Characterization and Performance Analysis of Natural Fibres as Reinforcement in Polymer Composite

by

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CERTIFICATE OF APPROVAL

The thesis titled **"Characterization and Performance Analysis of Natural Fibres as Reinforcement in Polymer Composite"** submitted by Subhankar Biswas, Roll No.100611104F, Session: October, 2006 has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Master of Philosophy (M. Phil) in Materials Science on February, 2010.

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DECLARATION

It is hereby declared that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma.

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Subhankar Biswas
Dhaka, 2010

ABSTRACT

A systematic study has been carried out in the current study to investigate the mechanical (tensile strength, Youngôs modulus and strain to failure) and physical properties (SEM, FTIR and TGA) of jute, bamboo and coir (brown and white) single fibres. Subsequently, unidirectional as well as woven fabric composites were manufactured and tensile, flexure (longitudinal and transversal both directions were conducted for unidirectional [UD] composites) and impact properties of the composites were determined. Void free composite have been made by using vacuum technique in case of unidirectional composites. On the other hand, Hot press and Resin Transfer Molding (RTM) processes were conducted to fabricate woven jute fabric composites. Water absorption tests were also carried out in this study for woven jute fabrics composites using various fibre volume fractions and polymers. The tensile properties (tensile strength, Youngôs modulus and strain to failure) were determined by varying span length in case of single fibres. Tensile properties were carried out for woven jute fabric composites before and after water absorption test. Scanning Electron Micrograph (SEM), Fourier Transformation Infra Red (FT-IR) and Thermo Gravimetric Analysis (TGA) were also carried out to determine the physical properties of fibres in order to correlate with their strength; Youngôs modulus and strain to failure and physical properties were observed in terms of composites.

The study has revealed that with increasing test span length of single fibres, Youngôs modulus increases and tensile strength as well as strain to failure decreases. This is because no extensometer could be used in this test set-up and machine displacement (denoted by Ŭ) is used for the modulus determination. It is also attributed that larger span length helps to minimize the machine displacement compared to smaller ones. At longer span lengths, the relative effect of slippage in the clamps is smaller. The Youngôs modulus and strain to failure were corrected by using newly developed equations. Among all fibres, bamboo fibres had the highest Youngôs modulus values. Jute fibre had

smoother surface and good thermal properties (burnt at å 256^0C) compared to other three examined fibres. In case of UD composites, analytical results showed good agreement with theoretical values. In comparison between jute and bamboo fibre UD composites, it is observed that bamboo fibre showed better results in terms of tensile strength and jute fibre showed better values in terms of Youngôs modulus. Bamboo fibre showed superior flexure strength with longitudinal distribution while jute fibre composite showed the good results in strength with transverse fibre distribution. Fibre distribution was not aligned uniformly for both bamboo and jute fibre in UD composites and in case of jute fibre composites some fibre have broken during processing. Composite containing higher percentages of fibre showed good tensile and impact behaviour. 4 ply shows better flexural properties for both polyester and polyvinylchloride (PVC) composite. Both tensile and flexural properties decreased after water absorption. It is observed from the SEM image that fibre at first debonded during loading tensile force and then fibre pulled out from the composite. Jute/Polyester composites showed better flexural properties. Tendency of resistance to water absorption of polyvinylchloride composite was higher than that of polyester composites because of its interfacial bonding. SEM images suggested that there is a good interlocking between jute and polyester composite compare to jute-PVC composite interlocking.

Chapter 1
INTRODUCTION

Natural fiber composites have recently attracted a considerable amount of attention in the composite materials research community as well as in industry. This is due to a range of potential advantages of natural fibers, especially with regard to their environmental performance. Natural fibers are renewable resources and even when their composite waste is incinerated, they don't cause net emission of carbon dioxide to the environment (i.e. these materials are CO_2 neutral). There is some effective amount of CO_2 emitted during their processing (due to energy consumption), but this quantity is much lower than the effective amount emitted during manufacture of synthetic fibers like glass and carbon fiber. Natural fibers are inherently biodegradable, which may be beneficial. Due to their relatively low density, high specific mechanical properties comparable to those of synthetic fibers are obtained for some fibers like jute and bamboo. Other advantages are potential low cost (e.g. jute, coir etc.) and relatively low investment needed when cultivating natural fibers. Furthermore, these fibers are typically less abrasive than glass or carbon, e.g. leading to lower wear in textile processing and to potentially lower occupational health risks due to fiber dust. Also, the general public typically appreciates the use of natural materials.

In the present work, thermoplastic polymers namely polypropylene and polyvinylchloride, and thermoset polymer namely unsaturated polyester and epoxy resin were used as the matrix material. Polypropylene and Polyvinylchloride are semicrystalline polymers and their property and classification depends on its percent of crystallinity. The melting temperature of commercial polypropylene lies in the range of 160-170^0 C. For thermosetting polymer, to generate optimum mechanical properties for this system an elevated temperature cure is required. The minimum cure schedule of epoxy resin is 7 hours at 65^0 C. In this study, jute, bamboo and coir fibres were used for

characterization. Among them woven jute fabrics and bamboo fibres were used as reinforcing materials to prepare composites.

Bangladesh is an agricultural country. It produces large amount of jute every year. Jute is the cheapest lignocellulosic, long vegetable bast fibre and abundantly available here. It was called as the ôGolden Fibreô of Bangladesh as it earned huge foreign currency for the economic growth of the country by exporting jute and jute products. Jute was an important foreign exchange earner of Pakistan during ô60s. Even during the ô70s, jute was an important commodity of Bangladesh. However, during the ô80s, bulk handling techniques and synthetic substitutes entered the market and jute started losing its predominant position in the market.

In order to overcome the declining market of jute products, new technologies have been developed for bulk use of jute, as a raw material in the production of high value added and price competitive products. These products for new alternative and non-traditional use of jute are generally termed as diversified jute products. Among the various diversified jute products, jute reinforced composites have high potential for wider use and applications. The interest in using jute fibres as reinforcing agent in plastic composites has increased dramatically during the last few years. Production of jute reinforced composites using thermosets and thermoplastics can replace a varity of products including carbon and glass fibre composites. Processing system of jute-based composites is simple and highly cost effective. So the diversified use of jute in composites has a bright future to increase the economic stability and growth of our country. It can be used for such products as doors, windows, furniture, gaskets, ceiling tiles, partition boards, automotive interior parts, packaging, molding etc.

The main objectives of the work are to improve the mechanical properties of jute composites and compare with other natural fibers and composites. The specific objectives are:

- To improve mechanical properties at low cost fabrication route (i.e. Vacuum Infusion Technique, Resin Transfer Mould and Hot Compression Mould).
- To obtain better interfacial bond between fibers and polymer.
- To get better resistance to water absorption by using different polymer.

The aim of this study is to evaluate the mechanical properties of several natural fibers (Vietnamese coir and bamboo and Bangladeshi jute). Tensile testing of jute, bamboo and coir fibers was carried out by varying span length (5, 10, 15, 25 and 35 mm). The Youngôs modulus and strain to failure were corrected by using newly developed equations in order to correlate actual Youngôs modulus and strain to failure of natural fibers. Thermo Gravimetric Analysis and Scanning Electron Microscopy were also carried out to determine the physical properties of fibers in order to correlate with their strength, Youngôs modulus and strain to failure.

The other aim of the present thesis is to explore the possibilities of using Bangladeshi jute fibres as reinforcement in thermoset and thermoplastic resins.

The second chapter of this thesis presents an analysis of the relevant literature about natural fibres, natural fibre composites specially jute fibres. Moreover, comparative studies of natural fibres in both thermoset and thermoplastic matrices are given in order to allow comparisons with the obtained results for jute composites.

In the third chapter experimental techniques are described that were used during the study. First, the technique used to perform single fibre tensile tests is explained. Next, a description of correction method by using some newly developed equations is given. Then the production of fibre composites is highlighted. Several methods that were used to characterize the composite such as tensile test, three point bending test (3PBT), impact test, water absorption test, Thermo Gravimetric Analysis (TGA) and Environmental Scanning Electron Microscope (ESEM) are described.

In the fourth chapter the experimental results are given, discussed and analyzed (comparisons with similar studies are also given).

Finally, in chapter five general conclusions and future works are drawn based on the obtained results.

Chapter 2
LITERATURE REVIEW

2.1 Generalities

Usually, all types of natural fibre are classified in three categories:

1. Mineral fibres
2. Animal fibres
3. Plant fibres

Among these three types of natural fibre, plant fibres (jute, bamboo and coir) in particular are described in this chapter.

2.1.1 Plant fibres

Concerning vegetable fibres, these are classified depending on the place of the plant (stem, leaves, seeds, grass etc) from where they are extracted. Fig. 2.01 shows the classification of plant fibres according to their origin.

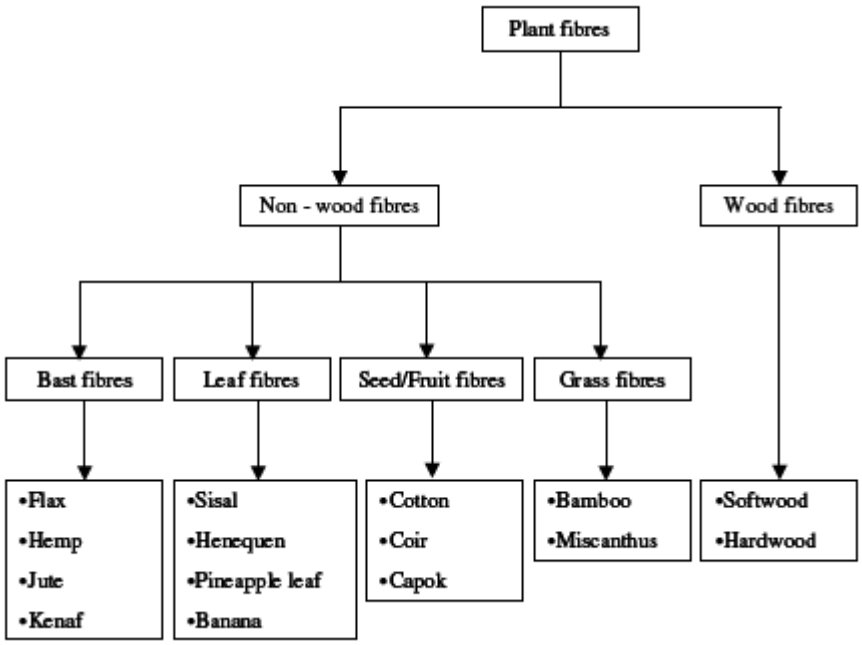


Figure 2.01: Classification of plant fibres according to their origin [01].

Vegetable fibre in itself is a composite; it consists of rigid cellulose microfibrils embedded in a soft lignin and hemicellulose matrix.

The microstructure of natural fibres is extremely complex due to the hierarchical organization at different length scales and the different materials present in variable proportions. On a mesoscopic scale, fibres consist of two types of cell wall arranged as concentric cylinders with a small channel in the middle called lumen [02] which is shown in Fig. 2.02.

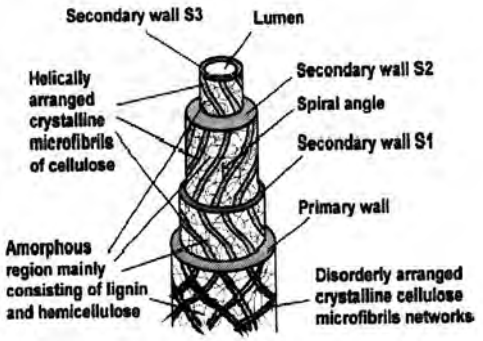


Figure 2.02: Structural composition of a natural fibre cell [02].

Each fibre has a complex layered structure, of a thin primary wall encircling a thick secondary wall. The secondary wall is made up of three layers and the thick middle layer (called S2) determines the mechanical properties of the fibre because this secondary wall makes up ~80% of the total thickness and thus acts as the main load bearing component. The middle layer consists of a series of helically wound cellular microfibrils formed from long chain cellulose molecules; the angle between the fibre axis and the micro fibrils is called micro fibril angle.

2.1.1.1 Chemical constituents

Natural fibres are composed principally of cellulose, hemicellulose and lignin. The amount of these three constituents varies considerably among the plant fibres (Table 2.01). Climatic conditions, age and the maturation process influence not only the structure of fibres but also their chemical composition. On the other hand, mechanical properties of plant fibres depend on their physical, chemical and morphological properties such as the micro fibril angle orientation, cellulose content and diameter/ cross-sectional area of the fibre [03 - 09].

Table 2.01: Composition and microfibril angle of several plant fibres.

Fibre	Microfibril angle (degree)	Cellulose (%)	Hemi-cellulose (%)	Lignin (%)
Jute	**8.1**	**61-71.5**	**13.6-20.40**	**12-13**
Banana	11	65	-	5
Coir	**30-49**	**43**	**0.15-0.25**	**45**
Cotton	-	82.7	5.7	-
Flax	10	71	16.7	2
Hemp	6.2	78	17.9-22.4	0.6
Henequen	-	60	28	8
Kenaf	-	50.5	-	17
Ramie	7.5	68.6	13.1	0.7
Sisal	20-25	70	12	12
Bamboo	**2-10**	**60.8**	**-**	**32.2**

2.1.1.1.1 Cellulose

Cellulose is the essential component of all plant-fibres. In 1838, Anselme Payen suggested that the cell walls of large numbers of plants consist of the same substance, to which he gave the name ócelluloseô. It is generally accepted that cellulose is a linear condensation polymer consisting of D-anhydroglucopyranose units (often abbreviated as anhydroglucose units or even as glucose units for convenience) joined together by ß-1,4-glycoside bonds. It is thus a 1,4-ß-D-glucan. The pyranose rings are in the $^4C_1$ conformation, which means that the ð CH_2OH and ð OH groups, as well as the glycoside bonds, are equatorial with respect to the mean planes of the rings [10]. A schematic representation of the 3D cellulose structure are shown in Fig. 2.03 [11].

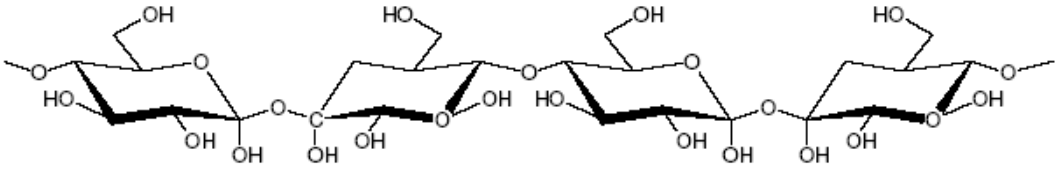


Figure 2.03: Schematic representation of the 3D cellulose structure [11].

Solid cellulose forms a microcrystalline structure with regions of high order, i.e. crystalline region. And regions of low order, i.e. amorphous region. Naturally occurring cellulose crystallizes in monoclinic sphenodic structures (Fig. 2.04). The molecular chains are orientated in fibre direction:

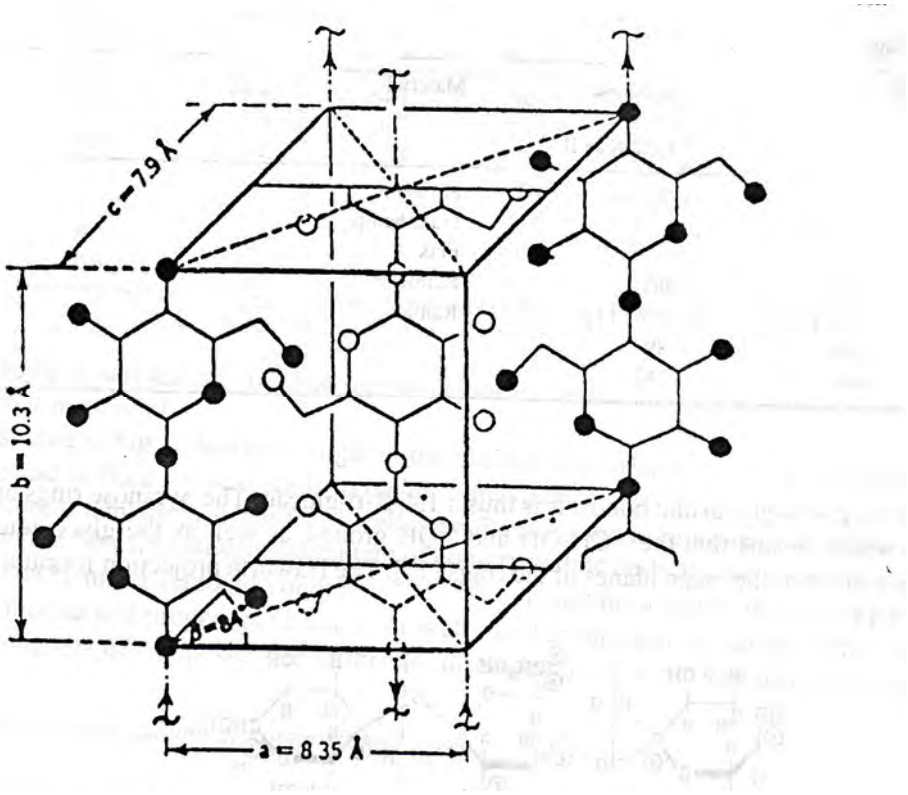


Figure 2.04: The geometry of the elementary cell of cellulose.

2.1.1.1.2 Hemicellulose

Hemicelluloses are polysaccharides like cellulose, but compared to the latter their chains are rather short and branched [08, 12, 13]. Therefore, they are amorphous and possess a low molecular weight, which explains their low resistance to chemical attack. They are very hydrophilic and are largely responsible for the water asorption behaviour of the fibres. Hemicelluloses can be found in between the cellulose microfibrils, binding them together. The most important hemicelluloses are xyloglucan, xylan, glucomannan and arabinoxylan, which all occur in the cell wall in a certain composition that depends on the plant species. Partial structures of common hemicelluloses are shown in Fig. 2.05.

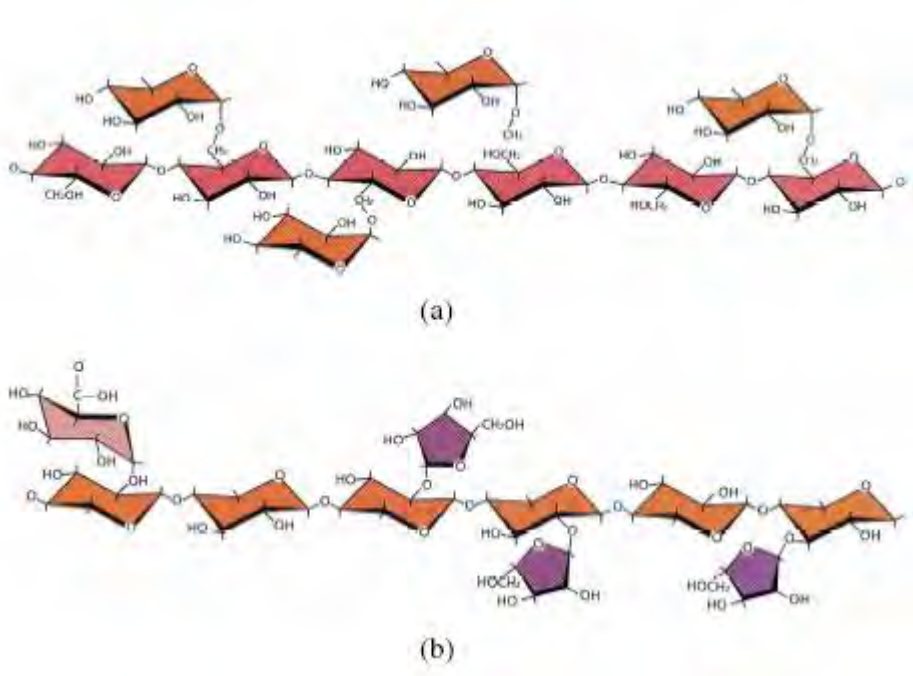


Figure 2.05: Partial structures of some hemicelluloses: (a) xyloglucan with a glucan backbone (i.e. a linear chain of glucose residues) and xylose side chains and (b) glucuronoarabinoxylan with a xylan backbone and side chains containing arabinose and glucuronic acid [13].

2.1.1.1.3 Lignin

Lignin, an amorphous structure with a high molecular weight, gives rigidity to the plant. It is a complex, three-dimensional, cross-linked, polyphenolic network [08, 12, 14], which is situated between the hemicellulose regions surrounding the microfibrils. The exact chemical nature of this component still remains obscure due to the lack of a suitable method to isolate lignin in the native state from the fibres [01]. However, it is believed that lignin gives a certain degree of hydrophobicity to the fibre, is insoluble in neutral solvents, but can be degraded under acidic or alkaline conditions [12]. Fig. 2.06 shows a partial structure of a lignin molecule as can be found in beech wood. It should be noted that this structure differs between plant types.

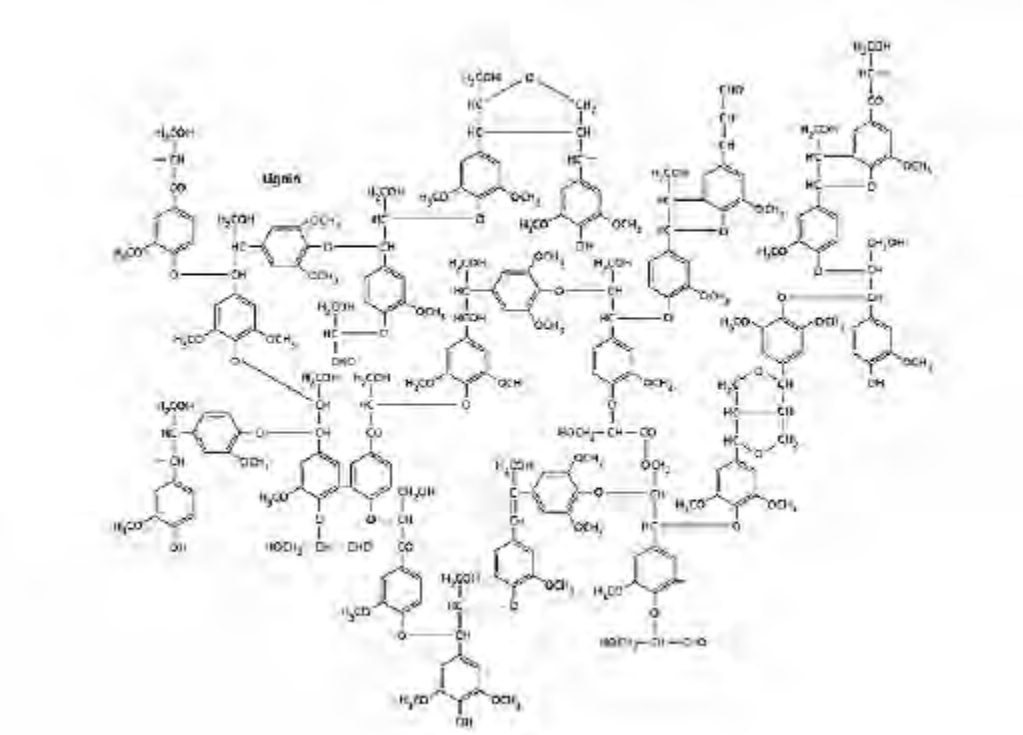


Figure 2.06: Partial structure of lignin molecule from beech wood [13].

2.1.1.2 Mechanical properties of plant fibres

The strength and stiffness of plant fibres depend on the cellulose content and the spiral angle as well as their source, age, environmental conditions, etc. Natural fibres are in general suitable to reinforce plastics due to their relatively high strength and stiffness and low density that gives good specific properties. Table 2.02 presents some mechanical properties of natural fibres compared to glass and carbon fibres. Nevertheless, an important disadvantage of natural fibres, as can be seen from the data ranges in tensile and modulus values, is their variability in mechanical properties due to unpredictable agricultural conditions and the extraction process. These two factors play an important role in the final quality of the fibre.

Table 2.02: Mechanical properties of some plant fibres compare to glass and carbon fibres [03 - 09].

Fibre	Density (g/cm^3)	Diameter (µm)	Elongation (%)	Tensile Strength (MPa)	Modulus (GPa)
Bagasse	-	490	-	70.9	-
Coir	**1.2**	**-**	**30**	**175**	**4.0-6.0**
Cotton	1.5-1.6	20	7.0-8.0	287-597	5.5-12.6
Curaua	1.38	66	3.9	913	30.3
Flax	1.5	50-100	2.7-3.2	345-1035	50-70
Hemp	1.10	120	1.6	389-900	35
Henequen	-	180	3.7-5.9	430-570	10.1-16.3
Jute	**1.3**	**260**	**1.5-1.8**	**393-773**	**26.5**
Kenaf	1.31	106	1.8	427-519	23.1-27.1
Pineapple	1.32	-	2.4	608-700	24.7-29.3
Ramie	1.50	34	3.6-3.8	400-938	24.4-32
Sisal	1.5	50-80	2.0-2.5	337-413	8.3-9.9

Bamboo	**1.44**	**300-500**	**2.4**	**512-833**	**21.1-36.5**
E-Glass	2.5	9-15	2.5	2000-3500	70
Carbon (PAN)	1.4	5-9	1.4-1.8	4000	230-240

2.2 Thermal degradation

Due to the inherent organic composition of natural fibres, it is very important to have knowledge about the influence of the natural composites processing temperatures in relation to the processing duration. Thermal degradation caused during the composite production is one of the most critical aspects since it determines the work temperatures and parameters where the fibre is not suffering any damage.

As is well known, thermal stability is one of the major drawbacks of natural fibres where the first degradation occurs typically at temperatures above 180^0C. It has been established that there is no degradation taking place until 160^0C. Above this temperature thermal stability gradually decreases and decomposition of the fibres occurs. Hemicelluloses are generally thought to decompose first, followed by cellulose and lignin. In addition, the amount of impurities may accelerate the beginning of thermal degradation [15 - 17]. The decrease of tensile strength owing to the higher temperature and duration of exposure can be seen clearly in Fig. 2.07.

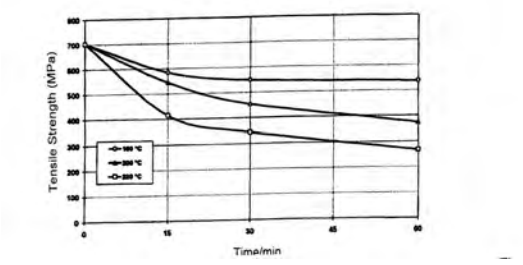


Figure 2.07: Effect of thermal stress on the mechanical properties of retted flax fibres. The fibres were exposed to air at varying temperature.

In the case of cotton fibres rapid deterioration of strength occur above 160^0C. The stiffness remains constant between 80 and 140^0C. Above 180^0C it begins to decrease relatively rapidly [15 - 17].

2.3 Natural fibres

2.3.1 Jute plant

Jute is one of the worldôs most important fibre crops, being exceeded in quantity only by cotton. It is a bast fibre obtained from the stalks of the dicotyledonous plant that belongs to the genus corchorus and order Tiliaceae. It is collected mainly from two commercially important species, namely, White Jute (*Corchorus capsularis*) and Tossa Jute (*Corchorus olitorius*). The material reffered to in the Bible as sack cloth is thought to have originated in Eastern and Southern Africa in prehistoric times. The name jute came from the native name ójhootô. Before general industrial use it was used for ropes, twines and ópattaô, indigenous cloth locally made from jute, by hand spinning and occasional weaving. These fabrics were used by farmers as apparel of medicinal value particularly for rheumatism. Leaves and roots of jute plants were also used as vegetables and medicines in certain areas of Bangladesh and India. It was first used as an industrial raw material for making packaging materials as a replacement for European-grown flax and hemp. Both *capsularis* and *olitorius* are annual plants and similar in general appearance. They have major difference in stem colour, leaf structure, seed pod structure, flower ans taste. The plant grows from 152.40 to 406.40 cms height and stalk is from 1.27 to 1.95 cms in diameter.

