by hydrolysis.

5.7.2 Vf determination

In order to determine accurately the Vf of laminates produced, the mass loss measured after processing was considered.

For the PP laminates produced, all mass loss was assumed to come from fibre degradation, as the values correlate to the TGA result. This correlation in results makes the fibre degradation values more reliable for the PP than the PA11 laminates, which exhibited abnormally high mass loss.

The fibre mass loss for the PA11 laminates produced was thus estimated from the fibre mass-loss measured for PP laminates, and the rest is considered polymer degradation.

The fibre degradation values used for calculation of real Vf of laminates are presented in Table 5.4 below.

Material	**PP**					**PA11**		
Temperature (°C)	170	180	190	200	210	195	205	215
Fibre Degradation (%)	5	6	7	13	17	10	15	20

Table 5.4: Fibre Degradation PP and PA11

In order to calculate the real Vf of laminates, the real (decreased) fibre mass was used, instead of the initial material mass. Also, for PA11 laminates the loss in polymer mass was accounted for.

5.8 Conclusion

How does the processing temperature influence bonding of TP polymers to mechanically extracted Bamboo fibres and corresponding mechanical properties?

To conclude, the influence of processing temperature is highly dependent on the polymer used. Indeed, PP samples having a low fibre-matrix bonding efficiency even at temperatures where no fibre burning is recorded, the increase in temperature did not portray a noticeable increase in bonding.

On the other hand, PA11 samples showed much greater bonding efficiency on all samples within its temperature processing range. Indeed, the PA11 composite exhibits higher properties thanks to the additional hydrogen bonds created at the fibre-matrix interface. The increase in hydrogen bonding was valitaed by FTIR analysis and literature. As the processing temperature increases, the number of bonds formed can increase thanks to the greater number of hydroxyl groups available at the fibre surface. However, possible hydrolysis in PA11 can cause a reduction of the amide groups available to bond, therefore not increasing further the number and total strength of hydrogen bonds.

On a composite level, the thermal degradation of fibre and polymer can be counter-acted by enhanced mechanical interlocking achieved through additional wetting of the fibre.

Looking into the inter-facial properties while taking into account the theoretical polymer and fibre degradation and decrease in performance, enabled us to understand on a deeper level the composite properties exhibited and determine the k bonding efficiency factor in function of temperature.

Even though a plausible hypothesis was found to better understand the interaction between fibre and polymer properties in function of processing temperature, these mechanisms and their individual contributions to the composite performance should be investigated further.

Finally, it should be highlighted that the best results were achieved with PA11 and a processing temperature of 205°C. Overall, this discussion helps to better understand the physical phenomena taking place when processing Bamboo-TP laminates at high temperatures, in order to better control and tailor processing parameters to achieve desired properties and avoid undesired ones.

Chapter 6

Results and Discussion: Influence of fibre processing on bamboo fibre-epoxy laminates

This chapter has for focus to answer the following questions:

- *What is the theoretical maximum tensile and flexural performance of mechanically extracted Bamboo fibre without any treatment?*

- *How does fibre processing influence composite properties?*

6.1 Tensile and Flexural performance

6.1.1 Real fibre Modulus

In order to determine the real fibre tensile modulus, additional data processing was required. Indeed, contrarily to the expected behaviour of a sample being tested under tension, as can be observed in Fig. 6.1, the modulus of the sample increases past a certain stress / strain threshold, being approximately 0.005 strain. This is a phenomena which was observed for all samples, with both PP and Epoxy polymer matrices.

This can be due to several factors.

- **1. Fibre straightening / realignment:** Due to the poor alignment of fibres with the longitudinal direction, the fibres can possibly begin to straighten and align better with the load direction in the initial phase of testing.

- **2. Progressive fibre engagement:** A similar mechanism which can be at play is a progressive fibre engagement. Indeed, since the fibres were not pre-tensioned upon manufacturing and certainly have some initial waviness, there can be an onset time where the matrix is first mostly load carrying. When a strain level is reached, the fibres are then under tension and

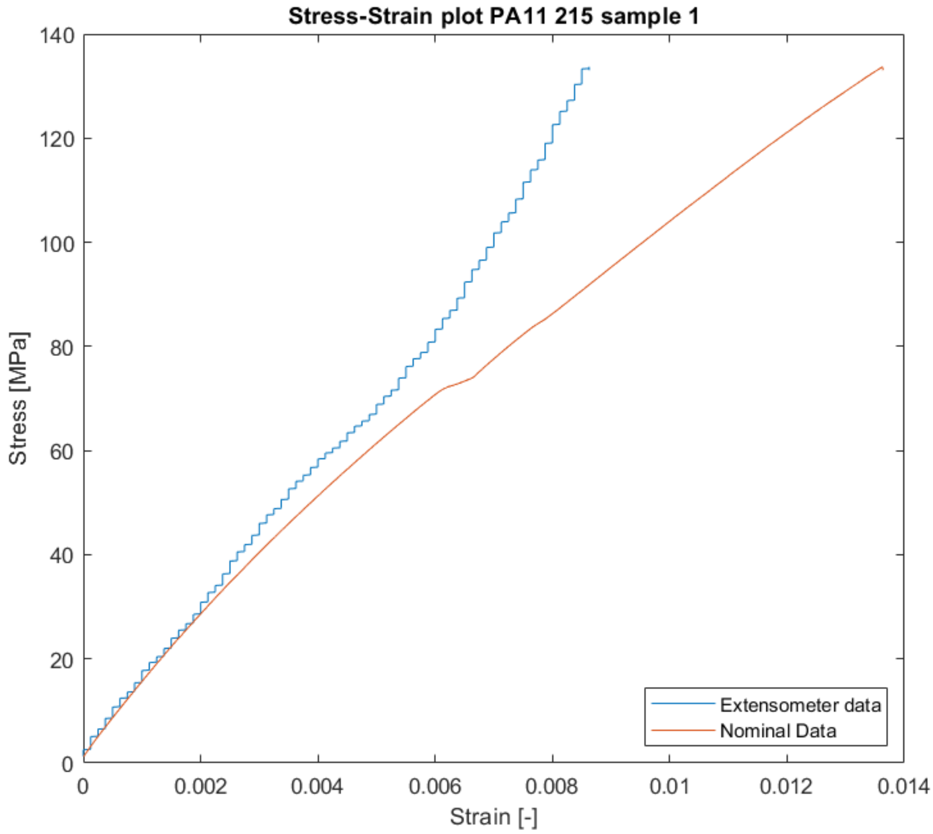


Figure 6.1: Stress-Strain Plot of PA11 215 Sample

fully engage. The significant difference in modulus between matrix and fibre can explain the sudden increase in modulus once the fibres take over the load carrying in the composite.

