Hybrid composites with natural fibres

by

Hyeyoung Kim

A dissertation submitted to the

University of Birmingham

for the degree of

Master of Research

School of Metallurgy and Materials

College of Engineering and Physical Sciences

University of Birmingham

November 2014

Abstract

The primary aim of this study was to demonstrate that bamboo and coir fibres, with an epoxy resin matrix, can be fabricated to produce unidirectional composites. A secondary aim was to demonstrate the production of intra-ply hybrids with unidirectional bamboo fibres and spread E-glass fibres.

The methods explored in this work to produce the unidirectional arrays of bamboo and coir fibre preforms involved the use of a carding process to align the as-received bamboo fibres. A new method for spreading E-glass bundles or tows was developed in the author's research group. The feasibility of using the spread E-glass fibre bundles with the uni-directional bamboo preforms to manufacture a new class of intra-fibre hybrids was undertaken. A resin infusion fabrication method was used to manufacture the uni-directional bamboo and E-glass/bamboo . Tensile testing was used to determine the mechanical properties of the bamboo and E-glass/bamboo hybrid composites. The as-fabricated cross-sections and the post-tensile tested fracture surfaces were characterised using optical and scanning electron microscopy respectively.

This study developed and demonstrated a method to fabricate uni-directional arrays of bamboo and coir fibre preforms and a technique to produce intra-ply hybrid bamboo/E-glass composites.

Dedication

This thesis is lovingly dedicated to my parents who have been my constant source of inspiration. There is no doubt in my mind that without their continued support, I could not have completed this thesis.

I also dedicate this dissertation to my many friends in the UK, Europe, Korea, Japan, Thailand and someone special who has supported me throughout the process.

너무 감사드립니다. 힘든것은 지금 분발하고 있기때문에, 헤메고 있는것은 나아갈려고 하고있기때문에! 라는 마음가짐으로 더 앞으로 노력해서 느긋하게 저의 길을 걸어가겠습니다. ありがとうございました. 努力は人を裏切らない。 つらいのは、頑張っているから。迷っているのは、進もうとしているから。

Acknowledgements

I want to start by expressing a sincere acknowledgement to my supervisor Professor Gerard Franklin Fernando who gave me the opportunity to research under his supervision, his great support and constructive suggestions for the completion of this work. His technical advice was essential to the completion of this dissertation and has taught me innumerable lessons and insights on the workings of academic research in general.

I would like to thank the following people for their assistance with mechanical testing of my specimens and analysing my data : Samuel Ojo, Mark Paget, Richard Murray, Weili Ning, all from the Sensors and Composites group of the School of Metallurgy and Materials. Without their support it would be impossible for me to finish my work.

I would like to express my great appreciation to Dr. Daesik Kim and Danial Khoshkhou for their support. They kindly read my manuscript and offered invaluable detailed advice on grammar, and organization of my thesis.

Finally, I wish to thank my family for their support and encouragement throughout my study. 이 논문을 세상에 내놓을 수 있게 되어 감사합니다. 학위 후 더 높은 곳을 바라보는 제가 되었으면 좋겠습니다. これまで、ありがとうございました。いろいろおしえて頂き、感謝しています。

Table of Contents

List of Tables

List of Figures

1 Introduction

The global interest in natural fibre composites has been growing in the last decade because there is a realisation that alternatives have to be found for man-made fibres such as carbon and glass fibres [1–3]. Synthetic fibre reinforced composites have excellent specific properties (property of interest divided by the density) but they have major limitations in aspects such as recycling and degradability at the end of their operational life. This problem is acute for thermoset-based fibre reinforced composites. On the other hand, natural fibres are not reliant on petroleum-based precursors such as polyacrylonitrile or silica and they do not consume significant power to manufacture. Natural fibres are available in abundance, they are comparatively cheaper to produce, manufacture and are eco-friendly. They can also provide an alternative to synthetic fibres in some applications. Furthermore, natural fibre composites have lower densities and higher impact energy absorption capacity when compared to glass fibre reinforced composites. [4,5]

Although natural fibres have the potential to replace synthetic fibres, they also have some well-known limitations, including: (i) a lack of long-range order because of the short fibre lengths (ii) poor water and fire resistance and (iii) poorer mechanical properties when compared to their synthetic counterparts [2]. State-of-the-art manufacturing techniques are unable to produce continuous natural fibre preforms [6]. Due to the low-cost and relatively easy processing, most researchers have used twisted fibres and woven/mat fabric preforms [7–10]. It is generally appreciated that randomly oriented fibre composites have lower mechanical properties when compared to their uni-directional counterparts**.**

With respect to the above-mentioned shortcomings, the focus of the current research project was to develop a manufacturing process to produce aligned preforms without inducing damage to the fibres. In other words, unidirectional fibre arrays were needed to be manufactured without subjecting the fibres to abrasion damage, twisting or excessive bending. In order to achieve these goals, a carding machine was used to manufacture unidirectional arrays of bamboo fibre preform. A procedure was developed to fabricate unidirectional preforms of coir fibres via a hand lay-up method. These fibre preforms were impregnated and laminated using the resin infusion process. Uniaxial tensile testing was carried out on the composites. The as-fabricated cross-sections and the post-tensile tested fracture surfaces were characterised using optical and scanning electron microscopy respectively.

Another aspect of the research project was to develop a manufacturing process for the fabrication of a natural-synthetic hybrid composite. The term "hybrid" is defined here as a composite with two or more types of reinforcing fibre in a single matrix. Hybrid composites offer a compromise between mechanical properties and environmental impact, which means that they potentially can have superior tensile, flexural and compressive strength compared to natural mono-fibre fibre-reinforced composites. They also can display improved stiffness and moisture resistance, which gives them better protection against environmental aging [11–15]. Compared to mono-fibre glass fibre-reinforced composites, hybrid composites have demonstrated improved environmental response and a reduction in cost and weight [16,17]. Properties for selected fibres are given in Table 1 where it is readily evident that natural fibres cannot rival the strength of synthetic fibres. However, as mentioned previously, hybrid composites provide a blend of properties such as stiffness, strength and ductility, which cannot be achieved by mono-fibre reinforced composites [17–19].

In order to optimise the performance of hybrid composites, it is necessary to hybridise the two fibre types at the filament level (intra-ply hybrids) in a unidirectional manner such that both fibre types aligned in the same direction as the applied load. Contrary to this however, previous research on hybrid composites has been generally limited to the use of pre-fabricated inter-ply laminates using glass mats and randomly oriented short woven/mat of natural fibres (less than 50mm) [15,16,20] as opposed to intra-ply hybridisation of fibres as considered in this current work. The specific hybrid composite considered in this work is a combination of unidirectional bamboo and glass fibres. Intra-ply hybrids of these fibres was achieved by spreading E-glass fibres prior to hybridisation by adapting a spreading technique developed within the author's research group. Bamboo fibres consisted of staples (un-twisted short-fibres) and a conventional carding machine was used to produce unidirectional short-fibre preforms. These preforms were used to manufacture single-fibre and hybrid composites.

Table 1 Summary of selected physical and mechanical properties for glass, carbon, Kevlar, coir, bamboo and silk fibres [2,3]

Fibre	Tensile strength (MPa)	Young's modulus (GPa)	Elongation at maximum (%)	Density (kg/m^3)
Bamboo	140-230	11-17	-	600-1100
Coir (coconut)	175	4-6	30	1200
Spider silk	1300-2000	30	19-30	1300
B. Mori silk	500	8.5-8.6	15	1300-1380
E-glass	3400	72	2	2500
Carbon (Toray T300)	3530	230	1.6	1760
Kevlar-49	3600-4100	130	2.8	1440

1.1 Aims and Objectives

The primary aims and objectives of this project were:

(i) To develop a methodology to manufacture unidirectional preforms of silk, bamboo and coir fibres.

A conventional carding process was adopted and used to produce unidirectional preforms of discontinuous short-bamboo and silk fibre preforms. A manual process was developed and used to align coir fibre preforms. The properties of the coir fibres did not make it suitable for processing via the carding machine.

(ii) To characterise the microstructure of bamboo, silk and coir fibres and bamboo/E-glass hybrid composites using optical and scanning electron microscopy.

The purpose of this characterisation was to study the surface morphology of the-as-received natural fibres and the tensile fracture surfaces (fractography) of the natural fibre-reinforced epoxy and bamboo/E-glass hybrid composites.

(iii) To investigate manufacturing techniques to produce filament-level hybrids (intra-ply) of bamboo and E-glass fibres.

The bamboo fibres were spread and aligned using a conventional carding machine. The E-glass fibres were spread using a new method developed within the author's research group. Following spreading, each uni-directional layer was laminated and impregnated using resin infusion.

(iv) To evaluate the mechanical properties of the manufactured coir, bamboo, silk and coir mono-fibre reinforced and bamboo/E-glass hybrid composites through uniaxial tensile testing.

The composites were end-tabbed and tensile tested to failure using a conventional mechanical test machine. The parameters recorded were the cross-sectional area, ultimate failure load and displacement.

2 Literature Review

2.1 Introduction

The use of natural fibres can accrue many environmental benefits when compared to reinforcing glass fibres. For example, the production of natural fibres has a lower environmental impact with regard to extraction, purification, processing and overall energy costs [6]. With reference to Table 2, the environmental impact of producing natural fibre (China reed fibre) is significantly lower than that synthetic fibre (E-glass fibre). As shown previously in Table 1 natural fibres can offer desirable specific properties due to their lower densities.

Table 2 Life cycle assessment: Environmental impacts from the production of glass fibre and China reed fibre [6–8]. BOD: Biological/Biochemical Oxygen Demand, a measure of water pollution. COD: Chemical Oxygen Demand, a measure of the amount of organic compounds in water. CML : A problem-oriented Life Cycle Assessment (LCA) method developed by the Institute of Environmental Sciences of the University of Leiden (CML). Dichl: dichloride.

Environmental impact	Glass fibre	China reed fibre
Non-renewable energy requirements (MJ/kg)	44.7	3.64
Energy use (MJ/kg)	48.33	3.64
CO_2 emissions (g/kg)	2.04	0.66
CO emissions (g/kg)	0.80	0.44
SO_x emissions (g/kg)	8.79	1.33
NO_x emissions (g/kg)	2.93	1.07
Particulate matter (g/kg)	1.04	0.24
BOD to water (mg/kg)	1.75	0.36
COD to water (mg/kg)	18.81	2.27
Phosphate to water (mg/kg)	43.06	233.6
CML-human toxicity (kg 1.4 dichl)	21.2	9.04
CML- terrestrial eco-toxicity (kg 1.4 dichl)	5250	4480
CML- green house effect (kg CO_2)	75.3	4.04

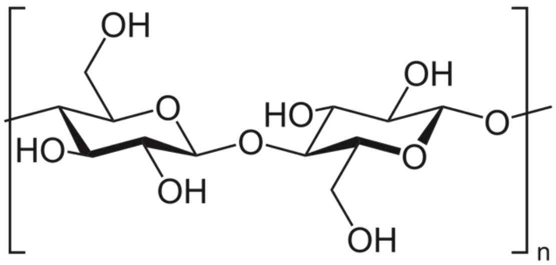
However, there are drawbacks associated with natural fibres such as higher moisture absorption [9,10], inferior fire resistance [11], lower mechanical properties, durability [10], variability in the quality of the fibres [12] and difficulties in using established manufacturing practices when compared to synthetic fibre composites [13].

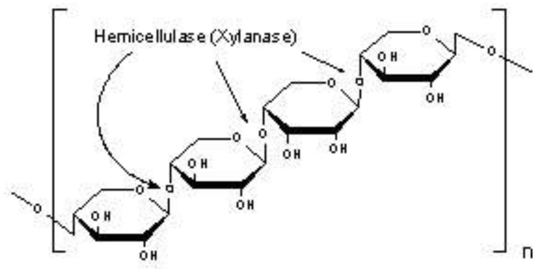
2.2 *Composition and chemical structure of selected natural fibres*

Plant fibres such as bamboo, coir, cotton, etc are composed of cellulose, hemi-cellulose and lignin. The exact composition of the fibres is specific to each species [4].

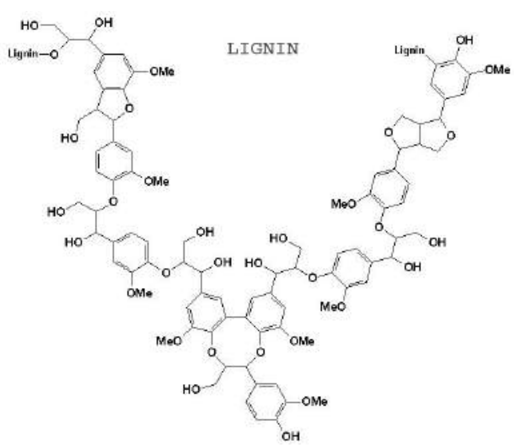
Natural plant fibres have a complex, layered structure consisting of a thin primary wall. The secondary wall is made up of three layers and the thick middle layer determines the mechanical properties of the fibre. The middle layer consists of a series of helically wound cellular micro-fibrils formed from long chain cellulose molecules [14,15]. The angle between the fibre axis and the micro-fibrils is called the micro-fibrillar angle, which affects the fibre property. Bismarck et al. [16] found coir fibre has a high fibrillar angle (45°), which increases the stiffness and reduces the strength.

There are lignin and hemicellulose components in the amorphous region between the cellulose micro-fibrils [17]. Lignin is a complex polymer of aromatic alcohols. Khalil et al. [17] found that the content made the fibre tougher and stiffer. Hemicellulose is a group of amorphous polysaccharides. It is said to form hydrogen bonds with cellulose and covalent bonds with lignin [18]. The general chemical structures for the various components are presented in Figure 1.





(a) (b)



(c)

Figure 1 The structure of: (a) cellulose, (b) hemicellulose and (c) lignin [4,12].

A summary of the primary composition of bamboo and coir fibres is presented in Table 3. With reference to Table 3, and in the case of bamboo, it is seen that the cellulose component is over 50% whereas it is 36-43% for coir. Gassan et al. [19] found an increase in the composite strength with increasing cellulose content. Cellulose fibres are aligned along the length of the bamboo providing higher tensile strength and rigidity in that direction when compared to coir

[16]. In the case of jute fibres, the cellulose content is 1.5 times higher than bamboo fibres (61-71.5%), as a consequence, jute fibres have a high tensile strength (398-773 MPa) compared with bamboo fibres (220-440 MPa) [21].

Table 3 The primary composition of bamboo and coir fibres and their resulting tensile strength [14,21].

Fibre	Cellulose (wt%)	Hemicellulose (wt%)	Lignin (wt%)	Tensile strength (MPa)	Strain to failure (%)
Bamboo	50-60	1-2	21-31	220-440	13.28
Coir	36-43	0.15-0.25	40-45	92-150	28-40
Jute	61-71.5%	12.9	11.8	398-773	1.5-1.8

2.2.1 The microstructures of bamboo and coir fibres

Optical and scanning electron microscopy (SEM) studies of the fibres have been conducted to understand morphology of bamboo and coir fibres [17,18,22]. In order to preserve the fibre structure, fibres were embedded in epoxy resin and then fine-polished for optical microscopy observation on the cross-section of coir fibre [16]. SEM analysis of the cross-section and longitudinal view of bamboo [20,22,23] and coir fibres [17,18,24] have been reported by a number of researchers.

Osorio et al. [22] carried out morphological studies on bamboo (G. angustifolia culm) using SEM. They reported that the fibres accounted for approximately 40 per cent of the culm by volume. As can be seen in Figure 2, bamboo culm consists of a series of axially oriented vascular bundles, which contain the fibre bundle embedded in parenchyma tissue (matrix). The region with high density in the vascular bundle is called the fibre strand and it is composed of elementary fibres.

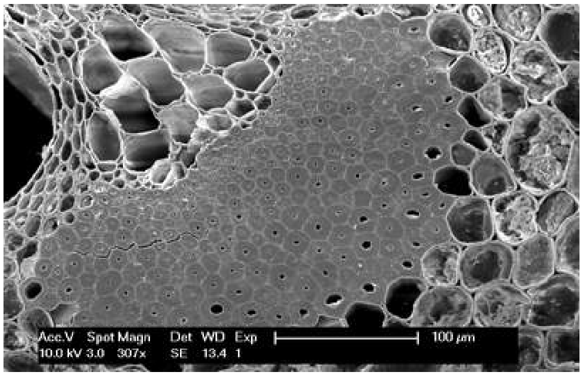
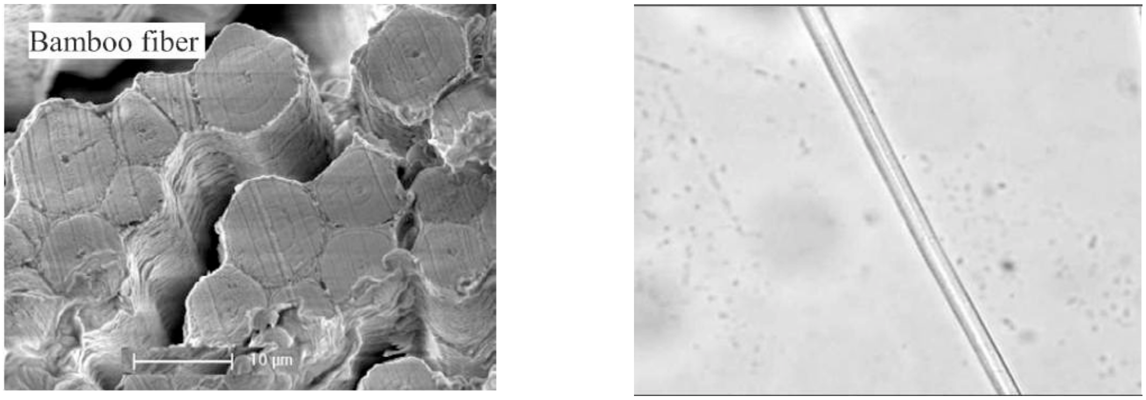


Figure 2 SEM micrograph of a transverse section of bamboo fibre [22].

Yueping et al. [23] carried out SEM imaging of the cross-section of bamboo fibre to investigate the surface morphology. As see in Figure 3(a), they observed that the cross-section of single fibre is round with a small round lumen and bamboo fibres had multi-lamellate cell walls with various layers. They also presented a longitudinal view of a bamboo single-fibre obtained via an optical microscope as illustrated in Figure 3(b). A small line of lumen can be seen in the longitudinal direction of the single bamboo fibre.



(a) **(b)**

Figure 3 (a) SEM micrographs of the cross-section of bamboo fibre and (b) optical micrograph of the longitudinal view of a single bamboo fibre [23].

With reference to the extraction of bamboo fibres, Wai et al. [14] investigated the effect of the “beating” of the pulp. Beating is a physical method of separating the fibres from the woody component. They found morphological changes in these fibres exemplified by the cracks in the fibre wall as illustrated in Figure 4. They proposed that these cracks were produced as a result of the external force applied to the fibre wall during the beating process.

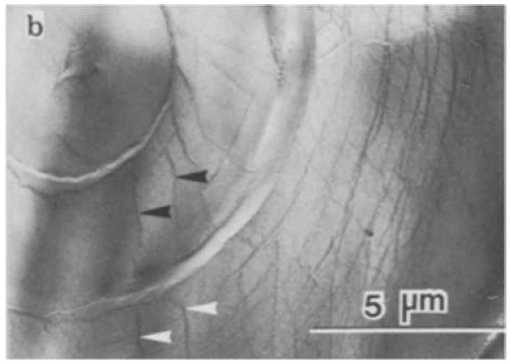


Figure 4 SEM micrograph showing the damage that is induced to the bamboo fibre after separation and extraction using the "beating" process. The damaged caused by this process is indicted by the arrows [14].

Khaili et al. [17] carried out microscopic studies on the transverse section of a coir fibre. In Figure 5, it can be seen that the fibre consists of different types of regularly arranged cells with lacuna in the centre. The cells of the vascular bundles embedded in the tissue are of a variable profile and dimension. They observed that each fibre-cell is united by the middle lamellae (blue strained region), which consists of lignin and hemicellulose.

With reference to Figure 6, Tomczak et al. [18] studied the tensile fractured surfaces of coir fibres and found the end of fibre contained pulled-out micro-fibrils. They found micro-fibril attributed to the ductility of coir fibres.

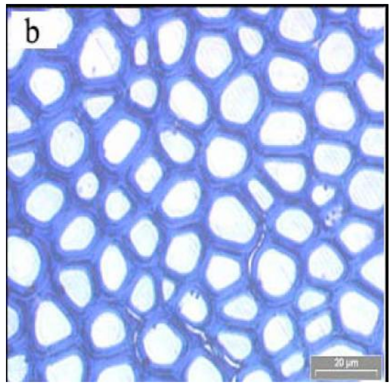
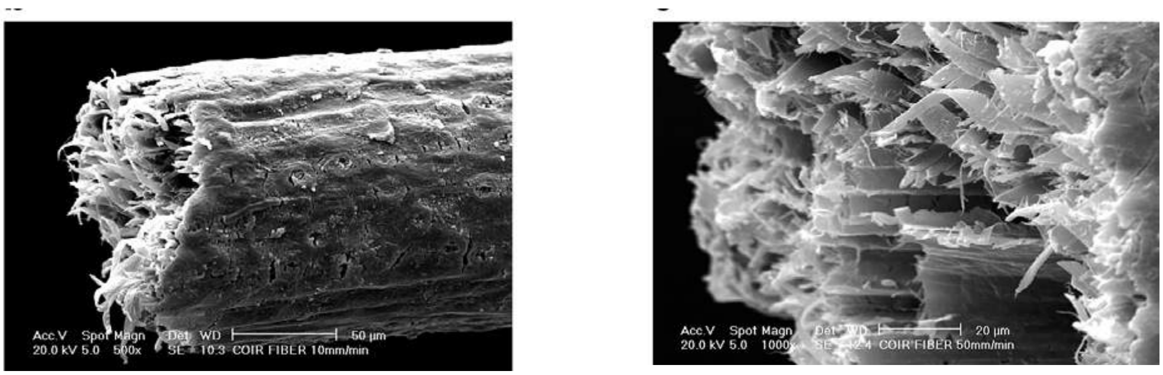


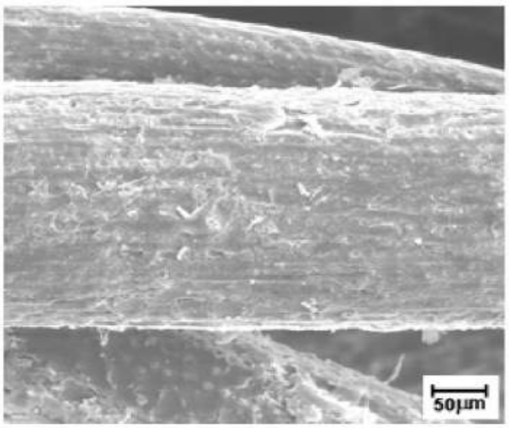
Figure 5 Optical microscopy of transverse section of coir fibre [18].

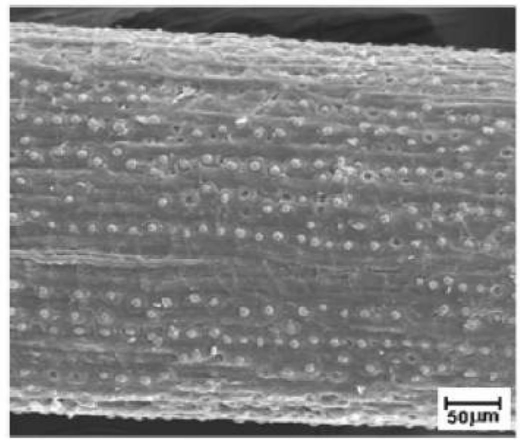


(a) **(b)**

Figure 6 Scanning electron micrographs of tensile fracture surface of coir fibre with (a) x500 and (b) x1000 magnification [17].

Calado et al. [24] and Rout et al. [25] studied the effect of a chemical treatment on the structure and morphology of coir fibres. As seen in Figure 7(a), Calado et al. [24] found that untreated fibres have an outer surface layer that is full of randomly distributed organic material. However, in the case of chemically treated fibre surfaces (Figure 7(b)), a rougher but more ordered structure was said to exists owing the removal of the outer layer. They also noted the presence of ordered, silica-rich white circular features on the surface of the treated fibres. Carvalho et al. [26] identified these features as tyloses and suggested that the porous surface of the fibre may offer better mechanical interlocking between the fibre and the matrix



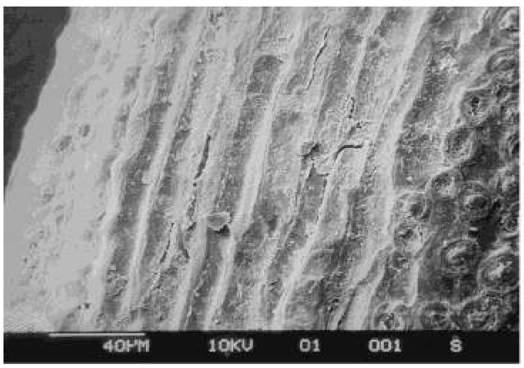


(a) **(b)**

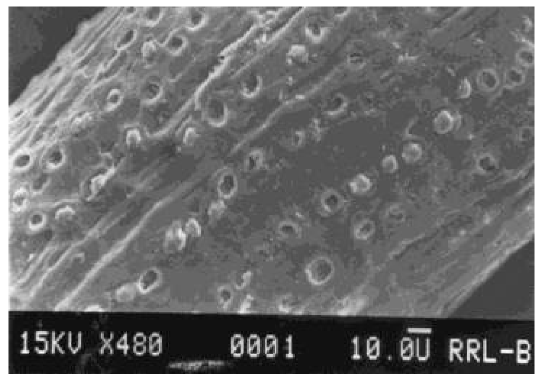
Figure 7 SEM images of the surface of coir fibres (a) before and after (b) chemical treatment [24].