A temperate, wet and humid climate with alluvial soil structure is conducive for the growth of jute. Jute is photo-reactive and for that, long hours of day light are necessary for its rapid growth.

Generally sowing time starts at the end of February and continuous up to the end of May as there are differences in the sowing time for different species. After approximately 4

months, harvesting starts. The open network of fibre strands from each plant is extracted by ripping, scotching, retting and hackling. Among other processes, retting is one of the most important steps upon which the fibre quality depends to a great extent. In retting, jute plants are exposed to a complex microbiological action for a definite time, preferably in clean slow moving water, during which the fibre bundles are separated from the woody stem, and then washed and dried to make them ready for marketing.

2.3.1.1 Fibre structure

The stem of the jute plant consists of ring vascular bundles, made up of three distinct regions viz. xylem (the innermost woody tissue), the cambium and the phloem, which contains sieve tubes, companion cells and bast fibres. The vascular bundles are surrounded by cortex tissue and a layer of epidermal cells (Fig. 2.08).

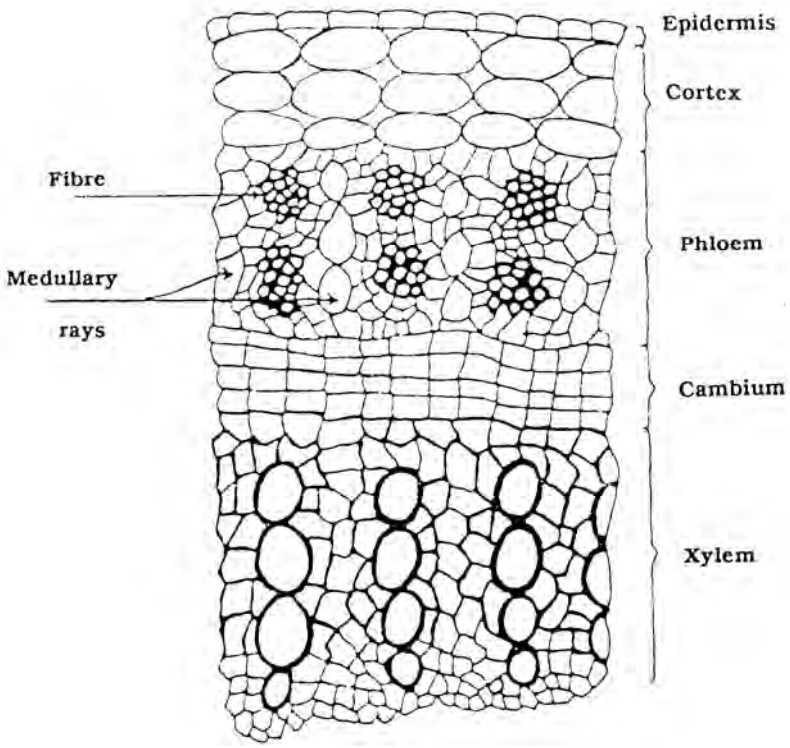


Figure 2.08: Cross-section of stem of jute plant.

Fibres are formed as a secondary growth from the Cambium in contrast to other bast fibres such as flax which are formed directly from primary tissue. Commercial jute fibres consists of strands (Fig. 2.09) i.e. bast bundles of short individual fibres with ends overlapping so as to produce continuous filaments throughout the length of the stalks.

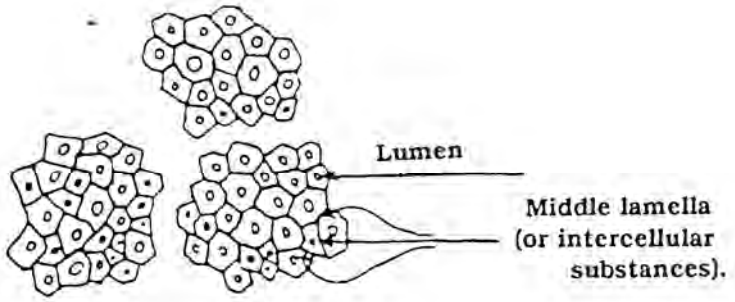


Figure 2.09: Cross-section stem of jute fibre.

As distinct from ultimate fibre this is a net-work built-up of thin polygonal cells. The sizes of these cells vary widely both in width and length.

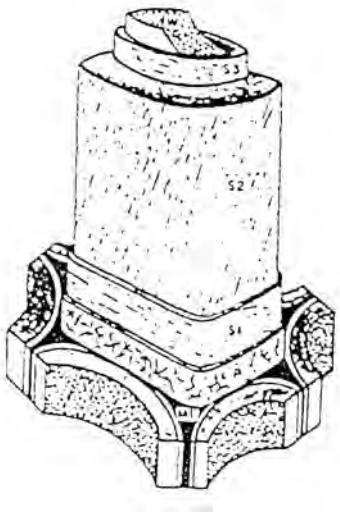


Figure 2.10: Structure of simple woody cell.

The individual fibres are held together by non-cellulosic materials such as lignin, hemicellulose, pectin etc. to form fibre strand. The cell wall of woody materials (Fig. 2.10) is built up of several layers known as middle lamella (M), primary wall (P), outer layer of the secondary wall (S_1), middle layer of the secondary wall (S_2), inner layer of the secondary wall (S_3) and the lumen (W). The middle lamella is located between the cells and serves the function of binding the cells together. Non-cellulosic constituents in jute especially lignin and hemicellulose are abundant in this region.

The lignin component is believed to be located partly in the middle lamella but the maximum lignin (70-80%) is located in secondary as well as primary walls. The primary wall is considered to be the outer sheath of cell wall which is laid down during the period of active elongation of the cell and more fatty materials are found in this layer. The secondary wall is that part which is subsequently deposited on the inside of the primary wall and responsible for the fibre axis in the Z-form (left to right) in contrast to other bast fibres.

2.3.2 Bamboo culm

The properties of bamboo are determined by the anatomical structure of its stem. According to Liese et. al. [80], the gross anatomical structure of a transverse section of any culm internode is determined by the shape, size arrangement and number of the vascular bundles and this is the basis to understand the mechanical behaviour in the different sections of the culm.

For specific zones shown in Fig. 2.10. The average number of vascular bundles per area and other characteristics specially for *Guadua angustifolia* are given in Table 2.03 (Londono. et. al. [81]).

Table 2.03: Characteristics of the different cross sectional zones of the bamboo culm (*G angustifolia*). Source: Liese et. al. [82].

Zone	Thickness (mm)	Characteristics	Wall thickness (%)	N^0 of vascular Bundles per cm^2
Periphery zone	0.65-0.77	It consists of small, circular and numerous vascular bundles, with little conductive tissue and few parenchyma cells between them	4.5	346-530
Transition zone	1.2-2.55	It consists of vascular bundles where the sclerenchyma sheaths amalgamate with fibre bundles.	10.7	346-530
Middle zone	4.9-16.34	It is the largest of the four zones. It consists of round shapes vascular bundles in random orientation	73.9	81-194
Interior zone	1.3-2.0	This zone has thick parenchyma layers with a large amount of lignin. The vascular bundlesdo not have any orientation	10.8	52-96

2.3.2.1 Vascular bundles and parenchyma tissue

Vascular bundles represent one of the main anatomic constituents of bamboo and moreover they are closely related to the fibres (Liese et. al. [82]). They can be detected easily because of their dark colour (Figs. 2.11 and 2.12a). These bundles are distributed densely in the outer region of the wall and sparsely in the inner region, and are concentrated in the upper part of the culm compare with the base (Fig. 2.13).

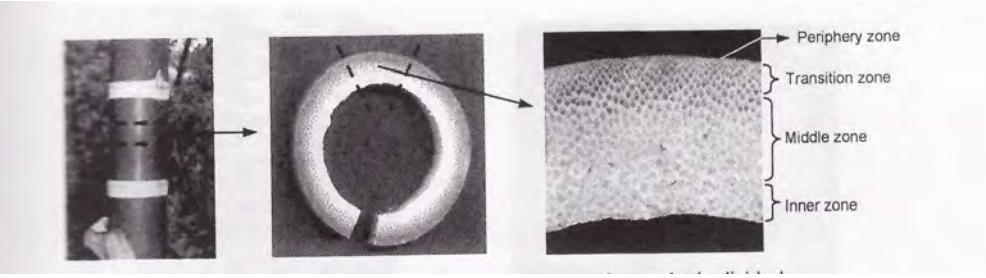


Figure 2.11: Four zones to which the cross section of the bamboo culm is divided.

The lower culm contains in its inner part mainly parenchyma tissue with fewer, large vascular bundles. The parenchyma tissue is reduced along the culm length. The upper part of the culm consists mainly of many smaller vascular bundles with a high portion of fibres [83].

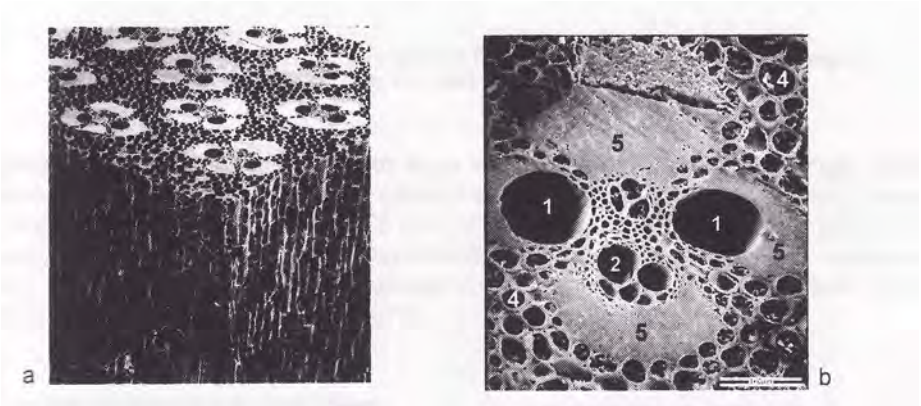


Figure 2.12: a) 3D view of the cross section of the culm showing some vascular bundles. b) Vascular bundle and its parts: 1) vessels, 2) floem, 3) parenchyma tissue, 4) fibres. Source: Liese et. al. [82]

The fibres and conductive tissue together form the vascular bundles (Fig. 2.12b). The conductive tissue has vessels to transport the water from the root, floema where the liquids go down and protoxylema which help with the transportation of water during growth [80].

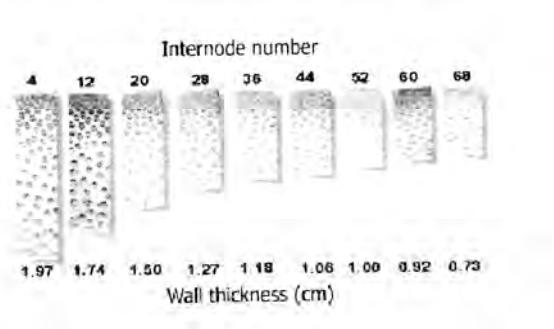


Figure 2.13: Wall thickness variations across the (*G angustifolia*) culm.

According to Jassen et. al. [84], parenchyma is a spongy tissue, composed of large cells that are mixed with some short cubic cells. Inside these cells, some nutrients in the form of starch grains are stored filling 50 to 70% of the tissue. In a similar way, in the cross section this amount decreases from the inside to the outside.

2.3.2.2 Microstructure of the bamboo fibres

According to Tono et. al [85], parameswaran et. al. [86] and Murphy et. al. [87] amongst others, bamboo fibres consist of thik and thin layers with different fibrillar orientation (Fig. 2.14). In the thick lamella (L1-L4) the fibrils are oriented at a small angle to the fibre axis, where as the thin ones (N1-N3) show mostly a more transverse orientation.

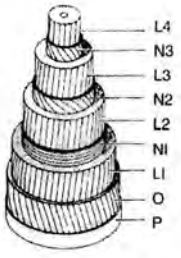


Figure 2.14: Model of the polylamellate structure of a thick walled bamboo fibre. P = primary wall, O = external sheet of secondary wall. Source: Liese et. al. [82]

This structure does not exist in the cell walls of fibre of normal wood. The structure is reffered to as a denominated polylamellate structure and appears specially at the periphery of the bamboo culm.

Different results have been reported about the number of lamellae. This can be partly attributed to the position of the vascular bundles, the location of the fibres within and the state of maturity the fibres. It can be said that the alternating lamella lead to an extremely high tensile strength of the culm [82].

2.3.3 Coconut husk

Coconut husk is the outer layer of the coconut fruit. It consists of long fibres, medium length fibres, short fibres, baby fibres and pith (coir dust or coir waste). Coir fibre is extracted from its husk. Coir fibre is a lignocellulosic, hard vegetable fibre extracted from the husk of coconut. The physical and chemical characteristics of fibreous materials are to a great extent, influenced by the ingredients, constituting the fibre and the nature of the dispersal of these ingredients in the fibre structure. Coir fibre contains about 40% lignin which is hard and stiff in nature. Improvement in the feel of the coir fibre could be attempted by two methods; (1) by treatment with selected chemicals which can modify the surfare properties of fibres and thus improve its physical characteristics and (2) by elimination of the incrusting substance to a desirable extent without adversely affecting the other properties.

There are two types of husks used for fibre extraction namely

1. Green husks
2. Brown husks

The husks are named green or brown (also called dry) after the colour of the husks. The fibre obtained from green husk is called white fibre, while the fibre obtained from brown husk is called brown fibre.

Based on the fibre length, Coir Fibre is classified into

1. Bristle Fibre (also called Long fibre)
2. Mattress Fibre (mixture of medium and short fibres)
3. Mixed Fibre (mixture of long, medium and short fibres)
4. Baby Fibre

2.3.3.1 Fibre Quality

Fibre quality is determined based on the length of the fibre and how well the pith is removed from the fibre.

2.3.3.2 Soaking Process

Soaking husks in water is the main criterion that determines fibre quality. By soaking, the hard portion of the husks get softened; the fibres get loosened and hence fibre extraction becomes easier, fibres donôt get cut a lot thereby sustaining fibre length and pith removal from the fibre is improved to a significant extent.

2.4 Natural fibre composites

2.4.1 General applications

Natural fibres are already widely applied in several composite parts, mostly in the packaging and automotive industry [18-25]. In the latter area, the fibreôs low density can be fully exploited, resulting in important weight savings and thus reduced fuel

consumption. Also the good thermal and acoustic insulation properties, due to the presence of the hollow lumen inside the fibres, are an asset for interior parts. Some other advantages of natural fibres that promote their use in automotive components are the low abrasion on tools and the favorable accident performance (less splintering during impact). Also recyclability of the parts is a major concern nowadays in automotive industry, favoring natural fibre composites over glass fibre reinforced polymers. In this regard, mainly thermal recycling or incineration with energy recovering benefits by natural fibre composites, because of the considerable residue after burning of glass fibre reinforced parts. Some researchers [26] hold the view that natural fibre composites can be reprocessed into parts with a superior performance compared to their recycled glass fibre counterparts, because the higher flexibility of the natural fibres in comparison with glass fibres would result in less fibre shortening during the recycling processes. However, bearing in mind the fibres vulnerability towards thermal degradation, this statement becomes rather questionable since a re-forming process at elevated temperature would eventually harm the natural fibres to a significant extent. Anyhow, a thorough research regarding the quality of recycled natural fibre reinforced polymer parts is still lacking and would be necessary to give a well-founded opinion on this matter.

In spite of all the benefits mentioned above, the applications of natural fibre composites are still limited to semi-structural parts, bearing no high mechanical loads. This is because of the mediocre interface properties between the fibres and a polymer matrix, resulting in low composite performance. Besides, these parts are highly moisture sensitive, have a limited heat resistance and exhibit significant variations in quality and homogeneity due to the non-constant fibre properties, as mentioned in previous paragraphs.

Other applications for flax material are particleboards, where flax shives compete with wood particles [27], and paper production [28]. These applications utilize the inferior

substances of the flax stem and fibre for a functional purpose, but are examples of cheap filler materials, rather than composite reinforcements.

To date, no full-load-bearing applications for natural fibre composites are known because of the mentioned problem of poor interaction between fibres and matrix. Therefore, pre-treatments of fibre and/or matrix are a prerequisite to obtain qualitative composite parts. This will raise of course the cost of the final product, excluding hereby applications where cost is a key issue.

2.4.2 Natural fibre reinforced composites

2.4.2.1 Production requirements

The production of natural fibre reinforced composites requires a matrix material that is processable at temperatures below 200 °C to prevent severe fibre degradation. Both thermoset and thermoplastic polymers can be qualified, each having their own advantages and disadvantages explained in the following paragraphs.

Thermoset resins usually have acceptable curing temperatures, and moreover it is expected that the hydroxyl groups of the cellulose in the fibre can react with the thermoset, forming strong bonds, favorable for the composite performance. Nevertheless, in practice, serious complications are still encountered when applying thermoset resins, due to the far from ideal surface composition of the plant fibres: instead of providing readily available cellulose molecules, which would assure a strong bond formation with the matrix molecules, the surface is covered with waxes and impurities (e.g. mineral substances from the soil and from the fertilizers). The waxy substances are made up of hydrophobic compounds [13] and originally protect the plant cells from the environment. However, their hydrophobicity impedes a good binding with the polymer molecules when the fibres are embedded in a resin. Therefore, the presence of waxes causes a deterioration of the interface quality between fibres and polymer.

Besides, processing cycles of thermoset based parts are generally long (easily more than one hour), which could affect the fibreôs properties and thus the quality of the part. Furthermore, the thermoset polymer cannot be directly recycled as is the case with thermoplastics. The latter are thus believed to surpass the thermosets in the near future, due to their recycling possibility and ease of repair and replacement. Moreover, the processing time of thermoplastic parts can be kept short up to a few minutes, but the temperature is then again rather high. Only thermoplastic polymers with a sufficient low processing temperature, mostly polyolefines such as polyethylene and polypropylene, are considered suitable for natural fibre reinforced parts. Additionally, the hydrophobic character of thermoplastics generates severe incompatibilities with the hydrophilic nature of plant fibres, creating the need to modify the fibre or matrix surface characteristics.

Independently of the kind of matrix used, it is also noticed that the kink bands in the fibres generate stress concentrations in the composite and initiate in this way fibre-matrix debonding or micro-cracking in the matrix. This would lead to early composite fracture [10, 29, 30]. A careful handling of the fibres during processing can minimize the amount and severity of the kink bands and could have a substantial effect on the composite properties [31].

2.4.3 Moisture absorption

The main drawback of natural fibre is their hydrophilic nature, which decreases the compatibility with hydrophobic polymeric matrices. Moisture sensitivity causes fibres to swell and ultimately rot through attack by fungi. By reducing the moisture sensitivity better adhesion is reached.

In this field, most of the research has been focused on improving interfacial properties between the polymer matrices and natural fibres, in order to enhance the physical and mechanical properties of the end products. According to Mahuya et. al [88], moisture is

a major obstacle which prevents extensive applications of natural fiber composites. Reducing the amount of hemicellulose reduces the swelling capacity of lignocellulosic fibres. This aspect is related to the quality of fibre extraction process, because the process determines the absence of defects along the fibre length as well as the non-presence of lignin, hemicellulose and impurities on the fibre surface.

Consequently, surface treatment, for example silanes treatment can make the fibres more hydrophobic by reducing hemicellulose, since it is largely responsible for the water absorption behaviour exhibited by plant fibres due to its hydrophilic nature. The investigations on unmodified jute-epoxy composites [32] regarding their moisture absorption (in distilled water 23^0C) showed that the kinetic of absorption and the moisture content at equilibrium distinctly increase with increasing fibre content. Semsarzadeh et. al. [33, 34] observed an improved water repellence in jute reinforced unsaturated polyester resin composites, treated with polyvinylacetate. This increasing moisture absorption is caused among others by the higher hydrophilic nature of the jute fibre compared to the matrix and the higher amount of interfacial area (capillary effect).

Composite with silanized jute fibres showed about 20% lowered moisture at equilibrium [32]. After the fibre modification, the applied silane reduces the amount of hydroxyl groups which were free to bind moisture.

Due to the surface treatment with silanes, these composites showed increased (approximately 30%) static characteristic values compared to unmodified composites at standard humidity (Fig. 2.15). Tensile strength of the silanized fibre composites is nearly independent of the moisture content of the composites. The same is known from glass-fibre reinforced plastics, where the usage of silane coupling agents reduces the dependence of the mechanical properties on moisture content. Unmodified jute-epoxy composites reach only 65% of the values of the dry-strength at the maximum moisture content of 5.2 wt%. Shan et. al. [35] Already provided similar results on composites without coupling agents used UD-jute-epoxy (fibre content = 33 vol.%) and jute-

polyester (fibre content = 22 vol.%) composites, which were stored for 2 h in boiling water. Tensile strength of these composites decreased from 10% to 16%. The decrease of Youngôs modulus (13-25%) is even more remarkable in the investigation results of Shan et. al. [35] than for the jute-epoxy composites.

The improved moisture resistance caused by the application of the coupling agents can be explained by an improved fibre-matrix adhesion. The coupling agent builds chemical bonds (silanol bonds) and hydrogen bonds, which reduces the moisture caused by fibre-matrix debonding. The Youngôs modulus of unmodified jute-epoxy composites follows the same trend as that for modified composites (Fig. 2.15), but moisture influence is distinctly lower, when the coupling agent was used. This might be explained by the decreasing Youngôs modulus of the jute fibres with increasing moisture content, where tensile strength of the fibres does not change with changing moisture contents.

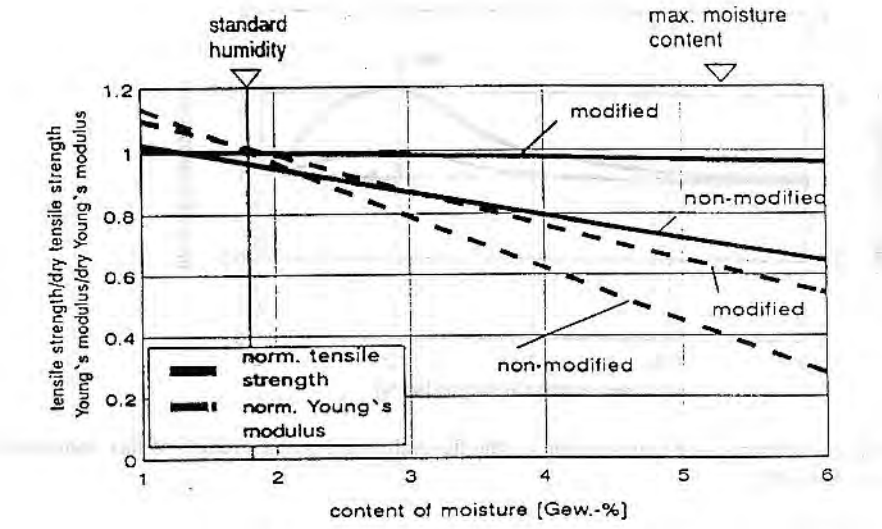


Figure 2.15: Influence of silane coupling agents on the strength of jute reinforced epoxy-risin composites at different moisture content [36].

Maldas et. al. [37] Investigated CTMP-aspen-HDPE filled materials modified with PMPPIC-isocyanate as coupling agent. These materials were stored for 4 h in boiling

distilled water. Similar to the results for the jute-epoxy composites in Fig. 2.15, a change of tensile strength and Youngôs modulus were not observed. For a full comparison, results of unmodified composites are missing.

In contrast to the results of tensile test in Fig. 2.15, a reduced influence of humidity on flexural strength and modulus was not attained by the silane application [32]. Whereas, the decline of flexural strength of the silanized jute-epoxy composites started at a 20% higher level. This tendency, that interfacial and matrix-dominated properties are distinctly more influenced by moisture was already shown by investigations at glass-fibre reinforced epoxy resins. Add to this that are entire cross-sectional area of a material submitted to tensile stress is loaded homogeneously, while flexural loading only afflict the marginal zone. Likewise it should be considered that natural fibres caused by their fibrillar structure, should looked at as composites. For jute fibres, submitted to flexural stresses, the fibrillar orientation of 8^0 causes a nearly transversal loading to the fibrils. So that, the hydrophilic properties of hemicellulose and lignin influence the properties of the composites much more, as they do under tensile stress.

No decrease of flexural strength was found by Bisanda et. al. [38] in investigations oil sisal epoxy composites (fibre content = 40 vol. %) modified with ɔ-aminopropyltriethoxy-silane, and stored for 72 h in water. While, strength of these unmodified composites was reduced from 15% to 20% after the same water storage. In this investigation tile silane application reduced the moisture influence on the flexural modulus in the same range. Bisanda et. al. [38] Explained these effects by an improved interfacial bonding.

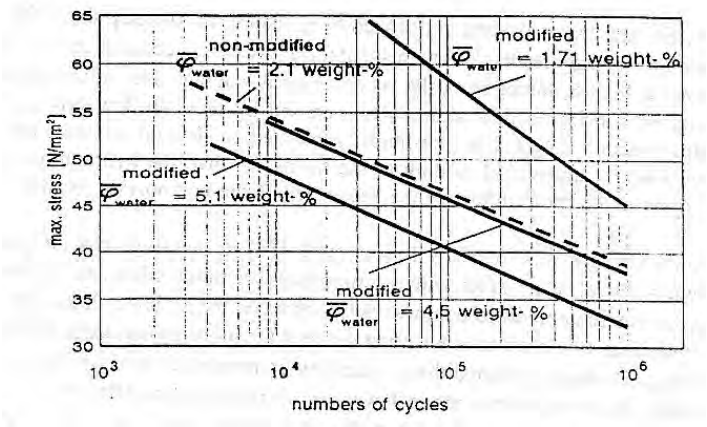


Figure 2.16: Wohler chart of silanized and unsilanized jute-reinforced-epoxy-resin at different moisture contents (stress ratio = 0.1, frequency = 10 Hz, fibre content = 40 vol.%) [51].

The fatigue tests yielded similar improvements as they were recorded at the tensile tests (Fig. 2.16). The surface modified composites at a moisture content of 4.5 wt. % show nearly the same curve as the unmodified composites at standard humidity (i.e.2.1 wt.% moisture). The quality of the fibre matrix adhesion call be rated also, as published by Gassan et. al. [32] and Kessler et. al. [36] for juteï epoxy composites, by regarding the dynamic modulus and the damping of such composites. Good adhesion between fibre regarding the dynamic and matrix led to low damping values and high values of the dynamic modulus. The damping of the modified composites was approximately two times lower than the damping of the unmodified composites, and it was nearly independent on the number of cycles. The damping of the silanized jute-epoxy composites was constant until damage initiation. The higher damping of the unmodified jute-epoxy composites was explained by the friction in the fibre-matrix interface. The increasing damping with increasing numbers of cycles was caused by this effect and by irreversible damages such as macro cracks in the matrix, delaminating, and fibre-matrix debonding. The damping of the silanized jute-epoxy composites was nearly independent on the number of

cycles. But, since both types of composites were identical, the fibre modification excepted, the increased damping at the unmodified composites is caused by interfacial effects.