- 3. Improvement in mechanical interlocking: A third hypothesis which can be relevant in explaining an increase in modulus here is the improvement in mechanical interlocking which can occur when straining the material. Indeed, the rough surfaces of the bamboo fibres can interlock better with the matrix as is conforms closer to the fibres under strain. Mechanical interlocking in between fibres themselves can also occur, this phenomena known as fibre bridging enables the load to better be transferred through the fibre bundles, explaining the observed increase in modulus.

These factors justify that in order to obtain the real fibre modulus, the latter should be measured between points later on the stress-strain curve than the ones specified in the ASTM standard for determination of composite modulus. Indeed, a key difference setting apart the results found in this research project from results found in literature is the use of raw lose fibres, presented in 4.2.1, in contrast to fabrics or yarns which have an inherent pre-tension.

6.1.2 UD Laminate properties

What is the theoretical maximum tensile and flexural performance of the Bambooder fibre without any treatment?

Tensile properties

		Epoxy	Epoxy UD	PP	PP UD
Processing Temp (deg)		-	-	175	175
Modulus (GPa)	- ASTM	11.9 ± 1.2	13.2 ± 1.5	10.6 ± 1.2	12.6 ± 1.6
	- MAX	23.9 ± 2.5	28.4 ± 3.1	18.9 ± 2.6	22.0 ± 1.3
Strength (MPa)		277.5 ± 15.6	284.9 ± 26.4	167.5 ± 18.2	191.2 ± 5.7

Table 6.1: Tensile Properties - UD

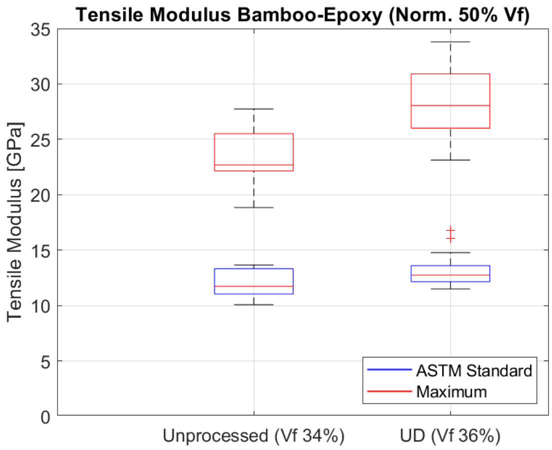


Figure 6.2: Tensile Modulus Bamboo-Epoxy

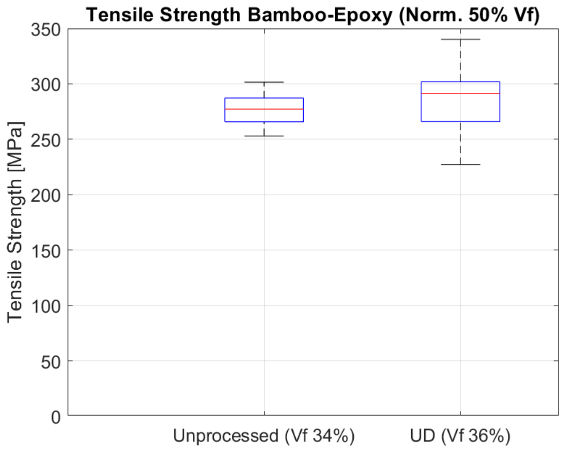


Figure 6.3: Tensile Strength Bamboo-Epoxy

The epoxy samples tested and presented in 6.2 and 6.3 exhibited a mean standard modulus and strength of 11.92 GPa and 277.47 MPa respectively, with corresponding standard deviations (S.Ds) of 1.19 GPa (10.0%) and 15.57 MPa (5.6%). The mean maximum modulus is equal to 23.86 GPa with a S.D of 2.51 GPa (10.5%).

Moreover, the epoxy UD samples tested exhibited a mean standard modulus and strength of 13.20 GPa and 284.93 MPa respectively, with corresponding standard deviations of 1.51 GPa (11.4%) and 26.38 MPa (9.3%). The mean maximum modulus of UD samples is equal to 28.36 GPa with a S.D of 3.08 GPa (10.8%).

On average, the UD samples thus performed 10.7% better for the standard modulus, 18.9% better for the maximum modulus and 2.7% better in strength. An increase in properties was expected however the increase in standard deviation is abnormal and will be further interpreted in 6.4.

Flexural properties

It was observed that the flexural modulus increase for the UD compared to the unprocessed laminate was significant with a 32% increase.

This increase in performance was even more significant for the flexural strength of UD epoxy samples versus unprocessed ones, with a 41% increase.

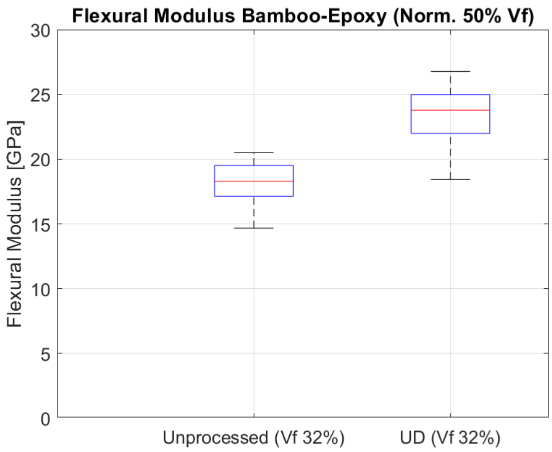


Figure 6.4: Bamboo-Epoxy Flexural Modulus

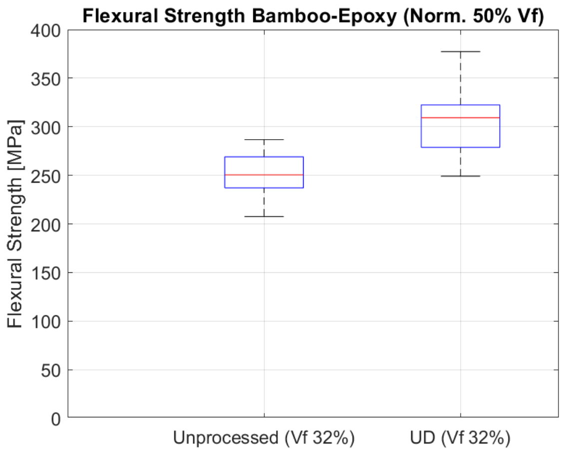


Figure 6.5: Bamboo-Epoxy Flexural Strength

6.1.3 Fibre properties

In order to answer the above question, the production of UD laminates with best fibre quality and orientation was attempted and samples tested. Results are summarized in Table 6.2 below. The back-calculated fibre properties were calculated for each laminate tested according to the methodology described in 4.2.3. Also, it should be reminded that the tensile modulus values used here are the maximum ones, not the ASTM Standard ones. The flexural samples however did not exhibit an increase in modulus upon loading thus their flexural modulus values do correspond to the ones according to ASTM standard.