Rout et al. [25] also observed the surface of alkali treated Bristol coir fibres and found a rough fibre surface with regularly spaced pits. As shown in Figure 8(b), they found these pits to be aligned longitudinally with roughly parallel orientations. Numerous globular pits were found to be embedded in the fibre surface at regular intervals. These pits were partially opened or filled up by lignin and fatty substance.

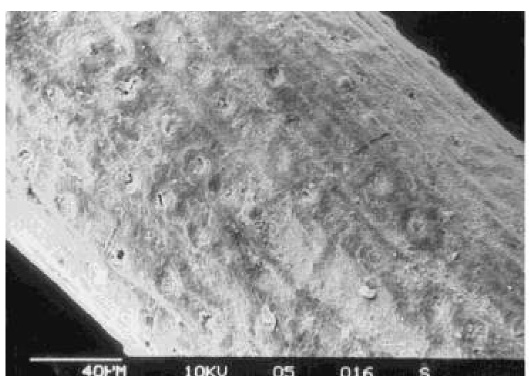
After partial removal of the waxy and fatty substances after treatment with a 5% alkali solution, a number of pits can be observed in Figure 8(b) when compared to the untreated coir fibres. The researchers assumed this to be caused by the removal of fatty deposit from the surface. In the case of PMMA grafted coir fibre, Figure 8(c) shows that PMMA has been deposited on the surface of the pits, creating a more uniform and smoother surface. They observed an increase in tensile strength for 8.56% PMMA-treated coir fibre and a decrease of 5% for the alkali treated fibre. They assumed that the uniform surface of the 8.56% PMMA-treated fibres may have caused the increase in the tensile strength. However, the formation of a numerous unfilled pits on the 5% alkali-treated fibre surface have also caused the reduction in strength.



(a)



(b)



(c)

Figure 8 SEM images of longitudinal view of (a) untreated coir fibre at x500, (b) SEM of 5% alkali–treated fibre at x480 and (c) 8.56% PMMA–grafted coir fibre at x500 [25].

Suttivutnarubet et al.[27] carried out morphological studies on the dust that was present on the surface of coir fibres. As observed in Figure 9, the isolated particles are between 170 – 520µm with a porous structure. They reported that the coir dust particles were light to dark brown and contained lignin and cellulose contents of 35-54% and 23-43% respectively. Due to the lignin and cellulose constituents bearing polyhydroxy groups, they assumed that coir dust was hygroscopic. Asiah et al. [28] also found that coir dust contained a porous surface with a total pore space of 96.2 vol%.

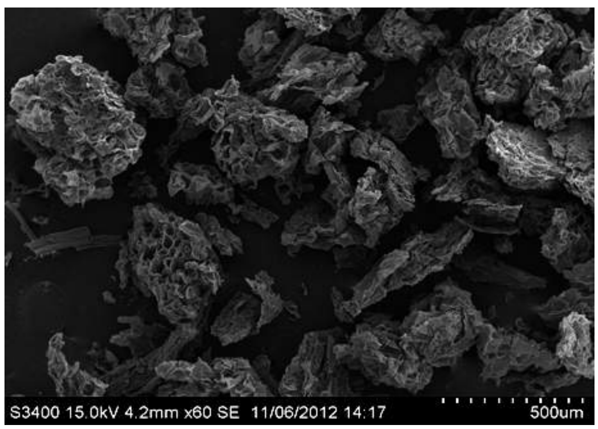


Figure 9 SEM micrograph of coir dust [27].

2.3 Matrices

The matrix serves as a medium that binds the fibres in the required spatial orientation. It also enables the transfer of the applied load to the fibres [29]. Commercially used polymer matrices are classified into two types, namely thermoset and thermoplastic resins. The most widely used thermoplastic matrices are polypropylene (PP) [30–32], polyethylene (PE) [32], polystyrene (PS) [21] and polyvinyl chloride (PVC) [21]. In the case of thermoset matrixes, polyester [15] and epoxy resin [10,30,33,34] are used commonly.

The common classes of thermoplastics and thermosets are summarised in Appendix 1. The mechanical properties of different matrices used in composites will be discussed in Section 2.6.

From Appendix 1, it is evident that the processing time for thermoset resins is longer than that for thermoplastic resins. However the processing temperature for thermosets is lower. It is thus important to choose the appropriate matrix, such that the processing temperature is lower than the temperature of the decomposition of the natural fibres [15].

2.4 Chemical surface-treatment

Chemical surface-treatment methods involving maleic anhydride (MAN) [35,36], acetylation [21], esterification [19], mercerization [21,35,37,38] and coupling agents [39–42] have been used to change the surface chemistry of natural fibres. The main functions of the chemicals used are to react with the hydroxyl group on the fibre surface, making the surface compatible with the matrix [21]. A summary of selected fibre types, the surface treatment and its effects is shown in Table 4 Summary of selected natural fibre types, the surface treatment and their effects [19,35,43–47]..

Table 4 Summary of selected natural fibre types, the surface treatment and their effects [19,35,43–47].

Authors	Natural Fibre Type	Surface-treatment condition	Comments
Venkata Subba Reddy et al. [43]	Bamboo fibres (Dendrocalamus Strictus) were procured from Tripura state of India	1 % NaOH solution for 30 mins	The elimination of amorphous weak hemi cellulose components from the bamboo fibres on alkali treatment improves chemical resistance to 40% Nitric acid 10% Hydrochloric acid, 8% Acetic acid and 10% Sodium hydroxide.
Raghavendra Rao et al. [44]	Bamboo fibres (Dendrocalamus strictus) were procured from Tripura state of India	1 % NaOH solution for 30 mins	Flexural modulus was increased by 30% with alkali-treated fibre-reinforced composite. (9133 MPa)
Noorunnisa Khanam et al. [45]	Coir fibres taken from local sources	2% NaOH solution for 1 hour	Alkali-treated composites showed 30% better compressive strength than untreated composite. (162.975MPa)
Hongyan Chen et al. [29]	The middle section of a mature bamboo plant (Phyllostachys pubescens)	20% aqueous solution of NaOH for 20 min at room temperature. 5% acetic acid for 2 hours and then decanted and immersed in acetic anhydride.	Reduction of about 17% moisture absorption for acetylated bamboo strips was obtained.
Donath et al. [46]	Wood pellet	2 wt% A tetraalkoxy silane, alkyl-trialkoxy silane, multifunctional oligomeric silane for 1 hour at 25 °C.	The water uptake of treated wood was reduced, but after a longer submersion time (24 hour), the reduction was diminished.
Pradeep. K. Kushwaha et al. [35]	Orthogonal bamboo strip mats acquired from the local market.	250 g of bamboo matting were soaked in 2 litres of NaOH solution of concentration 5% for 1 hour at room temperature. The alkali-treated fibres were soaked in 5% solution of UPE and methyl ethyl ketone peroxide (MEKP) (99:1) solution for 30 mins.	The tensile strength of treated bamboo-epoxy composite is 40% higher(133 MPa), and the elastic modulus is 35%(4000MPa) higher compared to that of untreated bamboo-epoxy composite.
Sun-Young Lee et al. [47]	Bamboo fibres of 40–60 mesh	2.0wt% NaOH at 25 °C for 1 hour + 3.0wt% Aminopropyltrimethoxysilane (AS), tetramethoxy orthosilicate (TMOS) for 1 hour at 25 °C.	The flexural modulus of the composites treated with 3wt% AS and TMOS was 34.6% (5255 MPa) and 23.5% (5022 MPa) higher than that of the untreated composite.
Gassan et	Coir	NaOH	The increase in the percentage

al.[39]			crystallinity index of alkali treated fibres.

A common method for the chemical modification of natural fibres is via alkali treatment (mercerization). With reference to Figure 10, alkalisation is generally used to remove or modify the OH groups on the surface of cellulose-based fibres to increase the resistance to water absorption. From a review of the research reported by Porras et al. [48] and Kazuya Okubo et al. [31], this type of treatment is said to remove a certain proportion of the lignin, wax and oils that cover the external surface of the fibre cell wall . Faruka et al. [21] found it to disrupt the hydrogen bonding in the network structure, thereby increasing the surface roughness. However, Mantia et al. [49] reported that alkalization causes the fibre to swell, leading to micro-cracking during mercerisation. This was reported to result in poor adhesion between the fibres and matrix. Mercerisation is also known to remove hemicellulose and other components such as waxes; this was reported to result in a change in fibre surface energy [22,37].

$$\text{Fiber} - \text{OH} + \text{NaOH} \longrightarrow \text{Fiber} - \text{O}^{-}\text{Na}^{+} + \text{H}_2\text{O}$$

Figure 10 Generalised reaction showing the process of alkalisation [48].

Another common technique for modifying the surface chemistry of natural fibres is via the use of silane coupling agents. Typical examples of silanes and the conditions that are used in the silanation of the surface of natural fibres are summarised in Table 5. The general chemical formula of a silane is X-Si-$(OR)_3$. One end of this molecule is designed to react with the cellulose fibre surface and the other with the matrix. The “R” functional group can react with the resin and the “X” functional group can hydrolyse to form a silanol group in an aqueous solution and these react with hydroxyl group of the cellulose surface. R-groups may be vinyl, γaminopropyl or γ-methacreloxypropyne etc. The X-group may be chloro, methoxy, ethoxy etc (see Table 5). Kushwaha et al. [35] reported that silane coupling agents may reduce the number of cellulose hydroxyl groups in the fibre–matrix interface. In the presence of moisture, hydrolyzable alkoxy group leads to the formation of silanols. The silanol then reacts with the hydroxyl group of the fibre, forming stable covalent bonds to the cell wall that are chemisorbed onto the fibre surface. Therefore, the hydrocarbon chains provided by the application of silane restrain the swelling of the fibre by creating a cross-linked network due to covalent bonding between the matrix and the fibre. Therefore, silane treatment results in improved chemical bonding between the surface of the fibre and the matrix (see Figure 11). This in turn results in better stress transfers between the fibre and the matrix [35,46,47] and also improves the mechanical performance of natural fibre composites [4,35,46,47,50].

Table 5 Selected examples of typical silanes and conditions that were used in the silanation of the surface of natural fibres [29,35,47,51–53].

Authors	Fibre/Silane	Surface-treatment Condition	Comments
Kushwaha et al. [35]	Orthogonal bamboo strip mats acquired from the local market/ɤ-Amino-propyltriethoxy silane	0.5wt% silane for 24 hours in pH 3.5–4. The fibres-to-silane aqueous solution was maintained at 1:10.	No improved property comparing to untreated bamboo-epoxy composite.
	Amino-propyltrimethoxy silane	Silane of 1% (with respect to mat weight) for 2 hours in pH 3–4.5.	The tensile strength of aminopropyltrimethoxy silane treated bamboo composite was 20% higher than untreated composite (99.62 MPa).
	n-Octyltrimethoxy silane	Silane of 1% (with respect to mat weight) in ethanol for 1 hour	10% higher flexural strength than untreated composite (127.47 MPa).
Min Zhi Rong et al. [51]	Untreated sisal fibres with diameters ranging from 100 to 200um/ɤ -amine propyl triethoxysilane	2% aminosilane in 95% alcohol at 100 °C for 2 hours in pH 4.5-5.5	Treated fibres showed a decrease in crystallinity (55.6%) comparing to untreated fibres, (62.8%) and increase in elongation at break (4.3-5.1%) comparing to untreated fibres. (2.2-2.8%)
Valadez-Gonzalez et al. [52]	Henequen fibres(agave fourcroydes) / vinyltris(2-methoxy-ethoxy) silane	1% silane and 0.5% dicumyl peroxide 1 hour in pH 3.5.	30% Higher interfacial shear strength (3 MPa) as compared with non-treated heneguen fibre.
Abdelmouleh et al. [53]	Technocel-2500 cellulose fibres / γ-Methacryloxypropyltrimethoxysilane	3 wt% silane for 2 hours.	20% higher Young's modulus (380 MPa)and tensile strength (17 MPa) than untreated composite.
Hongyan Chen et al. [29]	Bamboo fibres / vinyltrimethoxysilane	5 wt% silane for 1 hour in pH 3.5-4.	Treated fibres shows a n improve in bamboo's moisture resistance and the adhesion between bamboo and vinyl ester resin
Sun-Young Lee et al. [47]	Bamboo fibres / (3-Aminopropyl) trimethoxysilane	3wt% silane, for 1 hour in pH 6-7.	Water absorption of 3% silane treated bamboo composite was considerably lower than that of untreated bamboo composites. The flexural strength of treated composite shows 26.1% higher

			value (53.1 MPa) than that of untreated composite.

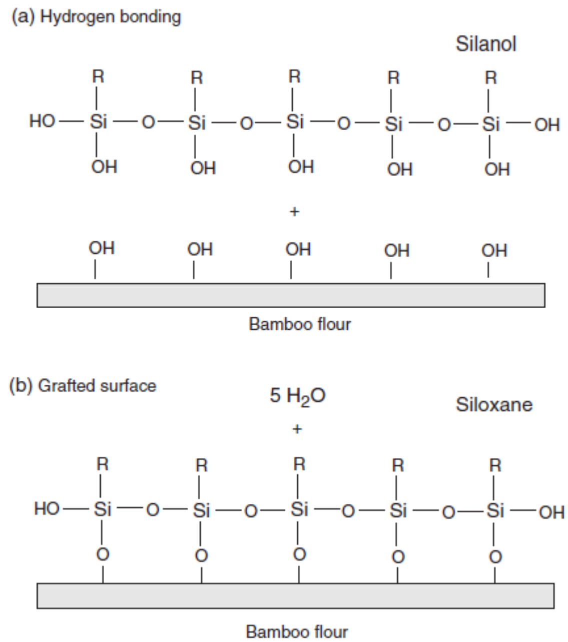


Figure 11 Bonding with a silane coupling agent with bamboo flour [47].

2.5 *Fabrication methods and properties*

The typical fabrication methods, material and matrix are summarised in Table 8 along with selected processing techniques [32,54–59]. Some typical problems related to the processing of natural fibres are due to their hydrophilic nature and also to their poor thermal resistance. The presence of humidity generally leads during processing, to the formation of water vapour that can lead to the formation of voids in the material and thus lead to poor mechanical properties [49]. Also, as previously mentioned, Chusheng et al. [60] observed a drop in tensile strength when the processing temperature increased from 100 °C to 120 °C. The hemicelluloses began to degrade above 100 °C, but cellulose is less affected due to the crystalline structure. Thus the processing conditions, especially temperature should be considered.

The processing techniques used for natural fibre-reinforced composites are generally designed for conventional fibre-reinforced composites [21]. These manufacturing methods are hand lay-up [55,56,59], extrusion and injection moulding [59], carding and hot pressing [30,32,58], film stacking and hot pressing [54,61], compression moulding [30,32,58] and resin transfer moulding (RTM) [56,58].

Nayak et al. [62] processed their composite using extrusion and injection moulding. PP–bamboo composites were compounded in a rotating twin-screw extruder. After compounding, the extrudates were cooled in water at room temperature, granulated in a pelletizer and then dried. These dried pellets were used as feedstock for specimen fabrication in an injection-moulding machine. Injection moulding can produce components with complex geometries at relatively high-speed. However, Herrera-Franco et al. [63] found natural fibres are generally distributed unevenly resulting in anisotropy in a moulded part, which is not found in compression mouldings.

Ouagne et al. [54] compared the tensile modulus of flax/PLLA composites fabricated using three different processes: injection moulding, compression moulding and film stacked hot press moulding. The assessment of the effect of different fabrication methods on the tensile modulus of flax/PLLA composites is seen in Table 6.

Table 6 Tensile modulus of Flax/PLLA composites from different fabrication methods [54].

Material	Process	Fibre content (weight fraction %)	Tensile modulus (MPa)
Flax/PLLA	Injection	30	6940-7700
Flax/PLLA	Film stacking	30.5	8559-9153
Flax/PLLA	Compression	30	7700-8900

It is evident that the film stacking hot-press moulded composites gives the highest tensile modulus (8559-9153 MPa) followed by the compression moulding technique (7700-8900 MPa). Injection moulded composite shows the lowest tensile modulus among the three techniques. They found two reasons for this result, reduction in the fibre length after fabrication and thermal degradation due to two heating cycles in the injection moulding process. When the fibres pass the extruder to be pelletized, the screw cuts the fibres. The length of flax fibres after injection moulding reduced to 0.33 mm from 4 mm. Similarly, Garkhail et al. [58] found that the average length of fibres dropped from ~10 mm to ~1 mm In the case of injection moulded flax/PP composite. Bodros et al. [61] also found that the fibres fabricated by injection moulding suffered from fibre degradation due to two heating cycles (170-180 °C for extrusion and over 180 °C for the injection moulding machine).

Similary, Idicula et al. [57] investigated the effect of different fabrication methods, namely compression moulding (CM) and resin transfer moulding (RTM), on the mechanical properties and void content of mixed banana and sisal hybrid fibre-reinforced polyester composites. In the case of the RTM method, the resin passed though the closed mould and infused into the fibres. Vacuum and pressure were applied and cured the material for 12 hours. The pre-preg of resin-impregnated fibres was compressed at a pressure of 10 kg/cm^2 at room temperature and cured for 12 hours. Assessment of the effect of the fabrication method on the tensile modulus, elongation at break, flexural modulus and void content of mixed banana and sisal hybrid fibre-reinforced polyester composites is summarised in Table 7.

Table 7 Tensile modulus, elongation at break, flexural modulus and void content of banana and sisal hybrid fibre-reinforced polyester composites having different fibre loading fabricated by CM and RTM CM: compression moulding, RTM: resin transfer moulding [57].

Fibre content (Volume fraction)	Tensile modulus (MPa)	Elongation at break (%)	Flexural modulus (MPa)	Void content (Vol%)
0.19 for CM/ 0.21 of RTM	1347 / 1621	4 / 4	2247 / 2276	5.6 / 4.8
0.32 for CM/ 0.29 for RTM	1443 / 1874	5 / 6	2375 / 2512	7.8 / 5.5
0.40 for CM/ 0.42 for RTM	1601 / 1941	7 / 6	2842 / 3010	8.2 / 6.2

It is apparent that resin transfer moulded composite shows a higher tensile modulus than compression-moulded composites at all fibre content levels. This is attributed to the lower void content for the RTM prepared composites. In the RTM process, the mould is compressed by a vacuum pump and resin is injected under pressure.

Table 8 The typical fabrication methods of natural fibre reinforced composites [32,54–59].

Researcher/reference number	Fibre	Matrix	Fabrication method	Condition
Chen et al. [32]	Fine bamboo chips	PP powder, a density of 0.920 g/cm^3 and melt flow index of 20.	Compression moulding	Bamboo chips and resin were heated and compress moulded at 210 °C for 25 mins under 5 MPa.
Byoung-Ho Lee et al. [55]	Kenaf and jute (bast) fibres	PP fibres, melt flow index of 12	Hot pressing	the preforms were pressed under a pressure of 70 kg/cm^2 for 5 mins at 200 °C.
Gochi et al. [59]	Kenaf fibre	PLA sheet of 2 mm thickness	Hot pressing	The pre-pregs were heated to 160 °C and hot-pressed at 10 MPa.
Phong et al. [33]	Moso (Chinese) bamboo/ Plain woven carbon cloth	Epoxy resin and modified aliphatic polyamines as a hardener	Hand lay-up technique.	The mixture of fibres and epoxy resin was hand lay-upped at 80 °C for 1 hour and 150 °C for 4 hour.
Ouagne et al. [54]	Hermes flax fibre	PLLA	Film stacking processing	The mixture of fibres and resin heated at 170-170 °C and compressed of 2MPa.
Hill et al. [56]	Nonwoven coir fibre mats	Polyester (Crystic 471 PALV, Scott Bader) and catalyst (methyl ethyl ketone peroxide, Scott Bader).	Vacuum assisted resin transfer moulding	The epoxy resin and fibre mat were placed in the liner connected to a vacuum pump. The resin flows into the mat in the vacuum condition. The mat was compressed and left at room temperature overnight to allow cure of the resin.
Idicula et al. [57]	Banana and sisal fibres	Polyester	Resin transfer moulding	The pre-preg of resin-impregnated fibres was compressed at a pressure of 10 kg/cm^2 at room temperature and cured for 12 hours.
Garkhail et al. [58]	Flax fibres	PHB polymer in power form	Compression moulding	The mixture of fibres and resin were hot-pressed and compressed for 5 minutes at 180°C, at maximum pressure of 1.5 MPa.
-	-	-	Film stacking processing	Fibre mat and resin were heated for 12 minutes at 180 °C, pressed at 8MPa and cooled at 60 °C.
-	-	-	Injection moulding	The mixed compound of resin and fibres was granulated and injection moulded at 160-180 °C, under a pressure of 764 kg/cm^2.

2.6 Carding process

Unlike synthetic fibres, natural fibres are not generally available in long or continuous form. Natural fibres are usually available as short-fibre reinforcements. The short-fibres or staples are spun and twisted to produce yarns to enable the production of weaves. Chopped discontinuous short fibres are used for the production of randomly oriented fibre mats. However, unidirectional arrays of continuous fibres will yield superior mechanical properties when compared to their short-fibre counterparts [30,59,64,65]. Carding is the mechanical action in which surface needles combs the fibres causing individual fibre separation into a parallel array. Figure 12 shows a basic carding machine and its constituent parts. The fibres are fed onto a roll by a chute. Lickerin helps the fibres to be fed onto the cylinder. The main cylinder moves faster than the doffer roll due to the difference in angular velocity, which pulls and teases apart fibre clumps. The worker roller on the top of the main cylinder and the stripper rollers work together to strip larger tufts and deposit them back onto the cylinder. After this entire process, the fibres are aligned unidirectionally below the needles of the main cylinder. [66]

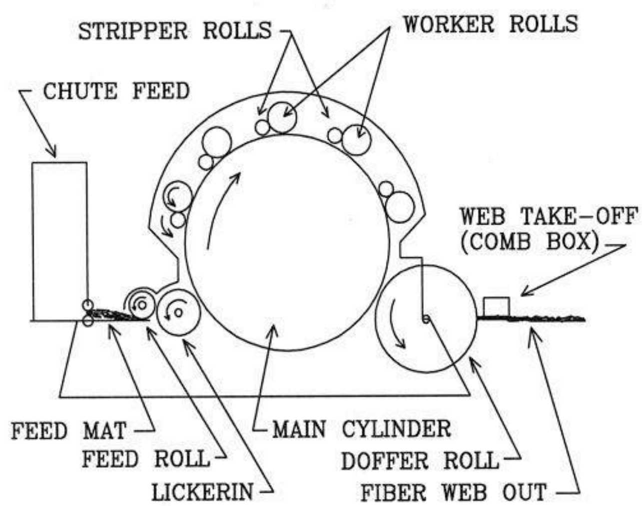


Figure 12 Basic construction of a carding machine and its components [66]

Hao et al. [67] also produced Kenaf/PP fibre felt using a carding machine with needle punching. They combed the individual fibres into a parallel array using the carding process. The fibres were then carded again in the perpendicular direction to the previous feeding direction. They investigated this combined processes for composite manufacture and found the out-of-plane stiffness of Kenaf/PP composites (3 kJ/m^2 impact strength) to be lower than the in-plane stiffness (9 kJ/m^2 impact strength).

Byoung-Ho Lee et al. [55] used a carding machine to prepare continuous fibre composites, which enables uniform blends of the kenaf and jute fibres with the PP fibres (Figure 13). The carded preforms were pressed by hot plates, then, the preforms were transferred to a hot-press. They were pressed under a pressure of 70 kg/cm^2 for 5 minutes at 200 °C. The carding process makes it possible to fabricate a continuous unidirectional preform with short fibres.

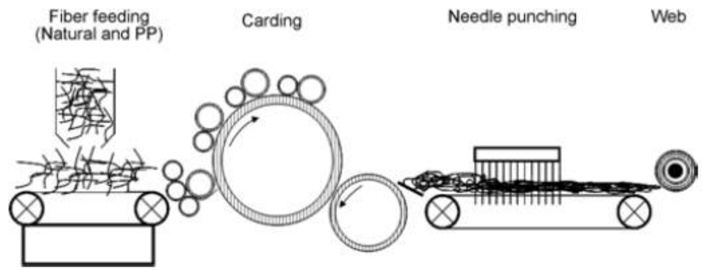


Figure 13 Carding process for mixing natural fibres with PP staple fibres [55].