2.5 Processing of natural fibre reinforced plastics

2.5.1 Influence of humidity on the processing of natural fibre reinforced composites

Drying of fibres before processing is an important factor, because water on the fibre surface acts like a separating agent in the fibreï matrix interface. Additionally, because of the evaporation of water during the reaction process, voids appear in the matrix (most of the thermosets have a reaction temperature over 100°C; processing temperature of thermoplastics lies distinctly over the evaporation temperature of water). Both phenomena lead to a decrease of mechanical properties of natural fibre reinforced composites. For juteï epoxy composites, tensile strength of maximally pre-dried fibres (moisture content: approximately 1 wt. %) rises for about 10% compared to minimally dried fibres (moisture content: approximately 10 wt. %), the increase of stiffness with 20% is remarkably higher (Fig. 2.17).

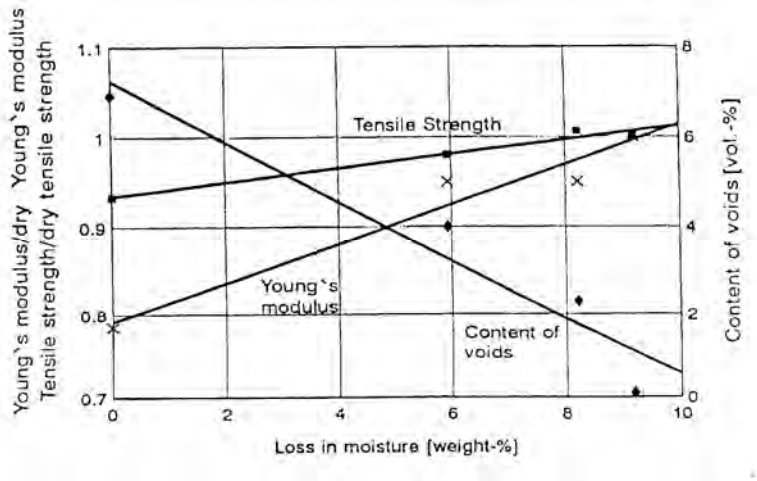


Figure 2.17: Influence of fibre dying on the characteristic values of jute-reinforced-epoxy-resin composites [36].

Fibre drying can be done in a vacuum stove at different temperatures. This results in different degrees of loss of humidity, as shown in Fig. 2.18.

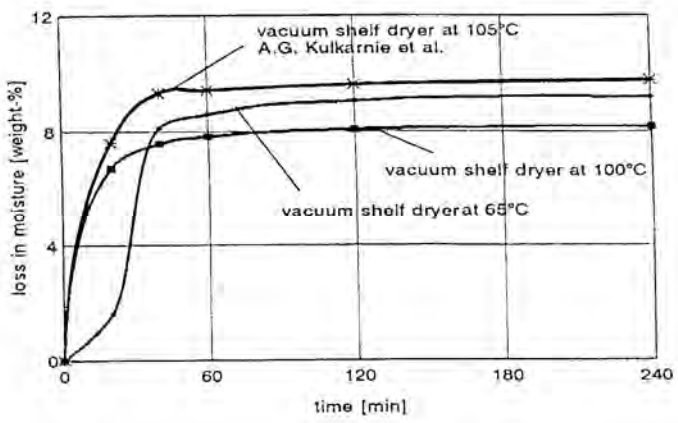


Figure 2.18: Loss of humidity during drying of jute-fibres as dependent on the temperature in vacuum oven [36].

2.5.2 Natural fibre reinforced thermosets

The economically most attractive glass-fibre reinforced plastics for special technical uses, are, next to RTM (Resin Transfer Molding) and winding technology, etc. semi product made of SMC (Sheet Molding Compounds) and BMC (Bulk Molding Compounds) systems.

2.5.2.1 Sheet Molding Compounds (SMC)

In the automobile and electronic industries, big amounts of pressed parts from SMC or BMC are used for bumpers, trunk covers and spoilers. In Fig. 2.19 pressed SMC materials based on flax-fibres are compared with those made of glass-fibres. It shows that the glass-fibre reinforced material attains higher characteristic values, except for tensile strength. However, if the measured values are regarded in reference to density, the results of the flax-fibre based SMC moulded plastics are located in the same range as the glass-fibre SMC moulded types. As already

mentioned, the characteristic values of natural fibre materials are clearly dependent on their moisture content (Fig. 2.20). After the fibres are dried, they reach values similar to the ones before the storage in damp stage [39].

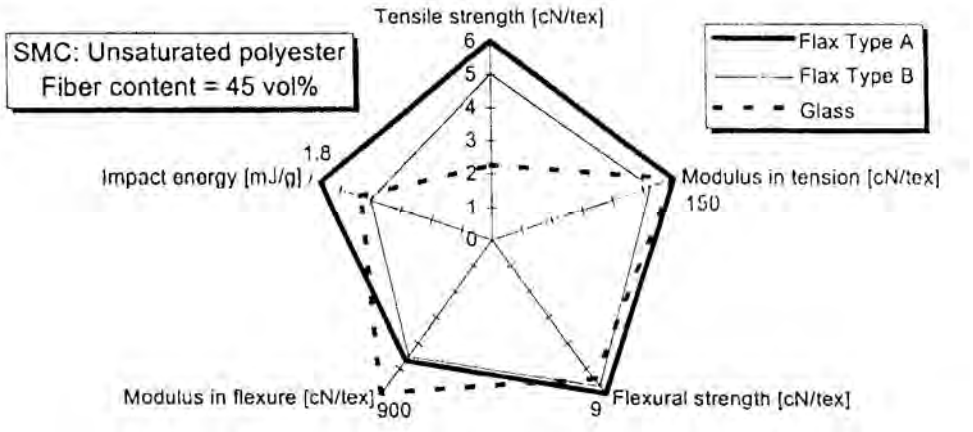


Figure 2.19: Characteristics values of glass-fibre and flax-fibre SMC moulded plastics (absolute values and in reinforce to density) [39].

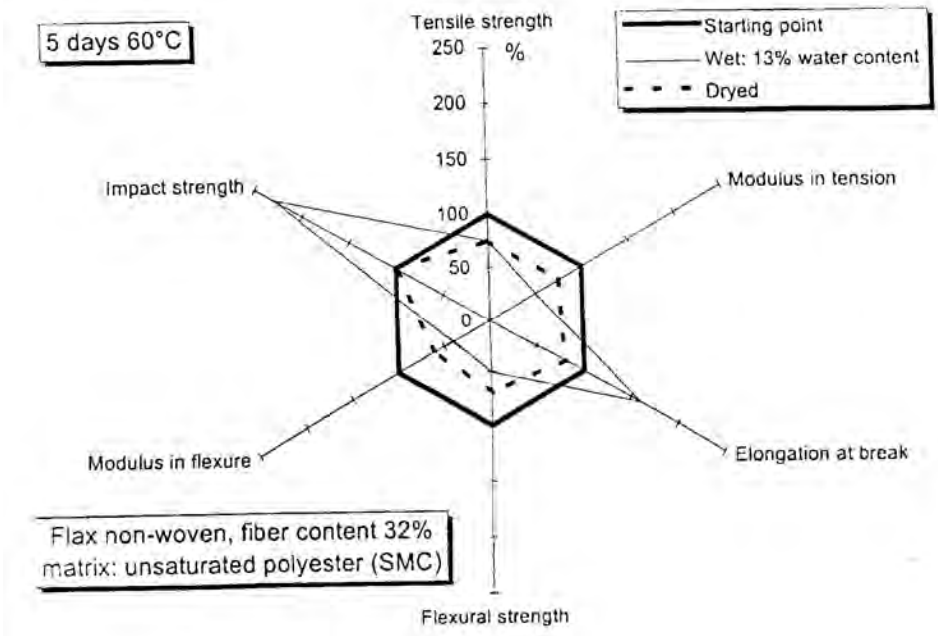


Figure 2.20: Influence of humidity on the characteristic values of flax fibre SMC moulded plastics [39].

2.5.2.2 Bulk Molding Compounds (BMC)

In addition to SMC moulded plastics, BMC composites with natural fibres, with good mechanical properties can be produced. Owolabi et al. [40] made such composites with coir-fibres, their basic recipe is shown in Table 2.04.

Table 2.04: BMC-recipe on the basis of coir-fibres (NMT).

Materials	Parts by weight
Unsaturated polyester resin	100
$CaCO_3$ filler	75
MgO	3
Styrene	12
Zinc-stearate	2.5
tert-Butylperbenzoate	1.25
Chopped fibrous reinforcement	100

In the examination, glass-fibres were replaced by coir-fibres. A proper treatment of the fibres improved adhesion and as a result tensile strength was increased (Fig.2.21).

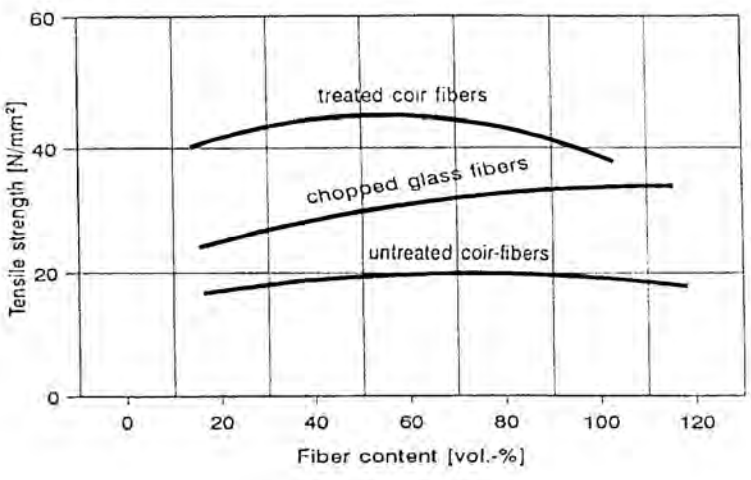


Figure 2.21: Tensile strength of BMC moulded plastics as dependant on their fibre content, % fibres/100 g UP resin [40].

2.5.3 Natural fibre reinforced thermoplastics

In compare to glass-fibres, the lower thermal stability of natural-fibres with up to 230° C, limits the number of thermoplastics to be considered as matrix material for Natural fibre thermoplastic Composites. Only those thermoplastics are useable for natural fibre reinforced composites, whose processing temperature does not exceed 230°C. These are, most of all, polyolefines, like polyethylene and polypropylene. Technical thermoplastics, like polyamides, polyesters and polycarbonates require processing temperatures >250°C and are therefore not useable for such composite procession without fibre degradation [41].

Other than the processes mentioned here, natural fibres are used as structural units, by applying hybrid non-woven, i.e. natural fibre staple-fibre-fleece [42].

2.5.3.1 Natural fibre mat-reinforced thermoplastics (NMT)

With the largest turn-over, glass mat thermoplastic matrix (GMT) is certainly the most important semi product in the group of reinforced thermoplastics. A special production process for natural fibre reinforced PP-semi products (NMT) has been developed by BASF AG [41]. For this process, natural fibres must be available in form of fibre-mats. Mats are produced, by stitching together layers of fibres which have been crushed before. This semi product is being produced by melt-coating the fibre-mats in a double coil coating press, which is provided with a heat- and cool-press zone. In such a coil coating press, the fibre mats are brought together with the polypropylene melt between circulating steel bands.

Wetting of the mats with the thermoplastic melt takes place in the hot-press zone. Then the laminate is being cooled under pressure in the cooling-press zone. Sisal-, flax- and glass-fibre MT can be classified by their mechanical properties, tensile strength and Young's modulus (Table 2.05).

Table 2.05: Tensile strength and Youngôs modulus of sisal, flax and glass-fibre MTs with a fibre content of 40 wt. % [43].

Materials	Tensile Strength (MPa)	Young's modulus (MPa)
PP-wood flour	19	2500
PP-sisal non-woven	38	3600
PP-sisal non-woven with surface treatment	55	4800
PP-flax non-woven	47	5100
PP-flax non-woven with surface treatment	67	6700
PP-glass non-woven	100	6000

2.5.3.2 "Express" -processing

The extrusion press processing (express-processing) was developed for the production of flax-fibre reinforced PP at the research center of Daimler Benz, Ulm/Germany [44]. In this process, natural fibre non-woven and thermoplastic melt-films are alternatively deposited and moulded in a tempered mould. The thermoplastic melt-films are laid on by a mobile extruder. If this process is optimally adapted to the element, a single passage by the extruder suffices. The structural order consists of three layers: two layers of non-woven on the bottom and one on top, with the melt-film in between. As to density, the values for tensile strength of flax-fibres polypropylene composites exceed the characteristic values of sisal-fibre reinforced polypropylene composites (Fig. 2.22).

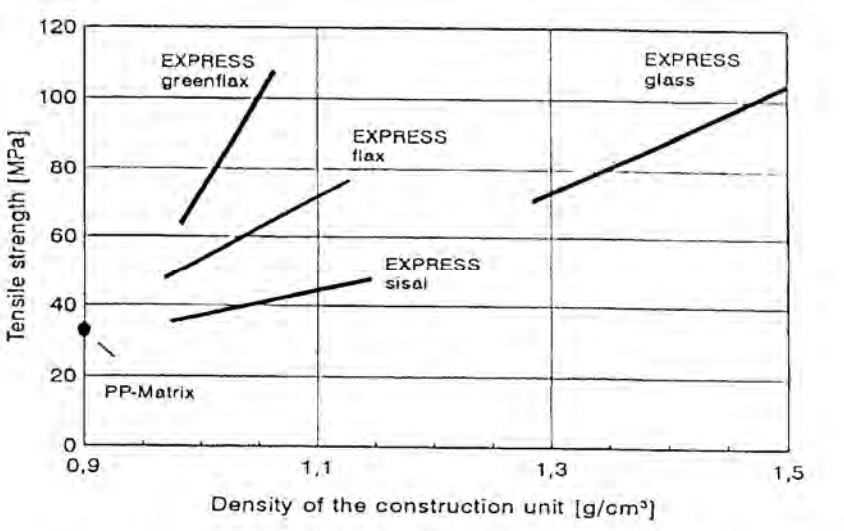


Figure 2.22: Tensile strength of different types of fibre reinforced composites, produced by express-processing [44].

2.6 Mechanical behaviour of natural fibre reinforced plastics

2.6.1 Impact behaviour

There are only a few studies known about the impact behaviour or natural fibre reinforced plastics compared with glass-fibre reinforced plastics. Pavithran et al. [45] determined the fracture energies for sisal-, pineapple-, banana- and coconut-fibreð polyester composites (fibre content of approximately 50 vol.%) in a Charpy-impact-test. They found out that, except the coconut-fibreð polyester composites, an increase in fracture energy was accompanied by an increasing fibre toughness (determined by the stressð strain diagram of the fibres). Natural fibre reinforced plastics with fibres which show a high spiral angle of the fibrils, indicated a higher composite-fracture-toughness than those with small spiral angles. That is why, according to Pavithran et al [45]., composites with sisal fibres (spiral angle = 25°) show all optimum impact properties. Pavithran et al. investigated a specific toughness of sisalð UHMPE composites, which is approximately 25% below that one of comparable glass-fibre based composites (same fibre-volume-content). By adding flax fibres Hock [46] stated an obvious increase in

damaging mechanism (determined at -400C) compare with pure PP, a silanization of the fibres led to a reduction of this effect. During examinations about the influence of silanes as coupling agent for jute-epoxy composites, from the impact resistance only small differences could be stated by the silanes, i.e. <10% [49]. Schlober et al. [44] determined the influence of thermal aging (storage at 1000C and 1250C) on the penetration properties of flax fibre reinforced polypropylene. Thereby these storages led to a remarkable decrease in maximum force.

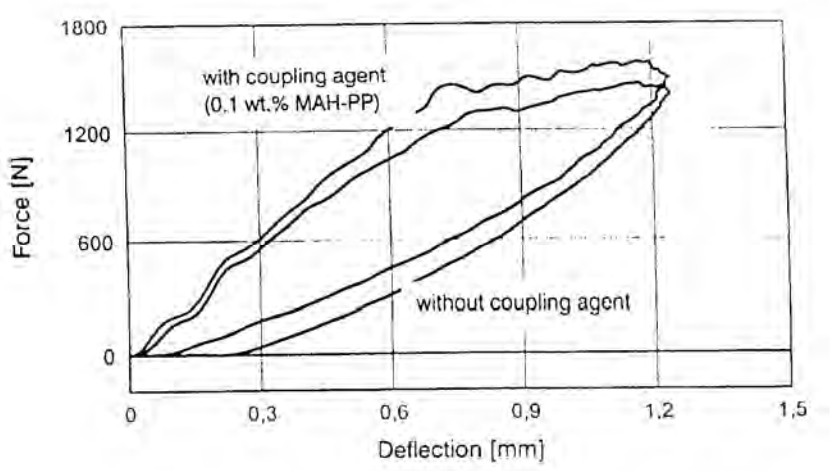


Figure 2.23: Influence of fibre treatment on force-direction behaviour of jute-polypropylene composites with untreated and MAH-PP treated fibres.

Tobias et. al. [47] examined the influence of fibre content and fibre length from banana fibres (Abaca) epoxy composites. In this connection an increase in impact strength was stated with increasing fibre content (fibre length = 20 mm). Smaller fibre lengths led to higher impact strength at constant fibre content. Usually at glass reinforced PP the impact strength increases with increasing fibre length.

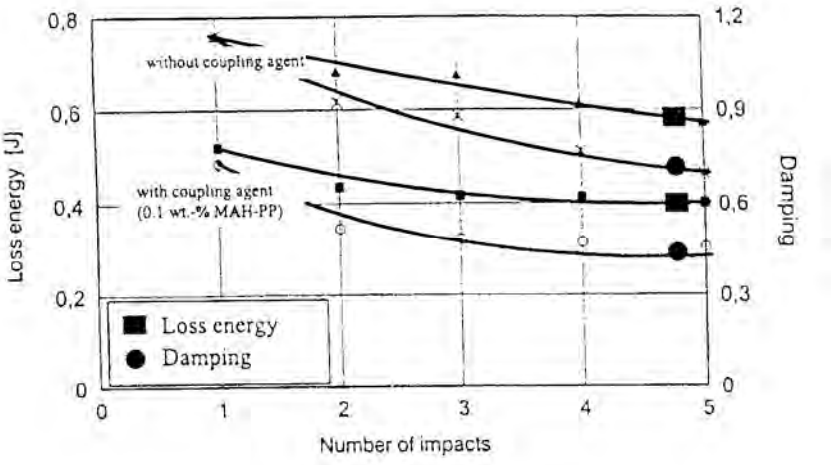


Figure 2.24: Influence of multiple impact events and fibre surface treatment on the loss energy and damping of jute polypropylene composites.

Further, impact investigations at juteï polypropylene composites were carried out with and without coupling agent (MAH grafted PP). In that process (Fig. 2.23) it turned out that the damaging initiation can be shifted to higher forces with a strong fibreï matrix adhesion, as composites with a weak fibre- matrix adhesion at smaller forces break down at a load perpendicular to the fibre. For these materials it could also be shown that the dissipation factor at the composites with MAHï PP modified jute-fibres with 0.52 J is clearly smaller than those of the composites with unmodified jute-fibres with a loss-energy of 0.76 J (each at impact energy of 1.5 J). When the composites have no coupling agent a part of the impact energy is degraded in the fibreï matrix interface, for example by debonding and friction effects. At these test conditions a multiple-impact-load, as shown in Fig. 2.24, leads to a decrease in loss-energy (until the third impact event), whereby, at the composites modified with MAHï PP after the third impact only slightly further damages occur, i.e. no macroscopic determinable damages. Concerning the composites without coupling agent this saturation of damage is not so pronounced.

2.7 Environmental effects

Whichever application of natural fibre, or natural fibre reinforced plastics, will be used, when and where depends on the different environmental conditions, which are likely to influence ageing and degrading effects. In contrast, such effects are often desirable, as is the case with compostable materials. Natural fibres are subject to degradation in acids and in alkaline solutions, as well as under UV rays. These effects however, can be minimized by using suitable modifications. Unmodified cellulose fibre, are normally degraded by enzymes after about 6-12 months, this can be altered through suitable treatment, so that no significant changes of mechanical properties can be noticed for two years. Within of 2.5 years, dry-stored fibres show only little changes in their mechanical properties. This is true especially with regard to strength and elongation at break. In this respect, sisal fibres arc comparably more stable than Henequen and Abaca.

Lower temperature, such as -70°C, clearly results in lesser strength, but this effect can be minimized by previous drying. Higher temperatures, such as 100-130°C, lead, in the case of cotton, to a notable degradation, after 80 days. Their strength is thereby reduced to 68%, which is 10% of the original value. Depending on the temperature applied, these values are reduced to 41 % and 12%, for flax-fibres, and to 26% and 6%, for ramie fibres. In composites, moisture content results in lower mechanical properties. This effect is greater when using ocean-rather than fresh water. With fresh water, it is more likely that bacteria and fungi appear on the scene. Against such influences, ramie, jute, and kopak fibres are more resistant than other plant fibres [48]. The low resistance of natural fibres, against environmental factors, decisively affects the mechanical properties of the composites (Table 2.06).

Table 2.06: Influence of chemicals on the change of bending strength of sisal-PP composites [50].

Chemicals/Time	Bending Strength (MPa)	Bending Modulus (MPa)
Reference samples	30	1.5
NaOH/50 h	24	1.1
NaOH/500 h	18	1.05
HCL/50 h	20	1.35
HCL/500 h	15	1.4

2.8 Concluding Remarks

As in the case of all natural products, the mechanical and physical properties of natural fibres vary considerably. These properties are determined by the chemical and structural composition, which depend on the fibre type and its growth circumstances. Cellulose, the main component of all natural fibres, varies from fibre to fibre.

The moisture sensibility is remarkable, naturals fibres are easily influenced by environmental effects. Generally speaking, rising moisture content lowers the mechanical properties.

The mechanical properties of composites are influenced by the adhesion between matrix and fibres. As in case of some fibres, the adhesion properties can be changed by pretreating the fibres. So special processing, such as chemical and physical modification methods were developed. Moisture repellency, resistance to environmental effects, and not last, the mechanical properties are improved by these treatments. Various applications of natural fibres as reinforcement in plastics have proved encouraging.

Several natural fibre composites reach the mechanical properties of glass-fibre composites, and they are already applied, e.g. in automobile and furniture industries. Till date, the most important natural fibres are jute, bamboo and coir.

Yet the development of processing and modification methods is not finished. Further improvements can be expected, so that it might become possible to substitute technical-fibres in composites quite generally.

Natural fibres are renewable raw materials and they are recyclable. In recognition of the discussion about recycling and preservation of natural resources, such a substitution seems desirable.

Vacuum assistant technique is necessary in order to make void free composites which increase the mechanical properties of composite.

Chapter 3
EXPERIMENTAL METHODOLOGY AND TESTING

3.1. Introduction

In recent years, the textile industry has developed the knowledge on processing of natural fibres into applicable material for clothing and apparel. Jute, bamboo and coir fibres are for examples which undergo a long series of treatment and refining steps, before they are suitable for the high-demanding and often fashionable textile market. With each step, the fibre properties change significantly in a physical, mechanical and even chemical way. However, when using bast fibres as reinforcement in composite materials a completely different end-use is aimed at and so an adapted processing route is probably needed.

3.2 Materials of jute fibre

Jute fibres that are used in the present studies were collected from Bangladesh Jute Research Institute (BJRI). Jute fibres are prepared from BT tossa, grade of jute and depending on the treatment condition the type are

i) Retted jute
ii) Bleached jute
iii) Woolenized jute

Retted jute simply the water retted that is widely done in many places of Bangladesh. The ponds, lakes, and the rivers are the main areas that are used for this purpose. Different treatment of jute fibres were carried out at BJRI. BJRI provided details information about retted jute and it is available in literature as well. Table 3.01 shows brief information regarding jute fibre types, treatment procedure and place of allocation.

There are five types of woven jute fabric namely-

a) Fine Jute Fabric Natural
b) Food Grade Benolla Twill Bag
c) Hessian Fabric
d) Fine Jute Fabric Full Bleached Stiff, and
e) Carpet Backing Cloth (CBC) Half Bleached.

Table 3.02 shows the type of woven jute along with their respective types, weight per squire meter and nomenclature. Half bleached were obtained from Bangladesh Jute Mills Corporation (BJMC) and the woven fabric that was collected from BJMC was the same treatment as the fibres, and no information about the treatment procedure of the CBC half bleached woven fabric was provided.

Table 3.01: Types of jute fibre.

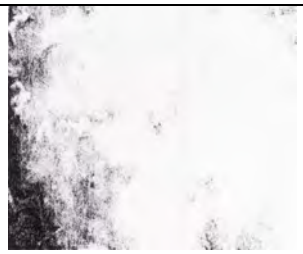
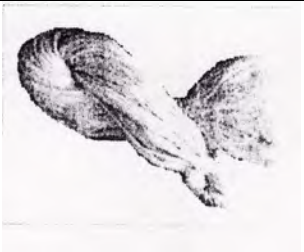
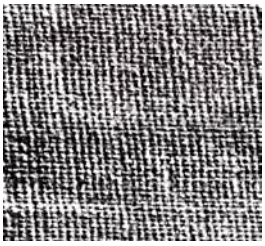
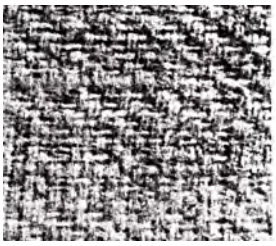
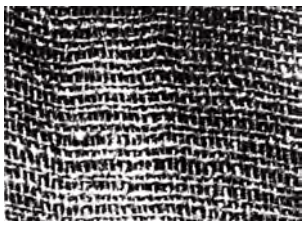
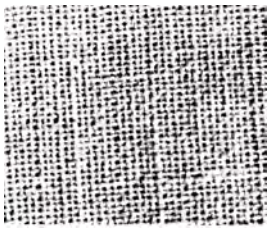
Name of jute fibre	**Treatment**	**Identification**	**Source**	**Pictorial View**
Retted	Simple water retting	ñ**JR**ò implies Jute Retted	BJRI	
Bleached	BJRI specified bleaching procedure	ñ**JRB**ò implies Jute Bleached	BJRI	
Woolenized	BJRI specified woolenization (Alkali treatment procedure)	ñ**JW**ò implies Jute Woolenized	BJRI	

Table 3.02: Identification of woven jute obtains from BJMC.

Name of woven jute fabric	Types/thickness (mm)	Unit weight (gm/m^2)	Nomenclature	Photograph
Fine Jute Fabric Natural	15 x 15 / $inch^2$ 1 mm	260	JRa1	
Food Grade Benolla Twill Bag	Not specified by BJMC å 2 mm	600	JRa2	
Hessian Fabric	Not specified by BJMC å 1 mm	190	JRa3	
Fine Jute Fabric Full Bleached Stiff	15 x 15 / $inch^2$ 1 mm	300	JRBa1	

Carpet Backing Cloth (CBC) Half Bleached	15 x 13 / inch^2 1 mm	335	JRBa2	

3.2.1 Identification of woven jute

It was found that the number of yarn that are needed to weave one square inch of woven fabric is the type of that fabric, e.g. for fine jute fabric natural mat is typed as 12/10 that implies each square inch of the woven jute fabric contains 12 yarn / 10 yarn placing there position 90^0 apart each other forming the fabric. This is shown in Fig. 3.01 where the 12 yarns/inch and 10 yarns/inch are used in warp and weft direction respectively. Jute mat of above configuration was used althrough in the study.