	Tensile		Flexural	
	Modulus (GPa)	**Strength (MPa)**	**Modulus (GPa)**	**Strength (MPa)**
PP	36.5 ± 5.3	317.5 ± 36.2	29.0 ± 3.2	295.7 ± 20.3
PP UD	42.7 ± 2.6	336.2 ± 50.1	34.1 ± 2.5	283.7 ± 25.8
Increase (%)	**17.0%**	**5.9%**	**17.6%**	**-4.1%**
Epoxy	45.2 ± 5.0	467.2 ± 26.2	33.2 ± 3.2	362.7 ± 31.7
Epoxy UD	54.2 ± 6.2	509.6 ± 49.7	44.6 ± 7.3	484.7 ± 67.3
Increase (%)	**20.1%**	**9.1%**	**34.3%**	**33.6%**

Table 6.2: Maximum modulus and strength of bamboo fibres back-calculated from PP and Epoxy laminates, and their percentage increase for UD fibres

From Table 6.2 is observed that the tensile properties have a similar increase for both PP and Epoxy laminates, exhibiting a much greater increase in Modulus than strength. A logical phenomenon which can explain this difference, is the improvement in fibre orientation. Indeed, improvement in fibre orientation will have a greater impact on the Modulus of the composite than on its strength, as better fibre alignment suggests that more load can be carried by the fibres simultaneously whereas the strength of the composite is more intricate and can be limited by other factors such as poor fibre-matrix adhesion or defects present in the composite.

Furthermore, the flexural properties exhibited a significantly greater increase for epoxy laminates than for PP laminates. This can be justified by the flexural modulus and strength relying much more on fibre-matrix adhesion than tensile properties. In consequence, the possible improvements on fibre orientation and quality have little influence on the PP performance due to the poor bonding efficiency previously demonstrated. On the other hand, epoxy having stronger bonding to the fibres, the physical improvements to the fibres have a large impact on the composite performance as the loads can be better distributed. The minimal drop in strength exhibited by the PP UD laminate is surprising. However, this anomaly may be due to several factors such as the poor fibre-matrix adhesion, making the strength of the bond the limiting factor and not allowing the load to be distributed efficiently in order to extract the full strength from the fibre.

Finally, the flexural properties obtained are slightly inferior to the tensile ones, but close enough to serve as validation of results. Additionally the consistency between flexural and tensile results adds to their reliability. Also, the difference of approximately 25% between flexural modulus and tensile modulus values makes the use of maximum tensile modulus values acceptable.

After observation of performance results and failure modes, it was logical that estimating the real fibre property could not be done using Bamboo-PP data as these showed poor properties in comparison to other polymers used and failed due to fibre pull-out, thus not representative of fibre strength. Therefore, the actual fibre properties should be estimated for the highest performing laminate and failing due to fibre rupture. The Bamboo-Epoxy UD laminates exhibited the best performance with a mean maximum modulus of 28.36 GPa and a strength of 284.93 MPa.

We thus obtain the following back-calculated properties:

- Standard Fibre Tensile Modulus: 23.89 ± 3,01 GPa

- Maximum Fibre Tensile Modulus: 54.23 ± 6,17 GPa.

- Fibre Flexural Modulus: 44.6 ± 7.3 GPa

- Fibre Tensile Strength: 500.91 ± 59,91 MPa.

- Fibre Flexural Strength: 484.7 ± 67.3 MPa

6.2 Fibre orientation

6.2.1 Unprocessed (LIST)

The results of the CT-Scan performed by LIST on a sample are showed in Figure 6.6 below. Important to mention that 90° here actually refers to fibres being in the longitudinal direction (0°).

Data was obtained for two samples. The first sample analysed exhibited a main scattering angle between 0 and 14°, with a mean of 9.7° and median of 5.9°. The second sample exhibited a main scattering angle between 0 and 23°, with a mean of 16.9° and median of 11.4°.

Unfortunately, no results were obtained for the UD samples, due to little availability of the researchers at LIST. However, the data above provides insight on the fibre orientation of unprocessed fibres.

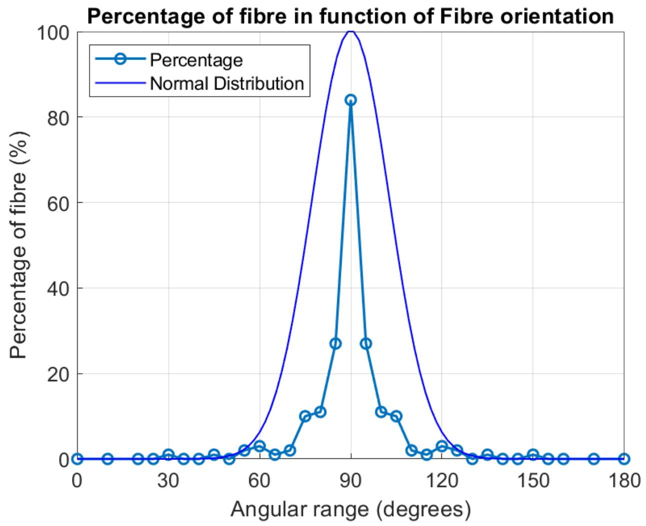


Figure 6.6: Percentages of fibre in function of Fibre orientation

6.2.2 Theoretical performance

The theoretical Young's Modulus of laminates for all fibre directions was calculated according to the methodology described in subsection 4.2.5.

The two samples analysed exhibiting a mean fibre orientation of 10 and 17 degrees respectively, it was assumed that the results of the laminate tested corresponded to a fibre angle of approximately 14 degree.