2.6.1 Mechanical properties of natural fibres composite

The mechanical properties depend on several factors such as the properties of fibre length [34,65], fibre content [2,30,31,38,61,63,65,68,69], fibre orientation [30,59,63,70] and fabrication method [32,54–59]. Therefore, it is not simple to compare their composite properties directly because the material, fabrication methods, conditions and analytical factors do not directly correspond. The mechanical properties of the composites according to different fabrication method are discussed in 2.5 (Fabrication methods and properties)**.** Tensile properties are the focus of this literature review.

2.7 Tensile properties as a function of the fibre length

A compilation of the tensile properties according to different fibre length (at a fixed total fibre content of 30% by weight) is shown in Table 9.

Thwe et al. and Biswas et al. [2,34,65] studied the effect of fibre length on the tensile/flexural properties of composites. Biswas et al. [34] carried out tensile testing on coir fibre reinforced epoxy composites with different coir fibre lengths ranging from 5 mm to 30 mm. They noted that the tensile properties of the composite increased with increasing fibre length.

However, Thwe et al. [2,65] found the tensile strength decreased with an increase the fibre length. They studied the effect of fibre length on the tensile/flexural properties of bamboo/glass fibres-reinforced PP composites. The ratio of bamboo to glass fibre content was 2:1. The length of glass fibre was 6 mm, and the lengths of bamboo fibres were 0.25, 0.5, 1-6, 6-12 mm. As seen in Table 9, increased bamboo fibre length did not increase the tensile strength, but shows a drop in tensile strength. However, the tensile modulus increased in the case of longer bamboo fibre lengths. 6-12 mm bamboo fibre reinforced composites show a 9% higher tensile modulus than the 0.25 mm bamboo fibre reinforced composites. They concluded that longer lengths could carry higher tensile loads because of increased transfer lengths. However, a decreased tensile strength cannot be easily explained. They found the stress on shorter fibres did not reach breaking stresses. In the case of flexural properties, the flexural strength and modulus of the 6-12 mm bamboo fibre reinforced composite were 25% and 35% higher than those of 0.25 mm bamboo fibre reinforced composites. An increase in flexural modulus is consistent with better load-bearing capacity of longer fibres.

Table 9 Tensile properties according to different fibre length at 30% fibre content [2,34,65].

Author	Gauge length (mm)	Load rate (mm / min)	Fibre	Matrix	Fibre length (mm)	Tensile strength (MPa)	Tensile modulus (GPa)
Thwe et al. [2,65]	Not indicated	1.5	Bamboo fibre of 4 different length range; 0.25,0.5,1-6,6-12 mm Glass fibre of 6 mm length.	Poly propylene (PP)	0.25	19	2.5
					0.5	18	2.6
					1-6	18	2.7
					6-12	17	2.8
Biswas et al. [34]	200	Not indicated	Coir fibres of 5 to 30 mm length.	Epoxy resin LY556 and Hardener HY951 of mixing ratio : 10:1 by weight.	5	3.208	1.331
					20	9.155	1.518
					30	13.05	2.064

2.7.1 Tensile properties as a function of the fibre loading

The tensile properties of natural fibre composites as a function of the fibre volume fractions are shown in Appendix 2. Khondker et al. [30] investigated the effect of different fibre contents on the tensile properties of jute fibre-reinforced PLA composites. They found that the improvement in both tensile strength and modulus was consistent with respect to the increase in the reinforcing fibre content as seen in Table 2.10. Increasing the fibre volume fraction from 22.5% to 38% caused the tensile strength to increase from 72 to 78 MPa. Bodros et al. [61] also found a gradual increase in the tensile strength and modulus of flax fibre-reinforced PLLA composite, 80-99 MPa and 7.5-9.5 GPa respectively with a fibre content of 20-30%.

Okubo et al. [31], Jena et al. [38], Sreekumar et al. [71], Thwe et al. [2,65], Lu et al. [68] and Geethamma et al. [72] found there is a critical fibre weight fraction, beyond which fibres effectively reinforce the composites. They found the tensile strength to improve with increasing total fibre content up to an optimum value and decrease or remain constant by further increasing fibre weight fraction beyond this optimum value. The critical volume varies with fibre and matrix, fibre aspect ratio, fibre/ matrix interfacial adhesion.

Okubo et al. [31] found the average tensile strength of bamboo fibre-reinforced composites improved when the weight content of bamboo fibre was increased up to 50 %. However, the opposite trend was observed for a further increase in the bamboo weight content. Sreekumar et al. [71] also found that up to 40% fibre fractions, the storage modulus of banana fibres (30 mm) reinforced polyester composites increases to 5118 MPa while beyond this loading (50%), it decreased to 4606 MPa. They assumed that the stress applied is evenly distributed between the fibre and matrix up to 40%. However, higher fibre loading (50%) makes the processing more difficult resulting in the uneven distribution of the fibres in the matrix. Higher fibre loading also increased fibre-to-fibre contact, and consequently caused the formation of voids. Samal et al. [73] also found at higher fibre loading, fibre to fibre contact can occur and breakage of fibres can increase in the composites, which reduces the effective stress transfer between the fibre and matrix resulting in reduction in the impact strength (48.7 J/m impact strength at 40 wt% bamboo fibre loading compared to 53.6 J/m at 30 wt% fibre loading)

Jena et al. [38] observed that at 43% fibre weight fraction, the quantity of resin is insufficient to impregnate the fibres. This influences the wettability of the fibre and fibre-matrix adhesion resulting in increased void content in the composite. They assumed that crack initiation and propagation would be easier in these composites, which reduces tensile strength with a 43% fibre weight fraction.

Geethamma et al. [72] found different results. They investigated the tensile strength of coir fibre reinforced natural rubber composites by varying fibre weight fractions from 10 to 60%. They found the tensile strength drops up to a certain amount of fibre and then increases. The tensile strength decreases with increase in fibre loading up to 30% and then shows an increase for composites containing 40% and 60% fibre loading. They explained that large stress can be developed at low strains and the distribution of these stresses cannot be uniform, but after a certain fibre loading (30% in their experiment), the stress distribution will be uniform and therefore the fibres start to act as reinforcement for the matrix.

Lu et al. [68] also found a tensile strength of 10wt% bamboo fibre reinforced composite was lower than that of 0% bamboo fibre reinforced composite. They proposed that this might be caused by the poor compatibility between reinforcing fibres and matrix. The tensile strength of composite increased with fibre loading up to 20wt% and decreased again with further fibre loading.

2.7.2 Tensile properties of natural fibre composites as a function of the fibre orientation

Goichi et al. [59] have investigated the mechanical properties of kenaf/PLA composites with 3 different fibre orientations as shown in Figure 14. To laminate unidirectional (UD) composites, the unidirectional kenaf sheet was made by pulling out the weft kenaf yarn bundles from the textile and then two unidirectional kenaf fibre sheets were inserted in the same direction between the PLA sheets.

Assessment of the effect of the fibre alignment on the tensile properties of kenaf fibre reinforced composites is seen in Table 10, it is apparent that UD composite possess the highest tensile properties. The tensile strength of UD composites was double that of PLA alone. They found the mechanical properties of short-fibre reinforced composite are dependent on the angle between the axis of the fibre orientation and the applied force. Consequently, the efficiency of stress transfer can be higher if fibres are aligned parallel to the direction of the applied force.

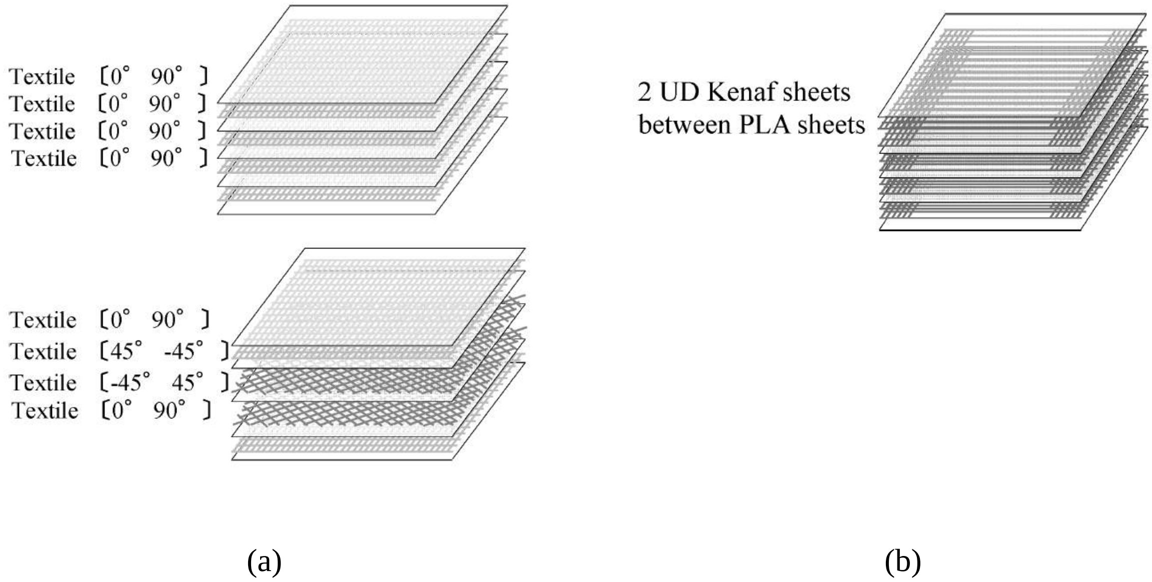
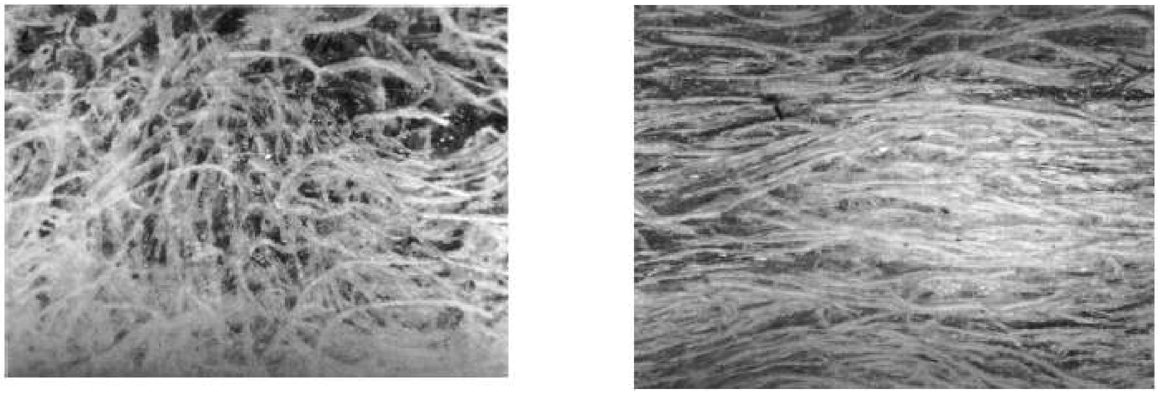


Figure 14 Laminate composition of textile composite A (top), B (bottom) and UD (unidirectional aligned fibre-reinforced) composite [59].

Manilcadan et al. [70] studied the effect of orientation of the fibres on the tensile properties of sisal fibre reinforced polystyrene composites. As seen in Figure 15, they fabricated two types of orientation composites, randomly oriented fibre composite and unidirectionally oriented fibre composites. At 10% fibre loading, the modulus of longitudinally oriented fibre composites show 40% higher value than that of randomly oriented fibre composites.



(a) (b)

Figure 15 Optical photographs of the surface of (a) randomly oriented fibre composite and (b) unidirectionally oriented fibre composite [70].

Khondker et al. [30] evaluated the tensile properties of jute fires-reinforced unidirectional PP composites with an intermediate material called “Microbraid yarn”. They used a unique tubular braid technique to produce a combination of fibres and matrix phases in a unidirectional direction (Figure 16). This microbraid yarn was placed in a parallel configuration onto metallic frames with springs to maintain the tension. This metal frame was placed in a pre-heated moulding die for compression moulding. The cooling stage was undertaken by a rapid cooling system for a uniform distribution of fibres in the matrix. As seen in Table 10

Table 10, the tensile strength of jute/PP unidirectional composites were 4 times higher than pure PP and the tensile modulus was 7 times higher than that of pure PP.

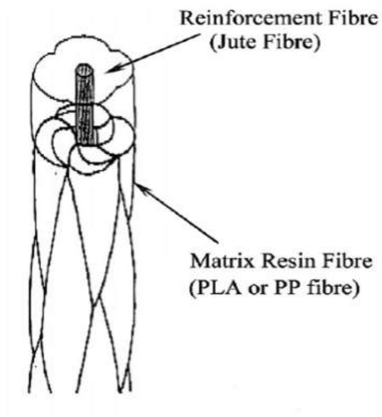


Figure 16 Fabrication process of microbraid yarns [30].

Thwe et al. [2,65] found mechanical properties to be improved when the axis of the orientation of the fibres is parallel to the loading direction. They found that the tensile modulus of a composite with well-oriented fibres increased by 10% compare to those with randomly oriented fibres (3.2 GPa). Similarly, Geethamma et al. [72] evaluated the tensile moduli of coir reinforced natural rubber composites in both directions and found the moduli in the longitudinal direction (1.6MPa) to be higher than those in the transverse direction (0.9 MPa). They concluded that high stress transfer could be achieved if the fibres are aligned longitudinal to the direction of the applied force.

Table 10 Tensile properties of natural fibre reinforced polystyrene composites with different orientation [30,59,70]

Authors	Gauge length (mm)	Load rate (mm/min)	Fibre	Matrix	Fibre orientation	Tensile strength	Tensile modulus
Manilcadan et al. [83]	50	5	Sisal fibres of length ranging from 2 to 10mm, 0% fibre loading.	Poly-styrene	Longitudinal aligned fibres (L), Randomly aligned fibre (R)	L: 34.90 R: 34.90	L: 390 R: 390
			10% fibre loading.		L,R	L: 21.36 R: 18.16	L: 629 R: 516.83
			20% fibre loading.		L,R	L: 43.20 R: 25.98	L: 999.9 R: 553.7
			30% fibre loading.		L,R	L: 45.06 R: 20.42	L: 998 R: 624.3
Goichi et al. [35]	150	1	Kenaf fibre	PLA sheet of 2mm thickness	PLA	55.4	1.4
					Composite A	66.5	4.2
					Composite B	54.0	3.5
					Uni-directional direction composite	111.6	5.9
Khondker et al. [31]	100 (ASTM D638)	5	Jute fibre (corchora solitorio)	PLA fibres	PP	36	1.6
					Microbraid composite	142	9.3

2.8 Hybridisation

The term hybridization means a combination of more than one type of fibres in the same matrix. By hybridization of natural fibres and synthetic fibres, it is possible to achieve a balance between performance properties and cost of the composites, which would not otherwise be obtained with a single kind of reinforcement [74].

2.8.1 Fabrication and tensile property of hybrid composite

The typical material, matrix and fabrication methods for hybrid composites are summarised in Appendix 3 along with selected processing techniques. Most of researchers [2,44,65,73–77] fabricated randomly oriented individual single natural fibre/E-glass fibre hybrid composite.

Assessment of tensile properties of natural/glass fibre reinforced hybrid composite is carried out using a universal testing machine in accordance with ASTM D638 [2,44,65,73–77]. Compilation of gauge lengths and load rates for tensile testing of hybrid composites and the resulting tensile properties are shown in Appendix 4. Dog-bone shaped specimens of hybrid composites samples were produced from the composite places for the testing.

Panthapulakkal et al. [74] Morye et al. [77] Kumar et al. [78], Samal et al.[73] Thwe et al. [2,65] all observed tensile properties of hybrid composites to increase with increasing glass fibre content of the hybrid composites.

Panthapulakkal et al. [74] observed tensile properties of hemp/glass fibres reinforced hybrid composite with different glass fibre loading. The tensile strength of the composite increased as the glass fibre content increase due to the higher strength of glass fibre compared to hemp fibre. The tensile modulus of hybrid composites showed a 6-17% increase with glass fibre loading ranging from 5 to 15wt%. Samal et al. [73] also found that the tensile strength and modulus of bamboo/glass fibre reinforced hybrid composite increased by 20% with 15wt% glass fibre loading. Thwe et al. [2,65] observed the tensile strength and modulus of 20wt% glass fibre/10wt% bamboo fibre reinforced hybrid composites to increased by 15 % and 18% respectively compared with 30wt% bamboo fibre reinforced composites.

However, Kushwaha et al. [79] found contradicting results. They fabricated bamboo/glass hybrid composite using two different forms of glass fibre, woven glass mat and glass strand mat. There was a decrease in the tensile strength of hybrid composite compared with 100% bamboo fibre reinforced composite. In the case of strand mat, they assumed that the load distribution in fibres was not homogeneous because the individual fibres were not loaded uniformly. However, the woven glass mat shows a positive hybrid effect. The tensile properties increase with increasing glass fibre loading. Also, in the case of woven bamboo/glass mat reinforced hybrid composite, the tensile strength and modulus were higher than that of woven bamboo/stand glass mat reinforced hybrid composite. This was said to be due to the higher tensile strength of woven glass mat composite, 306 MPa when compared to that of strand mat composite, 245 MPa.

Pavithran et al. [75] compared the mechanical properties of only glass fibre reinforced composites (GRP) with glass/coir fibre reinforced hybrid composites (CGP) at identical glass fibre volume fraction. As seen in Table 19, it can be seen that tensile properties of CRP hybrid composites was close to those of GRP containing 10% volume fraction of glass fibre. However, above this volume fraction, mechanical properties except tensile strength of CGP hybrid composites fall much below those of GRP containing equivalent volume fraction of glass fibre. They assumed that coir fibres behaved as defects in CGP hybrid composites. They found that the optimum volume fraction of glass fibre was around 10%.

Morye et al. [77] prepared two different types of composites, symmetric and asymmetric hybrid composites. In the case of symmetric composites, the sequence of composite was glass fabric / a random mat of flax fibre / glass fabric. In asymmetric composites, on the other hand, the two layers of glass fabrics were placed on top of the flax fibre random mat. They found an interesting point in that symmetric composite construction shows higher tensile strength than those for the asymmetric composites. They assumed that on tensile loading of asymmetric composites, the difference in the tensile moduli of the glass fibres and flax fibres caused shear stresses at the glass/flax interface resulting in delamination failure at the interface. Consequently the load is transferred to individual layers and the composite fails at a lower load.

3 Experimental Setup & Procedures

3.1 Introduction

A number of experiments were carried out to fulfil the aims and objectives mentioned in Introduction. This called for the preparation of different natural fibres and glass fibre preforms and composites. These samples were used for optical microscopy, scanning electron microscopy and mechanical testing.

3.2 Materials

3.2.1 Fibres

3.2.1.1 Bamboo Fibres

Bamboo fibres were supplied by Gaddum and Gaddum (U.K). Soft bamboo fibres were provided with subtle sheen in a natural white colour. The average length was 94.58mm showing a wide length distribution, the shortest 18mm and the longest 179mm. As received bamboo fibres are shown in Figure 17.

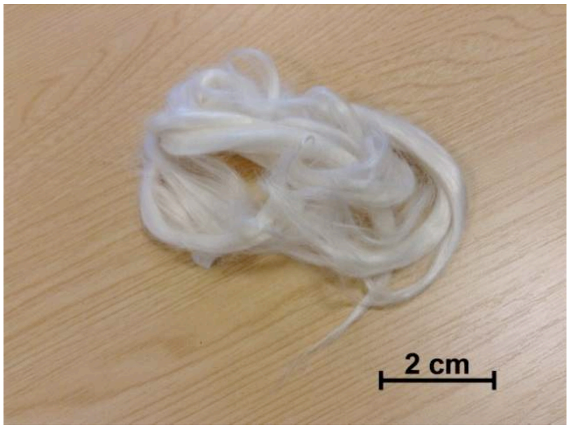


Figure 17 A photograph of as received bamboo fibres.

3.2.1.2 Coir Fibres

Coconut fibres were from Hayleys Ltd., Sri Lanka. These were supplied as bundles of long-fibres. It shows a natural brown colour in the retted state. The average length was 230 mm showing a range between 250 mm and 300 mm.

As received coir fibres are shown in Figure 18.

Figure 18 A photograph of as received coir fibres.

3.2.1.3 E-glass Fibres

E-glass fibres were supplied by Owens-Corning (R25H 2400 TEX). E-glass means electrically graded glass fibres. Each fibre bundle contained 2400 individual filaments. R25H is a specially designed fibre for use in filament and pultrusion applications in polyester/vinyl ester and epoxy resins systems.

3.2.2 Resins

(i) Laminating resin

Araldite LY 3505 Epoxy resin system and Hardeners XB 3403 were supplied by Araldite, U.K.

The mix ratio was 100(LY3505)/ 35(XB3403) parts by weight.

(ii) End-tab resin

Scotch-weld 9323-2 B/A (supplied by 3M, U.K) was used to bond aluminium end-tabs to the specimens. Scotch-weld 9323-2B/A consisted of Base (XA9320) and Hardener (XA9321). The mix ratio was 100/50 by weight.

3.2.3 Potting and mounting resin for optical microscopy

Epofix™ cold-setting embedding resin supplied by Struers was used to mount the manufactured composite. Mix ratio is15 parts by volume of resin with 2 parts by volume of hardener.

3.2.4 Preparation of samples for scanning electron microscopy

Raw individual bamboo, coir fibres and tensile-fractured bamboo and coir fibre-reinforced composites were mounted onto SEM stubs. Samples of each fibre types were prepared both in transverse and longitudinal directions. Tensile-fractured composites were sectioned in the longitudinal) and transverse directions. All samples the samples were stored in a desiccated cabinet until required. Prior to SEM analysis, the specimens were sputter-coated with a gold/platinum alloy for 3 minutes.

3.3 Production of unidirectional bamboo fibre preforms

3.3.1 Carding process

Bamboo fibre was processed using a carding machine to achieve a continuous preform. An Ashford 72ft fine Drum Carder (supplied by Handspinner Ltd.) was used for the carding process. “72ft fine” refers to 72 points (teeth) per square inch. A photograph of the carding machine is shown in Figure 19.

The carding machine consisted of different parts: two drums, doffer stick, carding handle, drum carder cramp and drive belt. The drum carder cramp keeps the drum carder from moving around on the working bench. The drive belt transmits drive from the motive power of a carding handle to turn the drums. The smaller drum catches fibres and transfers them onto the larger drum. The smaller drum firstly moves the fibre into contact with the big drum, and secondly holds the fibre such that they tend to straighten as they wind onto the larger drum to make the fibres parallel. The larger drum rotates faster than the small drum, so as the fibres come in contact with the large drum, they are drawn off into a thin layer on the big drum, rather than staying as a thick layer. A doffer stick was used to separate any clumps that did form and to spread fibres. Photographs of the carding process are shown in Figure 20. The carding process can be divided into 3 separate processes, carding (feeding), separating and removing.

A. Carding

1. The drum carder was positioned on a sturdy workbench.
2. Before feeding the fibres onto the drums, a hand carding brush was used to align the fibres to remove the entangled fibres in a unidirectional manner.

3. The fibres were pulled apart such that the fibres were spread across the drum rather than bunching up in an area.
4. The fibres were gradually fed under the smaller drum by turning the handle on the drum carder in a clockwise direction. The teeth on both drums comb the fibres apart.
5. Continued feeding of fibres onto the drum, making sure it distributes equally.
6. Turning the handle until the larger drum is covered and full to the top of the metal teeth. When the drum is full, it starts to overflow over the sides of the main drum.

B. Separating

7. Removal of the fibres from the drum using a doffer stick. Sliding of the doffer stick under the fibres on the open strip of the drum.
8. Gently lifting the doffer stick toward the right side of the drum. The fibres will pull apart and separate.

C. Removing

9. Slowly removing fibres by gently pulling the fibre from the teeth and turning the handle slowly counter-clockwise.
10. Lift the entire batt (spread fibres) up and away from the drum. The prepared fibres were wrapped in aluminium foil and dried in an oven at 80 °C for 4 hours before the resin infusion process.