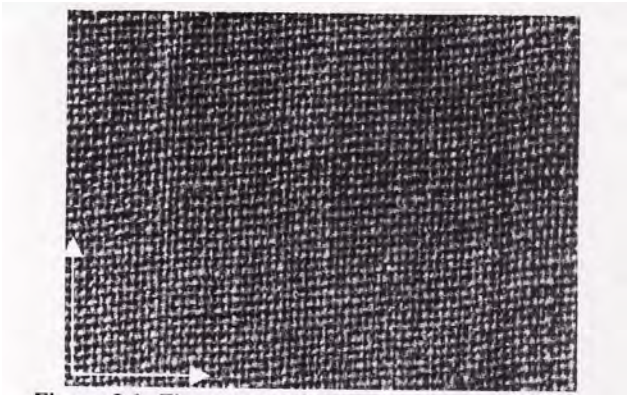


Figure 3.01: Figure represents about woven jute types. Arrows indicate the number of yarn/inch.

For woven jute fabric, grams per square meter were calculated using the following steps:

- Fabrics were cut to a particular length, breadth and with an area of 35/30 cm^2.
- The area of the woven fabric was converted to square meter.
- The weight of the cut piece of the woven fabrics was taken.
- The weight is divided by the calculated area in meter, which gives the unit gram weight of the woven fabrics.

3.3 Materials of bamboo fibre

Bamboo fibres are extracted from the culms of bamboo plants, family of the grasses. The fibres used in this study are extracted by steam explosion out of plants of the *Dendrocalamus membranaceus* species, which is a widely spread bamboo plant in Vietnam. These fibres were supplied by the Hanoi University of Technology, Vietnam.

3.4 Materials of coir fibre

Coir fibre is extracted out of the husk (*mesocarp*) of a coconut, the fruit of a coconut palm (*Cocos nucifera L.*) which is grown extensively in tropical countries. Fibres can be extracted from unripe nuts and are then called ówhite coirô, while óbrown coirô is extracted after ripening of the coconut. The colour of the fibres depends however also on the coconut palm species, the extraction method and eventually the time between retting and extracting. In this study white coir fibres, supplied by the Hanoi University of Technology, Vietnam were extracted only in a mechanical way, without any chemical solution. The brown fibres were kindly supplied by TEX-DEM, but the origin and extraction method of these fibres is not known.

3.5 Determination of density

3.5.1 Method

Density of jute, bamboo & coir fibres is measured by gas pycnometer (GUANTA CHROME) [Fig. 3.02].

3.5.2 Specimen preparation and measurement

In this method the fibers were cut down in small size and weight of sample was measured. It was put in the pycnometer (more than half of cell). Firstly pressure was measured by filled with gas in reference cell of the pycnometer. Secondly pressure was measured after the gas was distributed to the sample cell. Target pressure of reference cell was 17 psi. 15 samples for each fiber were taken for measurement.

Figure 3.02: Gas Pycnometer.

The volume was calculated using the mentioned formula:

V_F Ə V_C - V_R {($\frac{P_1}{P_2}$) ï 1} (Equation 3.01)

Where,

V_F = volume of fibre (cm^3)

V_C = volume of sample cell (cm^3)

V_R = reference volume (cm^3)

P_1 = pressure reading after pressurizing the reference volume.

P_2 = pressure reading after including V_C.

Density is measured using the following formula:

$$Ɉ = \frac{M}{V_F} \qquad \text{(Equation 3.02)}$$

Where,

M = weight of Sample.

V_F = volume of fibre (cm3)

Ɉ = density (g/ cm^3)

3.6 Single fibre testing

3.6.1 Determination of the cross-sectional area

3.6.1.1 Jute fibre

Cross sectional area, A of jute fibres was measured by using the following formula:

$$A = ´.(\frac{d}{2})^2 \qquad \text{(Equation 3.03)}$$

Where, d = diameter.

Diameter of the jute fiber were measured at least three places in between gauge length by using optical microscope [Fig. 3.03].

Figure 3.03: Optical microscope.

3.6.1.2 Bamboo and coir fibres

The cross-sectional area of each fibre was determined by using the density and the weight as well as the fibre length of each fibre using the following equations:

$$\rho = \frac{m}{V} \qquad \text{(Equation 3.04)}$$

Which is equivalent to: $\rho = \frac{m}{A * L}$ (Equation 3.05)

Where,

m = mass

V = volume

A = cross-sectional area

L = length

ρ = density

Therefore, $A = \frac{m}{\rho * L}$ (Equation 3.06)

3.7 Tensile test of single fibre

3.7.1 Method

Tensile properties of Jute, Bamboo and Coir (White and Brown) single fibres were measured by mini tensile testing machine developed in the Department of Metallurgy and Materials Engineering, K.U.Leuven, Belgium [Fig. 3.04]. For the condition of the samples, the fibres remained at least 40 hours in the tensile room before the test. This procedure was adapted by Van De Weyenberg et. al. [89] in order to make better comparisons.

3.7.2 Specimen preparation and measurement

In this process, randomly selected fibres were cut down in a particular length. Weights were taken for bamboo and coir fibres in order to get cross-sectional area. For jute fibre optical microscope was used for measuring diameter. Finally the fibres were glued between two ends of a ñCò shaped paper frame [Figs. 3.05 and 3.06] to conform a good gripping and to straighten it with the test clamps. The paper frame has clamped in the machine at top and at bottom and cut the leg of the ñCò shaped paper frame carefully [Fig. 3.07] before the test starts. Paper frame also offers clamping surfaces with sufficient friction to transfer the load without damaging the fibres and to avoid sliding inside the clamps. Tests were carried out by varying span length of fibers in order to observe its effect on the tensile properties.

In case of bamboo and coir fibers a 200 N loadcell was used with a cross-head speed of 1mm/min and 5 mm/min respectively and for jute fiber a 5 N load cell with cross head speed 0.5 mm/min was used.

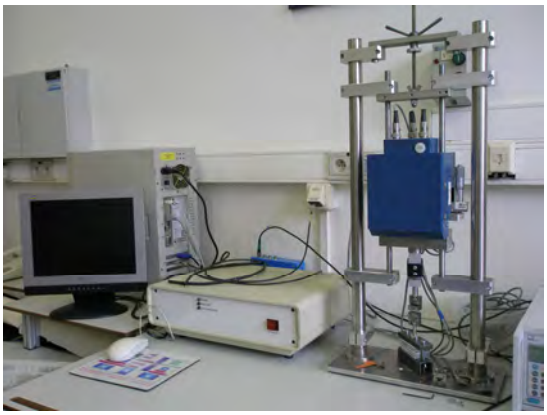


Figure 3.04: Mini Tensile Testing Machine.

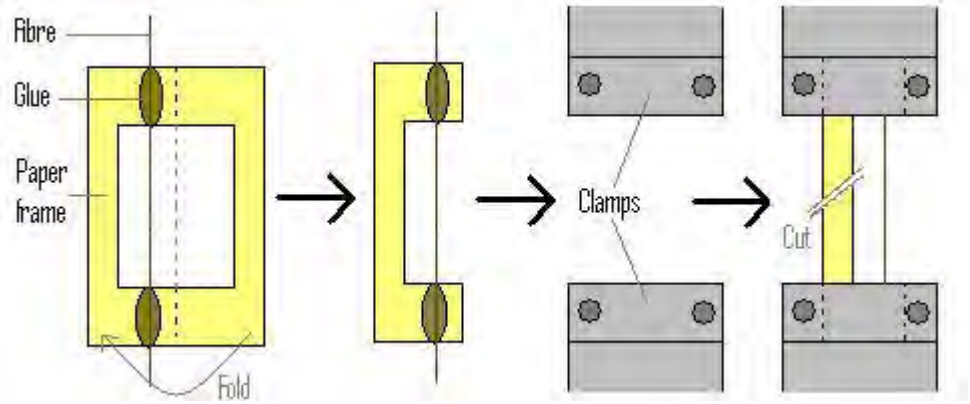


Figure 3.05: Use of a paper frame to put the fibre straight between the screwed clamps (analogous for pinching clamps).

Figure 3.06: Specimen for Tensile Test.

Figure 3.07: Specimen Clamping.

Tensile strength are calculated by following formula:

$$\text{ů} \quad \text{Ə} \quad \frac{F_{max}}{A} \qquad \text{(Equation 3.07)}$$

Where,

ů Ə tensile Strength

F_{max} = maximum force

A = cross-sectional area

As mentioned by Bledski et. al. [90], the longer the stressed distance of the natural fibre is, the more inhomogenities will be in the stressed fibre segment, weakening the structure. Thus strength decreases with increasing clamping length. For the fibre modulus, however, the situation is reverse. Because no extensometer can be used in this set-up and machine displacement is used for the modulus determination, at longer gauge lengths, the relative effect of slippage in the clamps will be smaller.

3.8 Tensile test of woven jute fabrics

3.8.1 Specimen preparation and measurement

In this process, woven jute fabrics were cut into 20 mm in gauge length, 10 mm in width in both cases of the warp and weft direction individually. Crosshead speed was 10 mm/min. and 50 kN loadcell was used during test. Youngôs modulus was measured from the linear region of the slope.

3.8.2 Method

The tensile tests were carried out by following DIN 53455 standard.

3.9 UD epoxy – natural fibre composites

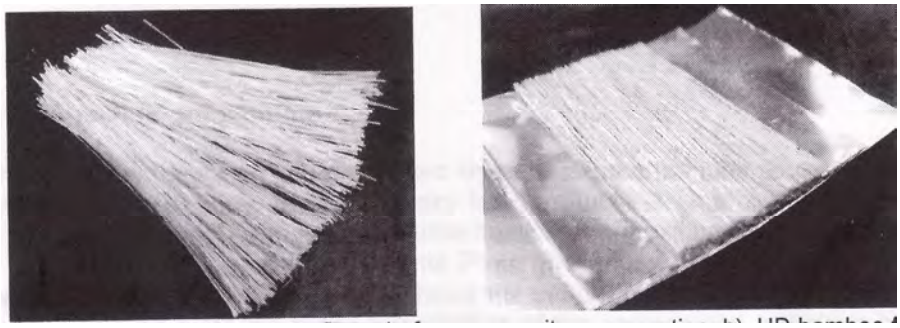
3.9.1 Fibres

The fibres were extracted as described before for the single fibre tensile test (see paragraph 3.2 and 3.3). The fibres were washed in distilled water in order to remove dust and impurities. For the set of experiments no chemical treatment were applied. A selection of the jute and bamboo fibres were done in order to obtain fibre diameter between 39 and 66 εm as well as 178 and 181 εm respectively.

3.9.2 UD jute and bamboo fibres

In order to make UD samples, the fibres should be arranged as parallel as possible. In addition, to get the same fibre volume fraction and hence the same properties within the samples, homogeneous fibre distribution is required. Therefore, the fibres were aligned manually, combed and glued at the ends in order to maintain the fibres aligned during

composite processing [Figs. 3.08.a and 3.08.b]. After assembling the UD mats they were kept in the oven at 70^0C for 1 hour, to prevent moisture absorption.



a. b.

Figure 3.08.a) Selected fibres before composite preparation; **b)** UD fibre samples.

3.9.3 Polymer matrix

3.9.3.1 Epoxy resin

PRIME^{TM} 20LV resin and the same hardener (fast) (100:26 by weight) is used as the resin component, supplied by Gurit (Kassel) GmbH, Germany. This resin is specially designed for use in a variety of resin infusion processes including RTM (Resin Transfer Moulding), SCRIMP^{TM} and RIFT (Resin Infusion under Flexible Tooling). According to the technical information supplied by the company, tensile strength (cured), modulus and densities of this epoxy resin are 68.6 MPa, 2.97 GPa and 1.15 g/cm^3 respectively.

3.9.3.2 Polyester

Terylene polyester resin was used as thermosetting polymer matrix which collected from local market in Bangladesh. Youngôs modulus of polyester resin is 1.5 GPa, tensile strength is (40-90) MPa and density is 1.65 g/cm^3.

3.9.3.3 Polyvinyl chloride

Thin Sheet film made of polyvinylchloride collected from local market name ñSTAEDTLER FILMò was used as polymer matrix component. Measured thickness of the film was 0.12 mm. Tensile strength and Youngôs modulus of the sheet is 41.4 MPa and 0.05 MPa respectively.

3.10 Determination of fibre volume fraction (V_f)

Unidirectional composites of jute and bamboo fibres were made with a fibre volume fraction of approximately 50%. The V_f is determined through weight measurements, assuming jute and bamboo fibres as well as epoxy resin densities of 1.39, 1.46 and 1.15 g/cm^3 respectively. The procedure is the following:

- The desired dimensions of the final composite samples are determined. According to this total volume, the partial volume of the fibres (50%) and matrix (50%) are also calculated.

- For each partial volume (fibre and matrix) the weight is determined taking into account the density of the components. Equation 3.04 is used:

$$m = V \times \rho \qquad \text{(Equation 3.08)}$$

Where,

m = mass of the component (matrix or fibre)

V = corresponding volume of the component

ρ = density of the component

- Then, the components are weighed and spread as uniformly as possible into the mould taking into account that for the UD mats, the jute and bamboo fibre bundles

should stay parallel to each other. In order to obtain volume fractions and properties as homogeneous as possible. Since, this is a manual operation, it is impossible to avoid some deviations in the alignment of the fibres; in this case these small deviations were maximum 8 degrees approximately for some fibres.

Finally, the fibre volume fraction was measured after prepared composites by using the following equation:

$$V_f = \frac{\rho_m \times W_f}{\rho_f \times W_m + \rho_m \times W_f} \qquad \text{(Equation 3.09)}$$

Where, V_f = Fibre Volume Fraction

W_f = Weight of fibre

W_m = Weight of matrix

ρ_f = Density of fibre

ρ_m = Density of matrix

3.11 Composite preparation

3.11.1 UD composite preparation (vacuum technique)

Using as defined stacking sequence (eight layers of aligned jute and six layers of bamboo fibres were arranged) across the aluminium plate. Upper side of the aligned fibres were covered by peel ply paper. A thick plexi glass sheet was used on the upper side to prevent rough surface of the composite. Finally the aligned fibres were surrounded by polypropylene sheet using tacky tape to make sure that there is no air flow [Fig. 3.09]. After that one side of the mould system was added with air vacuum machine and another side was doped in resin bath (mixed with hardener) with using

teflon tube. Void was removed from resin mixture using vacuum desiccator. Liquid resins are pumped into the system through the tube, infiltrate the fibres and consequently filled the mould cavity. When the mould filled up with resin, then the resin supply is suspended. Both resin and air vacuum tube was sealed and then processed in the Pinette press (hot press) [Fig. 3.10] in order to get desired thickness (2 mm thick aluminium bar was used on both edges of aligned fibres). Heat was applied (65^0 C for 1 hour) to cure of the resin. When the resin becomes completely cured, the composite was removed.

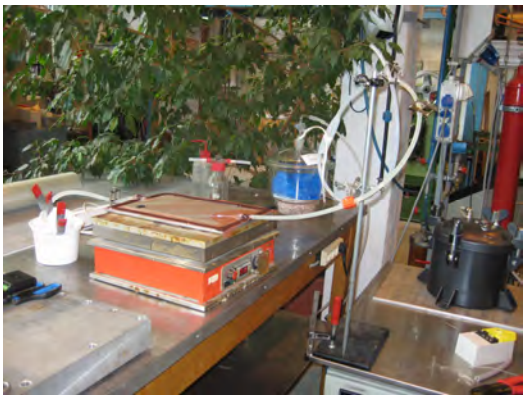


Figure 3.09: Resin Infusion Mould (Vacuum Technique).

Figure 3.10: Pinette press (hot press).

3.11.2 RTM (Resin Transfer Moulding) method

Resin Transfer Moulding (RTM) is a closed-mould process to manufacture fibre reinforced polymer matrix composites. In this process, first a dry woven jute fabric (the reinforcement) was placed into the mould cavity [Fig. 3.11]. Then the mould was closed and the epoxy resin was injected into the mould with low pressure (up to 7 bar, which was assisted by a vacuum). A flat 500 x 300 mm mould was used with a transparent top mould and with adjustable thickness and a hemispherical mould of 200 mm diameter. The transparent top of the flat mould allowed the visual measurement of the flow front advancement. When the woven jute fabrics were fully impregnated the injection port was closed and resin was allowed to cure (65^0C for 1 hour). When resin was cured the part was demoulded.

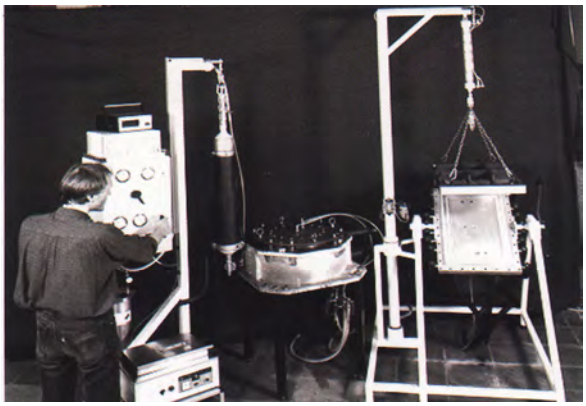


Figure 3.11: Resin Transfer Moulding (RTM).

3.11.3 Compression moulding (hot press) method

Firstly the woven jute fabrics were washed by distilled water and then preheated in an oven at 70^0C for 12 hours. The woven jute fabrics (4 ply) and Polypropylene sheet (8 sheet) (thickness was 100 εm per PP sheet) that set-up by Fig. 3.12 were immediately transferred to the compression moulding (Pinette press) under an automatic moulding

programme at 20 bar (2 MPa) pressure and 190^0C moulding temperature [Fig. 3.10]. The materials were pressed for 10 minutes and consolidated by cooling under the same pressure.

Figure 3.12: Polypropylene and PVC sheet stacking with woven jute fabrics.

In case of woven jute-polyester composites, 1 % calcium carbonate as a filler, 1 % dimethylketone peroxide (DMKPO) as an initiator was mixed all together with polyester. Then degassing using desiccator with the help of vacuum pump to ensure there is no bubble remaining. Pressure, temperature and time period was 180 kN and 110^0C and 10 minutes respectively.

3.12 Composite testing

3.12.1 Tensile properties

3.12.1.1 Method

The tensile properties of woven jute polymer composites were carried out by Instron 4505 machine [Fig. 3.13]. ASTM D 3039/D 3039M-00 standard was followed during tensile testing.

3.12.1.2 Specimen preparation and measurement

In this process the composite were cut down in 250 mm of length [Gauge length 150 mm and Grip (50+50 mm)] and 25 mm in width. Specimen was put on the gauges fixed with sand paper [Fig. 3.14]. Extensometer was put on the middle of the specimen. At least five samples were tested for each specimen. Loadcell used for test was 30 kN.

Tensile Strength was measured using the following equation:

$$\text{ů} \quad \text{Ə} \quad \frac{Load}{Width \times Thickness} \qquad \text{(Equation 3.10)}$$

Where, ů = Tensile Strength.

Displacement was directly measured by extensometer.

Figure 3.13: Instron machine (Model 4505).

Figure 3.14: Tensile test.

3.12.2 Three point bending test (3PBT)

3.12.2.1 Method

Three point bending tests (3PBT) of the composites were carried out by following ASTM D790-03 standard method.

3.12.2.2 Specimen preparation and measurement

Flexural three point bending tests (3PBT), both with a longitudinal and transversal UD composites and woven jute fabric composites as shown in Figs. 3.15a, 3.15b and 3.16 respectively, were performed on a universal testing machine (Instron 4426) [Fig. 3.17] based on the ASTM D790M: ñStandard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materialsò.

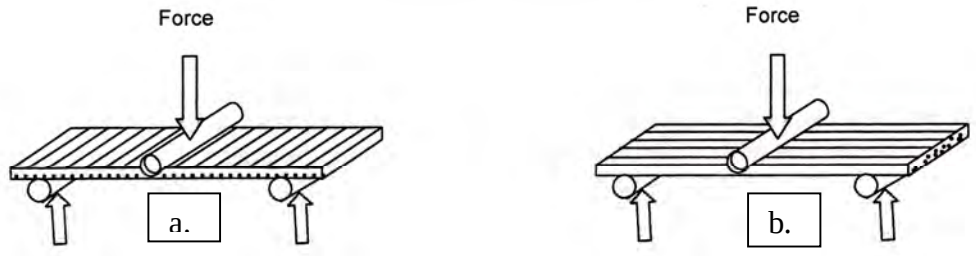


Figure 3.15.a) 3PBT with transverse distribution of the fibres. **b)** 3PBT with longitudinal distribution of the fibres.

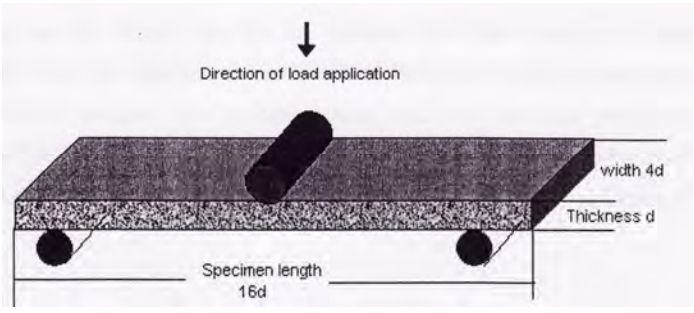


Figure 3.16: 3PBT set-up for woven jute composites.

The dimensions of the samples are shown in Table 3.03. After cutting, all the samples were dried in a vacuum woven at 60^0C during 24 hours and then they were left in the tensile testing room 72 hours before testing to assure a good conditioning.

Table3.03: Dimensions of the fibres-epoxy composite sample for 3PBT.

Distribution of the fibre	**Span Length (L) (mm)**	**Width (mm)**	**Thickness (d) (mm)**	**L/d**
Longitudinal	35	11.8 ± 0.3	2.05 ± 0.07	å 17
Transversal	35	5.10 ± 0.2	2.05 ± 0.07	å 17
Bidirectional	16d	12.7± 0.3		å 17

The relation between the length and thickness (L/d) is big enough (more than 16) to ensure a tensile failure at the bottom of the specimen reducing the probability to have a shear failure during the test.

Bending tests in the fibre direction (longitudinally) give mechanical properties that are fibre dominated. This test shows the performance of the composite it allows to determine if the fibres are reinforcing the polymer properly.

The transversal distribution of fibres in the composites is chosen with the purpose to evaluate the adhesion between the fibres. For this reason the bending strength in this configuration is an indirect measurement of the interface strength between fibres and matrix.

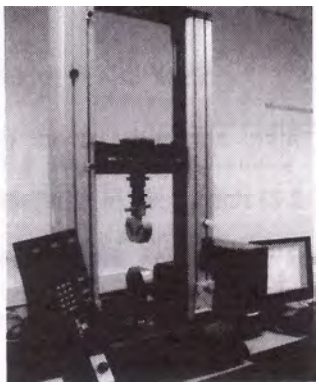


Figure 3.17: Instron machine (4426). Laboratory of composites at K.U.Leuven, Belgium.

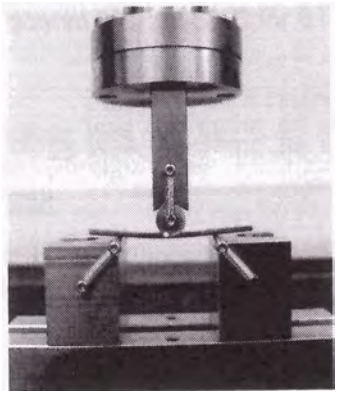


Figure 3.18: Configuration of 3 point bending test for woven jute-polyester composites.

The maximum stress (MPa) in three point bending (σ_{3PB}) is calculated using equation 3.11, where ‘F’ is the recorded force (N), ‘L’ is the span length (mm), ‘w’ is the specimen width (mm) and ‘t’ is the specimen thickness (mm). The strain (%) was determined using equation 3.12, where ‘D’ is the flexural displacement (mm),‘t’ is the specimen thickness (mm) and ‘L’ is the gauge length (mm).

$$\sigma_{3PB} = \frac{3FL}{2wt^2} \qquad \text{(Equation 3.11)}$$

$$\varepsilon_{3PB} = \frac{6Dt}{L^2} \qquad \text{(Equation 3.12)}$$

The bending modulus of each sample was determined by calculating the slope of the stress-strain curve at a very low load in the initial linear region.

$$E_B = \frac{L^3 m}{4wt^3} \qquad \text{(Equation 3.13)}$$

Where, E_B = modulus of elasticity in bending, (MPa)

L = support span, (mm)

w = width of beam tasted, (mm)

t = thickness of beam tasted, (mm)

m = slope of the tangent to the initial straight-line portion of the load-deflection curve, (N/mm)

Interlaminar Shear Stress (ILSS) can be calculated for laminated composites by using the following formula:

$$\text{ILSS} = \frac{0.75 \times F}{w \times t} \qquad \text{(Equation 3.14)}$$

Where, F is the maximum load (N), ówô and ątô are width and thickness respectively.

At least five samples were tested in each configuration. The temperature and relative humidity was approximately 20^0C and 50% respectively. The crosshead speed was set at 0.85 mm/min. and 50 kN loadcell was used during the test. The load and the flexural displacement are registered during the complete test. The bending test set-up is shown in Fig. 3.18.

3.12.3 Impact test

3.12.3.1 Method

Impact tests were conducted on notched composite specimens according to ASTM D 6110-97 using a universal impact testing machine.

3.12.3.2 Specimen preparation and measurement

The dimension of the specimen was 60 mm x 12.7 mm x Thickness (mm).

Impact strength is calculated in the following equation:

$$\text{Impact strength} = \frac{impact(J)*1000}{width(mm)*thichness(mm)} \text{ kJ/m}^2 \quad \text{(Equation 3.15)}$$

3.12.4 Water absorption test

3.12.4.1 Method

In order to determine water absorption test, ASTM D-570 were followed.

3.12.4.2 Specimen preparation and measurement

Water absorption is used to determine the amount of water absorbed under specified conditions. Factors affecting water absorption include: type of plastic, additives used, temperature and length of exposure.

The test specimens (3 inch/1 inch) were cut from the molded composite sheets. All samples edges of the samples were sealed with gel coat (usually polyester resin). Samples were dried for 24 hours at 50^0C and then placed in a desiccator to cool. Immediately upon cooling, the specimens are weighted. Conditioned samples were then immersed in distilled water at room temperature. Samples were periodically taken out from the water (1.5 hour, 24 hours, 48 hours, 96 hours, 168 hours, 216 hours and 576 hours respectively), surface water was wiped off with tissue paper and weighted and were re-immersed in distilled water immediately.

Water absorption is expressed as increased in weight percent are as in the following equation:

$$\% \text{ Water absorption} = \frac{W_f - W_i}{W_i} \times 100 \qquad \text{(Equation 3.16)}$$

Where,

W_f = final weight (after absorption)

W_i = initial weight (before absorption)

3.13 Scanning Electron Microscopy (SEM)

Environmental Scanning Electron Microscope (ESEM) [Fig. 3.19] was used in order to observe the surface of longitudinal single fibre and its cross-sectional area of single jute, bamboo and coir fibre.

Figure 3.19: Environmental Scanning Electron Microscopy (ESEM).