This would provide a reference point for calculation of the longitudinal modulus E1 in fibre direction, which in turn allows for estimation of Young's Modulus for fibres in all directions, as plotted in Figure 6.7.

The UD laminate tested exhibited higher performance than the theoretical modulus of a composite at 0 degree fibre orientation. This discrepancy can be due to several reasons.

- 1. Assumptions in Formula neglecting some elements which could contribute

- 2. Additional effects of fibre processing discussed in the following section 6.3, enhancing fibre performance.

Although some other factors might come into play to explain the higher performance of the UD laminate, the latter confirms that the UD laminate produced has a majority of fibres aligned in the O direction.

The back-calculated fibre modulus for perfectly aligned fibres, without additional processing was thus calculated to be: **51.19 GPa**, from the assumption that the tested laminate had a fibre orientation of 14 degree. This modulus value is slightly less than the fibre modulus calculated to be **54.2 GPa** for the UD laminate. However, the results being fairly close, validates the theoretical approach used for estimation of the Young's Modulus in function of fibre orientation.

Finally, the values above consider in their calculation, using the ROM, perfect bonding of the polymer to the fibre. If this assumption is not made, the same bonding efficiency factor can

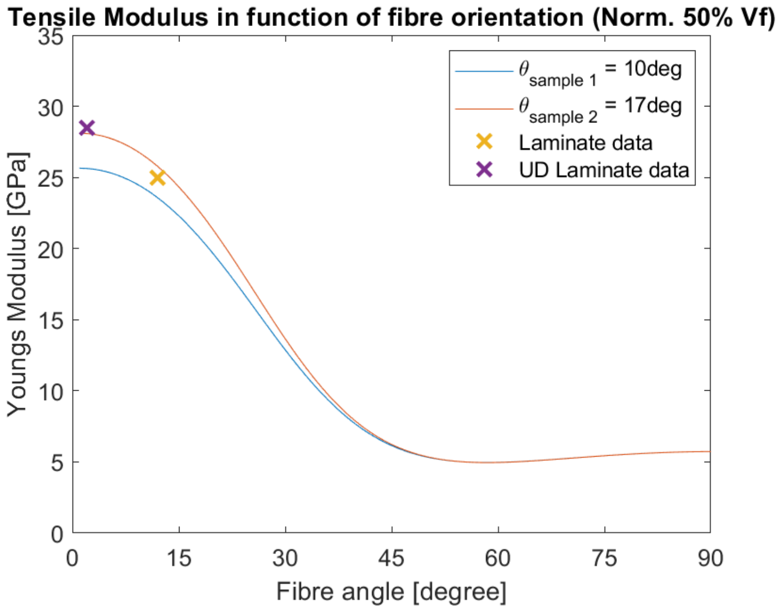


Figure 6.7: Young's Modulus in function of fibre orientation

be used than in the work of Woigk et al. [31], which determined a k bonding efficiency factor of 0.96 between epoxy and flax fibre. To estimate the true fibre tensile modulus with more precision, this factor was applied and the following fibre tensile modulus were obtained: 56.67 GPa for the back-calculated UD laminated fibres and and 53.32 GPa for the fibre orientation estimation fibres.

6.3 Additional effects of Fibre processing

The improvements of composite performance observed for UD laminates, achieved through additional combing of the fibres can be caused by three major phenomena described in this section.

6.3.1 Fibre Orientation

The results presented in 6.2.1 confirmed the poor fibre alignment within epoxy samples. These results therefore show that the fibre orientation in the unprocessed samples has potential to be significantly improved.

Unfortunately, this improvement through additional combing was not quantified as no CT-Scan and analysis was performed on the UD samples. However, this data provided insight on the fibre orientation of unprocessed fibres. Although a perfect fibre alignment of 0° is physically not achievable through simple hand manipulation of fibres, it can be assumed that additional fibre combing helped get closer to it. Additionally, as seen in Figure 6.7 the performance of the UD laminate being close to the calculated performance of a UD laminate from the unprocessed laminate, validates the improvement in fibre orientation.

6.3.2 Fibre Quality

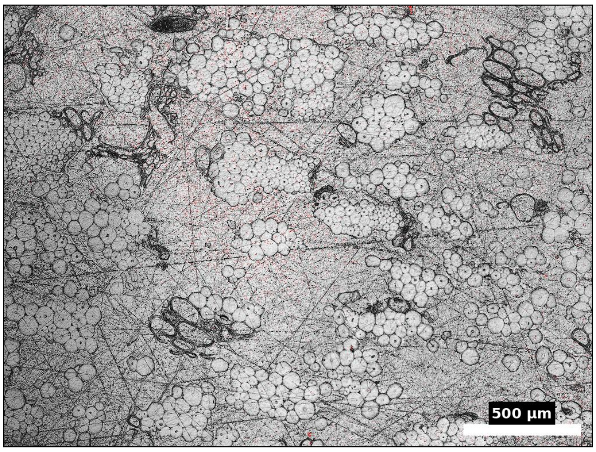


Figure 6.8: Cross-section of unprocessed Epoxy sample [20X Zoom]

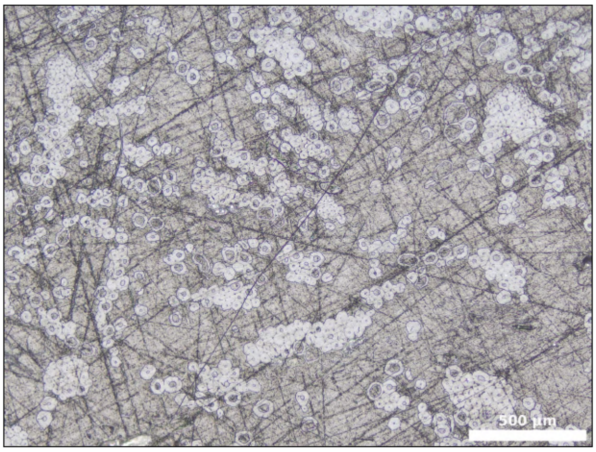


Figure 6.9: Cross-section of UD Epoxy sample [20X Zoom]

An improvement in fibre quality is observed since the parenchyma, characterised by the black bundles of circles visible on the unprocessed cross-section in 6.8, is not visible anymore after extra processing of the fibres. The parenchyma was thus effectively removed or broken down, leading to an enhanced and more controlled fibre quality. Elimination of parenchyma present between fibre bundles enables the load to better be transferred from a fibre to another, thus enhancing composite performance. Additionally, elimination of parenchyma increases the effective technical fibre volume ratio of the composite.