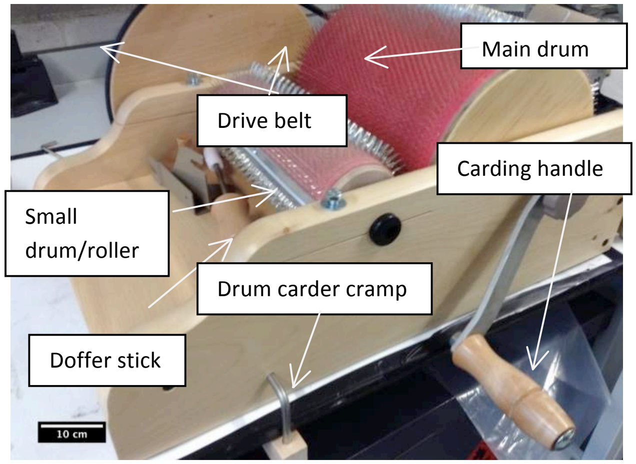
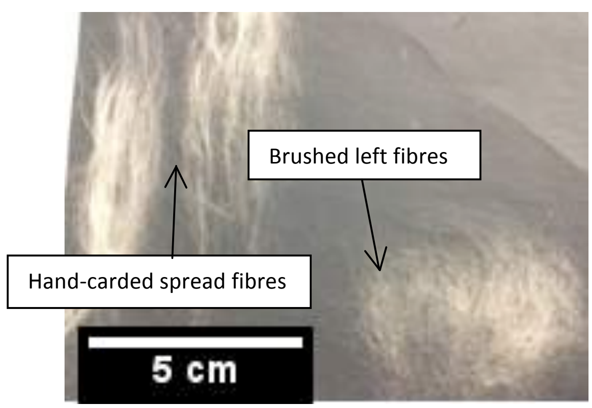
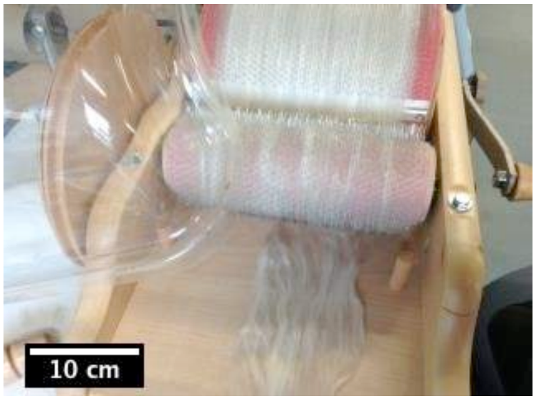


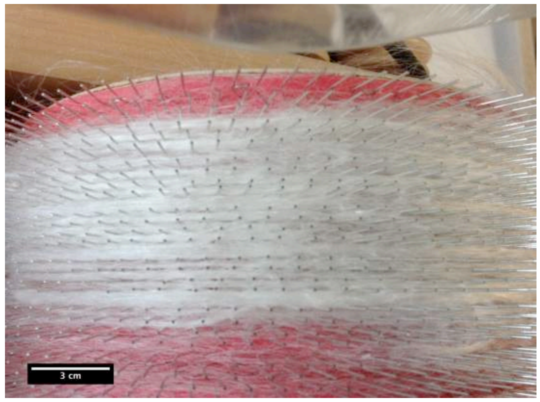
Figure 19 Photograph of the carding machine.



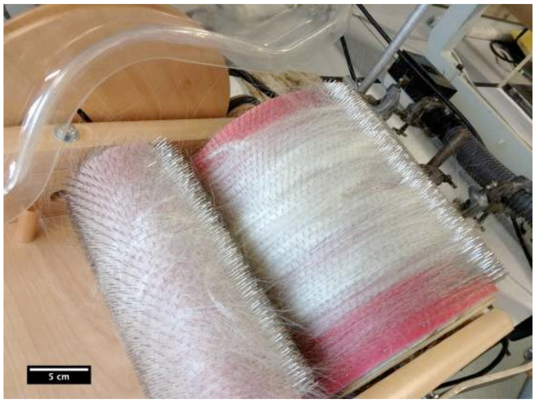
(1) **(2)**



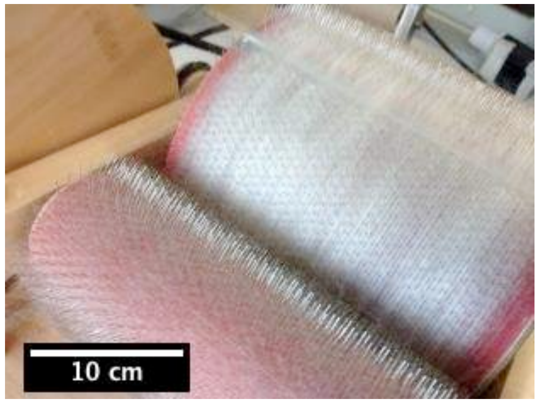
(3,4)



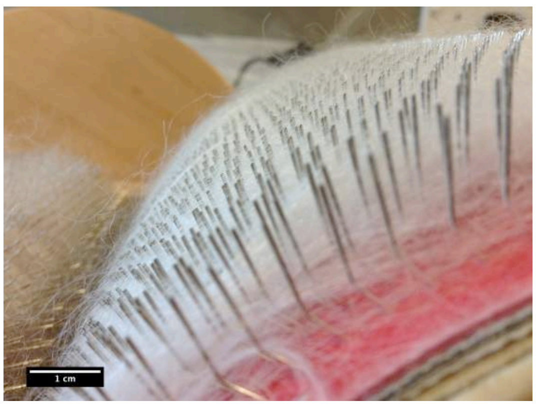
(5-1)



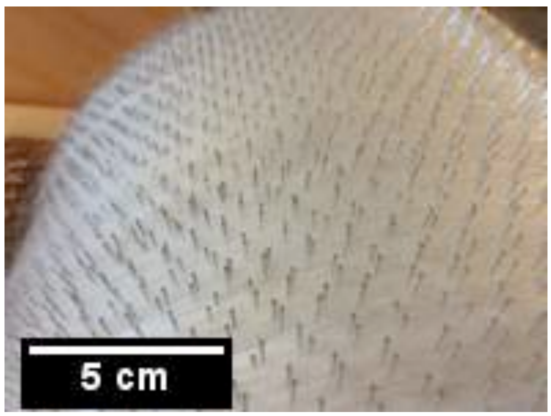
(5-2)



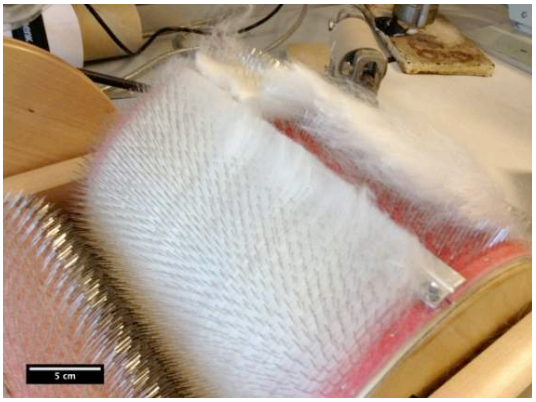
(5-3)

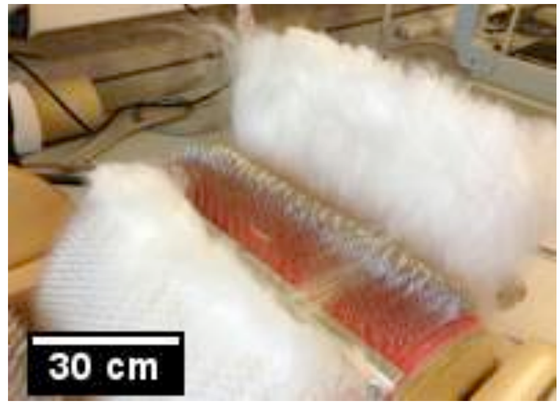


(6-1)

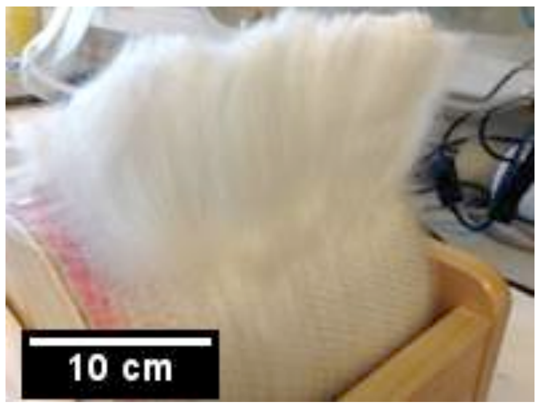


(6-2)





(7,8) **(9)**



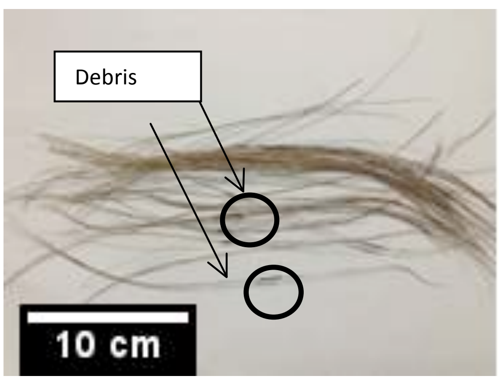
(10)

Figure 20 Photographs of the carding process.

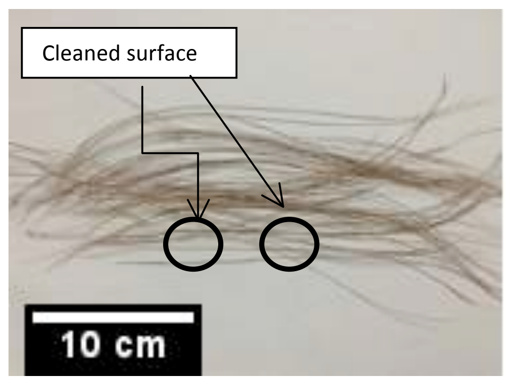
3.3.2 Production of coir fibre preforms

A manual technique was used to manufacture preforms of coir fibres where single fibres were secured on an adhesive-backed paper to create unidirectional alignment. The aligned fibres are shown in Figure 21.

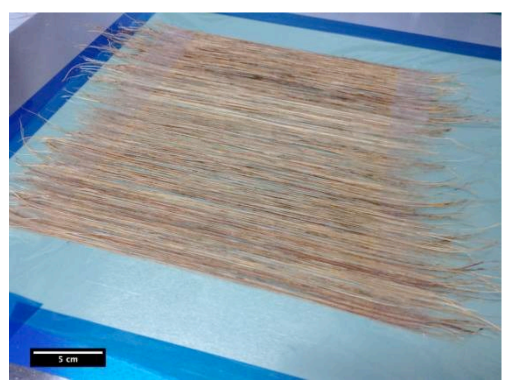
1. The coir fibres were dried at 80 °C for 6-hours.
2. The surface contamination was brushed off with a laboratory brush and rubbed gently to remove the debris.
3. Guide paper was positioned on a stable work surface and a strip of double sided tape was attached to both ends of the guide paper.
4. Single natural fibres were individually aligned and attached to the guide paper such that no gaps existed between the fibres.
5. If more than two layers were being prepared, single fibres were again aligned on top of the first layer.



(1)



(2)



(3) **(4)**

(5-1) **(5-1)**

Figure 21 Photographs of the aligning process for coir fibres.

3.3.3 E-glass fibre spreading

The spreading of the E-glass fibres was carried out using a procedure that was developed in the Sensors and Composites Group using the so-called "tension-release" process [80]. The spreading of the E-glass fibres used in this study was carried out and supplied by Kate Elizabeth, of the Sensors and Composite group, University of Birmingham.

3.4 Fabrication of composites

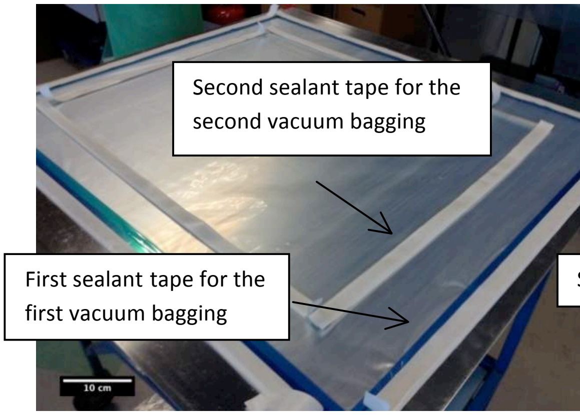
3.4.1 Resin infusion process

The natural fibre preforms were impregnated using a resin infusion process. Figure 22 presents a sequence of photographs to provide a description of the resin infusion process.

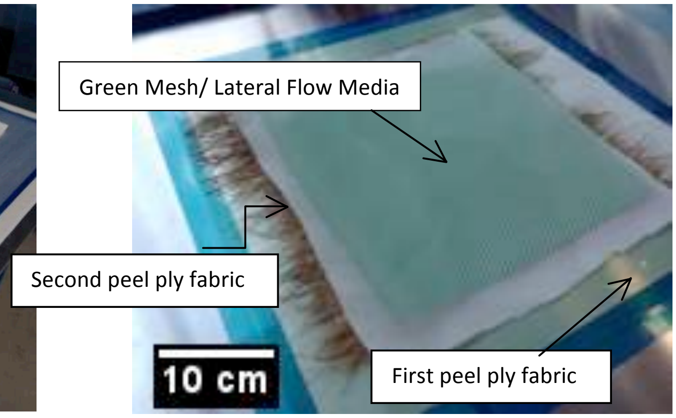
1. A plastic film is placed on to a metal plate in order to allow easy removal of the cured composite.

   Sealant tape is stuck onto the plate at the outer edge of the plastic sheet. A smaller concentric square of tape is created in the centre of the plastic film (spread natural fibres are placed in this region).
2. The first peel ply fabric is placed on the plastic film. The size of the peel ply fabric must be larger than the size of composites.
3. The natural fibres are spread and then placed onto the peel ply. The second peel ply fabric is then placed onto the spread natural fibres. Resin Flow media (Green Mesh) is then placed onto the second peel ply. The size of the flow media must be smaller than that of the second peel ply.
4. Omega tube is used as the inlet and is placed onto the resin flow media (on the top of the spread fibres) and another omega tube as the outlet is placed onto the first peel ply (next to the spread fibres).
5. Plastic hoses are inserted into two omega tubes. The entire fibre layup is covered (for the vacuum bagging system) with a plastic sheet and the fibre region is sealed without any gaps between the bottom plate and the covering plastic sheet.

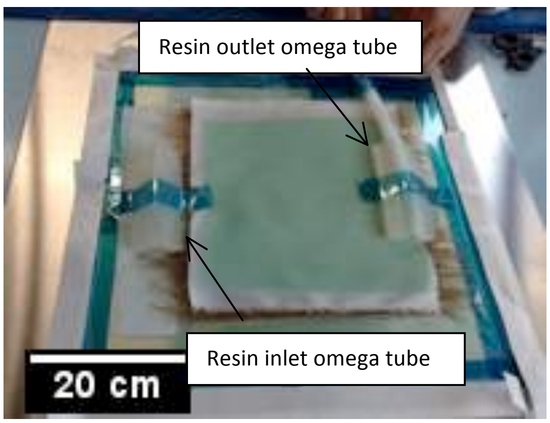
6. Other two omega tubes are placed onto the First plastic film (outside of the spread fibres) for a better vacuum condition. Plastic hoses are inserted into these omega tubes. The first film (the first bagging system) is covered with a second plastic sheet and the system is double sealed (to ensure a good vacuum condition).
7. The plastic hose inserted into the resin inlet is clamped.
8. The three plastic hoses are connected to the resin trap and then the vacuum pump is switched on. The vacuum pressure is maintained at approximately 0.9 bar.
9. The end part of the resin inlet hose is immersed into a resin tank/container. Araldite LY 3505, an epoxy resin mixed with Hardeners XB 3403 (supplied by Araldite, U.K.) is prepared in the resin container. Release of the clamp allowed resin to infuse between the fibres.
10. Clamping back the hose when the resin has completely infused between the fibres stops the impregnation process.
11. The samples are placed in air for 24 hours then all plastic sheets, mesh and ply were scraped from the system.
12. Samples are cut from the layups using a diamond saw and water-jet cutting to extract specimens appropriate for mechanical testing.


Second sealant tape for the second vacuum bagging
First sealant tape for the first vacuum bagging

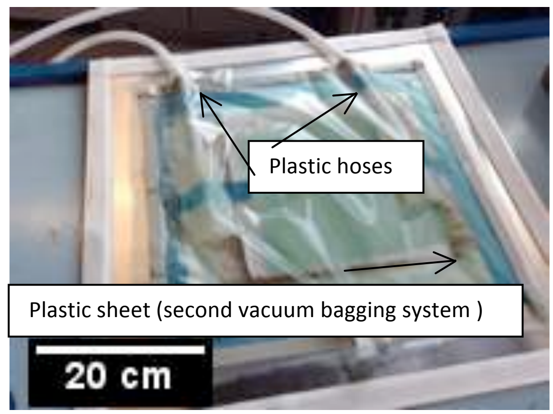
(1,2)


Green Mesh/ Lateral Flow Media
Second peel ply fabric
10 cm
First peel ply fabric

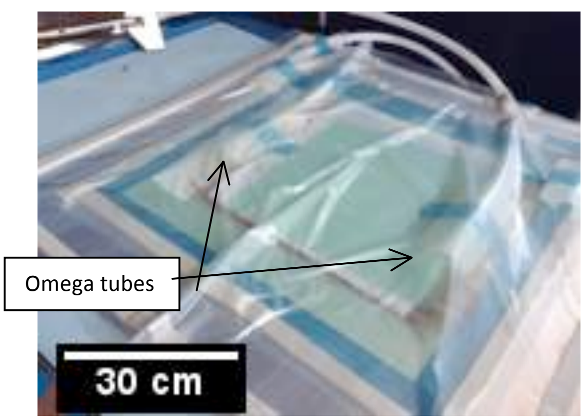
(3)


Resin outlet omega tube
20 cm
Resin inlet omega tube

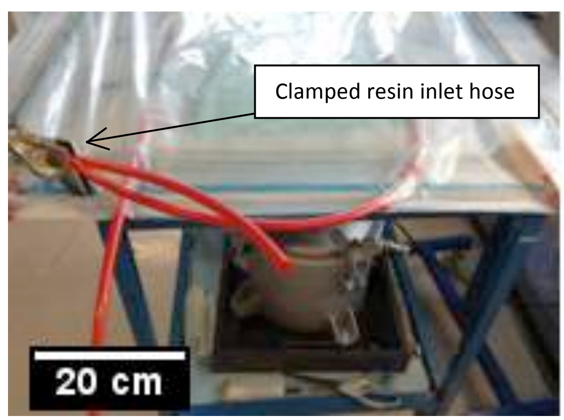
(4)


Plastic hoses
Plastic sheet (second vacuum bagging system)
20 cm

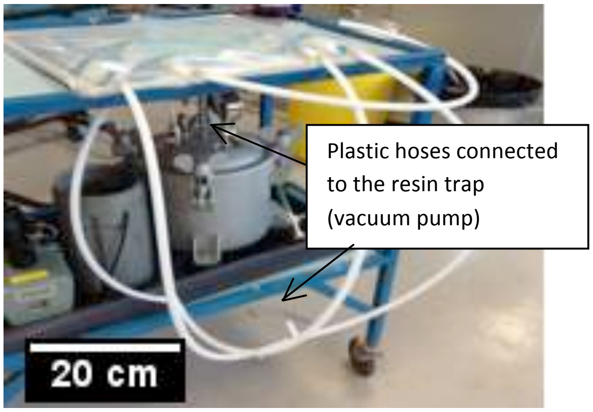
(5)


Omega tubes
30 cm

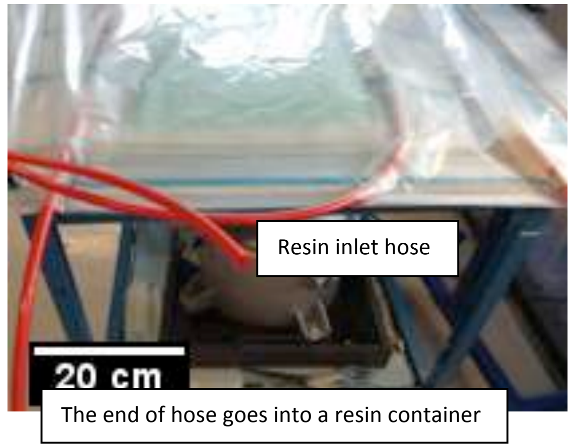
(6)


Clamped resin inlet hose
20 cm

(7)



(8)



(9)

Figure 22 Photographs of resin infusion process.

3.5 Characterisation

3.5.1 Microstructural inspection

(i) Scanning electron microscopy

The microstructural features of the bamboo and coir fibres were characterised using a JEOL6060 SEI Scanning Electron Microscopy (SEM). Prior to SEM analysis, the fibre samples were sputter-coated (using an SC500 manufactured by Emscope, U.K.) with gold/palladium using 0.1 Torr vacuum and 25 mA current held for approximately three minutes.

(ii) Optical microscopy

The microstructural features of the bamboo and coir fibres were also characterized by an optical microscope, Axioskop 2 MAT mot with data logging via AxioVision software. (supplied by Carl Zeiss Ltd, U.K.). Prior to optical microscope analysis, samples were cut into a small section from the bamboo and coir fibre reinforced composites were previously prepared for tensile testing using a hand-saw. Epofix™ cold-setting embedding resin supplied by Struers was used to mount the manufactured composite. The mould (also supplied by Struers) was used for pressing mounts to fit polishing machine sample holders. Specimens were placed in the centre of the wupty. 15 parts by volume of resin were mixed with 2 parts by volume of hardener (25 parts by weight of resin with 3 parts by weight of hardener) in a paper cup and stired carefully for at least 2 minutes. The mixture was carefully poured over the specimen in the mould so that no air bubbles were trapped and the mixture was allowed to harden. The samples are cured in a furnace at 75°C for 8 hours, in accordance with the materials data sheet.

The mounted samples were then polished using silicon carbide abrasive papers discs (supplied by MetPrep Ltd, U.K.) at 400,800,1200,2000,2500 grit in a GP-2B Grinder Polisher with a PH100 Grinder/Polishing head (supplied by Sinowon Instrument Co., Ltd, China) and gently polished using aqueous suspension gamma, 0.05 micron liquid (supplied by MetPrep Ltd, U.K.). After polishing, samples were cleaned using an ultrasonic bath and dried in an air-circulating oven for 30 minutes at 75°C.

3.5.2 Mechanical properties

The tensile testing of bamboo, coir and hybrid unidirectional composite was carried out using an Instron 5566 machine with data logging via Merlin TM software. The tests were conducted at ambient laboratory temperatures. The dimensions of the test specimens used are shown in Figure 23, in compliance with ASTM D3039M-08. The samples were cut using a diamond cutter and then the cut edges were polished using P800 abrasive paper (supplied by Met Prep Ltd, U.K.). In the case of tensile test specimens, Scotch-weld 9323-2 B/A (supplied by 3M, U.K) was used to bond aluminium end-tabs to the specimens. The prepared samples are shown in Figure 24, the dimensions of the aluminium end-tabs were 50 mm long × 25 mm wide x 1mm thick.

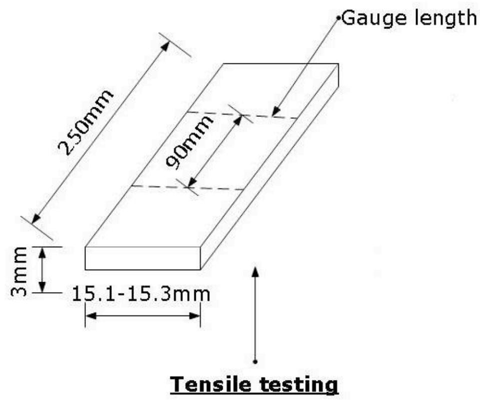
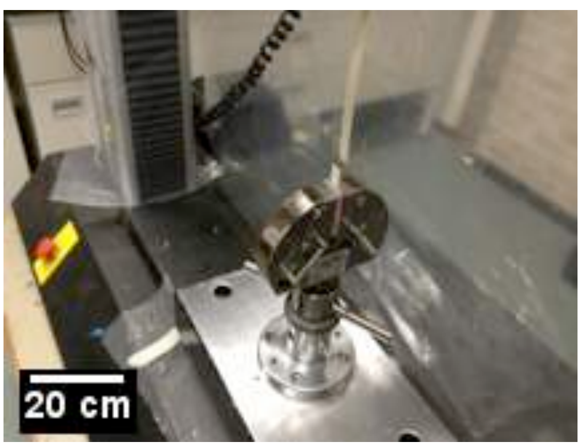
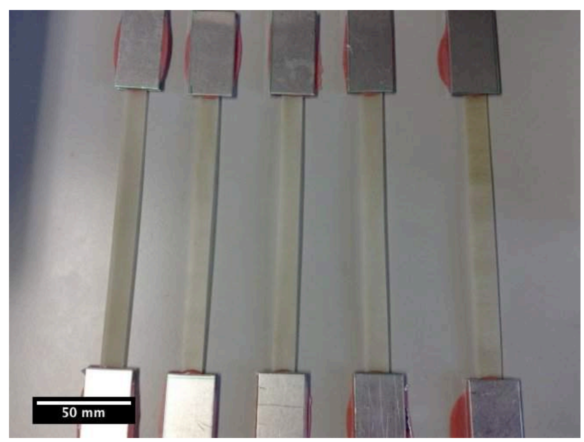


Figure 23 Dimensions of the tensile test specimen.





(a) (b)

Figure 24 A photograph of the (a) tensile testing machine and (b) end-tabbed samples respectively.

4 Results and Discussion

4.1 Introduction

This chapter summarises the results obtained in this study and presents a detailed discussion on the following topics:

(i) The development of a manufacturing method for unidirectional arrays of bamboo and coir fibres.

(ii) A feasibility study into the production filament level hybrids (intra-ply) of bamboo and E-glass fibres.

(iii) Fibre impregnation and lamination of preforms using a resin infusion process.

(iv) Characterisation of the microstructures of bamboo and coir and their fracture surfaces in the mono-fibre and hybrid composite configurations.

(v) Determination of the tensile properties of the manufactured bamboo-glass hybrid and coir and bamboo mono-fibre composites.