In this study, Scanning Electron Microscope (SEM) was also used to characterize the fracture surface, crack profile of woven jute fabrics composites. For all of the works, 10 KeV source for imaging was used. In order to assess the fracture behaviour of the composite specimens, characterization of small portion of fracture face of specimen were placed in a Scanning Electron Microscope (SEM) (Model No. XL-30, SL No.-

D1276, Philips, The Netherlands). A vacuum unit sputters coater (Model No. - B7341, SL No.- A1934, Belgium) was implemented to deposit a thin metallic layer of gold of 70nm thickness on the fracture surface. The reason of depositing such amount of gold is that when natural materials are examined with SEM, damage from electron beam may occur. In order to avoid this problem, the operating voltage was kept constant and a thick layer of gold was deposited. [Zafeiropoulos, 2002].

3.14 Thermo Gravimetric Analysis (TGA)

Carefully selected jute fibres were cut into 2 ï 3 mm length and it was oven dried for some hours and then it was put into a small crucible (about 2 ï 3 mg) and then Thermo Gravimetric Analysis were carried out with the process parameter set for this process.

Figure 3.20: SDT (Simultaneous DSC and TGA) Q600 T.A Instruments.

Fig. 3.20 shows Thermo Gravimetric Analysis (TGA) machine (SDT Q600 T.A Instrument) under nitrogen atmosphere for jute, bamboo, brown coir and white coir fibre with untreated conditions.

Chapter 4
RESULTS AND DISCUSSION

4.1 Density of natural fibres

The measured densities of jute, bamboo and coir (brown and white) fibres are mentioned in the Table 4.01. Three measurements are taken for each case. The values are quite compatible with the values found in literature. Among these brown coir fibres have reported the lowest values. The bamboo fibres are denser than jute and coir fibres. In case of coir fibre white coir fibre has shown the higher value than brown one [Table 4.01].

Table 4.01: Density of natural fibres measured by Gas Pycnometer.

Fibre species		**Measured density (g/cm^3) ± STD**	**Literature density (g/cm^3)**	**References**
Jute		1.39±0.05	1.3-1.45	[52,53]
Bamboo		1.46±0.02	0.6-1.4	[54,55]
Coir	Brown	1.00±0.02	1.15-1.25	[56 - 58]
	White	1.18±0.07		

4.2 Tensile properties of single fibres

The values for tensile strength, Youngôs modulus and strain to failure of jute, bamboo, brown coir and white coir fibres are shown in table 4.02, 4.03, 4.04 and 4.05 respectively. Tables also contain corrected Youngôs modulus and strain to failure which were obtained by using formula adopted by some newly developed equations (equations 4.01 - 4.05 respectively).

The stress/strain curves of jute [Fig. 4.01] and bamboo fibres [Fig. 4.02] have similar trends. i.e. show a linear elastic region followed by brittle failure with almost no plastic deformation. For stress/strain curves, both brown and white coir fibres [Figs. 4.03 and 4.04 respectively] have smaller elastic region with large plastic regions and strain to failures are almost 10 to 15 times higher than that are jute and bamboo fibres.

Table 4.02: Properties of uncorrected and corrected jute fibres.

Span length (mm)	**Diameter (µm) ± STD**	**Tensile strength (MPa) ± STD**	**Uncorrected Young's modulus (GPa) ± STD**	**Corrected Young's modulus (GPa) ± STD**	**Uncorrected strain to failure (%) ± STD**	**Corrected strain to failure (%) ± STD**
5	55 ±11	414 ±183	8.68 ± 3.05	29 ± 5.34	4.93 ± 1.15	1.51±0.79
10	53 ± 9	399 ± 100	14.43 ± 3.85	29.75± 9.82	2.93 ± 0.73	1.49±0.39
15	54 ± 9	361 ± 159	17.95 ± 5.5	27.22± 8.37	2.14 ± 0.69	1.37±0.47
25	52 ± 10	341 ± 104	21.68 ± 5.47	26.44± 6.08	1.58 ± 0.21	1.29±0.18
35	51 ± 12	331 ± 116	27.3 ± 8.51	29.73± 8.81	1.22 ± 0.36	1.16 ± 0.34
Average	**52.80±10. 39**			**28.80± 9.51**		

Table 4.03: Properties of uncorrected and corrected bamboo fibres.

Span length (mm)	**Diameter (µm) ± STD**	**Tensile strength (MPa) ± STD**	**Uncorrected Young's modulus (GPa) ± STD**	**Corrected Young's modulus (GPa) ± STD**	**Uncorrected strain to failure (%) ± STD**	**Corrected strain to failure (%) ± STD**
5	342 ± 23	862 ± 131	9.84 ± 2.23	34.33 ± 14.08	7.53 ± 2.39	2.50 ±0.45
15	308 ± 27	810 ± 139	22.68 ± 1.45	36.10 ± 4.03	3.90 ± 0.74	2.46 ±0.53
25	344 ± 37	676± 185	23.75 ± 1.92	30.00± 4.33	3.02 ± 0.91	2.42 ±0.80
35	229 ± 51	615 ± 91	33.36 ± 3.15	41.38± 4.14	2.00 ± 0.72	1.68 ±0.43
Average	**287 ± 72**			**35.52± 8.29**		

Table 4.04: Properties of uncorrected and corrected brown coir fibres.

Span length (mm)	Diameter (µm) ± STD	Tensile strength (MPa) ± STD	Uncorrected Young's modulus (GPa) ± STD	Corrected Young's modulus (GPa) ± STD	Uncorrected strain to failure (%) ± STD	Corrected strain to failure (%) ± STD
5	250 ± 54	222 ± 31	2.00 ± 0.22	3.72 ± 1.08	63.78 ± 4.17	51.64± 15.23
15	201 ± 49	212± 42	2.77 ± 0.32	3.79 ± 0.50	44.99± 10.62	40.36 ± 11.67
25	195 ± 36	194 ± 28	3.67 ± 0.90	3.76 ± 0.85	28.11 ± 5.96	27.33± 6.11
35	225 ± 44	165 ± 21	3.69 ± 0.38	3.90± 0.50	27.04 ± 6.77	27.04 ± 6.34
Average	**218 ± 49**			**3.80± 0.75**		

Table 4.05: Properties of uncorrected and corrected white coir fibres.

Span length (mm)	Diameter (µm) ± STD	Tensile strength (MPa) ± STD	Uncorrected Young's modulus (GPa) ± STD	Corrected Young's modulus (GPa) ± STD	Uncorrected strain to failure (%) ± STD	Corrected strain to failure (%) ± STD
5	181 ± 24	237 ± 54	1.95 ± 0.30	4.28 ±1.41	55 ± 16	48 ± 14
15	187± 38	202 ± 31	3.14 ± 0.61	4.08 ±1.06	33± 7	29 ±9
25	227± 27	195 ± 37	3.40 ± 0.41	3.86± 0.65	31± 6	28.5 ± 6
35	217 ± 29	185 ± 38	3.56 ± 0.65	3.69± 0.72	30± 6	28.30 ± 6
Average	**202 ± 35**			**3.99± 1.00**		

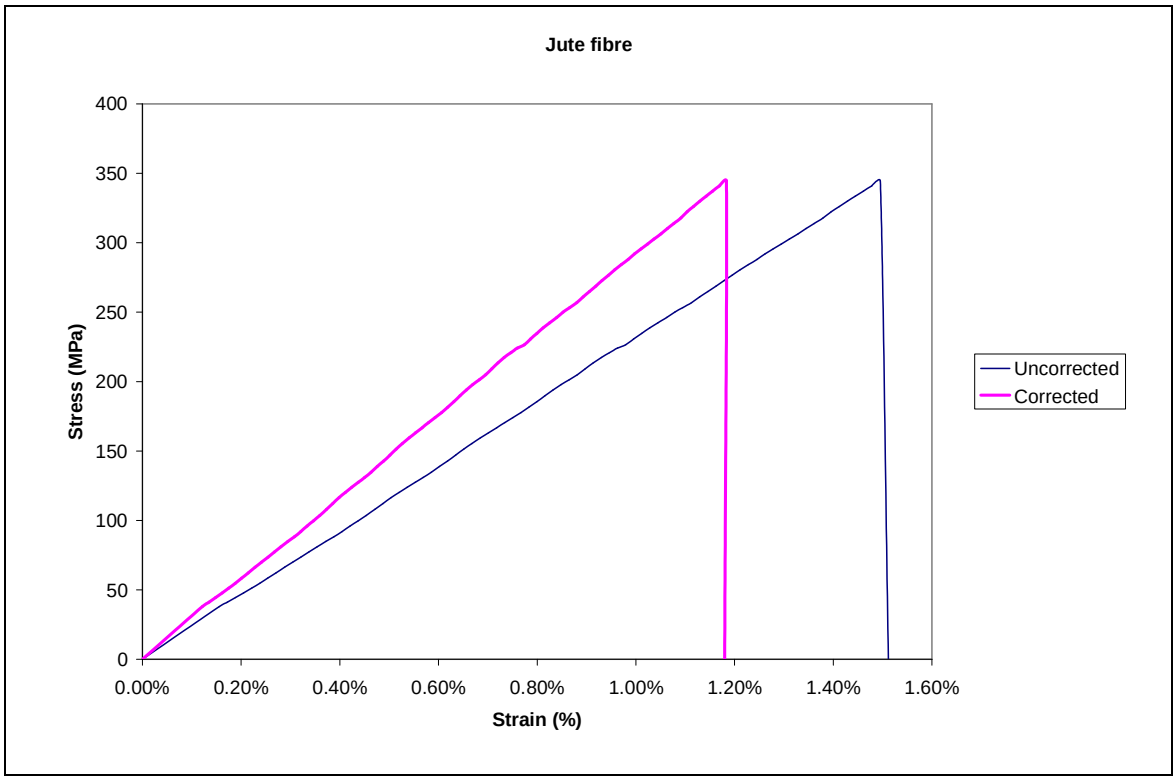


Figure 4.01: Stress-strain curve for jute fibre of 25 mm span length.

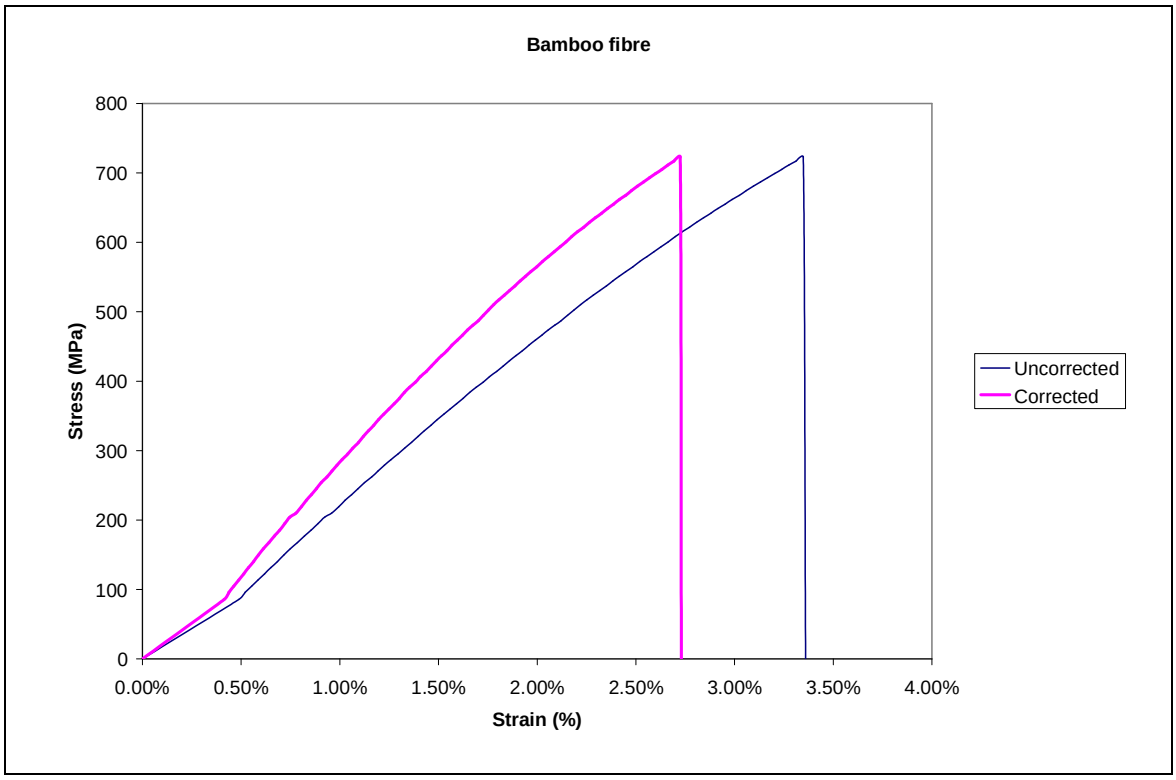


Figure 4.02: Stress-strain curve for bamboo fibre for 25 mm span length.

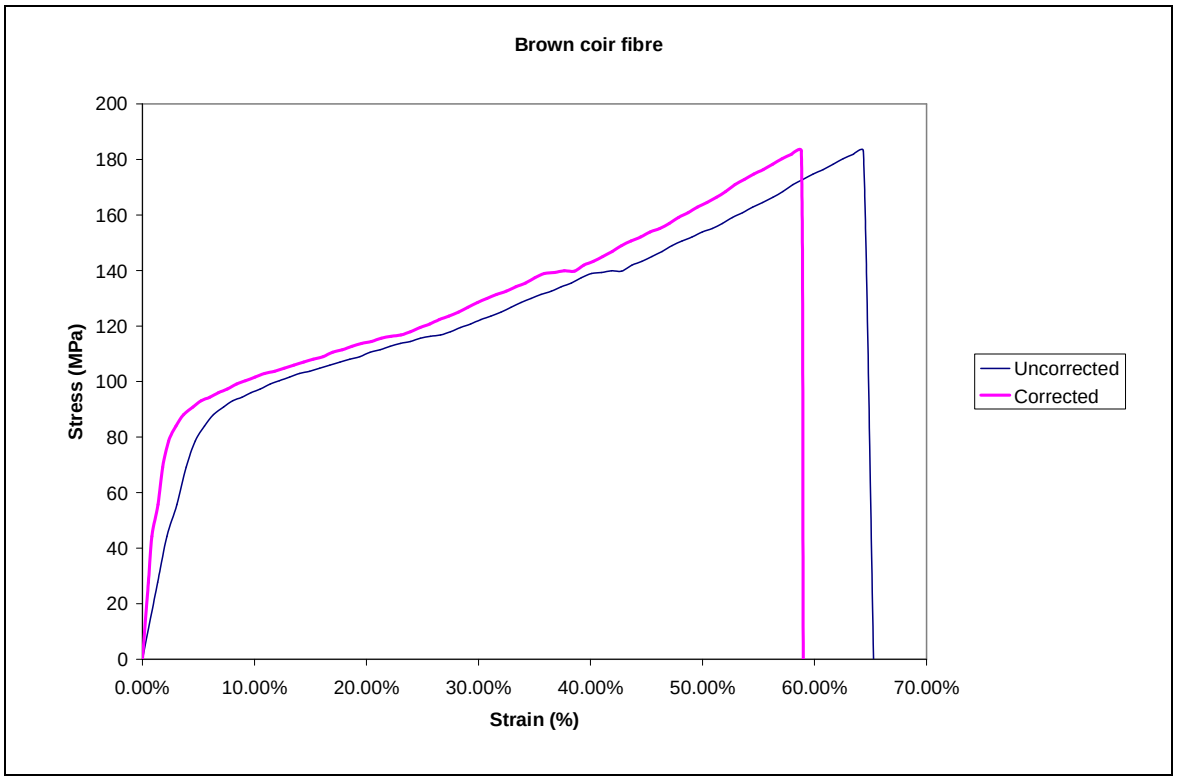


Figure 4.03: Stress-strain curve for brown coir fibre for 5 mm span length.

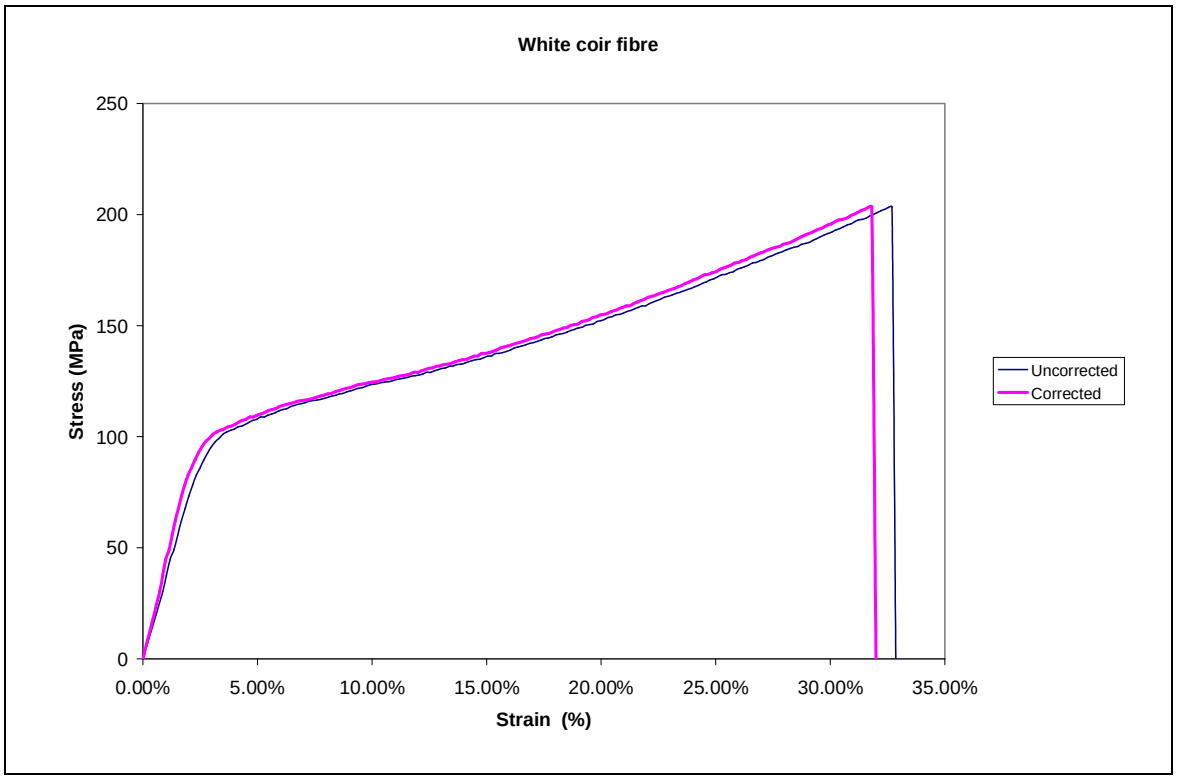


Figure 4.04: Stress-strain curve for white coir fibre for 15 mm span length.

4.2.1 Analysis of tensile strength

Average tensile strength for jute, bamboo, brown and white coir fibres are shown in Figs. 4.05, 4.06, 4.07 and 4.08 respectively. It is clearly observed that tensile strength of all fibres decreased with an increase of span length. This is due to more flaws in longer span length fibres that make the probability of failure larger. Fibres with longer span length have larger surface area which indicates more surface defects as compared to short span length. Detection of flaws can be measured by loop test [L. R. Osorio Serna and T. De Los R. et. al, 2007].

As mentioned by Bledski et. al. [90], the longer the stressed distance of the natural fiber, the more inhomogenities will be in the stressed fibre segment, weakening the structure. Thus strength decreases with increasing clamping length. It is also observed that the standard deviation of 5 mm span length is higher and then following decreasing trend. Because 5 mm span length has affected too much by other testing parameter. i.e. machine displacement where slippage portion of fibre from the grip contributes more incorrect result to 5 mm span length.

Among all fibres, bamboo showed the highest values in tensile strength in the same span length which is mentioned in Table 4.06. This may linked to the quality of fibres where bamboo fibres have highest values. As mentioned in Chapter 2, the presence of kink bands are defects along the length of the fibre, creates weak points of stress concentration reducing the strength of the fibres. Also all the fibres have showed the results in wide range between 5 and 35 mm span length. This may be caused by extracting method as mentioned in chapter 3. Bamboo fibres were extracted by steam explosion method where jute and coir fibres are found by mechanical process. L. R. Osorio Serna et. al. [2004] mentioned that the extraction process highly influences the quality of fibre and, therefore, its mechanical properties.

It is observed that tensile strength of jute fibres are lower than bamboo and higher than coir fibres.

Table 4.06: Tensile strength of natural fibres compare to literature values.

Fibre species	**Average diameter (µm) ± STD**	**Tensile strength (MPa) (5mm to 35 mm span length range) ± STD**	**Tensile strength from Literature (MPa)**	**References**
Jute fibre	53 ± 10	331 ± 116 ï 414 ± 183	393 - 1000	[59,60]
Bamboo fibre	287 ± 72	615 ± 91 ï 862 ± 131	140 - 800	[61,62]
Brown coir fibre	218 ± 49	165 ± 21 ï 222 ± 31	120 - 304	[58,63]
White coir fibre	202 ± 35	185 ± 38 ï 237 ± 54		

The surface quality of the fibres is observed in Figs. 4.09, 4.10, 4.11 and 4.12 respectively. It is clearly observed that jute fibre shows more smooth and compact structure in comparison to bamboo and coir fibres. Bamboo fibre shows rough structure because of its extraction process. In case of coir fibres white fibres seems denser than brown one. It is also observed form Figs. 4.09 - 4.12 that the cracks start from the defect point (flaws) and propagate through the flaws under tensile load which are shown in Figs. 4.09 - 4.12 respectively for jute, bamboo, brown and white coir fibres (after deformation).

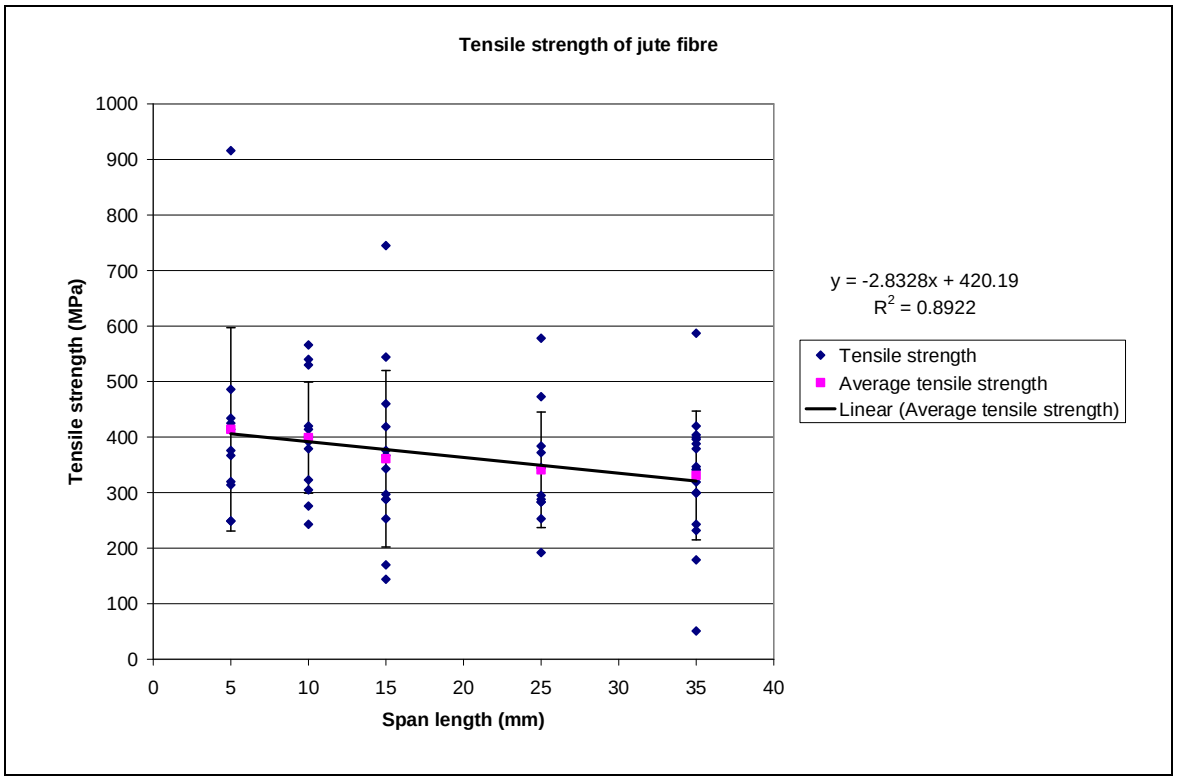


Figure 4.05: Tensile strength of jute fibre as a function of span length.

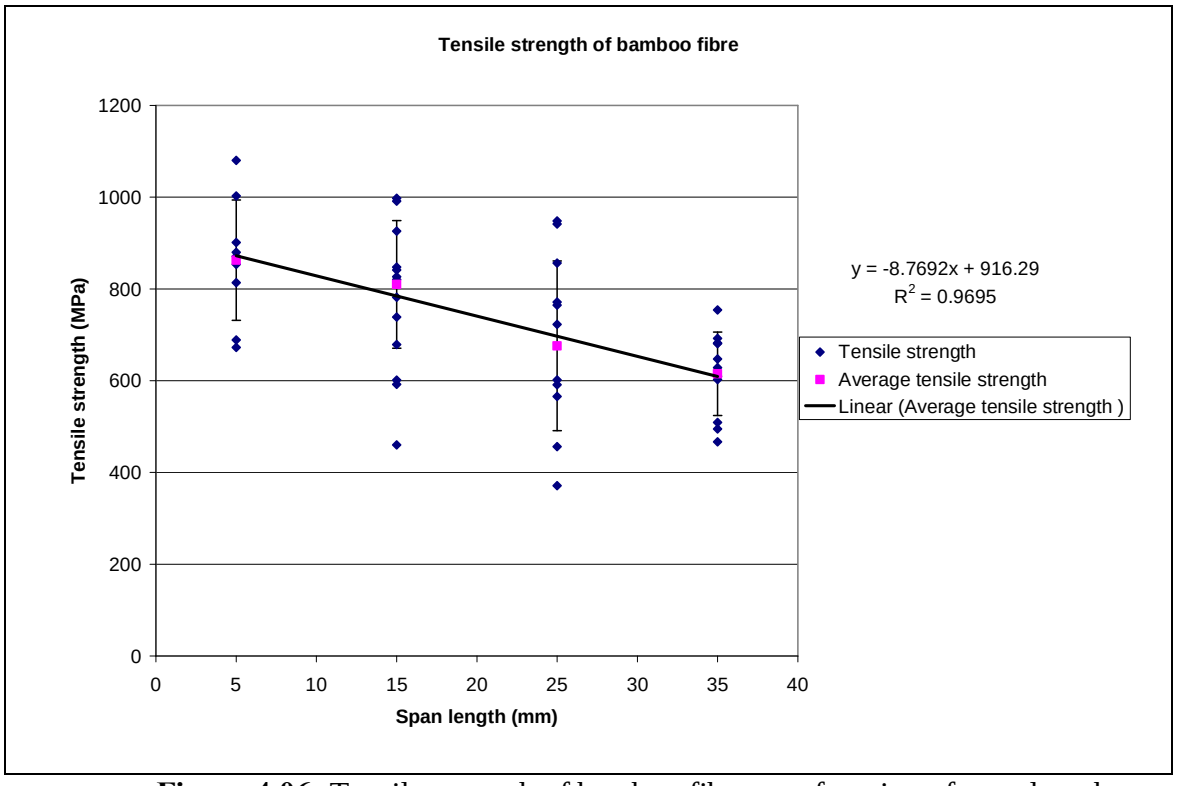


Figure 4.06: Tensile strength of bamboo fibre as a function of span length.