The additional fibre processing performed can also improve the fibre quality itself. Indeed, combing leads to a better selection of fibres, elimination of surface impurities as well elimination of shorter and split pieces of fibres. This can thus lead to enhanced mechanical interlocking between fibre and matrix. [52] [57]

Although the increase in fibre quality is hard to quantify, it is a non-negligible factor that should be considered in the improvement of composite mechanical performance.

6.3.3 Fibre Dispersion

After observation of the cross-sections of epoxy and UD epoxy laminates, it can be said that the extra processing and combing of fibres led to a better and more even distribution of the fibres. Indeed, 6.9 displays fibres better spread on the surface observed, in comparison to 6.8 which displays more concentrated bundles of fibres.

Improved fibre dispersion within the matrix can significantly increase the composite properties. [58] Indeed, in addition to the enhanced impregnation, a greater internal cohesion and distribution of load can be achieved. Therefore, better fibre dispersion is also a factor responsible for the increased mechanical properties of UD laminates.

6.4 Material Scatter

The natural properties of organic materials such as bamboo fibre makes a certain amount of material scatter inevitable. In order to estimate the material scatter of the fibre only, all other factors which could influence composite performance should be kept constant.

For the material characterisation performed, the manufacturing process offering most control is compression-moulding. Indeed, this process allows for more control over the material distribution within the laminates produced, over the fibre and polymer quantities used and thus the vf, as well as during the process with controlled pressure and temperature. Moreover, the UD laminates have less variation in the quality and distribution of their fibres thanks to the additional fibre selection done through combing. Furthermore, flexural laminates being much thicker than tensile laminates, the quantity of fibre present within the laminate is much greater. A greater sample size allows for more accurate determination of the material scatter. Therefore, PP laminates produced for flexural testing are the best option for estimation of the material scatter.

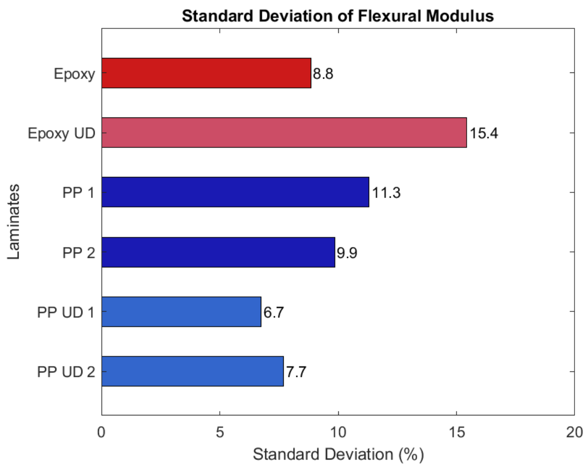


Figure 6.10: S.D percentage of Flexural Modulus

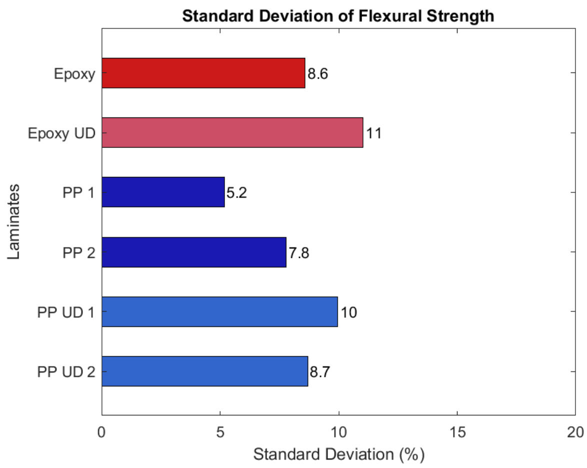


Figure 6.11: S.D percentage of Flexural Strength

The material scatter can thus be obtained by taking the standard deviations (S.D) of samples tested. The S.Ds of all flexural laminates tested are presented in Fig. 6.10 and 6.11. As expected, for the modulus, the lowest SD is achieved for the PP UD samples.

However, some unexpected results were also observed. Indeed, the S.D of the modulus of the UD epoxy laminates increased considerably. This is opposite to the expected result, however it can certainly be justified by the increased variation in sample thickness. Indeed, the additional combing performed on the fibres lead to a greater concentration of fibres at the middle length, thus creating UD laminates thicker in its middle than at its extremities. This phenomenon was of much greater impact for the epoxy laminates produced with resin-infusion than for compression moulded samples. Indeed, the backing plate used during resin-infusion could deform under vacuum pressure to comply with the variations in thickness whereas the geometry of the compression-moulded samples was fixed.

Furthermore, the increase in SD of the strength of PP samples when using UD fibres is also an unexpected result. Indeed, same than for the modulus, a lower S.D was expected. However, as mentioned in the previous section 6.1.2, the poor fibre-matrix adhesion of PP samples produced leads to more complex failure mechanisms not limited by the fibre performance itself. Therefore, the SD of the strength values obtained can be considered irrelevant in the estimation of material scatter.

To conclude, the fibre material scatter has an impact on the composite modulus performance of approximately **7.2%**.

6.5 Conclusion

To conclude, it was demonstrated that with additional mechanical processing of Bambooder fibres, the tensile modulus and strength of composites could respectively be improved by 17% and 6% for PP, and 20% and 9% respectively, for Epoxy. Although the flexural modulus and strength of PP laminates showed little increase in performance due to its poor fibre-matrix adhesion, both the flexural modulus and strength of epoxy samples exhibited a significant increase of 34%.

The influence of fibre orientation on tensile modulus was theoretically quantified, with results matching the performance measured for both the unprocessed and UD laminates.

However, several physical phenomena are responsible for this increase in performance. Indeed, in addition to the initial objective of improving fibre alignment, improvements in fibre quality as well as fibre dispersion through the matrix are also responsible for enhancement of mechanical performance. Therefore, it is not possible with the current fibre processing method and available data to accurately quantify the influence of each separate physical phenomena on the overall improvement in composite performance.

Part III Conclusions

Chapter 7

Summary

First, through literature review the current performance of bamboo fibre as reinforcement in polymer composites was assessed and its viability for structural applications validated. Additionally, research on the environmental impact of bamboo fibre extraction and its use in fibre reinforced polymers confirmed its attractiveness for development of sustainable composite materials.