4.2 Production of aligned natural fibre preforms

Geethamma et al. [72] found that the fibre orientation and the fibre/matrix interfacial adhesion are two critical factors that affect the mechanical properties of natural fibre composite. Herrera-Franco et al. [63] also found the mechanical properties in composites depend mainly on fibre orientation. They also found that the mechanical properties are improved if fibres are aligned parallel to the direction of the applied loading. If the fibres are aligned in the transverse direction, fracture of the composite takes place mainly through the matrix, because the fibres do not contribute significantly to the strength of the composite.

The majority of researchers have used mats and woven fibre forms presumably because of the difficulties associated with the extraction and enable the alignment of natural fibres due to: (i) their relatively short lengths; (ii) non-uniform cross-section; and (iii) fibre entanglement [66,81,82].

Thus processing techniques are needed to orient and produce long-fibres preforms. In this current project, bamboo fibres were processed via carding to produce unidirectional preforms. However, a manual process was used to produce the unidirectional coir preforms. This following section discusses the outcome of procedures that were developed for carding and the manual processing of bamboo and coir fibres.

4.2.1 Carding process

In order to achieve the unidirectional preform of bamboo fibres, a carding process was used. Unlike previous researchers [60,67,81,82], relatively long discontinuous fibres (average length was 180 mm) were used to produce silk and bamboo preforms.

The carding process used by previous researchers was used to make randomly oriented felt-type preforms. They also used short fibres, which cannot produce the continuous unidirectionally aligned preform using carding process as this results in fibre entanglement on the needles on the carding drums.

Rui-Hua Hu et al. [81] fabricated their composites using a carding process to blend PLA fibre and the fiber uniformly. Jute and PLA fibers were mixed, combed and fed into a carding machine to be further mixed. The mixture was then cross-lapped and needle punctured to make felt.

Hao et al. [67] carded kenaf / PP fibre mixtures and carded once again, this mixture, but fed perpendicular to the first carding direction to ensure a web form. They found fibres to be laid randomly in the fabric plane, but the in-plane properties were less anisotropic than other types of fiber composites such as randomly oriented composite.

The carding process was described previously in 3.3.1. The fibres were fed onto a pair of mechanically inter-connected drums until the fibres filled evenly. Figure 25 shows spread bamboo fibres after drying at 60 °C. There are three important considerations regarding the drum carder.

Firstly, it is difficult to control the feed speed of the natural fibres. The drums were spun manually at different speeds and fibres were reintroduced when the drum reached specific rotation angles (because of the relatively short length of the discontinuous fibres). To produce more uniform pre-forms, the speed was optimized after several trials. If the drum speed was too high, the fibres would not be combed thoroughly and would lead to entanglement. The fibres were fed again when the drums reached four specified angles, 90 °, 180 °, 270 ° and 360 °. The fibres were fed onto the first drum; the drums were rotated manually using a handle, until the fibres were spread evenly on the second drum. Once the fibres were fed onto the second drum, the rotation was stopped intermittently every 90^0 to avoid thicker regions in the final preform.

Secondly, it was difficult to control the volume of the natural fibre-feed that is introduced to the carding machine. The solution to this problem was to pre-weight a bundle of the fibres and to pre-comb it manually, prior to introducing it to the carding machine. This was found to prevent the fibres from entanglement. Furthermore, it provided a means for controlling the fibre volume fraction. It was observed that when entangled fibres were fed to the carding machine (without manual pre-combing), the fibres were overlapped and miss-oriented in the preform. As the volume of the fibres that were transferred to the second drum is larger, the amount of fibres introduced on the first drum should be lower. Once the carded fibres reached three-quarters of the height of the drum guide needles (see Figure 26), the feeding was stopped. Above this point, it was found that the fibres could not be combed and aligned to produce unidirectional preforms.

Figure 27 illustrates the presence of intrinsic entanglement due to the fibre-feeding process. When the fibres were fed onto the drum, on occasions, the fibres were tangled due to the needles meshing between the two drums. When the drum is rotated, the needles on both the drums comb the fibre. However, during this process, if the manual pre-combing was not adequate or if the spatial orientation of the fibres was significantly off-axis, this resulted in entanglement when they were fed onto the second drum.

Figure 28 shows the general appearance of a carded bamboo fibre preform. It can be seen that the fibres aligned continuously in a unidirectional manner.

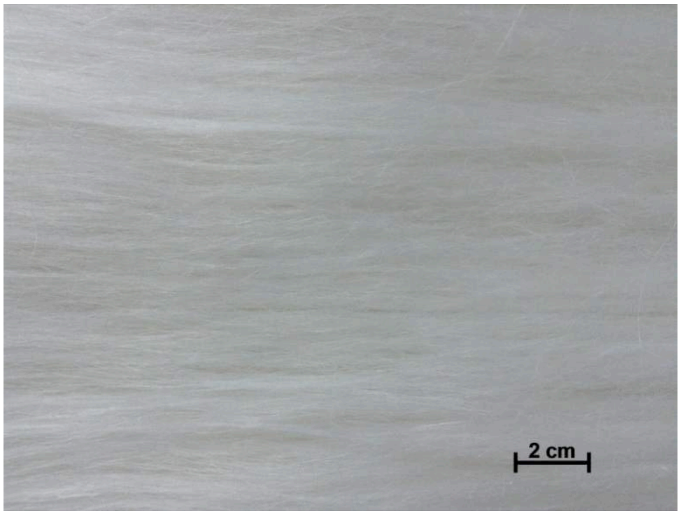


Figure 25 Photograph showing the macroscopic appearance of a bamboo fibre preform obtained via the carding process.

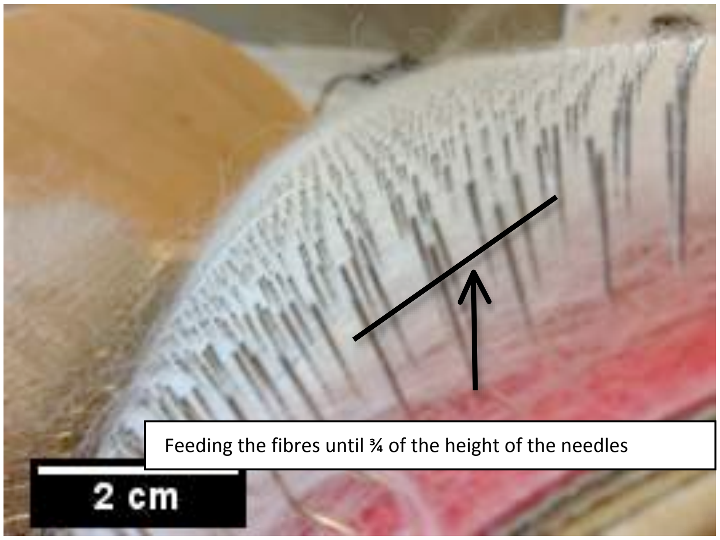
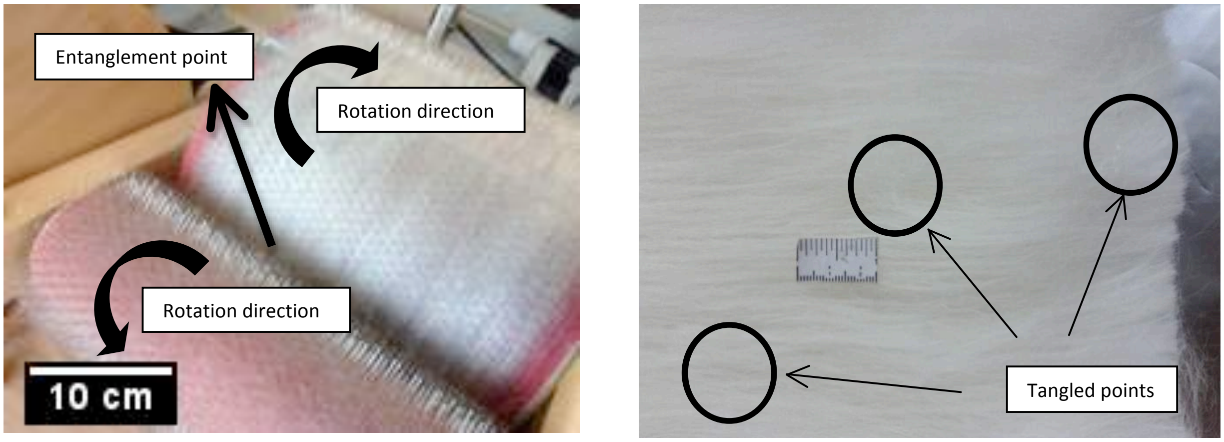


Figure 26 Photograph showing the relative height of the bamboo fibres on the needles on the carding machine. The fibre-feed was terminated after 75% of the heights of the needles were filled.



(a) (b)

Figure 27 Photographs of: (a) illustrating the presence of intrinsic entanglement (b) illustrating tangled bamboo fibres

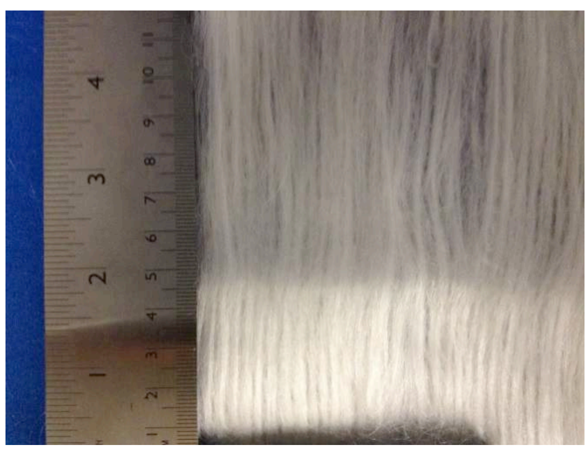


Figure 28 Photograph showing the unidirectional alignment of a bamboo fibre preform obtained via the carding process

4.2.2 Production of unidirectional coir preforms

Unlike previous researchers [40,45,56,72,83], in the current study individual coir fibres were picked and aligned manually to produce uniaxial coir fibre preforms.

In this process developed by the author, the fibres were aligned manually onto two strips of double-sided tape that were located 25 cm apart. Both end of individual coir fibres were secured as illustrated in Figure 29. As these fibres were not treated with alkali to remove the substances mentioned previously (i.e. lignin and waxes), the surface contamination was brushed off with a laboratory brush and rubbed gently to remove the debris. The above-mentioned process where the fibres were aligned manually and secured on the double-sided tape, was time-consuming but it provided a technique for the production of preforms where a dense array of aligned coir fibres could be produced without gaps between fibres. The length of the coir fibre was in the range of 250-300 mm and the dimension of the laminate that was fabricated was 250 x 250 mm. Three layers of unidirectional assembled coir fibre laminates were stacked prior to resin infusion. A photograph of single-ply laminate is presented in Figure 30, where it is readily apparent that the gaps between fibres are negligible. The fabrication procedure developed by the author was capable of producing coir fibre preforms that were well-aligned without any significant gaps between the filaments.

Goichi et al. [59] made unidirectional kenaf sheet by pulling out the weft kenaf yarn bundles from the textile. But the interval (gap) of the fibre bundles was 1.9mm and they called their composites quasi-isotropic composites, suggesting the fibres were not fully aligned unidirectionally. In this configuration, the gaps between the fibres can make unevenly distributed composites and the thickness cannot be uniform when the fibres are stacked / layered.

Manilcadan et al. [70] combed and hand aligned sisal fibres ranging from 2 to 10mm in length. The fibres were not fully aligned unidirectionally and show uneven distribution. Khondker et al. [30] fabricated uniaxial jute fibre preform using 'micro-braid yarn' (MBY). Continuous jute yarns were used as axial fibres around which, PLA fibres were braided. However, to enable jute fibres to maintain orientations, the matrix fibre needed to sustain the alignment and tension was needed during the whole process.

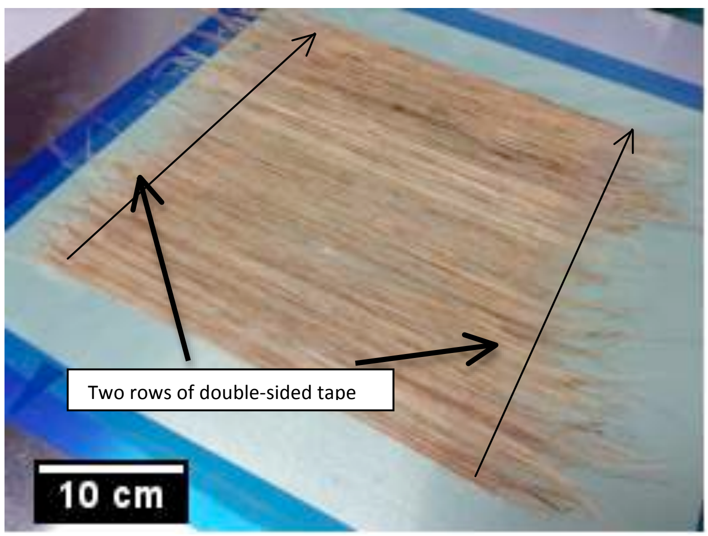


Figure 29 Photograph illustrating the degree of alignment that was achieved via the manual procedure for producing uni-axial preforms of coir fibres.

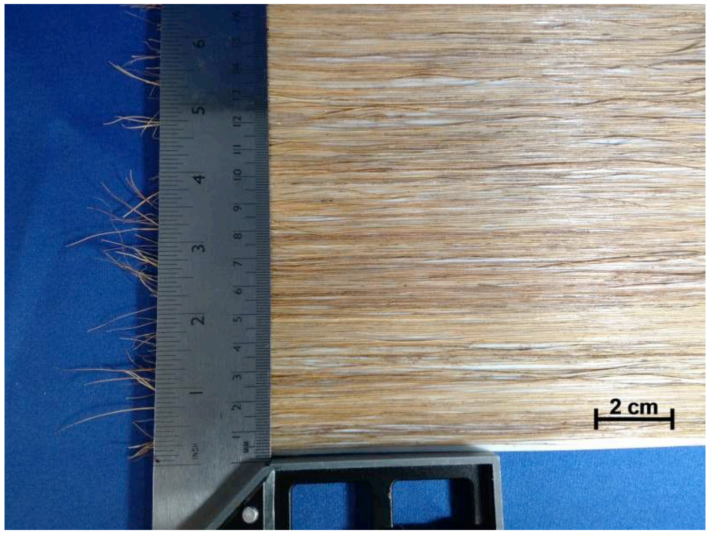


Figure 30 A photograph showing a magnified view of the of manually aligned coir fibre preform.

4.2.3 Lamination of the coir preforms

In order to manufacture composites of a specified thickness, it was necessary to stack three layers of the previously mentioned coir preforms. When the fibre arrays were not secured with the two rows of tapes as mentioned previously, during lamination the fibres on the top-layer tended to drop into the interstitial spaces and thus, it resulted in a single layer instead of distinct layers. Moreover, this made the thickness of the composites uneven. To avoid this problem, two rows of double-side tapes were used to apply tension and to the preforms. The retention of the tension until they were stacked together was achieved by attaching the preforms.

4.3 Hybridisation

In this current work, alternate layers of bamboo and spread E-glass fibres were used to manufacture hybrid composites. Three layers of the bamboo fibre preform as shown in Figure 31(a) were prepared using the carding process outlined previously.

In the case of the E-glass fibre, the fibres were supplied as a bundle consisting of 2400 individual filaments. In order to enable inter-filament interactions or hybridisation, it was necessary to spread the filaments in the E-glass bundle. The spreading of the E-glass fibres was carried out using a procedure that was developed in the Sensors and Composites Group using the so-called "tension-release" process [80]. The spreading of the E-glass fibres used in this study was carried out and supplied by BSc project student within the group namely, Kate Elizabeth Franklin.

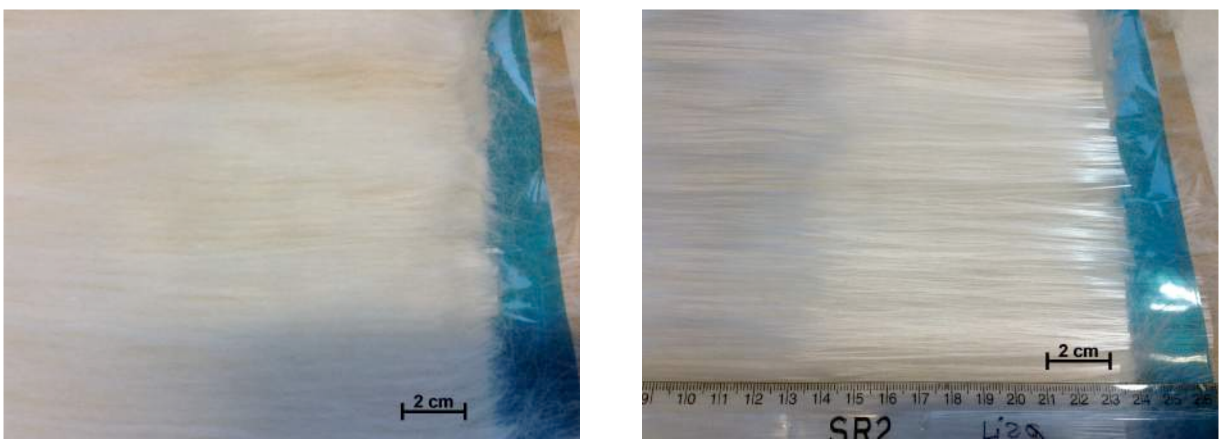
Most researchers [2,44,57,62,73,75,77] have used short length glass fibres to hybridise natural fibres. (not inter-filament interactions)

It is commonly known that longer fibres can carry more stress, which leads to higher mechanical properties. Jin Woo Yi et al. [84] found that short glass fibres were not easy to align unidirectionally and could not predict the direction during the fabrication (especially injection moulding). They also found short glass fibres can easily agglomerate in the composites instead of mixing evenly with kenaf fibres. In the current work, long and continuous glass fibres were used to produce hybrid composites.

As seen in Figure 31(a and b), the bamboo fibres and glass fibres are well- aligned. However, in Figure 31(a) it can be seen that there is an uneven fibre distribution due to the carding process. When the fibres were fed onto the drum, the amounts of fibres were not the same each time resulting in fibre- rich and fibre-deficient areas. Further research is needed to overcome this problem. The width of spread glass fibres was 30mm in average, so glass fibres may have overlapped when 8 bundle of spread glass fibres were layered unidirectionally on the top of 250mm wide bamboo fibres.

Figure 32 shows a hybrid preform where the spread E-glass bundles are stacked alternately (bamboo/E-glass/bamboo/E-glass/Bamboo/E-glass) via a manual process. The fabrication is then completed via a resin infusion process.

A photograph of the laminated hybrid composite consisting of alternating layers of the bamboo and spread E-glass fibres is shown in Figure 33. At the time of writing, the author was not aware of any previous publication involving hybridisation involving aligned bamboo preforms and spread E-glass fibres.



(a) (b)

Figure 31 Photographs of (a) bamboo fibre preform and (b) spread E-glass fibres.

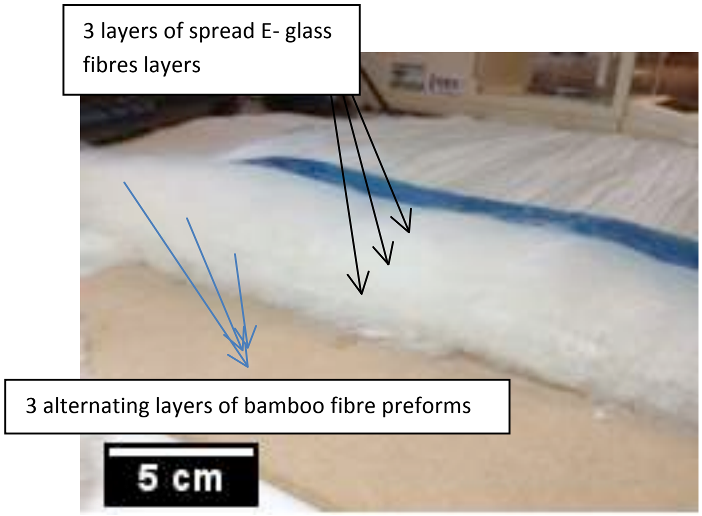


Figure 32 Photograph showing a 6-layer of alternating bamboo preform/spread E-glass fibre preform.

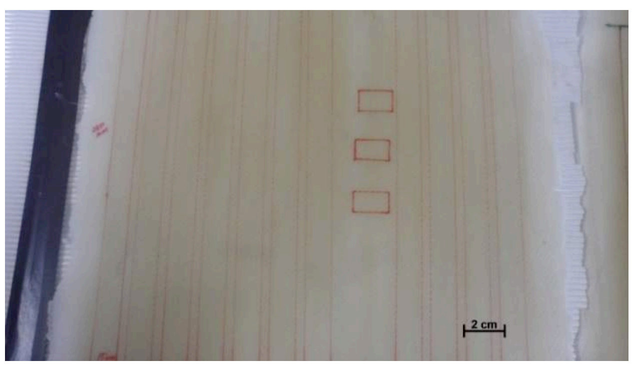


Figure 33 Photograph of hybrid composite.

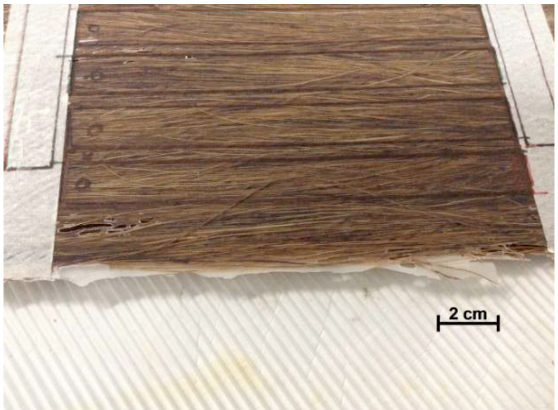
4.4 Resin infusion process

The bamboo, silk, coir and hybrid composites were fabricated/laminated using the resin infusion technique. The details of this process are presented in the Experimental Setup & Procedures section.

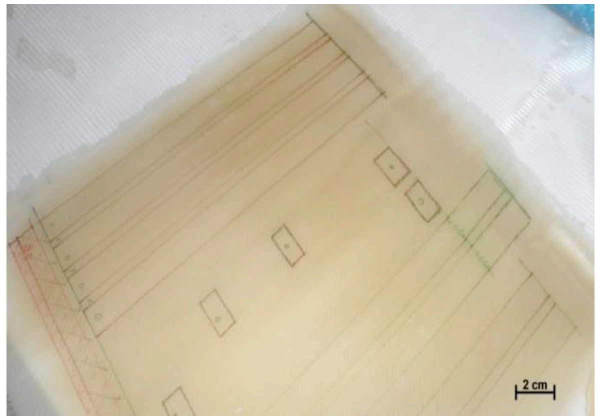
The processing techniques used for natural fibre-reinforced composites are generally designed for conventional fibre-reinforced composites [21]. However, for natural fibre-reinforced composites, a more delicate, low processing temperature, pressure, etc. processing is needed. Idicula et al. [57] compared the tensile properties of compression moulding (CM) and resin transfer moulding (RTM) of mixed banana and sisal hybrid fibre-reinforced polyester composites. They found composites fabricated by RTM (1941 MPa) showed a higher tensile strength than by CM (1601 MPa). This is attributed to the lower void content for the RTM prepared composites. During the RTM process, the fibres are pressed by a vacuum pump and resin is injected at pressure. This process makes the resin move forward by pushing the air out, which decreased the voids. However, RTM used both solid moulds, which makes it difficult to produce non-flat composites. Also, there can be trapped air inside of solid moulds and total cost of fabricating equipment is high.

Similary, Hyunbum Park et al. [85] used vacuum assisted RTM (VARTM) in their project, which is similar to this author's resin infusion process. They used a solid mould one side and a vacuum bag on the other side. However, the surface of composite was not even due to resin filling one side. The composite near the resin filling tube was thicker than the other side and showed uneven distribution of resin. This uneven resin filling creates voids in the composites. In this research, two resin filling tubes was used with a pressure (1 bar), which gives an even distribution of resin and faster processing.

Figure 34 shows a photograph of the composites processed by resin infusion process and after curing for 24 hours. An assessment of the merits of the resin infusion process will be discussed in 4.6 with SEM images of the fracture surface/optical microscope images.



(a)



(b)

Figure 34 Photographs of (a) coir fibres and (b) bamboo composites produced through the resin infusion process.

4.5 Characterisation of bamboo and coir fibres

4.5.1 Optical microscopy and Scanning electron microscopy (SEM) of bamboo fibre

In the case of bamboo fibre, previous researchers carried out morphological studies on bamboo culm, not on individual bamboo fibres [14,22,23]. But in this work, the morphology of individual bamboo fibres was studied.

Bamboo culm consists of three major parts; a large amount of vascular bundles (main fibre bundles), extra vascular fibre strands and a dense tissue of parenchyma, which is the main strengthening element in bamboo culm. The vascular bundle is surrounded by parenchyma and the fibre bundles are dense, formed by thick walled fibres with a small diameter. The number of bundles is variable according to the species. Some species show extra vascular fibres connected to the main vascular bundle, which have larger diameters and a variable fibre thickness of the fibre wall [22,23].