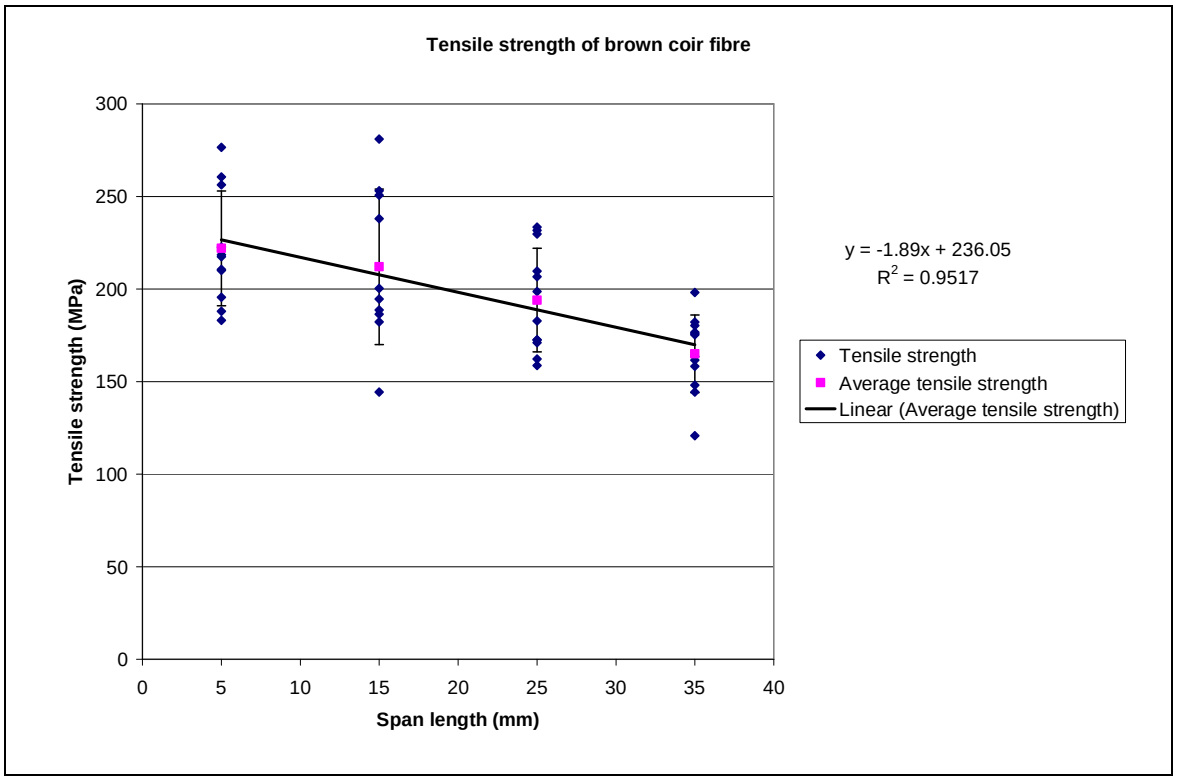


Figure 4.07: Tensile strength of brown coir fibre as a function of span length.

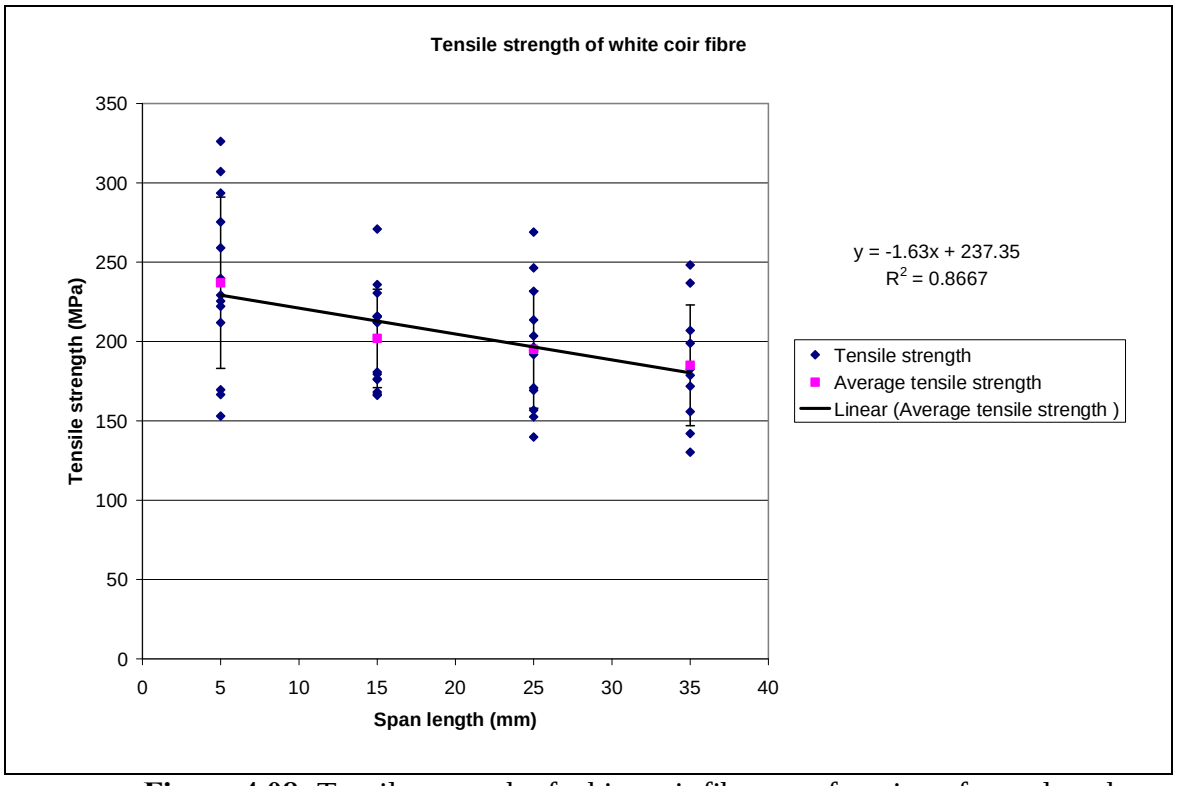


Figure 4.08: Tensile strength of white coir fibre as a function of span length.

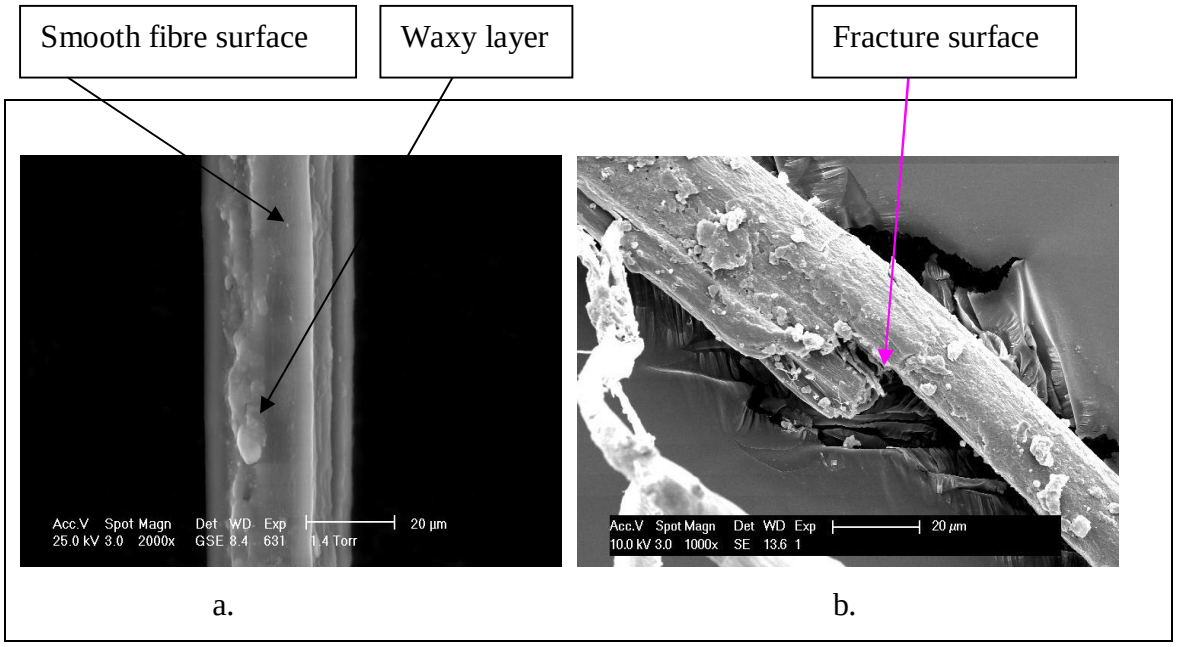


Figure 4.09: ESEM micrographs of jute fibres in longitudinal direction- a) before and b) after tensile test.

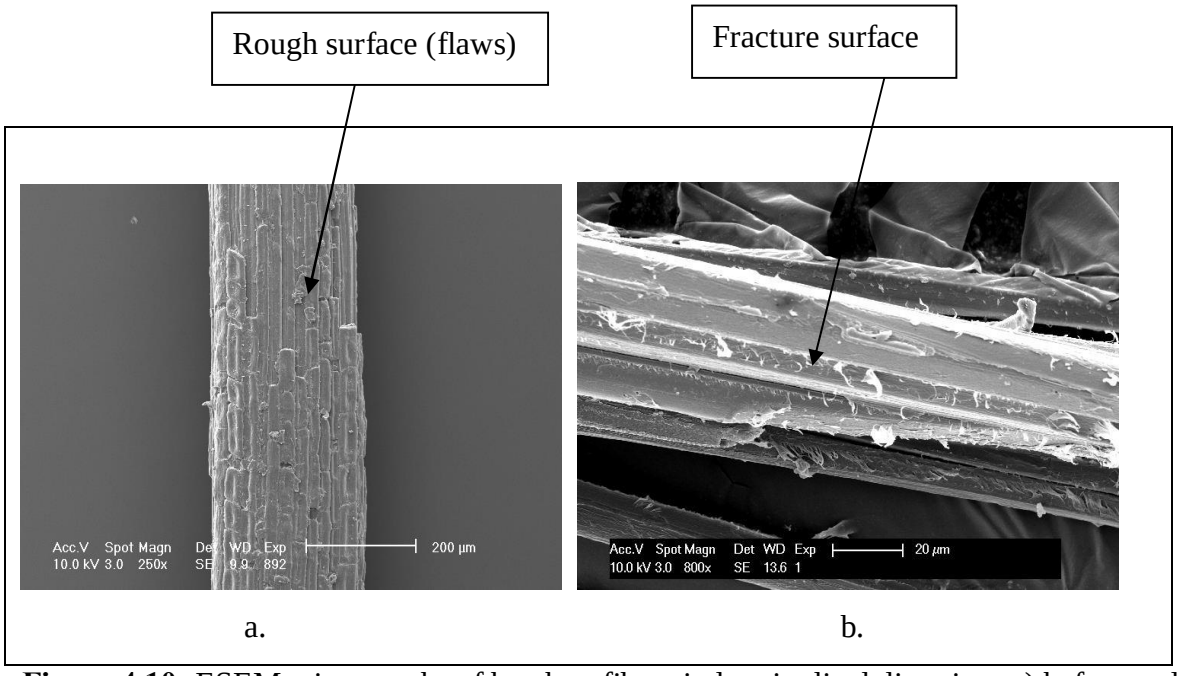


Figure 4.10: ESEM micrographs of bamboo fibres in longitudinal direction- a) before and b) after tensile test.

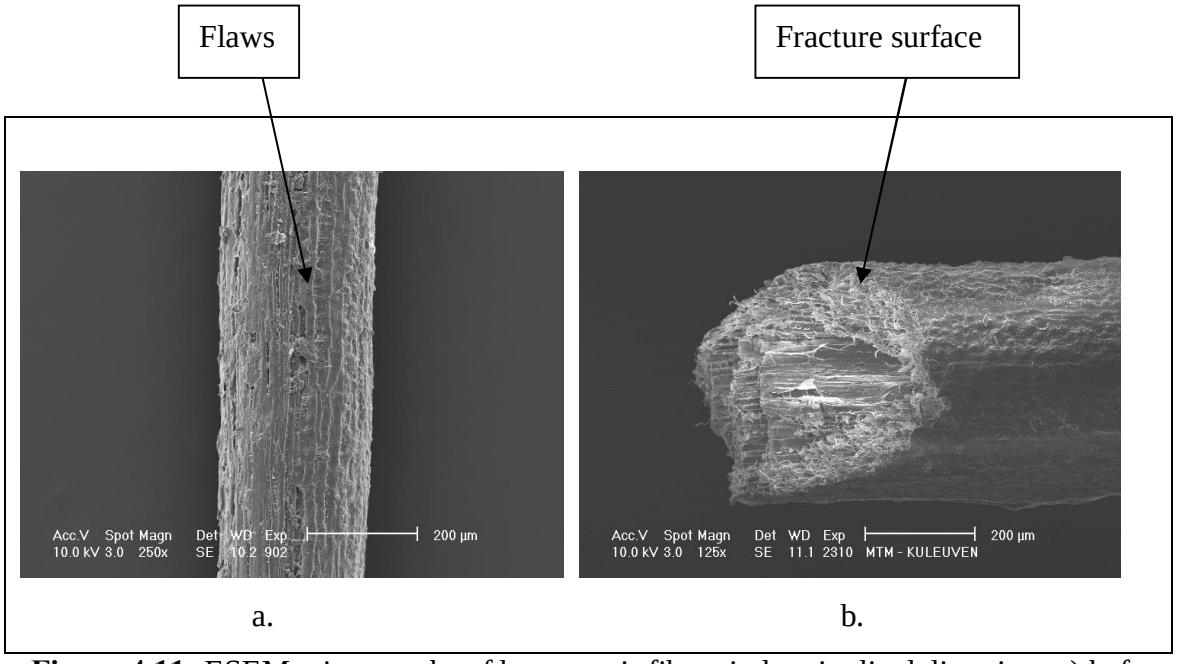


Figure 4.11: ESEM micrographs of brown coir fibres in longitudinal direction- a) before and b) after tensile test.

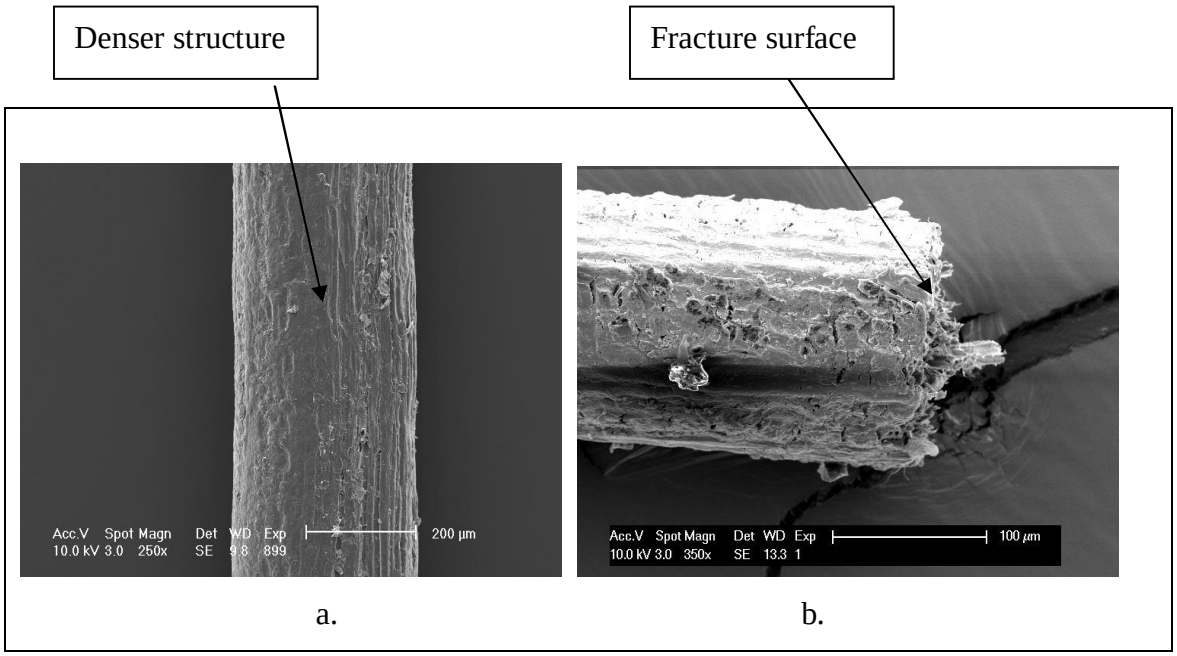


Figure 4.12: ESEM micrographs of white coir fibres in longitudinal direction- a) before and b) after tensile test.

The cross-sectional view of jute, bamboo, brown and white coir fibres are shown in Fig. 4.13. It can be seen that all fibres have porosity in the middle portion of the cross-section. Among all fibres bamboo contains low porosity, where jute and both the coir fibres shown much more porosity. In comparison between jute and coir fibres (both brown and white), it can be observed that jute fibres have small number of porosity, where both brown and white coir fibres shows huge number of porosity. That is why tensile strength of coir fibre has the lowest value as compare to other tested fibres but possess the highest strain to failure.

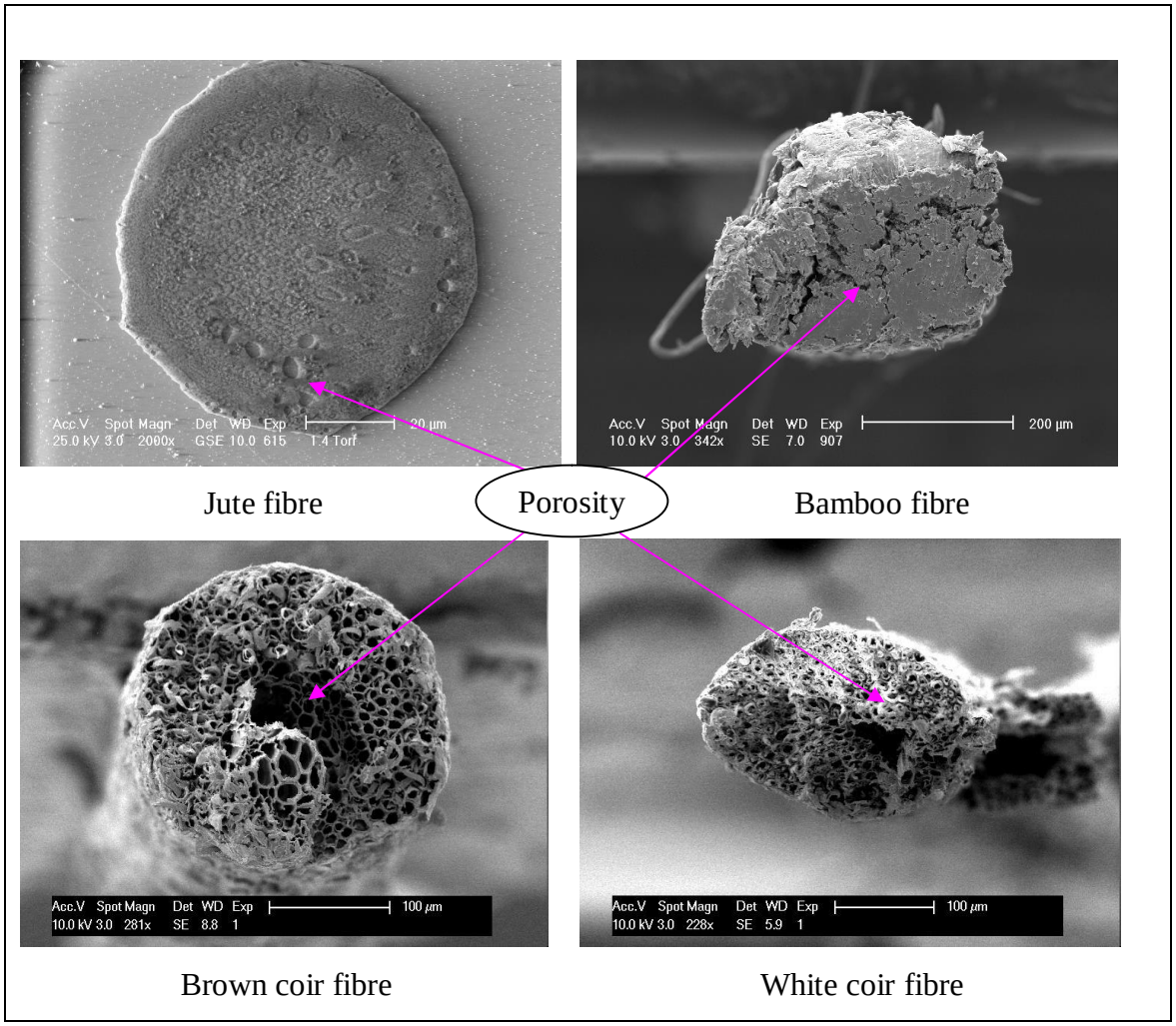


Figure 4.13: ESEM view of jute, bamboo, brown and white coir fibres in cross-sectional direction.

4.2.2 Analysis of Young's modulus

Corrected and uncorrected Youngôs modulus is presented in Figs. 4.18, 4.19, 4.20 and 4.21 respectively. . It is clearly observed from uncorrected curves that with an increase in span length, the Youngôs modulus increased. This is because no extensometer can be used in this test set-up and machine displacement (denoted by Ŭ) is used for the modulus determination. So at longer gauge lengths, the relative effect of slippage in the clamps will be smaller.

The uncorrected extrapolated Youngôs modulus is 26.93, 34.48, 3.86 and 3.78 GPa respectively for jute fibre, bamboo fibre, brown coir fibre and white coir fibre. These values are used for correction method. Alpha values (machine displacement) are calculated for all tested fibres and mentioned in Figs. 4.14 - 4.17 respectively for jute, bamboo, brown coir and white coir fibres accordingly. Line values from these curves are used for the correction.

Figs. 4.14 - 4.17 indicate that alpha value also depend on span length. With increasing span length alpha values decreased slightly. Among all fibres the alpha values of bamboo fibres have showed the lowest. It caused by used thicker diameter which are shown in Table 4.02 - 4.05. Jute fibre showed the highest alpha value (machine displacement) because its diameter is smaller in compared to other fibres.

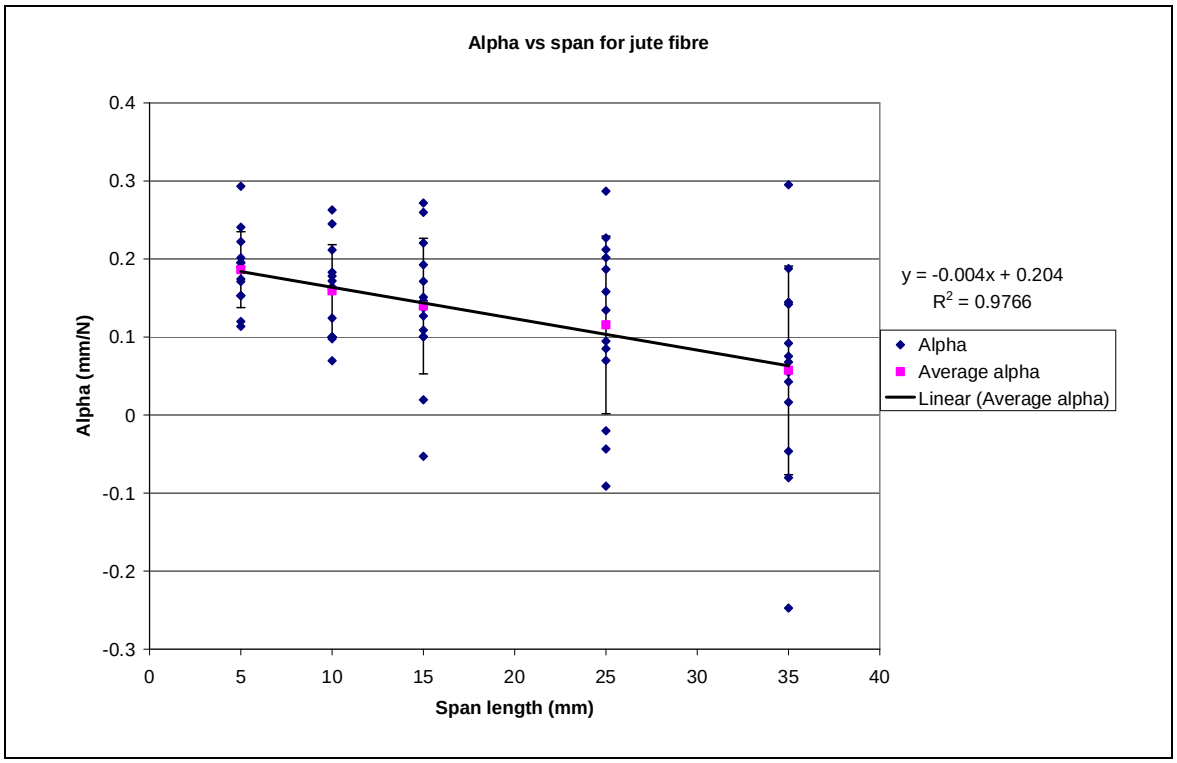


Figure 4.14: Line values of alpha in function of span length for jute fibre.

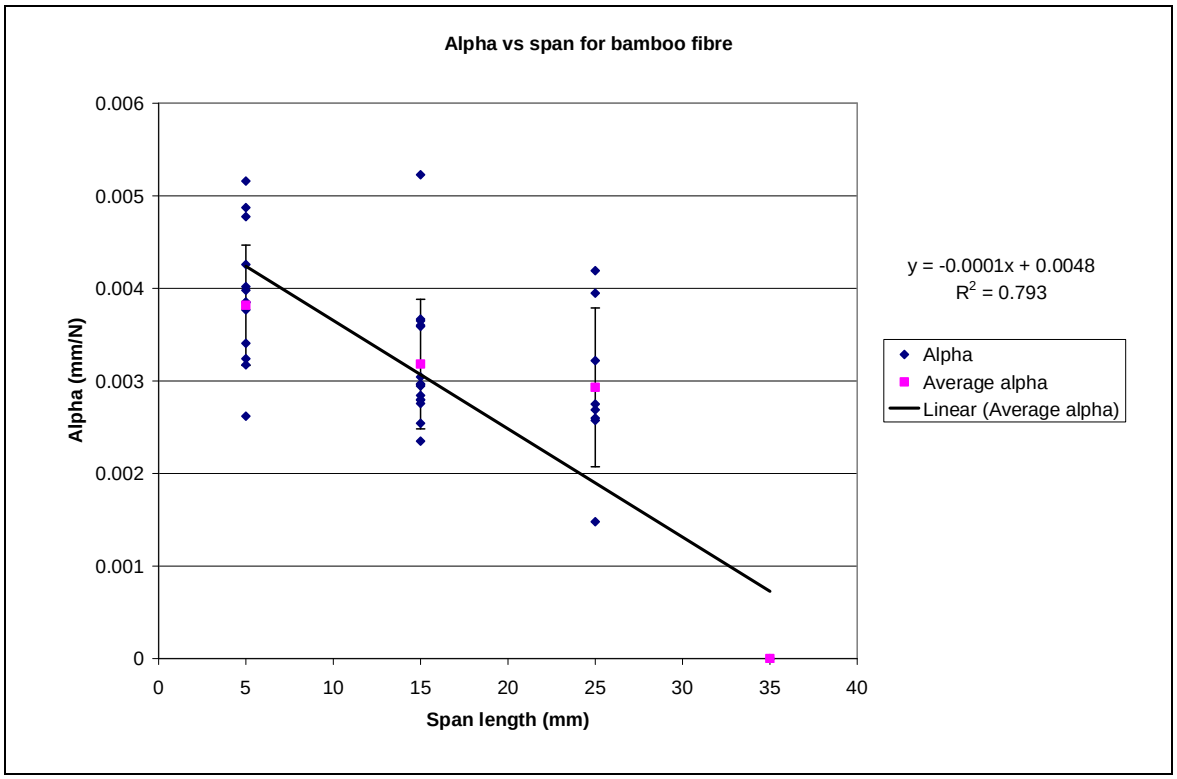


Figure 4.15: Line values of alpha in function of span length for bamboo fibre.