The research question was then defined to be: *Are mechanically extracted bamboo fibres a sustainable alternative to glass fibres for use in structural composites?*

In order to answer this research question, the research objective was set to characterising the mechanical performance of a mechanically extracted bamboo fibre provided by Bambooder, assessing its processability by producing and testing laminates at limiting temperatures.

In order to get a broader view of mechanical performance, through compression moulding of PP and PA11 laminates and resin-infusion of epoxy laminates, both TP and TS composites were produced with the fibre and mechanically tested in tension and in bending, according to ASTM standards. Employment of other methods such as density measurement, TGA, CT-Scan, FT-IR and microscopy imaging enabled greater material analysis and understanding of composite mechanical performance observed.

A mean fibre density of 1.16 g/cm^3 was measured. Highest composite performance achieved with epoxy revealed a tensile back-calculated fibre modulus of 54.3 GPa and strength of 509.6 MPa. Similarly, flexural back-calculated fibre properties revealed a 44.6 GPa modulus and 484.7 MPa strength. Also, PA11 laminates overall performed better than PP laminates, visible from the poor bonding of PP samples which failed due to fibre pull-out, whereas PA11 and epoxy samples failed due to fibre fracture.

Influence of processing temperature on bonding of TP laminates revealed the high dependency on the type of polymer used. Increased interfacial bonding of PA11 was observed, thanks to the creation of hydrogen bonds due to the non-polarity of the polymer. The tensile modulus stayed approximately constant over the processing temperature range whereas the strength showed a decrease. Little increase in bonding of PP was found, however debatable due to increase in fibre modulus possibly caused by observed fibre-fusion.

Impact of material Scatter on composite modulus was estimated to be 7.3%. Additional processing of fibre showed to improve mechanical performance by up to 20% and and 9% for tensile modulus and strength, respectively. This performance enhancement was achieved through better fibre quality, improved fibre orientation and increased fibre dispersion, although the influence of these factors could not individually be quantified.

To conclude, after motivating the development of bamboo fibre within the composite industry, mechanical testing confirmed their performance. Next, influence of processing temperature and fibre combing on composite performance was assessed. Additionally, the low environmental impact of mechanically extracted bamboo fibres confirmed their competitiveness as sustainable fibre for composite materials.

Chapter 8

Outlook

8.1 Significance of current work

In this section the main findings from this research will be discussed and put in context of current state of research.

8.1.1 Research objective

It can be said that the research objective was achieved by successfully characterising the bamboo fibres. Indeed, the mechanical performance was assessed, the influence of high processing temperatures, additional fibre processing on mechanical performance was defined and the environmental impact was assessed. However, many limitations in the study, presented in 9.1 should be considered to increase the significance of results and conclusions.

8.1.2 Knowledge expansion

Optimising performance in NFRPs

1. Influence of polymer

   Non-polar polymers bond better due to bonding with hydroxyl groups present in fibre, allowing thermoplastic polymers to compete with thermosetting polymers when used with natural fibres.

2. Influence of Processing Temperature

   Mechanical properties of thermoplastic bamboo composite materials can be optimised and tailored to desired properties according to the processing temperature used during compression moulding. Indeed, depending on the polymer used, an increase in modulus can be achieved at the cost of a reduced strength.

3. Influence of fibre processing

   Additional fibre processing, in the form of combing, leads to an improvement in fibre quality, fibre orientation and fibre dispersion in the matrix which can enhance fibre modulus and strength by up to 34%, depending on initial fibre state and polymer used.

8.1.3 Performance in State-of-the-Art

Mechanical performance

The results obtained for tensile, as well as flexural, modulus and strength of bamboo fibres are compared here to results found in literature. Thus providing a more recent view on performance of bamboo fibres in comparison to current industry standards.

	Bambooder	Bamboo	Bamboo-Alk	Flax	E-Glass
Young's Modulus (GPa)	45.2	38	46	80	70
Strength (MPa)	467.2	750	810	700	1500
Density (g/cm3)	1.2	1.4	1.4	1.5	2.5
REF	(6.2)	[59]	[59]	[60]	[2]

Table 8.1: Fibre Properties comparison

Bambooder results are taken from the back-calculated maximum modulus and strength values for UD epoxy composite, presented previously in 6.2.

Bamboo and Bamboo-Alk are results found in literature for mechanically extracted long bamboo fibres untreated and after alkaline treatment, also when used as reinforcement in epoxy polymer. [59] It is important to find literature obtaining results through similar methods, as results obtained from single-fibre testing can differ significantly. Indeed, alkali treated fibres show a reduced performance as the treatment partially degrades the fibre. However, when used in a composite laminate, the increased surface roughness of the fibre allows for greater mechanical bonding with the polymer matrix. Common Flax and E-Glass values were found in literature. [60] [2]

The values found and presented in 8.1 are represented in Fig. 8.1 below.

Environmental Impact

The values found for the embodied energy and C02 emissions provide information on the environmental impact of producing composite materials with bamboo fibre extracted from a novel extraction method and proved to further increase the environmental friendliness of using natural fibres as polymer reinforcement, in comparison to other more energy intensive fibre extraction processes.

8.2 Bamboo fibre composite applications

This research project having confirmed the viability of bamboo fibres for use in structural composites, it is interesting to take a look at specific applications where bamboo fibres would

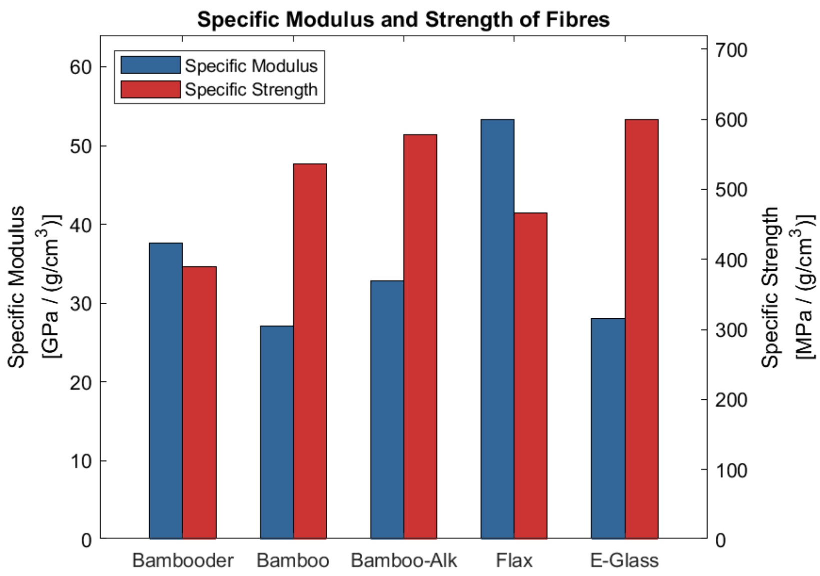


Figure 8.1: Comparison of specific Modulus and strength for different fibre types