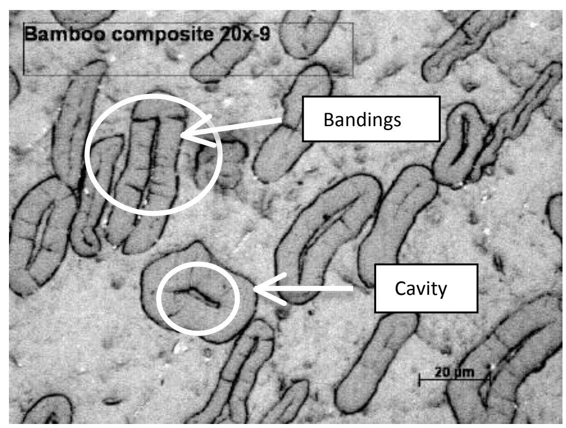
Fibres appear as vascular bundle sheaths of different shapes and the individual fibres are of different lengths and diameters, influenced by their position within the culm. As shown in Figure 35(a), the fibre cross-sections and thickness distributions are uneven.

The cross- section of a single bamboo fibre is an irregular oval shape with a central cavity. Bendings in the bamboo fibres can be seen in Figure 35(b), which may have been caused during fibre processing [14]. Wai et al. [14] investigated the effect of "beating" the pulp. Beating is a physical method of separating the fibres from the woody component. They found morphological changes in these fibres exemplified by cracks in the fibre wall as illustrated in Figure 35(b). They also proposed when the external force was applied to the fibre during the beating process, these transverse bendings are produced within the fibre wall.

However, In the case of bamboo culm, Osorio et al. [22] found no cracks in the vascular bundle and is composed of elementary fibres. This can be explained by the fact that there was no bending / cracks before separating the fibres from the fibre bundle.

The dispersion of fibres within the matrix varied however, it is evident from Figure 35(a) that bamboo fibres are aligned unidirectionally aligned in the composites.

(a)

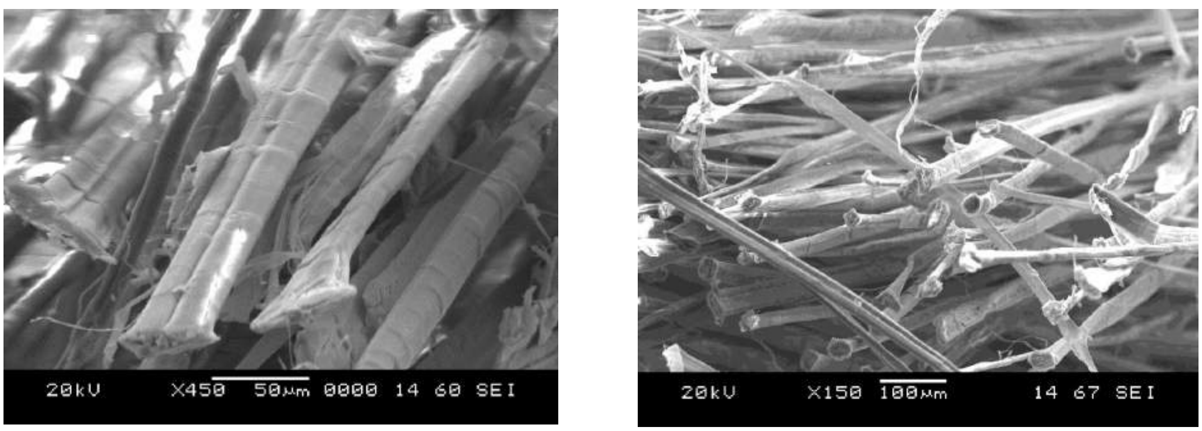


(b)

Figure 35 Optical micrographs of a bamboo-epoxy composite x20 magnification that was manufactured by the author.

A number of techniques were investigated to prepare natural fibre samples for SEM inspection. This was necessary as it was important to ensure that the sample preparation method did not damage the microstructure. The techniques investigated included immersing the bamboo and coir fibres in liquid nitrogen then cleaving them with a fresh portion of a scalpel blade. An investigation was also carried out to establish if cleaning the fibres with acetone followed by drying at 103 °C would aid in retaining the integrity of the microstructure when the samples were cut with a fresh portion of a razor blade. It was found that drying the fibres provided the best route to preparing the samples for SEM [14,16,18,22].

Figure 36(a and b) represent micrographs for as-received and dried (80 °C for 24 hours) respectively. Figure 36(a) shows the cross-section of as-received dry bamboo fibres where it is apparent that the act of cleaving the fibres resulted in them being flattened. This is probably due to the fact that the fibres are hollow where the cleave-end collapses as shown in Figure 36(a). However, the cross- section of bamboo fibres are well maintained the structure as shown in Figure 36(b).



(a) (b)

Figure 36 Typical SEM micrographs for: (a) as-received fibres x450 magnification; and (b) dried bamboo fibres x150 magnification.

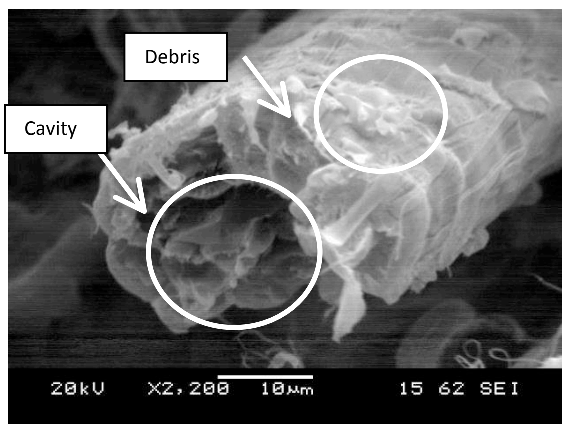
Figure 37 shows the general features of a transverse and longitudinal profiles of untreated bamboo fibres where it can be seen that the bamboo fibres vary in shape and width. Figure 37(a) shows that the bamboo fibre is round shape and has a hollow as seen in Figure 37. Yueping et al. [23] carried out SEM studies on bamboo culm, they also observed that the cross-section of single fibre is round with a small round lumen and a hollow inside. They also showed that bamboo fibres had multi-lamellate cell walls with various layers, and bamboo single fibre cells had a small cavity inside like culm itself. Water can easily accumulate in the cell cavity and strength is related to the content of water in the fibre. Thus it is important to fully dry bamboo fibres before fabrication.

Debris on the fibre surface is likely to be the residual micro-fibrils when individual bamboo fibres were separated from the fibre bundle [22,23]. Wai et al. [14] also found a number of transverse cracks, generated in the outer layers during the beating process, which caused internal fibrillation. Osorio et al. [22] also found that culm consists of a series of axially oriented vascular bundles, which contain the fibre bundle embedded in parenchyma tissue (matrix). When individual fibres were separated from the matrix, part of the matrix can be left on the surface of fibres.

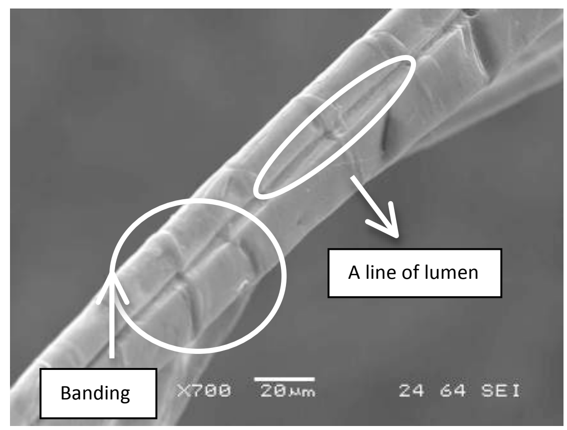
In Figure 37(b), the surface of the bamboo fibre shows the periodic banding, also possibly caused by the beating process during the extraction of the fibres. The surface of bamboo fibre is relatively smoother than that of coir fibre, which may cause the relatively poor interfacial bonding with the matix when compared to coir fibre-reinforced composites.

A line of lumen can be seen in the surface, as described in optical micrographs, the fibre is of a hollow shape, such that it shows the lumen (cavity) inside of the fibres. Yueping et al. [23] also found a small line of lumen can be seen in the longitudinal direction of single bamboo fibres.

A line of living cells are surrounded by a growing sheath of plant fibres. When the cell dies, a cavity within this sheath of plant fibres remains, also called lumen. The fibre cell is therefore tubular in shape, which allows the fibres to transport water into a composite. [17,18]



(a)



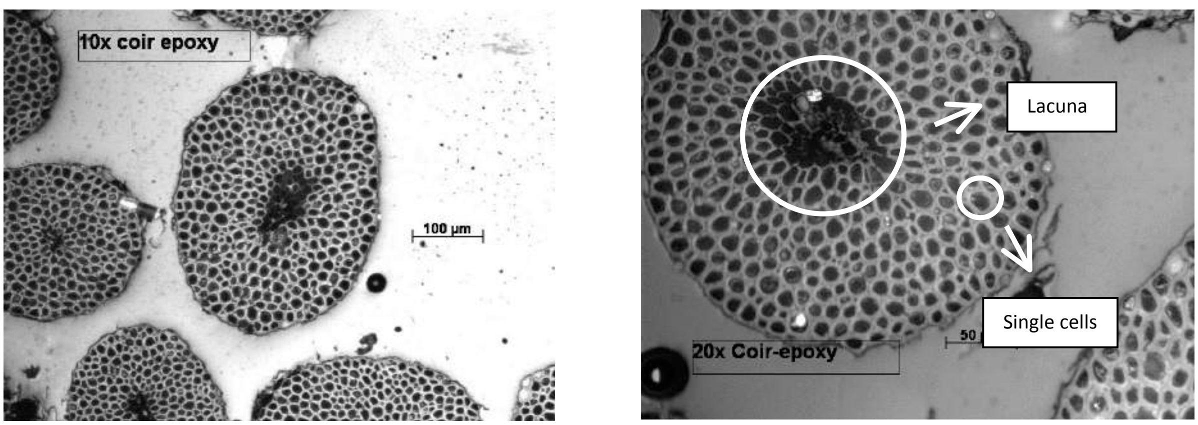
(b)

Figure 37 Typical SEM micrographs for as-received bamboo fibres: (a) cross-section x2200 magnification and (b) longitudinal view x700 magnification.

4.5.2 Optical and scanning electron microscopy of coir fibre

Figure 38(b) shows a typical cross-section of coir fibres. The individual fibres show a broad range of distributions of fibre diameter. The coir fibre is multicellular and each fibre cell is polygonal or round in shape [18]. The individual cell size is approximately 13 µm in diameter and the length to diameter ration is 35. The surface of individual cells appears smooth and the walls are ralatively thick. The individual fibres are narrow and hollow with thick walls made of cellulose. The fibre cells are joined by the middle lamellae consisting of lignin and hemicellulose [18].

Figure 38(a) shows the distribution of cells around the central cavity called ‘lacuna’. Lacuna is a medium to large in size, approximately 6 - 7 μm in diameter. Lacuna is an air cavity in the cellular tissue of plants. Like bamboo fibres, Lacuna can enhance the movement of water into the composite, aided also by the porous structure of coir fibre. As such it is essential to keep the fibres dry and fully dry the fibres before the manufacturing process. [17–19]



(a) (b)

Figure 38 Optical micrographs for a coir-epoxy composite with (a) x10 magnification and (b) x20 magnification.

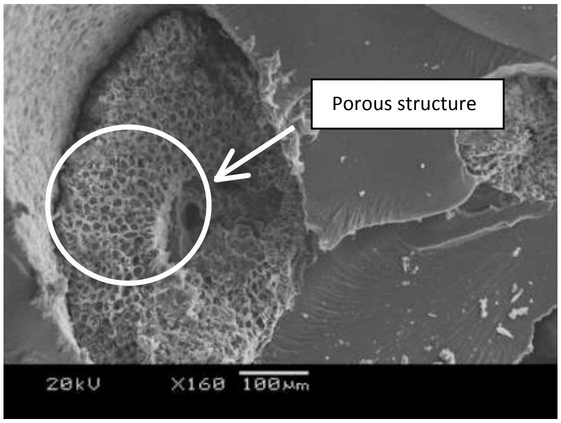
Figure 39(a) shows the porous structure as seen in an optical micrograph of coir fibres and illustrates how the pore spaces have different sizes and shapes. This air filled porosity and water holding capacity gives coir fibre a low density, but increases the likelihood water absorption.

The longitudinal view of coir fibres can be seen in Figure 39(b). The outer layer of a coir fibre exhibits randomly distributed debris and significant microstructural features [4,17,24]. The surface of the coir fibre can be seen in more detail in Figure 39(c) and (d). In these figures, numerous white pits embedded in the fibre surface are present. Carvalho et al. [26] described these features as 'tyloses' and they have been noted in studies associated with coir fibres [24,25]. These pits were partially opened or filled by the binder lignin and fatty substance (tyloses), which hold the unit cells firmly in the fibre [25]. These globular shaped filled pits are aligned longitudinally at distributed at regular intervals [24].

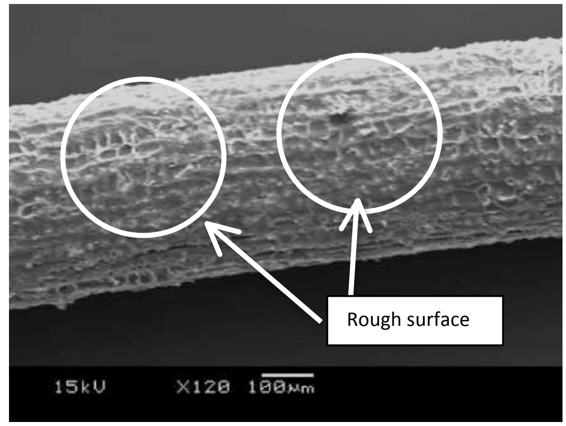
When the tyloses are not present, they leave behind empty pits on the fibre surface. The overall fibre surface is rougher than that of bamboo fibre, which may lead to better interlocking between the fibre and matrix.

Calado et al. [24] and Rout et al. [25] studied the effect of chemical treatment on the structure and morphology of coir fibres. Calado et al. [24] found that untreated fibres have an outer surface layer that is full of randomly distributed organic material. However, in the case of chemically treated fibre surfaces, a rougher but more ordered structure exists owing the removal of the outer layer, which may result in better interfacial bonding with the matrix.

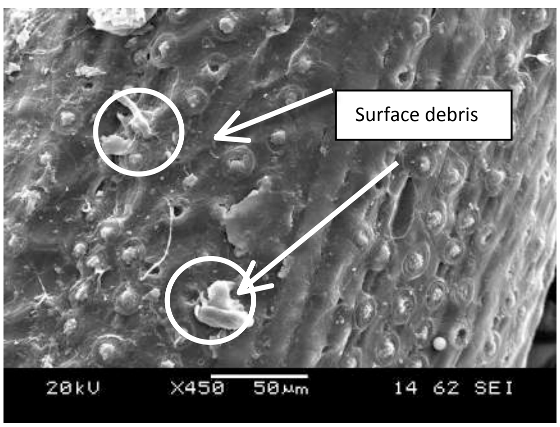
Rout et al. [25] also observed the surface of alkali treated coir fibres and found a rough fibre surface with regularly spaced pits.



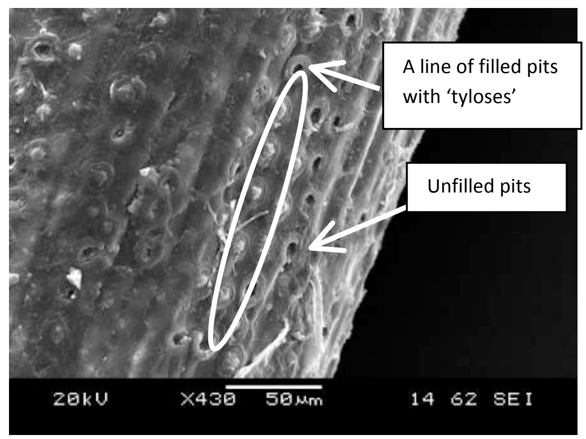
(a)



(b)



(c)



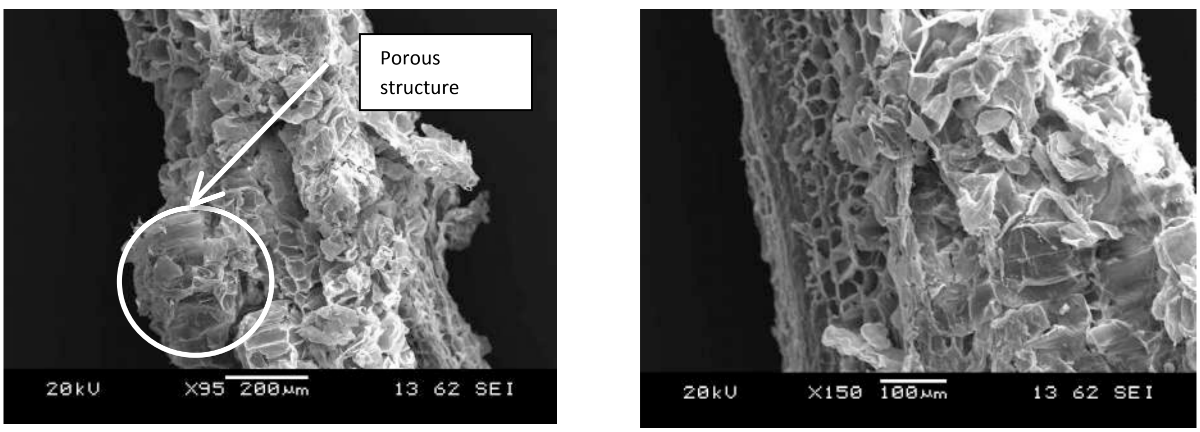
(d)

Figure 39 Typical SEM micrographs for as-received coir fibres: (a) cross-section and (b) longitudinal view. (c) and (d) respectively show globular protrusion and surface pores on the surface of coir fibres.

As the coir fibres are embedded in the husk, when the individual coir fibres are separated, some of coir dust can be left on the surface. [27,28] It was light to dark brown in colour and porous structure as seen in Figure 40. Asiah et al. [28] also found that coconut coir dust contained a porous surface with a total pore space of 96.264 vol%. They assumed this total pore space could be filled with water and air.

Coir dust was found on the outer surface of coir fibres in the as-received case and it is said to consists of a high lignin and cellulose content [27,28]. Suttivutnarubet et al. [27] observed that coir dust contained a high lignin content (35-54%) and cellulose content (23-43%).

It has been reported that coir dust is hydrophilic due to the lignin/cellulose constituents bearing polyhydroxy groups [27,28] and can hinder the wetting and impregnation of the hydrophilic natural fibre by the hydrophobic matrix. [4,49]



(a) (b)

Figure 40 SEM micrographs showing the presence of "coir-dust" on the surface of as-received coir fibres.

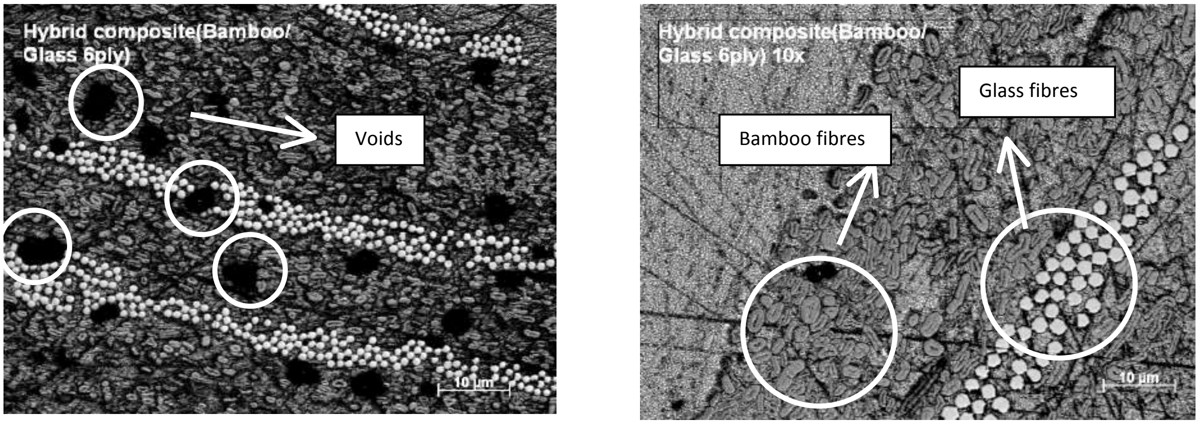
4.5.3 Optical microscopy of hybrid composite

Figure 41 shows that in the case of the bamboo/glass fibre hybrid composite, the glass and bamboo fibres are well distributed in the matrix. The spread glass fibre layers are also uniform throughout the 6-layer composite. It is readily apparent in Figure 41(a) that voids are present near the bamboo/glass fibre interface; it is likely that the voids may have been introduced during laminating and processing. Larger voids can be seen near the interface between glass fibres and bamboo fibres, which may be due to the difference in surface properties.

It is generally accepted that voids can have an adverse effect on the mechanical properties of composites. In the current study, voids were present predominantly inter-laminar thus suggesting that the lamination and resin infusion processes needs to be improved to minimise this void content.

Also, the thickness of spread bamboo fibres layers are not even, however, spread glass fibre layers show relatively even distribution. This may be due to the carding process, as it is difficult to control the amount of fibres when the fibres were fed into the carding machine. This can cause a non-uniform thickness and distribution in the composites. There are also some overlapping spread glass fibres as mentioned previously.

As per Figure 41(a), Bamboo and glass fibres are unidirectionally aligned and there are 3 layers of glass fibres and alternately 3 layers of bamboo fibres, suggesting that the fibres were well laminated during the resin infusion process.



(a) (b)

Figure 41 Optical micrographs of the hybrid bamboo/E-glass composite.

4.6 *Tensile testing and SEM studies on tensile fractured surface of bamboo/coir/hybrid composites*

Tensile test results for the bamboo/coir/hybrid composites are summarised in Table 12, Table 13 and Table 14. To understand the tensile properties, the tensile fractured surface of bamboo/coir/hybrid composites was also studied. Table 11 shows the material data sheet for the mechanical properties of the epoxy resin used in the resin infusion process. It can be clearly seen that the tensile properties of bamboo/coir/hybrid composites showed higher values in comparison with pure epoxy composite. With the addition of natural fibres, that reinforced the pure epoxy composites and showed higher tensile properties.

Lu et al. [68] compared the tensile fracture of pure epoxy and bamboo fibre reinforced epoxy composites. They found the tensile fracture surface of pure epoxy was very smooth indicating brittle fracture. However, the fracture of bamboo fibre reinforced composites shows a rougher fracture surface than pure epoxy, resulting in a higher degree of toughness and enhancement in impact strength. The impact strength increased gradually from 3 kJ/m^2 to 7 kJ/m^2 with an increasing fibre content from 0 wt % to 20 wt %.

Table 11 Mechanical property of the epoxy resin (resin, LY 3505 and hardener, XB 3403) used for laminating the preforms.

Resin system	Tensile strength (MPa)	Tensile modulus (MPa)
LY 3505 *XB 3403*	70 - 74	3180 - 3280

4.6.1 Tensile testing and SEM studies on tensile fractured surface of bamboo fibre reinforced epoxy composite

In order to enable a comparison between this author's results and other researchers' results, the parameters that must be considered include the species of plant from where the fibres were obtained, the fibre extraction procedures, the drying conditions and the residual moisture content, the fibre orientation, the nature of the interfacial bond strength, fibre volume fraction and the void content. A number of these issues were considered previously in Literature Review. However, in this researcher's project, a unique carding process was used to fabricate unidirectional long bamboo fibre reinforced composites. Also, Coir fibres were manually aligned without producing gaps between fibres. Hybrid composite was processed using so-called "tension-release" process, which was developed in the Sensors and Composites Group [80]. Other researchers previously mentioned in Literature Review did not use the same process or same origin of materials, thus the mechanical properties cannot be directly compared.

Lu et al. [68] reported a lower tensile strength (14 MPa) for randomly-oriented short bamboo fibre reinforced epoxy composites compared with the aligned 95 mm average length bamboo fibres used in the current study. This again reinforces the view that unidirectional aligned fibre reinforced composites show higher tensile strengths. However, the tensile properties from different researchers cannot be compared easily.

The tensile strengths of the coir and bamboo fibre composites were 28.3 MPa and 27.8 MPa respectively. Accepting that fact it may not be straightforward to correlate the degree of interfacial bonding from SEM micrographs, it can be seen from Figure 42 and Figure 43 that the adhesion between the fibres and matrix of coir fibres is “better” than bamboo fibres respectively. It is also noted that voids were created during the processing, which was barely found in coir fibre reinforced composites.

Table 12 Summary of tensile test results for 6-ply bamboo composites.

	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Average
Modulus, GPa	2.4	2.7	2.8	2.9	2.7
Strength, MPa	26	26.5	29.2	29.6	27.8

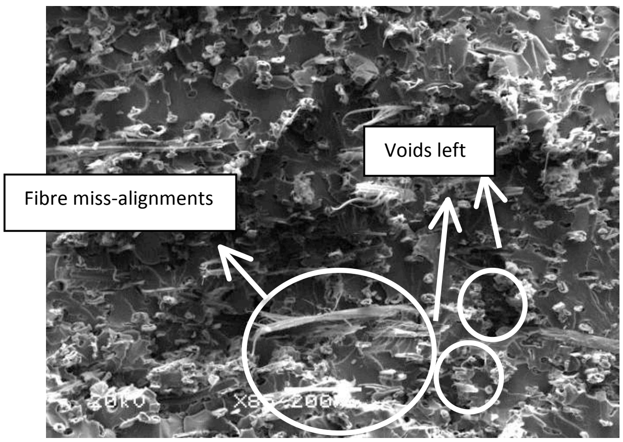
Figure 42 shows the tensile fracture surface of bamboo composites. As seen in Figure 42(a), the fibre–matrix bond appears to be intact indicating that the fibres were well trapped by the matrix, but there is clear evidence of fibre pull-out and some voids.