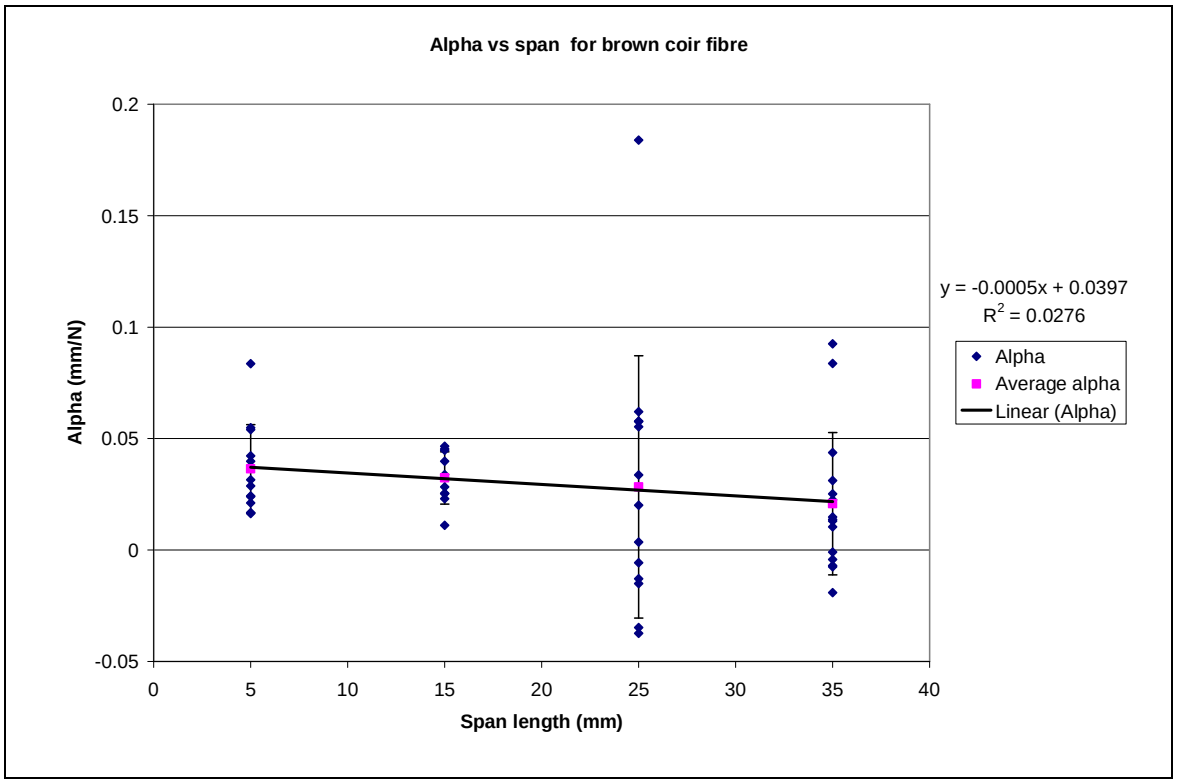


Figure 4.16: Line values of alpha in function of span length for brown coir fibre.

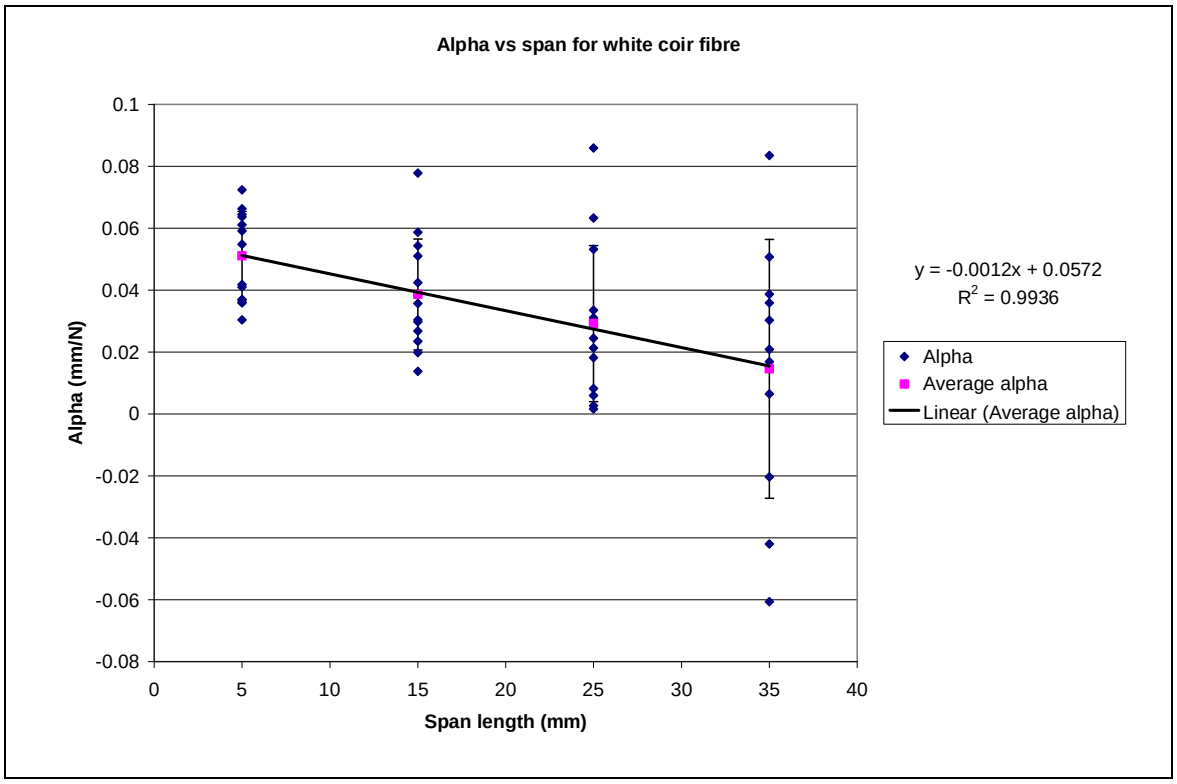


Figure 4.17: Line values of alpha in function of span length for white coir fibre.

Corrected Youngôs modulus and strain to failure are calculated by measured alpha (Ŭ) values and it can be calculated by using the following newly developed equations:

æL $_{total}$ = æL $_{fiber}$ + æL $_{grip}$ (Equation 4.01)

Machine displacement (α) is calculated by using the following newly developed equations [91]-

$$\alpha_i = \frac{\Delta L_{total}}{F} - \frac{L_0}{E_0 \times A_i} \quad \text{(Equation 4.02)}$$

Where,

$$\frac{\Delta L_{total}}{F} = \frac{\varepsilon \times L_0}{\sigma \times A_i} = \frac{1}{E} \times \frac{L_0}{A_i} \quad \text{(Equation 4.03)}$$

α_i = machine displacement for each fibre (e.g.1, 2, 3é é é .)

L_0 = original span length

E_0 = extrapolated Youngôs modulus

A_i = cross-sectional area for each fiber (e.g.1, 2, 3é é é .)

E = Youngôs modulus for each fiber

ε = strain

σ = stress

F = force

Corrected strain to failure has been calculated by using the equation 4.04. Youngôs modulus is calculated from the slope of corrected strain-stress curve.

$$\frac{\Delta L_{fiber}}{L_0}\langle Corrected \rangle = \frac{\Delta L_{total}}{L_0} - \frac{\Delta L_{grip}}{L_0} \quad \text{(Equation 4.04)}$$

Where,

$$\frac{\Delta L_{grip}}{L_0} = \frac{\alpha_l * A_i * \sigma}{L_0} \qquad \text{(Equation 4.05)}$$

α_l = line value of α (average value was taken from every span length). Subsequently the linear trend line was plotted and equation was obtained. The values (for span length 5, 10, 15, 25 and 35) of óxô were put on this equation and finally line value of alpha was obtained)

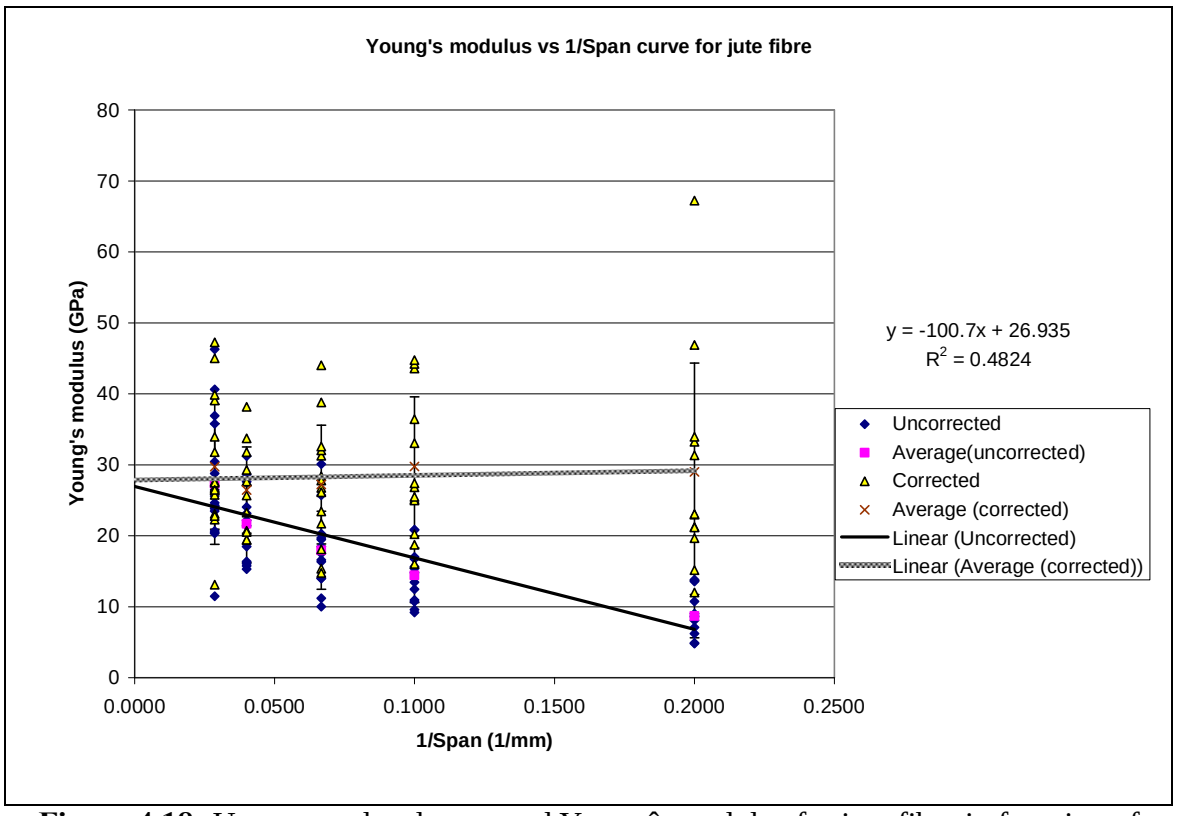


Figure 4.18: Uncorrected and corrected Youngôs modulus for jute fibre in function of span length^{-1}.

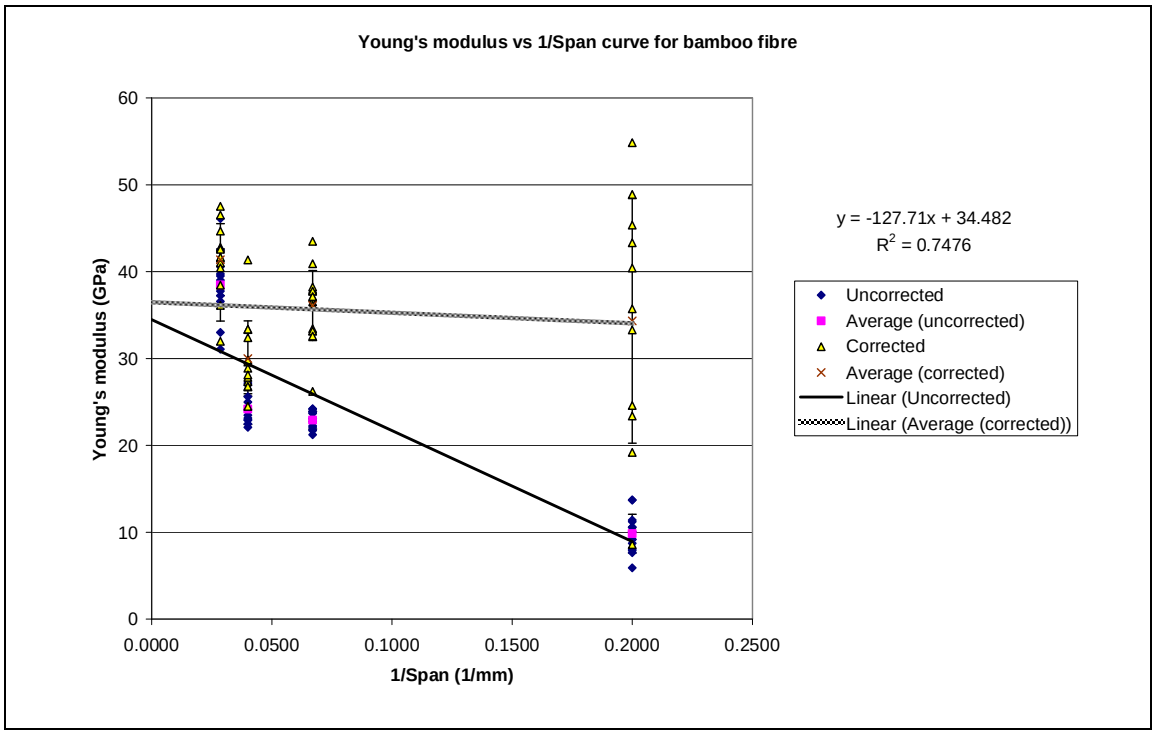


Figure 4.19: Uncorrected and corrected Youngôs modulus for bamboo fibre in function of span length^{-1}.

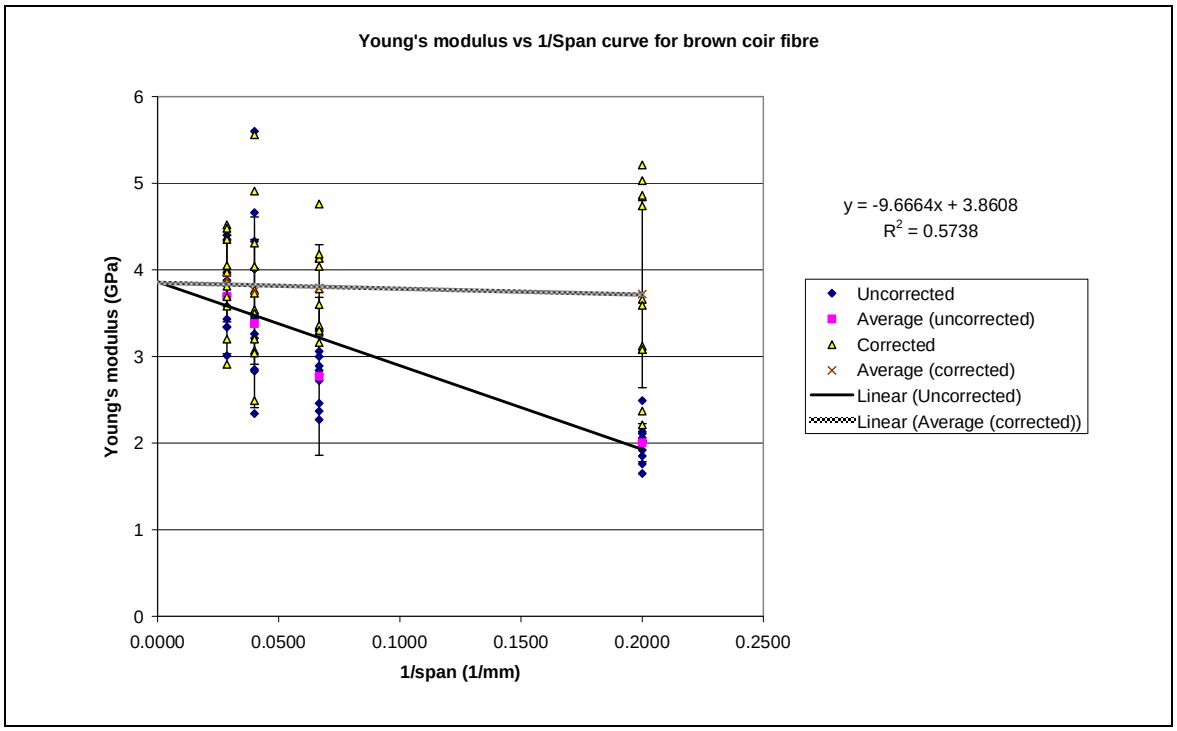


Figure 4.20: Uncorrected and corrected Youngôs modulus for brown coir fibre in function of span length^{-1}.

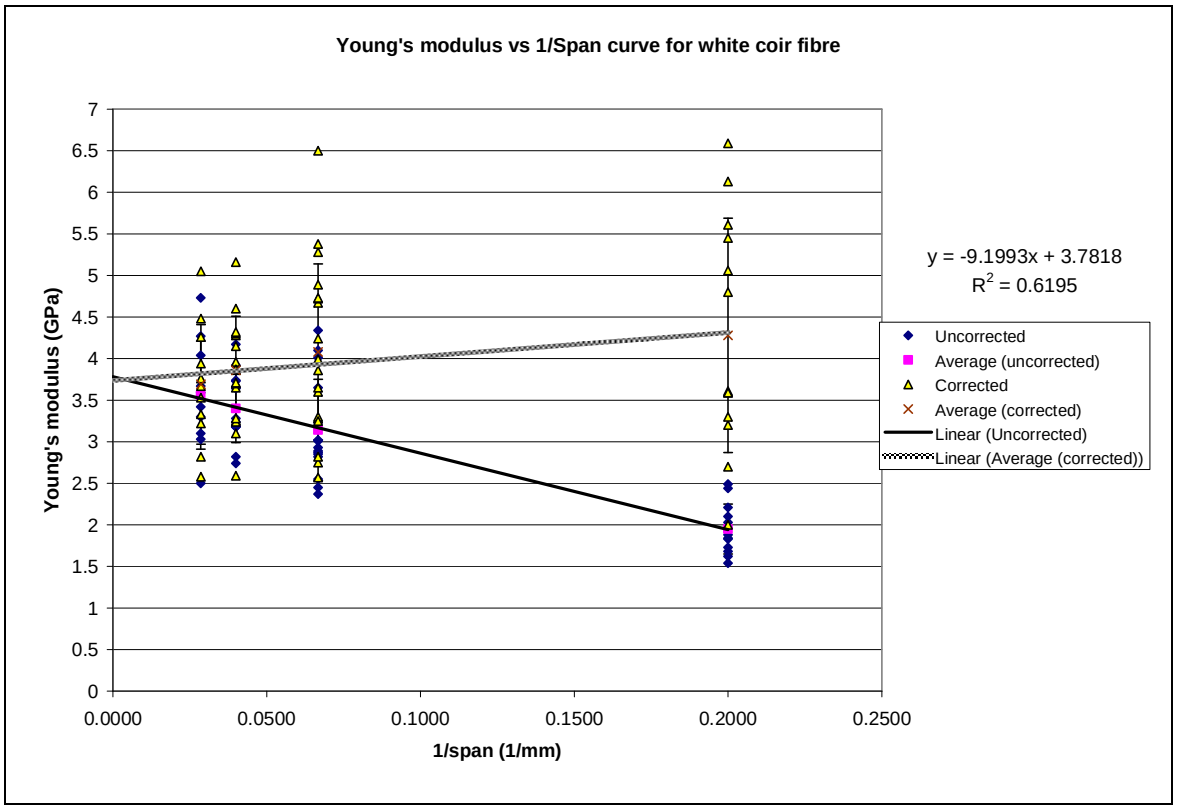


Figure 4.21: Uncorrected and corrected Youngôs modulus for white coir fibre in function of span length^{-1}.

Corrected Youngôs modulus is also shown in Figs. 4.18 - 4.21, while comparison between corrected and uncorrected results is shown in Table 4.07. Average Youngôs modulus of all the test results after correction have found closed to literature values. It is also observed that the larger scattered values are found in 5 mm span, while the smaller scattered values are found for 35 mm span. Again the average Youngôs modulus found is very close to extrapolated (E_0) values after correction by using the mentioned developing equations 4.01 to 4.05.

Table 4.07: Uncorrected and corrected Youngôs modulus of natural fibres compare to literature values.

Fibre species	Uncorrected Young's modulus (GPa) (5 mm to 35 mm span length range) ± STD	Corrected Young's modulus (GPa)	Young's modulus from Literature (GPa)	References
Jute fibre	8.68 ± 3.05 - 27.3 ± 8.51	28.80	13-54	[59,63]
Bamboo fibre	9.84 ± 2.23 ï 33.36 ± 3.15	35.52	11-30	[61,62]
Brown coir fibre	2.00 ± 0.22 ï 3.69 ± 0.38	3.80	4-6	[64,65]
White coir fibre	1.95 ± 0.30 ï 3.56 ± 0.65	3.99		

4.2.3 Analysis of strain to failure

Uncorrected and corrected strain to failure is presented in Fig. 4.22 to Figs 4.25 respectively for jute, bamboo, brown coir and white coir fibres. It is observed from the uncorrected curves with increasing span length strain to failure is decreased. After correction, the strain to failure stays dependent on the span length, which is logically linked to the breaking possibility theory. The longer the fibres length, there are more flaws and weaknesses in the fibres that make the probability of failure earlier.

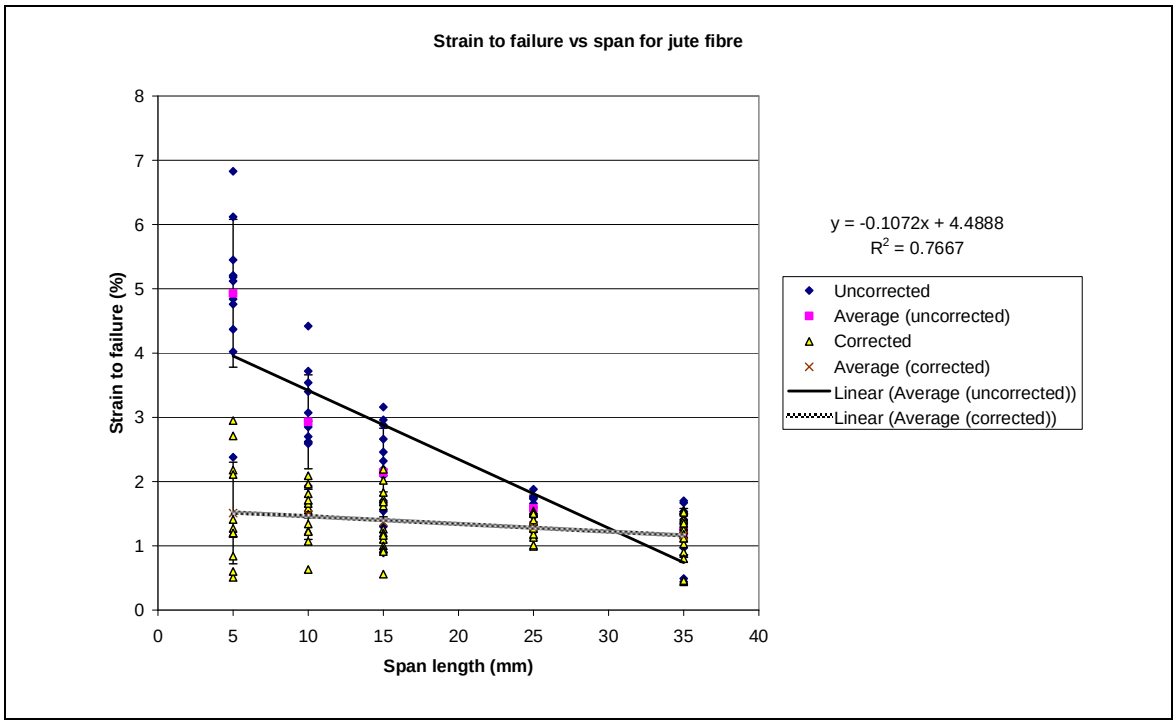


Figure 4.22: Uncorrected and corrected strain to failure for jute fibre in function of span length.

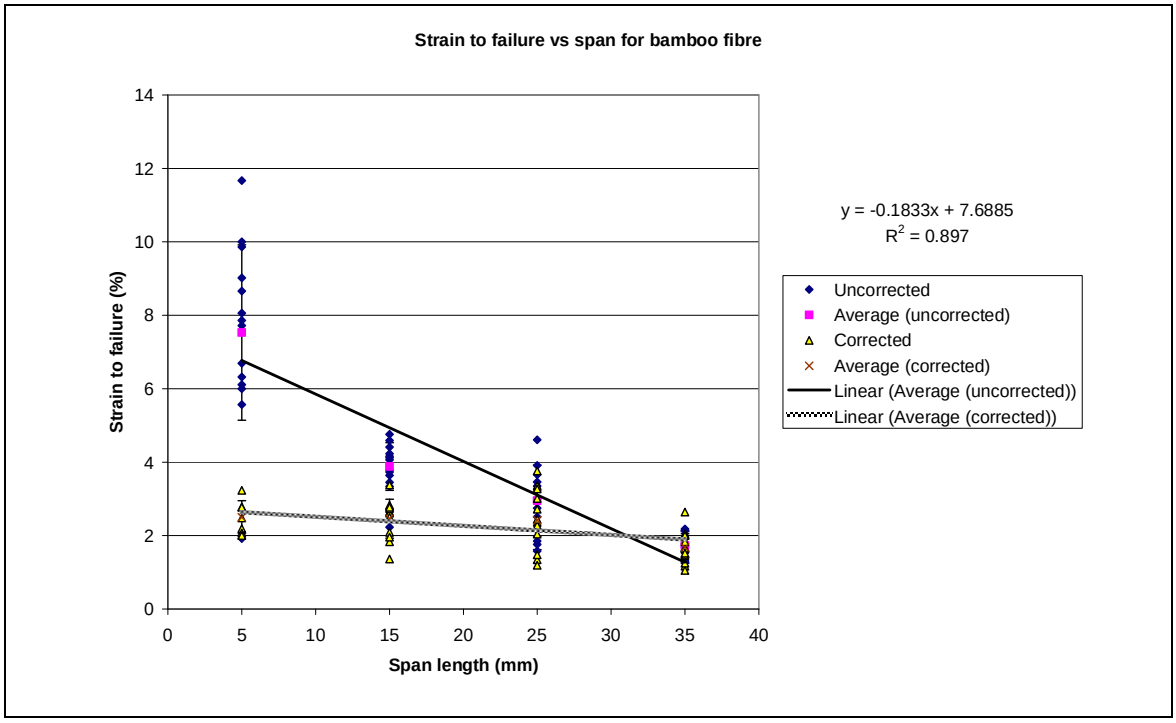


Figure 4.23: Uncorrected and corrected strain to failure for bamboo fibre in function of span length.