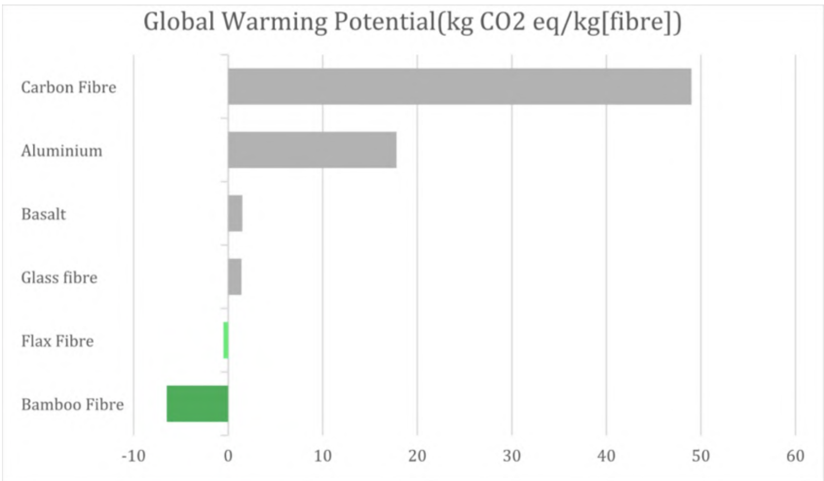


Figure 8.2: CO2 emissions of different fibres (Source: Bambooder)

add value. First, in order to identify prospect applications, the competitiveness and limitations of bamboo fibres should be identified.

8.2.1 Properties overview

Competitive properties

Other than the low environmental impact responsible for the main attractiveness of bamboo fibres, other properties can also add value to composite applications.

First, the excellent specific mechanical properties demonstrated are an attractive property for the use in stiffness-driven design of lightweight structures. Indeed, thanks to its superior specific modulus, bamboo is a promising alternative to glass.

Additionally, natural fibres feature good inherent damping properties which are beneficial to structures which can suffer from vibrations. Also, natural fibres can effectively be used in combination with carbon fibres in hybrid composites in order to dampen the peak vibrational frequencies of carbon.

Finally, its enhanced impact absorption and safety, due to ductile fracture behavior, as well as its low cost, can also drive design-making decisions.

Limiting properties

Although hygroscopic properties are often a limitation for the use of natural fibres in outdoor applications, bamboo fibre exhibits greater durability than most natural fibres [REF].

The lower thermal stability in comparison to synthetic fibres is a limitation; however, it was demonstrated that even when processed at initial fibre degrading temperatures, the structural integrity was preserved.

Furthermore, variability in fibre quality and dimensions can impact the consistency of the end products, making it a notable challenge. The length of fibres, being limited by the inter-nodal length, can also pose a problem when longer fibres are required.

Also, polymer matrix compatibility is a concern. Bamboo fibres have more limitations than synthetic fibres, which bond more easily to most polymers. This necessitates chemical treatments or more careful polymer selection to ensure proper interfacial bonding and performance.

8.2.2 Specific application cases

Automotive Bodywork

An example of a stiffness-driven design application in automotive industry is the bodywork of a car. Indeed, these parts are optimised for stiffness-to-weight as their shape is important and should have minimal deflection under aerodynamic loads, making their strength not a design-driving property.

Figure 8.3: Usage of natural (Flax) fibre in motorsport bodywork parts. Source: BCOMP

In figure 8.3 can be observed the usage of natural fibre bodywork parts in motorsport applications. Bamboo fibres could add value to these parts as they have an even lower environmental impact than flax fibre [61], and decrease issues linked to hygrothermal properties as bamboo generally exhibits better resistance to moisture than flax [62].

Bicycle Frame

Another specific application where bamboo fibre can bring added value is bike frames. Indeed, bamboo fibre's natural damping properties reduce vibrations, enhancing riding experience and reducing crack propagation within the material. Oppositely to carbon fibre, which has a lower impact resistance, bamboo fibre offers a smoother and more durable alternative, addressing the stiffness and vibration issues found in carbon fibre frames.

Figure 8.4: bamboo fibre composite bike frame by Soben [12]

Fig. 8.4 illustrates the use of bamboo fibre composite materials in the fabrication of bike frames. No details were found on the processing of these fibres. However, a high wood content is observable, meaning that the mechanical performance is certainly less than for the mechanically extracted bamboo fibres studied in this project.

Chapter 9

Perspective for future research

In this chapter are discussed certain limitations of this study, research that can be done to mitigate these limitations, and further research prospects.

9.1 Limitations of Study

While this study provides valuable insights into the sustainability and performance of bamboo fibre composites, certain limitations should be acknowledged. These include:

- Fibre quality and material scatter: Inconsistent fibre quality, possible differences between batches not considered, uncontrolled fibre storage conditions
- Composite production and quality: uniformity of fibres in composite, fibre orientation scatter, fibre distribution scatter leading to variations in Vf and thickness within same laminate.
- Polymer properties not characterized. Data taken from TDS or external research done by Bambooder and other master students.
- Effect of processing temperature on pure polymer properties neglected. Polymer properties assumed constant for all laminates produced.
- Partial LCA, generally available data used

9.2 Future Research

Future research can be done to achieve two distinct objectives. First, validating and increasing precision of results obtained by tackling the limitations of this study. Secondly, exploring further research directions to broaden the scope and scientific or socio-economic impact of the study.