Some miss-aligned fibres can also be seen due to entanglement during the carding process, which is not found in coir fibre reinforced composite. Rough matrix failure can be seen in Figure 42(b).

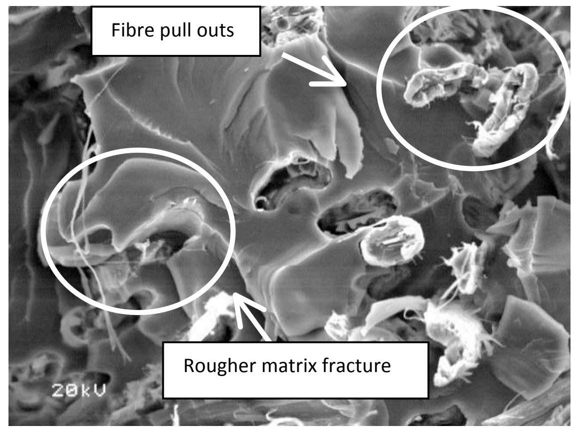
From Figure 42(a), it can be seen that there are resin and fibre-rich regions, which indicate that the carding process and lamination need to be improved to minimise this uneven fibre distribution. Also, during the resin infusion processes, the pressure needs to be higher to reduce the gaps between fibres.

Similary, Lu et al. [68] also found there was aggregation of bamboo fibres due to the incompatibility of the bamboo fibres and matrix. They assumed that the interactions between bamboo fibres were stronger than those between bamboo fibres and the matrix, resulting in aggregation of bamboo fibres.

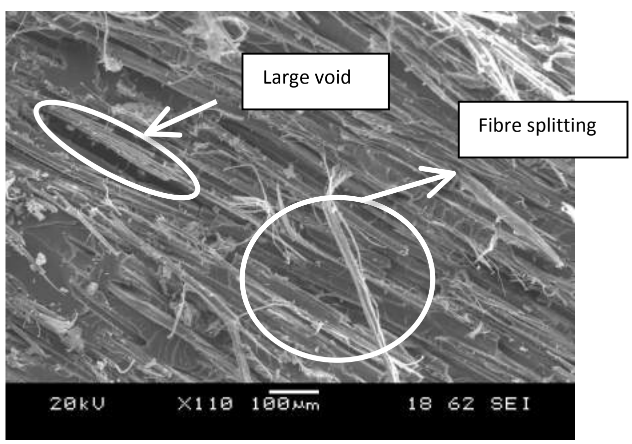
Figure 42(c) shows fibre tearing / splitting and a large void on the transverse fracture surface. It can be also seen that the bamboo fibres were not fully wet and impregnated by the resin. Voids were observed when resin filling was being carried out during the resin infusion process. Resin needs to fill into the vacuum bag with higher speed and pressure. There is fibre tearing/splitting, which indicates some bamboo fibres were well wrapped and trapped by the matrix.



(a)



(b)



(c)

Figure 42 SEM micrographs of fracture surface of bamboo composites: (a) Sample cut at 0° to the bulk composite orientation (longitudinal) x85 magnification (b) x600 magnification and (b) samples cut at 90° to bulk fibre orientation x110 magnification.

4.6.2 Tensile testing and SEM studies on tensile fractured surface of coir fibre reinforced epoxy based composite

In comparison with bamboo, coir showed similar mechanical properties. As seen in Table 4.3, the average Young's modulus and strength were 2.9 GPa and 28.3 MPa respectively. In comparison, the corresponding values for bamboo composite fibre composite were 2.7 GPa and 27.8 MPa respectively. As previously mentioned, this diffrence may be due to 'better' interfacial bonding between coir fibres and the matrix compared to bamboo fibres and matrix.

Table 13 Summary of tensile test results for the 6 ply coir composites.

	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Average
Modulus, GPa	2.8	2.9	2.7	3.2	2.9
Strength, MPa	29.2	31.5	27.0	27.2	28.3

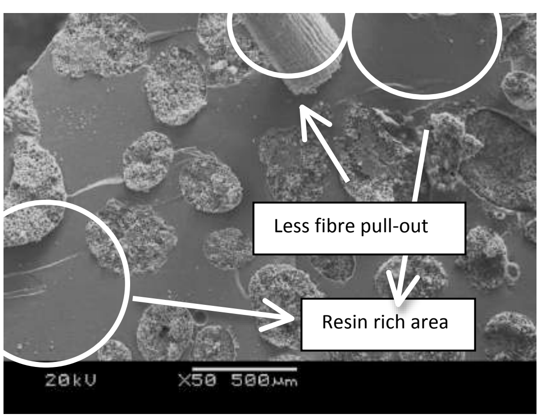
Figure 43 shows the tensile fracture surface of coir composites. In Figure 43(a), it can be seen that there is little fibre pull-out on the fracture surface, fibres are fractured near the matrix fracture demonstrating transverse fibre fracture. The surfaces of some fibre bundles were covered by resin, meaning that failure occurred throughout the matrix. It can also be observed that there were broken fibres instead of pulled out fibres [22]. Improved wetting of the fibre and fibre bonding to the matrix supports tensile testing results.

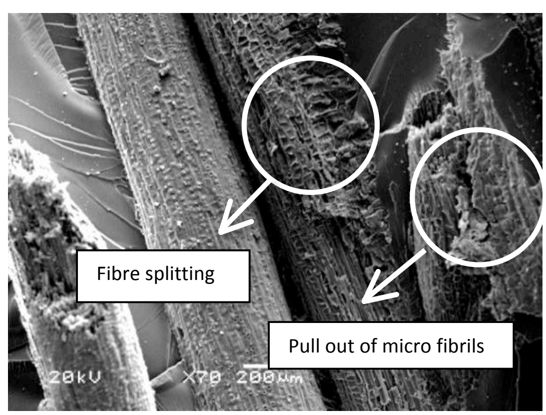
However, Bhagat et al. [78] investigated the fracture surface of coir reinforced epoxy based composites after tensile testing with different fibre lengths. The 20mm coir fibre reinforced composite showed fibre pull out from the matrix surface due to poor interfacial bonding. On the contrary, in 15 mm coir fibre reinforced composite, less fibre pull out was seen at the surface due to the better adhesion, which lead to better tensile properties. They found tensile strength and modulus of 15mm length fibre reinforced composite to show 17MPa and 1.7GPa respectively, which is higher than those of 20mm length fibre reinforced composites at 15MPa and 1.6 GPa respectively.

It can be also seen that the fracture surface of coir fibre reinforced composite was more brittle with less fibre pull-out, compared with bamboo fibre reinforced composites.

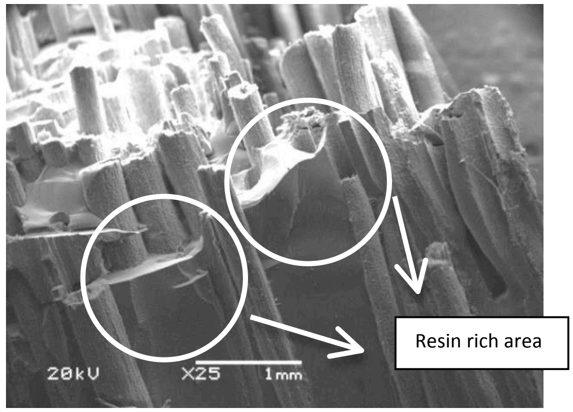
Figure 43(b) demonstrates fibre splitting and tearing which indicates possible better interaction with the matrix. Also, the end of fibre with pull out of micro-fibrils is attributed to the ductile property of coir fibres [17].

Figure 43(a and b) indicate a smoother fracture surface within a resin rich region. When the fibres are aligned manually, the gaps between the fibres can be generated due to the variation in fibre diameter. Compared with bamboo fibre reinforced composite, coir fibre reinforced composite show less fraction of fibres with large resin rich areas.





(a) **(b)**



(c)

Figure 43 SEM micrographs of fracture surface of coir composites: (a) Sample cut at 0° to the bulk composite orientation (longitudinal) and (b) samples cut at 90° to bulk fibre orientation x 70 magnification and (c) x25 magnification.

4.6.3 Tensile testing and SEM studies on tensile fractured surface of bamboo/glass fibre reinforced epoxy based hybrid composite

As seen in Table 14, glass-bamboo hybrid composites showed higher tensile strength and Young's modulus (35.16 MPa, 3 GPa) compared to bamboo fibre reinforced composites (28.3 MPa, 2.9 GPa). According to the literature [2,19,45,62,65,74,77] enhancements in mechanical properties of hybrid composites is expected when weaker and less stiff bamboo fibres are replaced by stronger and stiffer E-glass fibres.

Table 14 Summary of tensile test results for the 6 ply (bamboo/glass/bamboo/glass/bamboo/glass) hybrid composites.

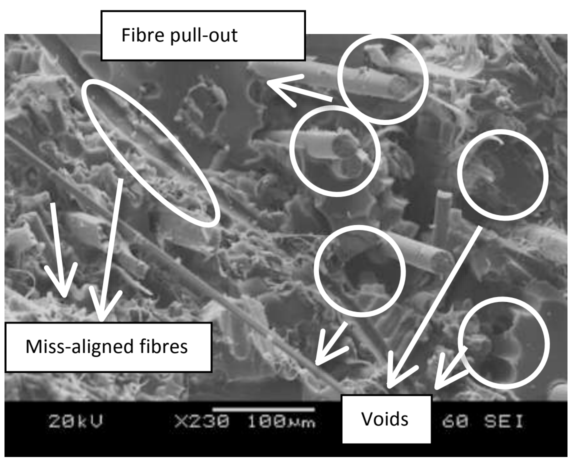
	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5	Average
Modulus, GPa	3.1	3.2	3.0	2.9	2.9	3.0
Strength, MPa	32.9	34.2	32.2	39.0	37.5	35.16

The fracture surface of a glass-bamboo hybrid composite sample is shown in Figure 44. Figure 44(a) shows numerous fibre pull-outs and voids. The miss-aligned bamboo fibres can be also seen due to entanglement during the carding process.

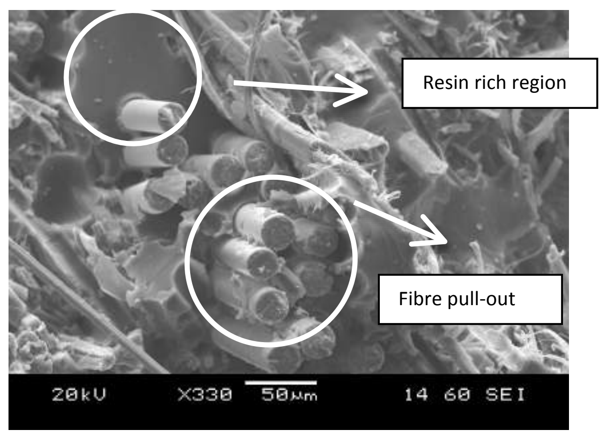
A bunch of glass fibres are pulled-out from the surface as seen in Figure 44(b), which is completely debonded from the matrix. Also, more pulled out glass fibres can be seen on the fracture surface indicating weaker interfacial adhesion than bamboo fibres. Similarly, Chen et al.

[32] observed clean surfaces on the pulled out fibres indicating poor adhesion between fibres and the matrix. However, some surfaces of glass fibres appear with traces of epoxy matrix, indicating better fibre-matrix adhesion as seen in Figure 44(d). There is also a resin rich region, which indicates that the glass fibres were not spread evenly.

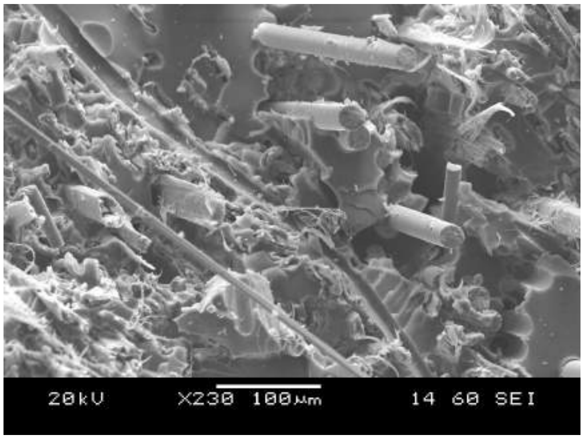
Large spaces/voids were found on the fracture surface as indicated on Figure 44(e). The source of these voids is likely to be gaps between stacked bamboo and glass fibres and the voids are formed at the cross-over points during the resin infusion process.



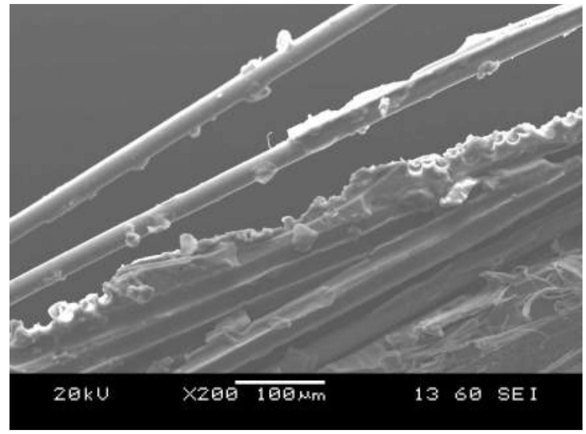
(a)



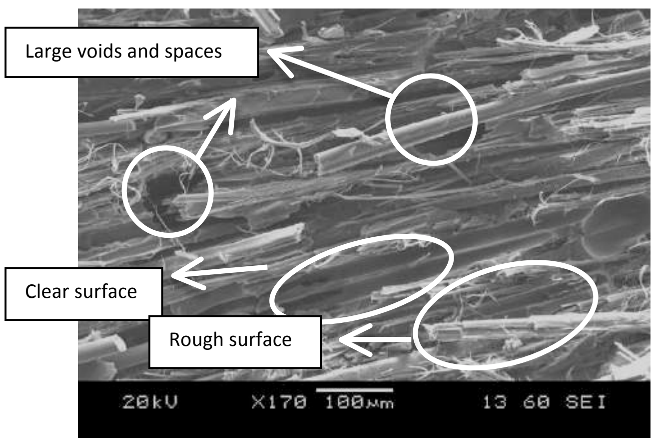
(b)



(c)



(d)



(e)

Figure 44 SEM micrographs of fracture surface of glass-bamboo hybrid composites: (a) Sample cut at 0° to the bulk composite orientation (longitudinal) x 230 magnification, (b) x330 magnification, (c, d) samples cut at 90° to bulk fibre orientation x170 magnification.

The stress-strain behaviour of bamboo, coir and hybrid composites under tensile load is plotted in Figure 45(a-c). The stress-strain curves were used to obtain the modulus of elasticity.

The ultimate tensile stress of bamboo, coir and hybrid composites increases in the following order hybrid, coir and bamboo composites.

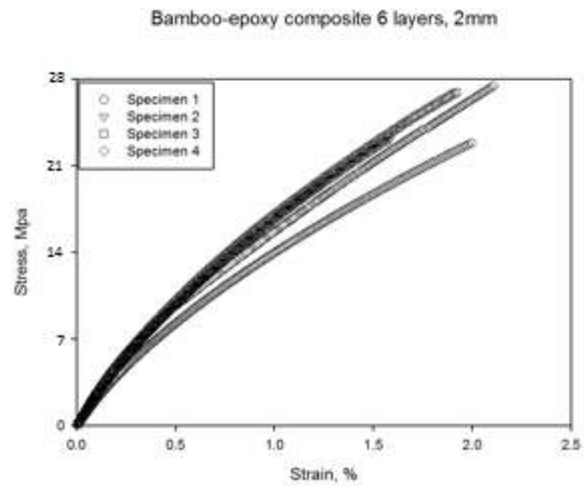
The stress-strain curves of bamboo, coir and hybrid composites show a linear behaviour at low strains followed by a slope showing a non-linearity, which continues up to the failure of the composites. Generally, fibres reinforced in the matrix show non-linearity in the stress-strain behavior due to the fibrous structure of reinforcement in the matrix allowing it to take higher loads.

Linear deformation at lower strains means the matrix and fibres behave linearly, however, at higher strain, microcracks propagate at the fibre/matix interface and gradual debonding of the fibres from the matrix takes place. Eventually, the fibres are completely pulled out from the matrix.

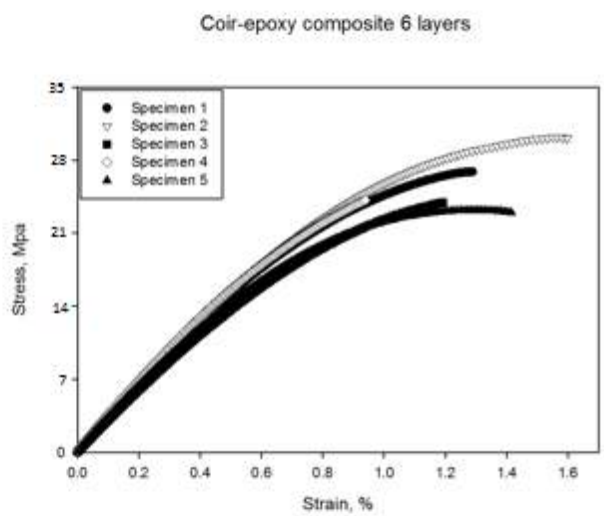
Osorio et al. [22] found similar stress-strain curve for bamboo fibre reinforced composites. After a non-linear region, the graph shows nearly linear elastic behaviour up to fracture of the fibres.

Coir fibre reinforced composites show the broadest ranges of curves as seen in Figure 45(b), which indicates ductile behaviour and higher toughness of coir fibre reinforced composites. However, the stress-strain curve of hybrid composites show a nearly linear behaviour with brittle fracture, as apparent from the stress-strain curves in Figure 45(c).

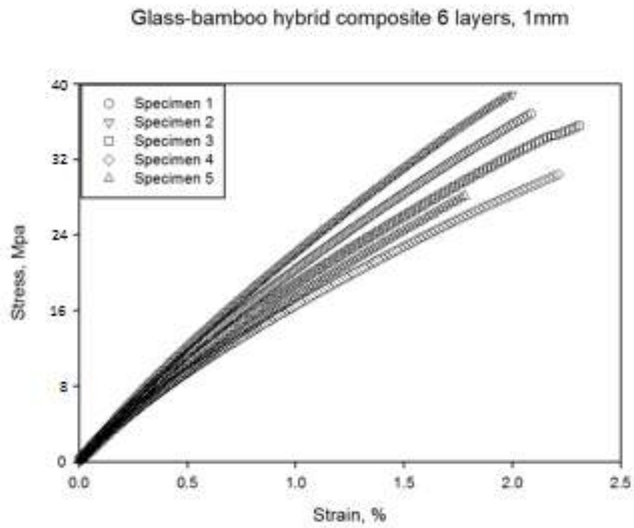
The stress-strain curves of bamboo and coir fibre reinforced composites were very close to each other, which indicates 5 specimens have similar properties (similar orientation, fibre weight fraction).


Bamboo-epoxy composite 6 layers, 2mm
Specimen 1
Specimen 2
Specimen 3
Specimen 4
Stress, Mpa
Strain, %
0
7
14
21
28
0.0
0.5
1.0
1.5
2.0
2.5

(a)


Coir-epoxy composite 6 layers
Specimen 1
Specimen 2
Specimen 3
Specimen 4
Specimen 5
Stress, Mpa
Strain, %
0
7
14
21
28
35
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6

(b)



(c)

Figure 45 Stress-strain graphs of (a) 6 layered bamboo epoxy composites, (b) 6 layered coir epoxy composites and (c) glass-bamboo fibres (each 3 layred, 6 layered in total) hybrid composites.

5 Conclusions

This study has demonstrated that unidirectional preforms of bamboo and coir can be produced. Hybrid composites have been also produced with unidirectional preforms of bamboo and spread glass fibre. The tensile properties of these composites have been determined. Optical/Scanning electron microscopy inspection has been undertaken to characterise the structure of bamboo and coir fibres and the tensile fracture surfaces of bamboo/coir/hybrid composites.

Previous researchers have demonstrated that unidirectional arrays of continuous fibres yield superior mechanical properties when compared to their short-fibre counterparts. However, natural fibres are not generally available in the long or continuous form, and also there is no common way to produce unidirectional preforms of natural fibres.

The main achievements of this current study were as follows:

1. In the first instance, optical/scanning electron microscopic inspection were carried out on the single bamboo and coir fibres. Single bamboo fibres show irregular oval shape with a cavity and coir fibres consist of individual cells and the centre called lacuna.

2. A manual technique was developed by the author to fabricate unidirectional arrays of coir fibre prepregs. Coir fibres were aligned unidirectionally without producing gaps between the fibres. From inspecting the micrographs of the tensile fractured surface, it was observed that the fibres were aligned successfully in a unidirectional direction.

3. A carding machine as used to enable unidirectional preforms of bamboo to be manufactured . It was shown that this technique was capable of preparing unidirectional composites of bamboo as seen in micrographs of the tensile fractured surface. The preforms were hybridized with spread glass fibres.

4. A hybrid composite was fabricated with unidirectional preforms of bamboo and spread glass fibres using resin infusion technique. Spread glass fibres have been obtained from a procedure developed in the Sensors and Composites Group using the so-called "tension-release" release process [80]. Glass-bamboo hybrid composites showed higher tensile strength and modulus than bamboo composites (31.16 MPa, 3 GPa vs. 27.8 MPa, 2.7 GPa). However, it does not show a significant increase in tensile properties due to the poor interfacial contact and the presence of voids generated during the resin infusion process.

5. The post-tensile fracture surfaces of the bamboo/coir/hybrid composites were investigated using scanning electron microscopy. Coir fibre reinforced composites show good interfacial bonding between the matrix and fibres. However the bamboo fibre reinforced composites and hybrid composites show more fibre pull out and voids. The presence of miss-aligned fibres was attributed to the entanglement of the fibres during the carding process.

This study has demonstrated that a manual technique and carding process can be used for producing unidirectional preforms of coir and bamboo fibres. Due to time constraints, other mechanical testing methods such as flexural, impact testing were not undertaken.

6 Recommendations for future research

In the current study, the fibre volume fraction was not measured. Composites with different fibre volume fraction will enable the effect of unidirectional preforms on the mechanical properties of composites to be determined. This will give new insights into unidirectional fibre preforms in composites.

With further research, it will be possible to relate the effect of unidirectional preforms to the fracture mechanism in the composites and mechanical properties.

The following future research is recommended:

1. Further work needed to be undertaken to improve the manual process to prepare unidirectional coir preform at high speed. A vacuum-based suction system can be used to speed up the process.

2. The mechanical properties of bamboo/coir/hybrid composites can be increased with chemical treatment. With chemical treatment, the interfacial bonding between the fibres and matrix can be improved, resulting increase in the mechanical properties.

3. This is required to reduce the void contents that were observed when resin filling was being carried out during the resin infusion process. High vacuum condition can be used to improve the quality of composites.

4. Different composition of hybrid composite can be used to determine the hybrid effect on the mechanical properties of hybrid composite.