Improvements to Study

Future research should address the limitations presented in the previous section by focusing on:

- Fibre density measurement with Pycnometer for more accurate result
- Developing standardized fibre processing and composite production methods for consistent quality. Methods to gain more control over fibre quality, fibre orientation and fibre distribution. Possibly through applying pre-tension on fibres during composite production to extract maximum performance.
- Validation of assumptions and outcomes of discussions
- Quantify fibre dispersion through microscopy image analysis of sample cross-sections. Achievable with "nearest neighbour" quantification.
- Quantification of reduction in parenchyma to quantify improvement in fibre quality achieved with additional combing
- Characterization of polymers used and effect of processing temperature. Perform TGA on fibres as well as TP polymers used with compressive moulding temperature cycle.
- Quantify and validate influence of hydrogen bonding on mechanical performance, possibly with FTIR specroscopy at fibre-matrix interface using FTIR microscope.
- Conducting full cradle-to-grave LCA to assess end-of-life impacts and recycling potential.

Further Research directions

Future research prospects include:

- Progressive TGA with hold period at a range of critical temperatures, ranging from 190 to 250 degrees.
- Estimation of properties through theoretical models such as Halpin-Tsai
- Exploring new polymer matrices to enhance fibre-matrix adhesion and composite properties.
- Explore alternative, eco-friendly fibre surface treatments and processing methods to improve fibre-matrix adhesion
- How much should the fibre extraction process be improved? Find optimal amount of additional fibre processing needed to extract more performance from fibres, for a reasonable effort (effort-gain curve). Extracting maximum performance theoretically achievable through a lot of processing, however getting close to max performance for reduced effort is more valuable.

- Quantifying hygrothermal effects: composite and fibre performance during and after exposure to a range of relative humidity levels, influence of composite cutting with water lubrication on mechanical performance.
- Investigating hybrid composites combining bamboo with other natural or synthetic fibres. Thus tailoring composite properties to design and application requirements and reducing environmental impact while maintaining highest performance.
- Assessing the socio-economic impacts of large-scale bamboo cultivation and composite production.

By addressing these improvements and further research prospects, the role of bamboo fibre composites in sustainable engineering can be solidified and their application potential across various industries expanded.

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Appendix A

Fibre Density measurement

A.1 Fibre Density

A.1.1 Fibre Density Measurement

The fibre density is an essential property in determining its mechanical properties, such as modulus or strength. Indeed, the fibre volume ratio (Vf) of composites is dependant on the density of the materials. Therefore, density of fibres was the first property measured before starting with composite production.

Figure A.1: Instrument used for fibre density measurement

The fibre density was measured using small pieces of fibre yarn (2 to 3cm) and the set-up visible in A.1. On Mettler Toledo precision scale (fig. 4.4) was placed a support structure in which a beaker with distilled water can be placed. A tray is then submerged in the water, while being suspended to the support structure. The measurements were done on a sample size was of 11 fibre yarn pieces.

The following formula was used, as specified in the instrument guideline sheet:

$$\rho = \frac{A}{A-B}(\rho_0 - \rho_L) + \rho_L$$

Where: ρ = Density of sample

A = Weight of sample in air

B = Weight of sample in auxiliary liquid

ρ_0 = Density of auxiliary liquid

ρ_L = Density of air

This measurement method uses the Archimedes principle. Indeed, the difference in mass between the subject when in air or when submerged in water is used in order to estimate its density.

The inaccuracy of this measuring method lies within the absorption of water by the fibre. The density measured then varies. In our case fibres were known to be slightly denser than water, around 1.3 g/cm3. Thus the water absorbed by the fibres will bring the overall density of the fibre down. Measuring the fibre sample after water submersion was attempted, however not representative due to the amount of additional water still present in the sample. Other, more precise density measurement methods such as gas pycnometry are preferable measurement methods which would yield more accurate results, however the device in the faculty lab being broken, this option was made unavailable.

A.1.2 Fibre Density Results

The results presented in this section were obtained according to the methods presented in A.1.1. However, it should be mentioned that the probability density is a weighted probability density. Indeed, in addition to the density values measured, the mass of each sample was taken into consideration, meaning that the density value measured will have a greater probability for a sample of greater mass.

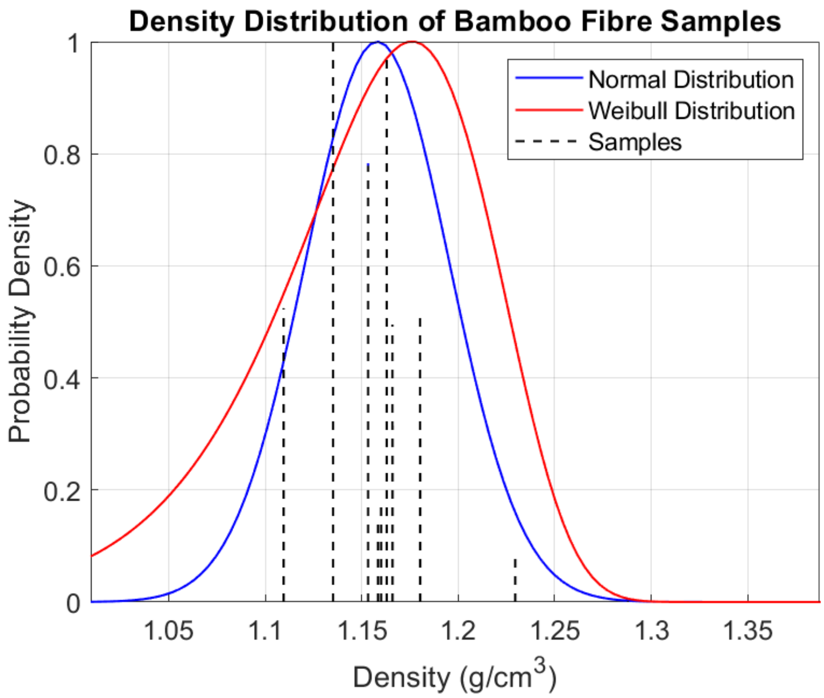

Figure A.2: Normal and Weibull distribution of fibre density measurements

The normal distribution of measurements plotted in fig. A.2 shows that the mean density of fibre samples measured is 1.1585 g/cm^3. For future calculations and for simplicity, this value was rounded to **1.16 g/**cm^3. The Weibull distribution of measurements shows a skew to the left, indicating that there is a greater probability of having samples with a lower density than the mean.

The standard deviation (S.D) from these measurements is 0.0464 g/cm^3, resulting in a **4%** S.D from the mean. Even though the accuracy of measurements may be discussed, as mentioned in A.1.1, the results showed to have reasonable precision. The precision of results naturally being affected by the inherent variations in fibre density from one sample to another, as well as some error in the measurement.

We thus have:

$$\rho_{fibre} = 1.16 \pm 0.05 g/cm^3$$