References

[1] Shrivastava S 2012 Natural fiber based hybrid composites

[2] Thwe M M and Liao K 2002 Tensile behaviour of modified bamboo–glass fibre reinforced hybrid composites *Plast. Rubber Compos.* **31** 422–31

[3] Loh K M K and Tan C K W Natural Silkworm Silk-Epoxy Resin Composite for High Performance Application

[4] Saheb D N and Jog J P 1999 Natural fiber polymer composites: A review *Adv. Polym. Technol.* **18** 351–63

[5] Beckwith S W 2003 Natural Fiber Reinforcement Materials Lower Cost Technology for Composites Applications 12–6

[6] Joshi S ., Drzal L ., Mohanty a. . and Arora S 2004 Are natural fiber composites environmentally superior to glass fiber reinforced composites? *Compos. Part A Appl. Sci. Manuf.* **35** 371–6

[7] Corbie T 2001 Life cycle assessment of biofibres replacing glass fibres as reinforcement in plastics **33** 267–87

[8] Diener J S U 1999 Okologischer vergleich von NMT-und GMT Bauteilen. 272(1–4)

[9] Deo C and Acharya S K 2010 Effect of Moisture Absorption on Mechanical Properties of Chopped Natural Fiber Reinforced Epoxy Composite *J. Reinf. Plast. Compos.* **29** 2513–21

[10] Alamri H and Low I M 2012 Mechanical properties and water absorption behaviour of recycled cellulose fibre reinforced epoxy composites *Polym. Test.* **31** 620–8

[11] Kozłowski R and Władyka-przybylak M 2008 Review Flammability and fire resistance of composites reinforced by natural fibers 446–53

[12] Madsen B., Mehmood S. A M 2012 Variability in properties of natural fibres

[13] Dittenber D B and GangaRao H V S 2012 Critical review of recent publications on use of natural composites in infrastructure *Compos. Part A Appl. Sci. Manuf.* **43** 1419–29

[14] N.N.Wai H N and K kurakam. 1987 A morphological study on the behaviour of bamboo pup fibres in the beating process 19: p211–222

[15] Kalia S, Kaith B S and Kaur I 2009 Pretreatments of natural fibers and their application as reinforcing material in polymer composites-A review *Polym. Eng. Sci.* **49** 1253–72

[16] Bismarck A, Aranberri-Askargorta I, Springer J, Mohanty A K, Misra M, Hinrichsen G and Czapla S 2001 Surface characterization of natural fibers; surface properties and the water up-take behavior of modified sisal and coir fibers *Green Chem.* **3** 100–7

[17] Khalil H P S A, Alwani M S and Omar A K M 2006 Distribution, and cell wall structure of malaysian plant waste fibres **1** 220–32

[18] Tomczak F, Sydenstricker T H D and Satyanarayana K G 2007 Studies on lignocellulosic fibers of Brazil. Part II: Morphology and properties of Brazilian coconut fibers *Compos. Part A Appl. Sci. Manuf.* **38** 1710–21

[19] Bledzki A K and Gassan J 1999 Composites reinforced with cellulose based fibres **24** 221–74

[20] Wai, • N. N., H. Nanko K M 1985 A morphological study on the behavior of bamboo pulp fibers in the beating process Volume 19, Issue 3, p 211–222

[21] Faruk O, Bledzki A K, Fink H-P and Sain M 2012 Biocomposites reinforced with natural fibers: 2000–2010 *Prog. Polym. Sci.* **37** 1552–96

[22] Osorio L, Trujillo E, Van Vuure a. W and Verpoest I 2011 Morphological aspects and mechanical properties of single bamboo fibers and flexural characterization of bamboo/ epoxy composites *J. Reinf. Plast. Compos.* **30** 396–408

[23] Yueping W 2009 Structures of Bamboo Fiber for Textiles *Text. Res. J.* **80** 334–43

[24] Quimica E De, Tecnologia C De and Janeiro R De 2000 The effect of a chemical treatment on the structure and morphology of coir fibers 2151–3

[25] Rout J, Tripathy S S, Misra S K N M and Mohanty A K 2001 Scanning Electron Microscopy Study of Chemically

[26] Cioffi M O H 2010 Chemical modification effect on the mechanical properties of hips/ coconut fiber composites **5** 1143–55

[27] Chatuma Suttivutnarubet, Thanyaluk Yokkloy E C and Jongsomji B 2013 Synthesis of coir-dust/PE composites via in situ polymerization with metallocene/mao catalyst.

[28] Iasiah A and Khanif Y 2004 Physical and Chemical Properties of Coconut Coir Dust and Oil Palm Empty Fruit Bunch and the Growth of Hybrid Heat Tolerant Cauliflower Plant **27** 121–33

[29] Cheung H, Ho M, Lau K, Cardona F and Hui D 2009 Natural fibre-reinforced composites for bioengineering and environmental engineering applications *Compos. Part B Eng.* **40** 655–63

[30] Khondker O a., Ishiaku U S, Nakai a. and Hamada H 2006 A novel processing technique for thermoplastic manufacturing of unidirectional composites reinforced with jute yarns *Compos. Part A Appl. Sci. Manuf.* **37** 2274–84

[31] Okubo K, Fujii T and Yamamoto Y 2004 Development of bamboo-based polymer composites and their mechanical properties *Compos. Part A Appl. Sci. Manuf.* **35** 377–83

[32] Chen X, Guo Q and Mi Y 1997 Bamboo Fiber-Reinforced Polypropylene Composites : 1891–9

[33] Phong N T, Gabr M H, Okubo K, Chuong B and Fujii T 2013 Enhancement of mechanical properties of carbon fabric/epoxy composites using micro/nano-sized bamboo fibrils *Mater. Des.* **47** 624–32

[34] Biswas S and Satapathy A 2010 A comparative study on erosion characteristics of red mud filled bamboo–epoxy and glass–epoxy composites *Mater. Des.* **31** 1752–67

[35] Kushwaha P K and Kumar R 2010 Influence of chemical treatments on the mechanical and water absorption properties of bamboo fiber composites *J. Reinf. Plast. Compos.* **30** 73–85

[36] Marcovich N E, Aranguren M I and Reboredo M M 2001 Modified woodflour as thermoset fillers Part I . Effect of the chemical modification and percentage of filler on the mechanical properties **42** 815–25

[37] Wong K J, Yousif B F and Low K O 2010 The effects of alkali treatment on the interfacial adhesion of bamboo fibres *Proc. Inst. Mech. Eng. Part L J. Mater. Des. Appl.* **224** 139–48

[38] Jena H, Pandit M K and Pradhan a. K 2013 Effect of cenosphere on mechanical properties of bamboo-epoxy composites *J. Reinf. Plast. Compos.* **32** 794–801

[39] Gassan J and Bledzki A K 1999 Possibilities for improving the mechanical properties of jute / epoxy composites by alkali treatment of ® bres **59** 1303–9

[40] Rout J, Misra M, Tripathy S S, Nayak S K and Mohanty a. K 2001 The influence of fibre treatment on the performance of coir-polyester composites *Compos. Sci. Technol.* **61** 1303–10

[41] Pothan L a., Oommen Z and Thomas S 2003 Dynamic mechanical analysis of banana fiber reinforced polyester composites *Compos. Sci. Technol.* **63** 283–93

[42] Kuruvilla Joseph S T and Pavithran C 1996 Effect of chemical treatment on the tensile properties of short sisal fibre-reinforced polyethylene composites 5139–49

[43] Venkata Subba Reddy E, Varada Rajulu a., Hemachandra Reddy K and Ramachandra Reddy G 2010 Chemical Resistance and Tensile Properties of Glass and Bamboo Fibers Reinforced Polyester Hybrid Composites *J. Reinf. Plast. Compos.* **29** 2119–23

[44] Raghavendra Rao H, Varada Rajulu a., Ramachandra Reddy G and Hemachandra Reddy K 2009 Flexural and Compressive Properties of Bamboo and Glass Fiber-reinforced Epoxy Hybrid Composites *J. Reinf. Plast. Compos.* **29** 1446–50

[45] Noorunnisa Khanam P, Ramachandra Reddy G, Raghu K and Venkata Naidu S 2009 Tensile, Flexural, and Compressive Properties of Coir/Silk Fiber-reinforced Hybrid Composites *J. Reinf. Plast. Compos.* **29** 2124–7

[46] Donath, S, Militz, H, Mai C 2006 Creating water-repellent effects on wood by treatment with silanes 40–6

[47] Lee S-Y, Chun S-J, Doh G-H, Kang I -a., Lee S and Paik K-H 2009 Influence of Chemical Modification and Filler Loading on Fundamental Properties of Bamboo Fibers Reinforced Polypropylene Composites *J. Compos. Mater.* **43** 1639–57

[48] Porras a. and Maranon a. 2012 Development and characterization of a laminate composite material from polylactic acid (PLA) and woven bamboo fabric *Compos. Part B Eng.* **43** 2782–8

[49] La Mantia F P and Morreale M 2011 Green composites: A brief review *Compos. Part A Appl. Sci. Manuf.* **42** 579–88

[50] George J, Sreekala M S and Thomas S 2001 A review on interface modification and characterization of natural fiber reinforced plastic composites *Polym. Eng. Sci.* **41** 1471–85

[51] Rong M Z, Zhang M Q, Liu Y, Yang G C and Zeng H M 2001 The effect of fiber treatment on the mechanical properties of unidirectional sisal-reinforced epoxy composites *Compos. Sci. Technol.* **61** 1437–47

[52] Valadez-Gonzalez a., Cervantes-Uc J M, Olayo R and Herrera-Franco P J 1999 Effect of fiber surface treatment on the fiber–matrix bond strength of natural fiber reinforced composites *Compos. Part B Eng.* **30** 309–20

[53] Abdelmouleh M, Boufi S, Belgacem M and Dufresne a 2007 Short natural-fibre reinforced polyethylene and natural rubber composites: Effect of silane coupling agents and fibres loading *Compos. Sci. Technol.* **67** 1627–39

[54] Ouagne P, Bizet L and Baley C 2011 Analysis of the film stacking processing parameters for PLLA / flax fibre biocomposites To cite this version : Analysis of the film stacking processing parameters for PLLA / flax

[55] Lee B-H, Kim H-J and Yu W-R 2009 Fabrication of long and discontinuous natural fiber reinforced polypropylene biocomposites and their mechanical properties *Fibers Polym.* **10** 83–90

[56] Hill C a. S and Abdul Khalil H P S 2000 Effect of fiber treatments on mechanical properties of coir or oil palm fiber reinforced polyester composites *J. Appl. Polym. Sci.* **78** 1685–97

[57] Idicula M, Sreekumar P a., Joseph K and Thomas S 2009 Natural fiber hybrid composites-A comparison between compression molding and resin transfer molding *Polym. Compos.* **30** 1417–25

[58] Beld V De and Peijs T Thermoplastic composites based on biopolymers and natural fibres

[59] Ben G, Kihara Y, Nakamori K and Aoki Y 2007 Examination of heat resistant tensile properties and molding conditions of green composites composed of kenaf fibers and PLA resin *Adv. Compos. Mater.* **16** 361–76

[60] Qi C, Guo K and Liu Y 2012 Preparation and properties of cotton stalk bundles and high-density polyethylene composites using hot-press molding *J. Reinf. Plast. Compos.* **31** 1017–24

[61] Bodros E, Pillin I, Montrelay N and Baley C 2007 Could biopolymers reinforced by randomly scattered flax fibre be used in structural applications? *Compos. Sci. Technol.* **67** 462–70

[62] Nayak S K, Mohanty S and Samal S K 2009 Influence of short bamboo/glass fiber on the thermal, dynamic mechanical and rheological properties of polypropylene hybrid composites *Mater. Sci. Eng. A* **523** 32–8

[63] Herrera-Franco P J and Valadez-González a. 2005 A study of the mechanical properties of short natural-fiber reinforced composites *Compos. Part B Eng.* **36** 597–608

[64] Xie Y, Hill C a. S, Xiao Z, Militz H and Mai C 2010 Silane coupling agents used for natural fiber/polymer composites: A review *Compos. Part A Appl. Sci. Manuf.* **41** 806–19

[65] Thwe M M and Liao K 2002 Effects of environmental aging on the mechanical properties of bamboo ± glass ® ber reinforced polymer matrix hybrid composites **33** 43–52

[66] Jirsak, O., and Wadsworth L C 1999 Nonwoven Textiles *Carolina Acad. Press* 68–9

[67] Hao A, Zhao H, Jiang W, Yuan L and Chen J Y 2012 Mechanical Properties of Kenaf/Polypropylene Nonwoven Composites *J. Polym. Environ.* **20** 959–66

[68] Lu T, Jiang M, Jiang Z, Hui D, Wang Z and Zhou Z 2013 Effect of surface modification of bamboo cellulose fibers on mechanical properties of cellulose/epoxy composites *Compos. Part B Eng.* **51** 28–34

[69] Jacob M, Thomas S and Varughese K T 2004 Mechanical properties of sisal/oil palm hybrid fiber reinforced natural rubber composites *Compos. Sci. Technol.* **64** 955–65

[70] Nair K C M, Diwan S M and Thomas S 1996 Tensile properties of short sisal fiber reinforced polystyrene composites *J. Appl. Polym. Sci.* **60** 1483–97

[71] Sreekumar P a., Selvin Thomas P, Saiter J M, Unnikrishnan G and Thomas S 2011 Viscoelastic and thermal properties of eco-friendly composites fabricated by resin transfer molding *J. Reinf. Plast. Compos.* **30** 1509–16

[72] Geethamma V G, Thomas Mathew K, Lakshminarayanan R and Thomas S 1998 Composite of short coir fibres and natural rubber: effect of chemical modification, loading and orientation of fibre *Polymer (Guildf).* **39** 1483–91

[73] Samal S K, Mohanty S and Nayak S K 2008 Polypropylene--Bamboo/Glass Fiber Hybrid Composites: Fabrication and Analysis of Mechanical, Morphological, Thermal, and Dynamic Mechanical Behavior *J. Reinf. Plast. Compos.* **28** 2729–47

[74] Panthapulakkal S and Sain M 2006 Injection-Molded Short Hemp Fiber / Glass Fiber- Reinforced Polypropylene Hybrid Composites — Mechanical , Water Absorption and Thermal Properties

[75] Pavithran C, Mukherjee P S and Brahmakumar M 1991 Coir-Glass Intermingled Fibre Hybrid Composites *J. Reinf. Plast. Compos.* **10** 91–101

[76] Kumar N M, Reddy G V., Naidu S V., Rani T S and Subha M C S 2008 Mechanical Properties of Coir/Glass Fiber Phenolic Resin Based Composites *J. Reinf. Plast. Compos.* **28** 2605–13

[77] Morye S S and Wool R P 2005 Mechanical properties of glass/flax hybrid composites based on a novel modified soybean oil matrix material *Polym. Compos.* **26** 407–16

[78] Bhagat V K, Biswas S and Dehury J 2014 Physical, mechanical, and water absorption behavior of coir/glass fiber reinforced epoxy based hybrid composites *Polym. Compos.* **35** 925–30

[79] Kushwaha P K and Kumar R 2009 The Studies on Performance of Epoxy and Polyester-based Composites Reinforced with Bamboo and Glass Fibers *J. Reinf. Plast. Compos.* **29** 1952–62

[80] Irfan M S, Machavaram V R, Mahendran R S, Shotton-Gale N, Wait C F, Paget M a., Hudson M and Fernando G F 2011 Lateral spreading of a fiber bundle via mechanical means *J. Compos. Mater.* **46** 311–30

[81] Hu R-H, Ma Z-G, Zheng S, Li Y-N, Yang G-H, Kim H-K and Lim J-K 2012 A fabrication process of high volume fraction of jute fiber/polylactide composites for truck liner *Int. J. Precis. Eng. Manuf.* **13** 1243–6

[82] Alimuzzaman S, Gong R H and Akonda M 2013 Nonwoven polylactic acid and flax biocomposites *Polym. Compos.* n/a–n/a

[83] Jayabal S, Natarajan U and Murugan M 2011 Mechanical property evaluation of woven coir and woven coir-glass fiber-reinforced polyester composites *J. Compos. Mater.* **45** 2279–85

[84] Jin Woo Yi, Jung Hoon Lee, Hyung Sun Hwang B S K 2009 Domestic/oversea market and technical issues of natural fibre-reinforced polymer composites

[85] Park H, Kong C, Lee J, Kim I and Lee H 2014 Investigation on Mechanical Properties of Flax/Vinyl Ester Natural Fiber Composite *Compos. Res.* **27** 19–24

Appendix 1

Summary of common classes of (a) thermoset and (b) thermoplastic polymers; some selected properties have been included [10,15,21,30–34,59,76,81].

Authors	**Matrix**	**Melting temperature (°C)**	**Glass transition temperature (°C)**	**Tensile strength (MPa)**	**Advantages**	**Disadvantages**
Almiri et al. [10] Khondker et al. [30] Phong et al. [33] Biswas et al. [34]	Epoxy resin	-	75	70-74	Relatively tensile strength, low water absorption rate.	Curing time needed.
Kumar et al. [76],Susheel Kalia et al. [15]	Unsaturated polyester	-	-	65	High water resistance.	Brittle.

(a)

Authors	**Matrix**	**Melting temperature (°C)**	**Glass temperature (°C)**	**Tensile strength (MPa)**	**Advantages**	**Disadvantages**
Goichi et al. [59], Rui-Hua Hu [81]	PLA (poly lactic acid)	148	58	55.4	Biodegradable ability. Relatively high melting point.	Brittle property.
Khondker et al. [30], Kazuya Okubo et al.[31], Chen et al. [32]	PP (poly propylene)	170	-10	34	Cheap Good chemical resistance.	Molten viscosity is high, makes it difficult to impregnate fibre bundles.
Chen et al. [32]	PE (Poly ethylene)	137	-125	15-30	High toughness, good thermal properties. .	Low thermal stability.

Omar Faruka et al.[21]	PS (Poly styrene)	230	94	46-60	Low moisture absorption rate, High tensile strength.	Brittle.
Omar Faruka at al.[21]	PVC(Poly vinyl chloride)	140	70-85	34-50	Good chemical resistance.	Low heat resistance.

(b)

Appendix 2

Compilation of gauge lengths and load rates for tensile testing of hybrid composites and the resulting tensile properties [2,65,74–77,79,83].

Author	Gauge length (mm)	Load rate (mm/min)	Glass fibre content (wt%)	Tensile strength (MPa)	Tensile modulus (GPa)
Panthapulakkal et al. [74]	50	50	0	52.5	3.8
(total fibre content fixed at 30wt%)			5	54	4
			10	57.5	4.25
			15	59	4.4
Morye et al. [77]	178	2	0.35 (symmetric)	127.8-129.8	5.1-5.3
(Total fibre content fixed at 40wt%)			0.25 (symmetric)	122.1-124.5	3.4-3.6
			Asymmetric	109.6-113.9	3.3-3.5
			0.23 (symmetric)	108.1-110.1 88.2-93	3.1-3.3
			Asymmetric	88.2-93	3.0-3.2
			0.16 (symmetric)	81.2-84	2.7-3.2
			Asymmetric	66.8-71	2.4-3.0
			0.00(symmetric)	24.4-27.8	1.8-2
Samal et al. [73]	Not indicated	Not indicated	0	43.96	1.2
(total fibre content fixed at 30wt%)			5	45.47	1.3
			10	47.22	1.38
			15	51.00	1.43
Thwe	Not indicated	1.5	0	14	2.5

et al. [2,65]					
(total fibre content fixed at 30wt%)			10	16	2.7
			20	17	2.9
Kushwaha et al. [79]	Not indicated	2	Only bamboo fibres	135	8.2
(Not indicated)			2SBE	124	7.7
			3SBE	120	7.2
			2WBE	128	9.0
			3WBE	160	9.4
Pavithran et al. [75]	50	5	Glass fibre (0.05 volume fraction) with coir fibre (0.35 volume fraction)	40	2.7
			Without coir fibre	48	2.5
(Total fibre content fixed at 40wt%)			0.1 (with coir fibre: 0.3)	53	3
			Without coir fibre	54	2.9
			0.15 (with coir fibre: 0.25)	75	3.1
			Without coir fibre	70	3.3
Jayabal et al. [83]	Not indicated	5	0	19.4-20.4	-
Total fibre content is not indicated			50wt% of total fibre content	46.2-49.2	-
Kumar et al. [76]	Not indicated	2	100:0 (vol % of fabric, coir: glass)	22.27	3.83
(Total fibre content fixed at 9 volume %)			2:1	34.63	8.46
			1:1	50.69	8.52
			1:2	71.58	8.54
			0:100	24.1	10.42

Appendix 3

Compilation of the typical material, matrix and fabrication method for hybrid composite [2,44,65,73,74,76,79].

Author	Natural Fibre Type	Synthetic Fibre	Matrix	Fabrication method
Panthapulakkal et al. [74]	Short hemp fibres of an average fibre 10–12 mm in length.	E-glass fibres of 10–12 mm in length.	Polypropylene, a density of 0.91 g/cc and melt flow index of 12 g/10 min. Compatibilizer was maleated polypropylene.	The mixture of resin and fibres were melt-blended at 170 °C and at 60 rpm for 5 mins and injection moulded at temperature 205 °C, injection time 8 secs, cooling time 25 secs, mould opening time 25 secs.
Morye et al. [77]	A random mat of flax fibre.	Woven E-glass fibres with an areal density of 0.75 kg/m.	Styrene resin was prepared by mixing acrylated epoxidized soybean oil (AESO) with 50 parts by weight.	Compression moulded of a pressure of 2.1 MPa, cured overnight at room temperature and post-cured at 110 °C for 2 h.
Samal et al. [73]	Bamboo fibre of 4–6mm in length, diameter 85–120 mm, density 0.863 $g/cm_{3.}$	Glass fibre of 6 mm in length, density 2.56 g/cm_3	Isotactic polypropylene, a density of 0.9 g/cm3 and melt flow index of 11 g/10 min.	Polypropylene with short bamboo fibres were pelletized at screw speed of 50 rpm and temperature range of 155-170 °C and then injection moulded at a temperature range of 160–180 °C and 1800 bar.
Rao et al. [44]	Bamboo fibres. (dendrocalamus strictus) of a thickened of 0.3mm in the mat form	Glass-chopped. strand mat	Epoxy resin. LY556 Hardener HY951 (Mix ratio: 100 and 10 parts by weight)	The matrix mixture, bamboo and glass fibre in random orientation was cured at 100 °C for 3h and removed from the moulding box.

Thwe et al.[2,65]	Bamboo fibre of 4 different length range ; 0.25,0.5,1-6,6-12mm.	Glass fibre of 6mm in length.	Polypropylene.	Bamboo, glass fibre and polypropylene mixed using a torque rheometer at 190°C, a rotor speed of 40rpm for 8-10 min, and then placed into the mould and then pressed at 190°C, 3.2MPa for 30 min.
Kushwaha et al. [79]	Orthogonal bamboo strip mat.	Glass strand mat. Woven glass mat.	Epoxy resin (CY230) Hardener (HY951) (resin mixed with 10% hardener) and unsaturated polyester resin (mixed with 2% hardener)	Polymer matrix was spread over bamboo/glass fibre mats and then compressed by 170KN for 24 h for epoxy-based composite and for 6h for polyester-based composite. And then composites were cured at 80 °C for 4 h and 1.5 h respectively.
Kumar et al. [76]	Coir fibres of a 20 mm in length.	Glass chopped strand mat.	Phenolic resin.	Resin and coir fibres were impregnated and compressed for 2 h at room temperature into the mould.
Bhagat et al. [78]	Coir fibre of 5-20mm in length.	E-glass fibre of 10mm in length.	Epoxy resin.	The composites fabricated by hand lay-up and cured under a load of about 50 kg for 24 h
Pavithran et al. [75]	Coir fibre of 10 mm in length.	10 mm long chopped from E-glass rovings.	Unsaturated polyester resin. (mixed with 2% each of MEK peroxide and cobalt naphthanate)	The resin impregnated fibres were pressed and kept at room temperature for 24h and then post-cured at 100°C for 2h.
Jayabal et al. [83]	Woven coir fabric. (10x10, 10 yarns in warp direction and 10 yarns in weft direction per strand) The weight was 1220 g/m².	The plain-weave glass fabric of weight of 610 g/m².	Unsaturated orthophthalic polyester, viscosity of 470cP and mass of 449.96 g/m².	Hybrid composite of woven glass/coir fibres was prepared by hand lay-up process in a mould. The mixture of woven glass/coir fibres was impregnated with polyester resin and then pressed with 1000N weight for 1h. After this, the composite was cured at room temperature for 24h.

Appendix 4

Tensile properties of natural fibre composites as a function of the fibre volume fractions [2,30,31,38,61,63,65,68,69].

Author	**Gauge length (mm)**	**Load rate (mm/min)**	**Fibre**	**Matrix**	**Fibre content (wt%)**	**Tensile strength (MPa)**	**Tensile modulus (GPa)**
Khondker et al. [30]	100 (ASTM D638)	5	Jute fibre. (corchoras olitorious)	PLA fibres	22.5	72	7.5
					27.5	73	8.3
					38	78	8.5
Bodros et al. [61]	Not indicated (ISO 527-1)	1	Hermes flax fibre.	PLLA	20	80	7.5
					25	82	9
					30	99	9.5
Maya Jacob et al. [69]	Not indicated (ASTM D421-68)	Not indicated.	Sisal and oil palm fibres of 10 mm to 6 mm in length	Natural rubber	10	1.5	0.8
					20	2.8	1.1
					30	7.5	1.25
					40	3.8	1.4
					50	3.5	2.1
Geethamma et al. [72]	Not indicated (ASTM D421-68)	Not indicated.	Coir fibre of 100 to 400 um in length.	Natural rubber	10	13	-
					20	7	-
					30	3	-
					40	4	-
					60	5	-
Okubo	80	1	Bamboo	Polypropyl	40	28	-

et al.[31]			fibre bundles of 125–210 mm in diameter.	ene (PP)			
					50	30	-
					60	26	-
Thwe et al. [2,65]	Not indicated (ASTM D638)	1.5	Bamboo fibre of 0.25-5mm in length.	Polypropyl ene (PP)	10	15	2
					20	15	2.5
					30	17	3
					40	12	3.3
Jena et al. [38]	170 (ASTM D3039-76)	2	Weave type bamboo fibre mat, density of 0.95 g/cc ,width of 4.5mm ,thickness of 1.5mm.	Epoxy of viscosity 9000-12000mPa. s, density of 1.1g/cc. (mixing ratio: 10:1 by weight)	3- layers (weight fraction of 18%)	49	-
					5- layers	60	-
					7- layers	90	-
					9- layers (weight fraction of 43%)	84	-
Lu et al. [68]	112	10	Bamboo cellulose fibres.	Epoxy E44 Curing agent T31.	0	14	-
					10	13	-
					20	14	-
					30	12	-