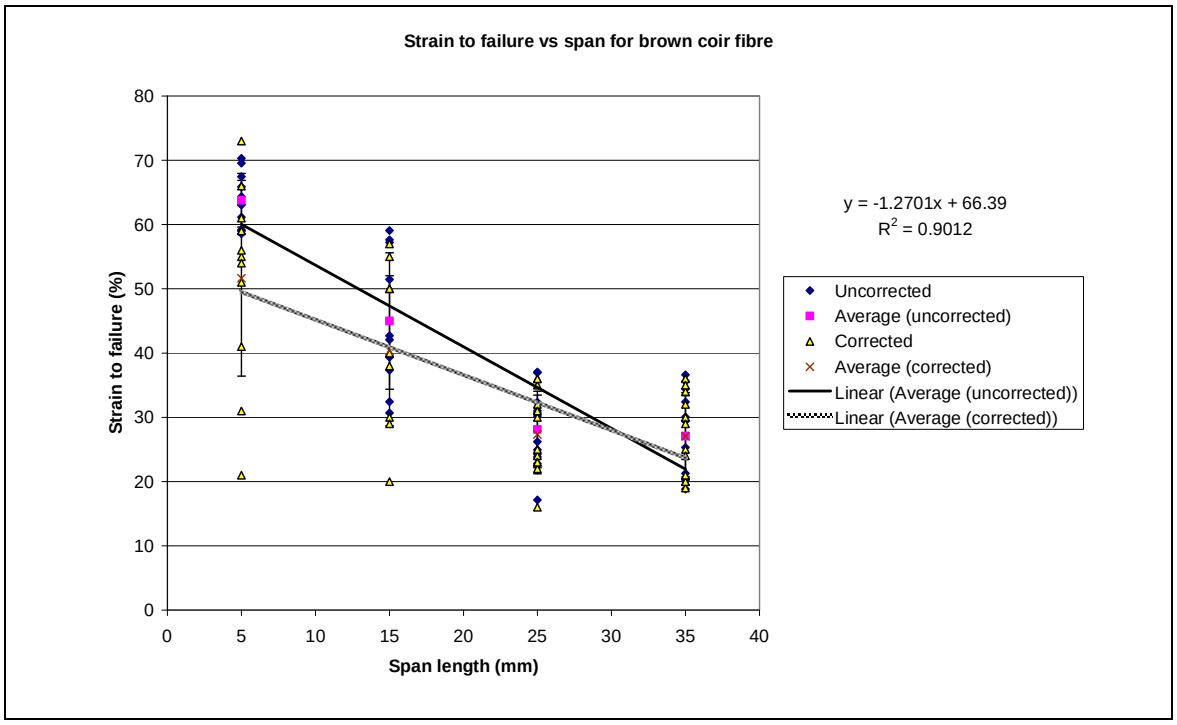


Figure 4.24: Uncorrected and corrected strain to failure for brown coir fibre in function of span length.

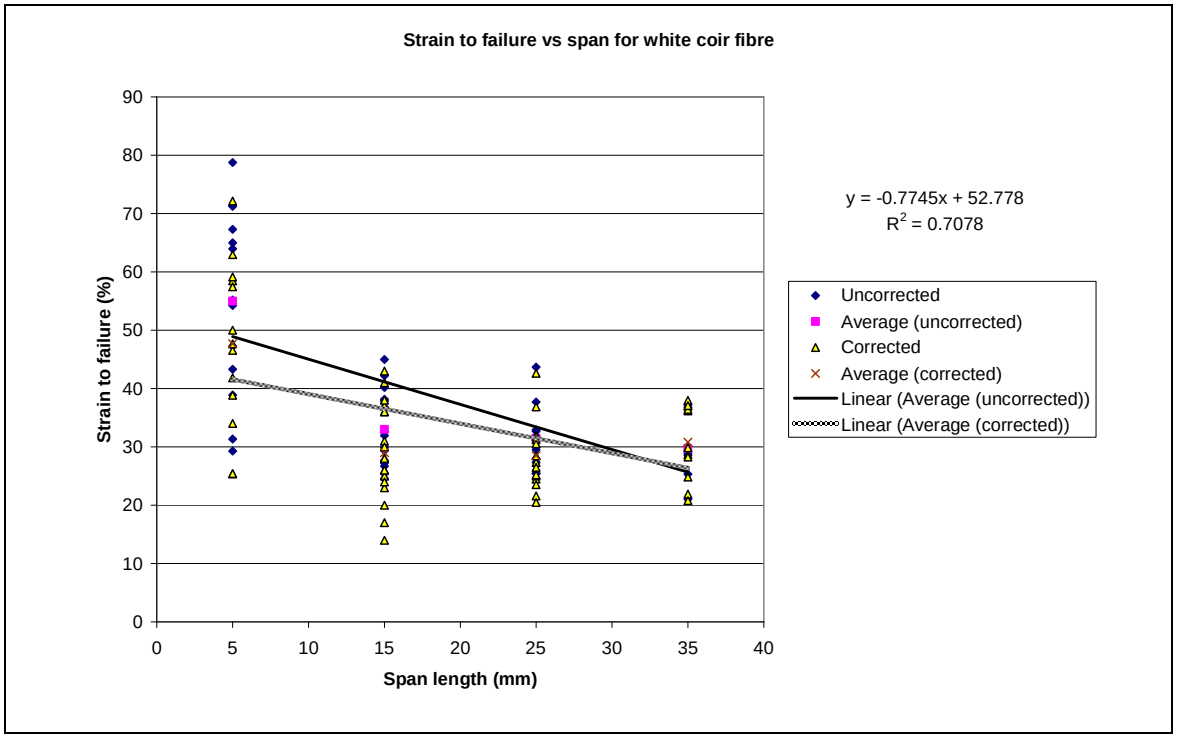


Figure 4.25: Uncorrected and corrected strain to failure for white coir fibre in function of span length.

Corrected strain to failure is also shown in Fig. 4.22 to Fig. 4.25, while comparison between corrected and uncorrected results are shown in Table 4.08. Corrected strain to failure of all the test results found are around the literature values. Bamboo fibre value found is bit higher than literature values.

Table 4.08: Uncorrected and corrected strain to failure of natural fibres compare to literature values.

Fibre species	**Uncorrected strain to failure(%) (5 mm to 35 mm span length range) ± STD**	**Corrected strain to failure (%)(5 mm to 35 mm span length range) ± STD**	**Strain to failure from Literature (%)**	**References**
Jute fibre	1.22 ± 0.36 ï 4.93 ± 1.15	1.16 ± 0.34 ï 1.51 ± 0.79	1.16 ï 2.50	[59,60]
Bamboo fibre	2.00 ± 0.72 ï 7.53 ± 2.39	1.68 ± 0.43 ï 2.50 ± 0.45	1.3	[54]
Brown coir fibre	27.04 ± 6.77 ï 63.78 ± 4.17	27.04 ± 6.34 ï 51.64 ± 15.23	15 - 44	[58,66]
White coir fibre	30.00 ± 06 ï 55.00 ± 16	28.30 ± 06 ï 48.00 ± 14		

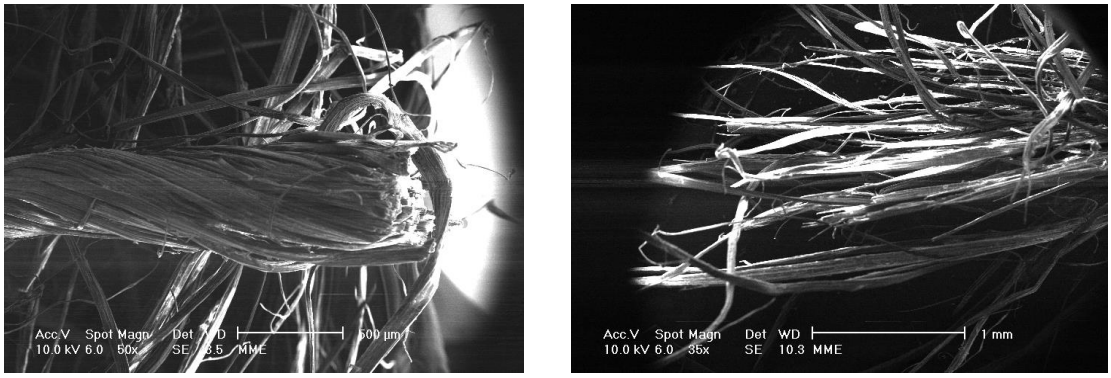
4.3 Tensile properties of woven jute fabrics

Tensile strength of single ply woven jute fabrics are given in Table 4.09. In this study, tensile tests both at warp and weft directions were carried out. Jute fabrics in weft direction have shown higher strength as compared to warp direction. Because in weft direction the number of yarn is 12 per inch and in warp direction there are 10 yarns per square inch. Tensile strength of woven jute fabrics showed smaller compared to single fibre because yarn is twisted in fabrics where single fibres were more straight and

smooth. Fig. 4.26 (b) showed the fracture surface of yarn in jute fabrics. It conform that fracture was occurred in a rough manner because twisted yarn did not take load uniformly. So it breaks earlier.

Table 4.09: Tensile strength of woven jute fabrics in warp and weft direction.

Yarn direction	**Tensile strength (MPa) ± STD**
Warp (10 yarn/inch)	12.98 ± 3.32
Weft (12 yarn/inch)	13.15 ± 2.59



(a) **(b)**

Figure 4.26: a) Surface of a jute yarn in woven fabrics. b) Fracture surface of a jute yarn in woven jute fabrics.

4.4 Tensile properties of UD composites

4.4.1 Analysis of jute and bamboo fibre/epoxy unidirectional composites

Table 4.10 shows tensile properties of jute and bamboo fibres/ epoxy composites. Fig. 4.27 shows typical stress-strain curve for unidirectional composites. The strength of epoxy, jute and bamboo fibres are 68.6 MPa, 370 MPa and 740 MPa respectively.

Table 4.10: Tensile properties of UD jute and bamboo composites.

Name of the fibre	Tensile strength (MPa) ± STD	Young's modulus (GPa) ± STD	Stain to failure (%) ± STD
Jute (52 wt %)	216.09 ± 1.02	26.99 ± 1.16	0.78 ± 0.42
Bamboo (57 wt %)	391.98 ± 8.51	28.66 ± 1.25	1.38 ± 0.02

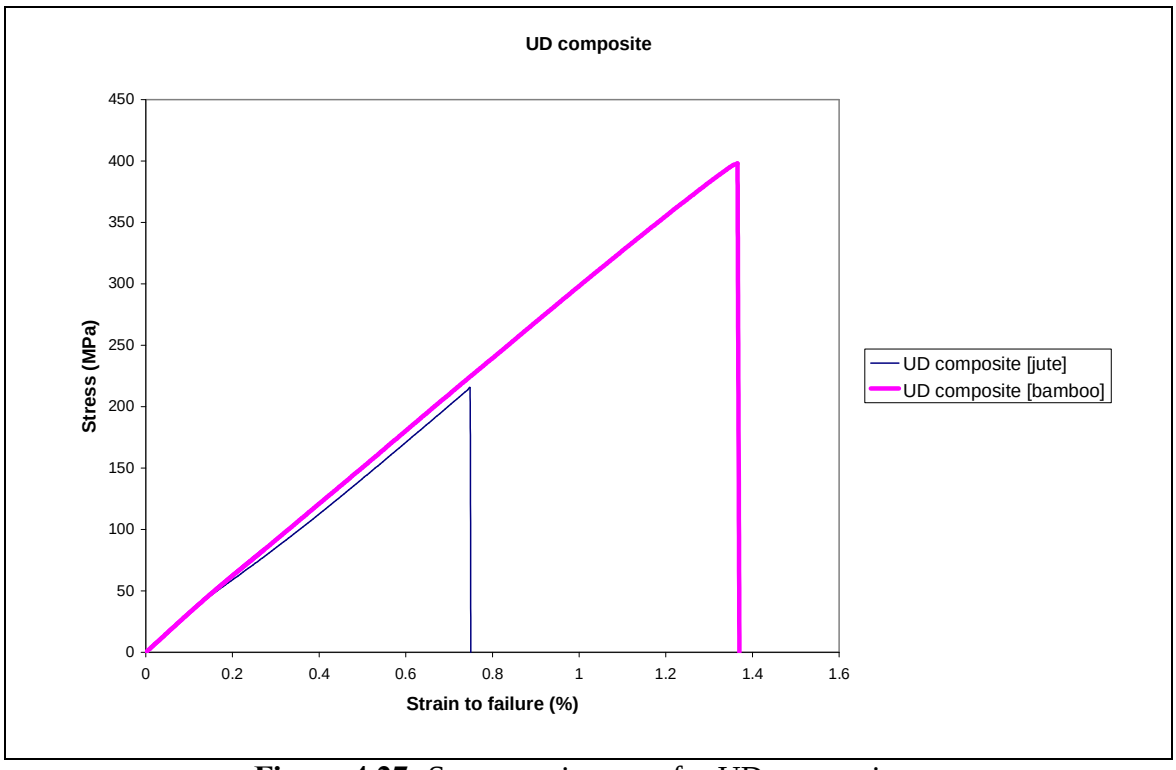


Figure 4.27: Stress-strain curve for UD composites.

In comparison to jute and bamboo fibre composites, bamboo shows the highest results in term of tensile strength and breaking of elongation which is approximately 392 MPa and 1.38 respectively. Jute fibre shows better modulus compared to bamboo fibres.

Using the equation 3.09 (cited in chapter 3), the final volume fraction of both jute and bamboo fibres found was approximately 52 % and 57% respectively. The rule of mixture was used to calculate the theoretical strength and modulus of jute and bamboo fibres epoxy resin composites by using the following equation (4.06 for stress).

$$\sigma_c^* = \sigma_f^*(V_f) + \sigma_m^{\cdot\cdot}(V_m) \qquad \text{(Equation 4.06)}$$

For jute fibre composite:

σ_c^* = 370 (0.52) + 68.6 (0.48)

σ_c^* = 192.4 + 32.93

σ_c^* = 225.33 MPa

For bamboo fibre composite:

σ_c^* = 740 (0.57) + 68.6 (0.43)

σ_c^* = 451.30 MPa

Comparing the value of tensile strength of jute (216 MPa) and bamboo (392 MPa) composites obtained experimentally with the value calculated theoretically (225 MPa for jute fibre and 451 MPa for bamboo fibre respectively), it can be seen that experimental results are bit smaller than theoretical value. Nevertheless, it is important to note that the fibres were not perfectly aligned which are shown in Fig. 4.28 and these deviation in some of the fibres affect the strength of the composite. Also in the case of jute fibre

composites, some of the fibres were crushed during processing of fabrication which is also observed from SEM morphology [Fig. 4.28].

The measured stiffness is 26.99 GPa for jute fibre UD composites and 28.66 for bamboo fibre UD composites respectively (which are shown in Table 4.10) where the theoretical results (in this study of single fibre) are 28.80 GPa for jute fibre and 35.5 GPa for bamboo fibre and other theoretical results are in the range of 13-54 GPa for jute fibres composite [59, 63] and 11-30 GPa for bamboo fibres composite [61, 62] respectively. This discrepancy is likely due to the difficulty to measure the displacement in the single fibre tensile test by an external tool and possible slippage in the clamps during the tensile test of single fibres, leading to an underestimation of fibre modulus. The contribution of matrix to the composites are very poor so that we can avoid the Youngôs modulus of epoxy resin was avoided when the result was calculated.

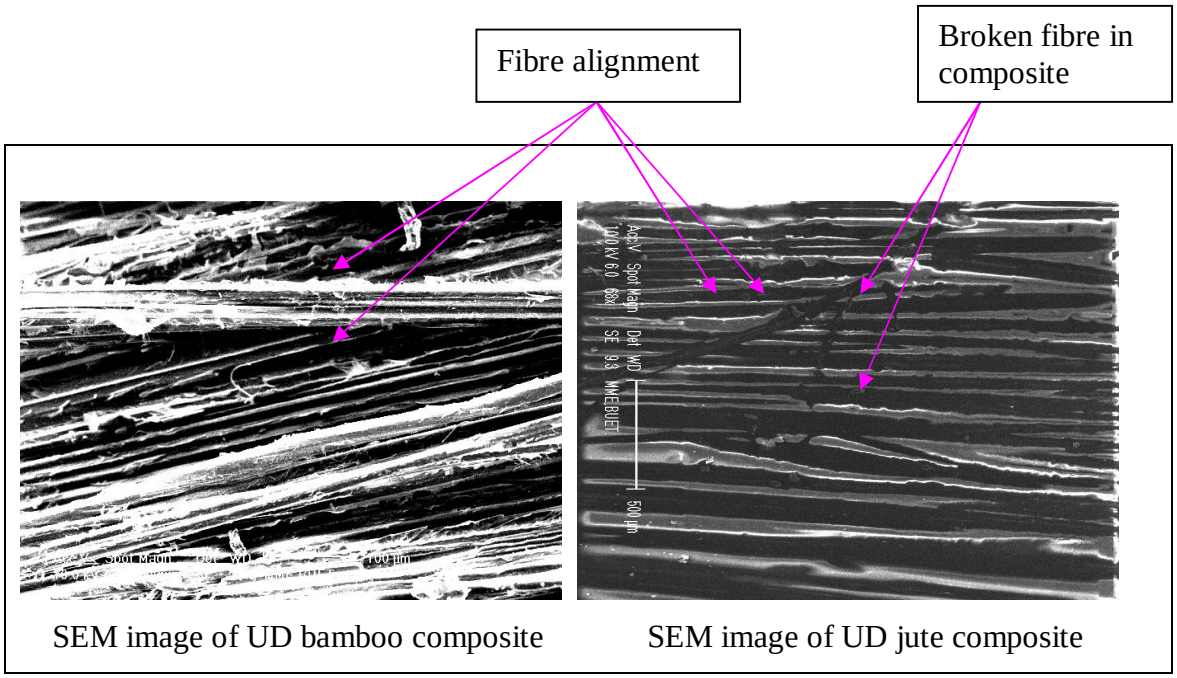


Figure 4.28: ESEM micrographs of UD jute and bamboo fibre composites.

When mechanical properties as strength of jute and bamboo fibre composites are compared with other natural fibre composites used, nowadays as reinforcement in

polymer composites, it is clear from the Fig. 4.29 that bamboo fibre composites have a good performance. As pointed out by several investigators, when the density has taken into account, some natural fibres have a performance comparable with synthetic fibres like glass fibres.

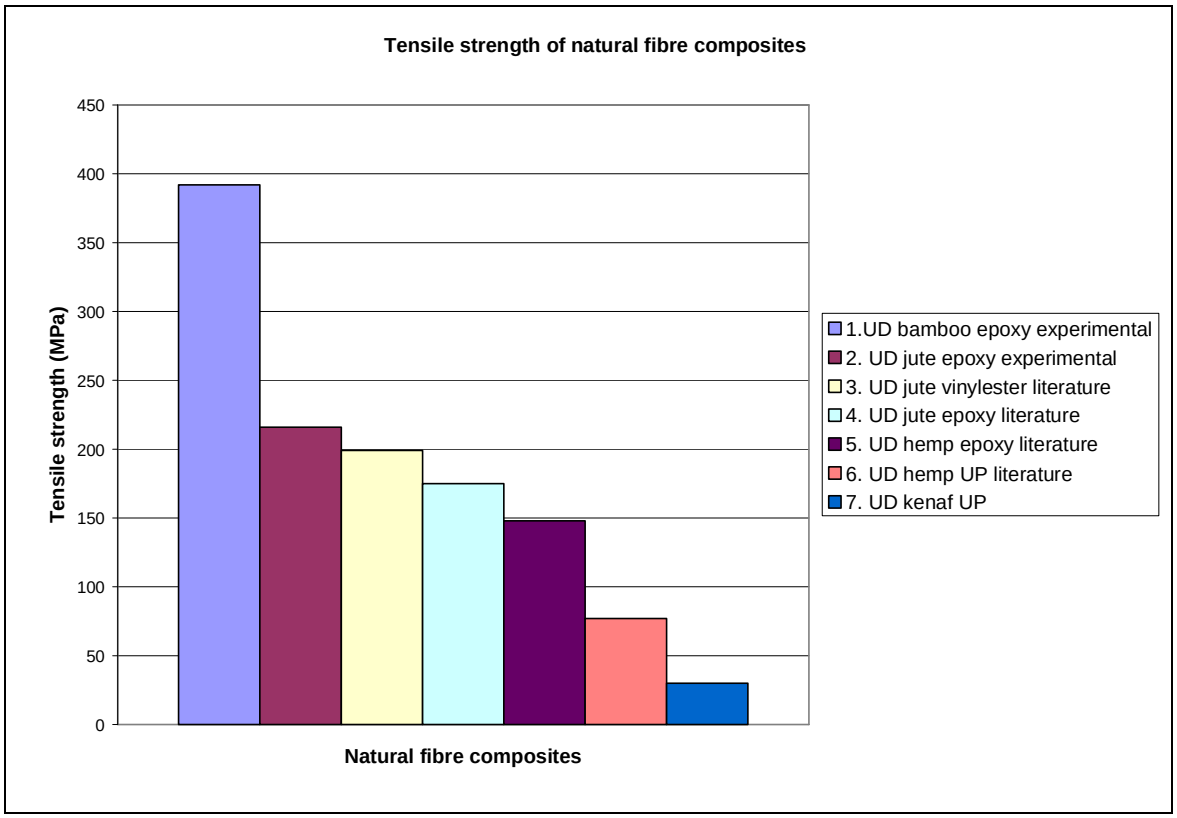
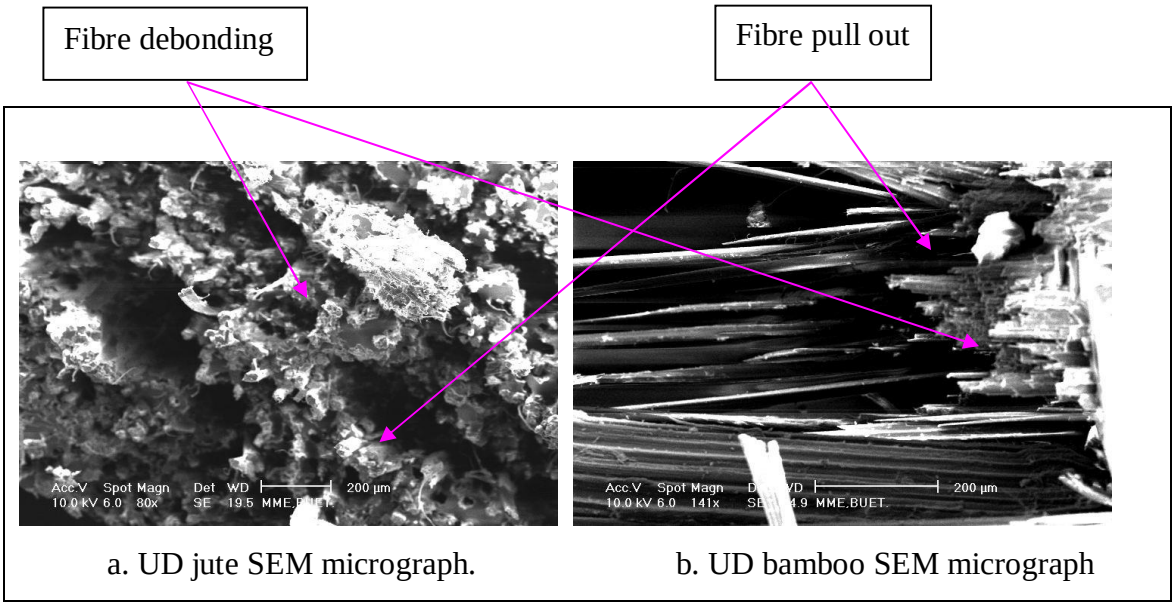


Figure 4.29: Tensile strength of the common natural fibre UD composites used nowadays as reinforcement in polymer composites. Source: Chapter 2.

SEM images are a practical way to conform the good adhesion between fibres and epoxy matrix. Images of fracture surfaces reveal if the fibre bundles are actually impregnated by the matrix. The good interface quality is demonstrated in Fig. 4.30 where it is possible to observe the fibre surface with trace of the matrix. These micrographs also show that the fibres are relatively more pulled out from the matrix than broken for bamboo fibre but vice versa for the jute fibres. Before pulling out fibres are debonded. This reveals that there may be some mechanical interlocking or chemical

bond has been formed. Obviously the shrinkage of the matrix will always impose a compressive load that insists the mechanical interlocking in between the fibres and matrix.



a. UD jute SEM micrograph. b. UD bamboo SEM micrograph

Figure 4.30: SEM image of the fracture surface of unidirectional jute and bamboo fibre reinforced epoxy composites after tensile test. Pull out is more in bamboo fibre.

4.5 Tensile properties of bi-directional composites

4.5.1 Analysis of tensile properties of woven jute reinforced polyester and PVC composites

The tensile properties of woven jute reinforced polyester and polyvinylchloride (PVC) are shown in Table 4.11 and 4.12 respectively for polyester and PVC composites.

Table 4.11: Tensile properties of woven jute fabrics polyester composites.

Number of ply (woven jute) (Fibre by weight fraction)	Tensile strength (MPa) ± STD	Young's modulus (GPa) ± STD	Strain to failure (%) ± STD
3 (29.41)	54.55 ± 2.55	7.26 ± 0.38	1.22 ± 0.11
4 (30.67)	65.69 ± 1.87	8.56 ± 0.24	1.30 ± 0.13
5 (30.90)	68.14 ± 1.08	8.63 ± 0.43	1.33 ± 0.11
6 (31.71)	70.74 ± 1.12	8.76 ± 0.67	1.41 ± 0.15

Table 4.12: Tensile properties of woven jute fabrics polyvinyl (PVC) composites.

Number of ply (woven jute) (Fibre by weight fraction)	Tensile strength (MPa) ± STD	Young's modulus (GPa) ± STD	Strain to failure (%) ± STD
3 (21.60)	41.06 ± 5.16	4.51 ± 0.24	1.45 ± 0.14
4 (22.88)	55.12 ± 2.44	6.61 ± 0.18	1.44 ± 0.05
5 (25.80)	62.39 ± 1.48	7.65 ± 0.39	1.21 ± 0.06
6 (29.24)	63.41 ± 2.59	7.95 ± 0.14	1.17 ± 0.03

Fig. 4.31 shows the number of ply vs tensile strength curve for both polyester and PVC composites. The fibre weight fraction of polyester is 29.41 %, 30.67 %, 30.90%, 31.71% for respectively 3, 4, 5 and 6 ply. In case of PVC the fibre volume fraction is 21.60 %, 22.88 %, 25.80 % and 29.24 % for respectively 3, 4, 5 and 6 ply. It seems that tensile strength increases with increasing weight fraction of fibre in both cases for polyester and PVC. As the fiber weight fraction increased, the interfacial area between the fiber and matrix increased, which consequently increased the tensile strength.

When polyester and PVC composites are compared, it is clearly observed that polyester composites showed the better result. This is due to interfacial bonding between matrix and fibre that are better in polyester composites compared to PVC which are shown in

Fig. 4.34. The trend line increased larger from 3 to 4 ply and then the increased slowly for both polyester and PVC composites from 4 to 6 ply.

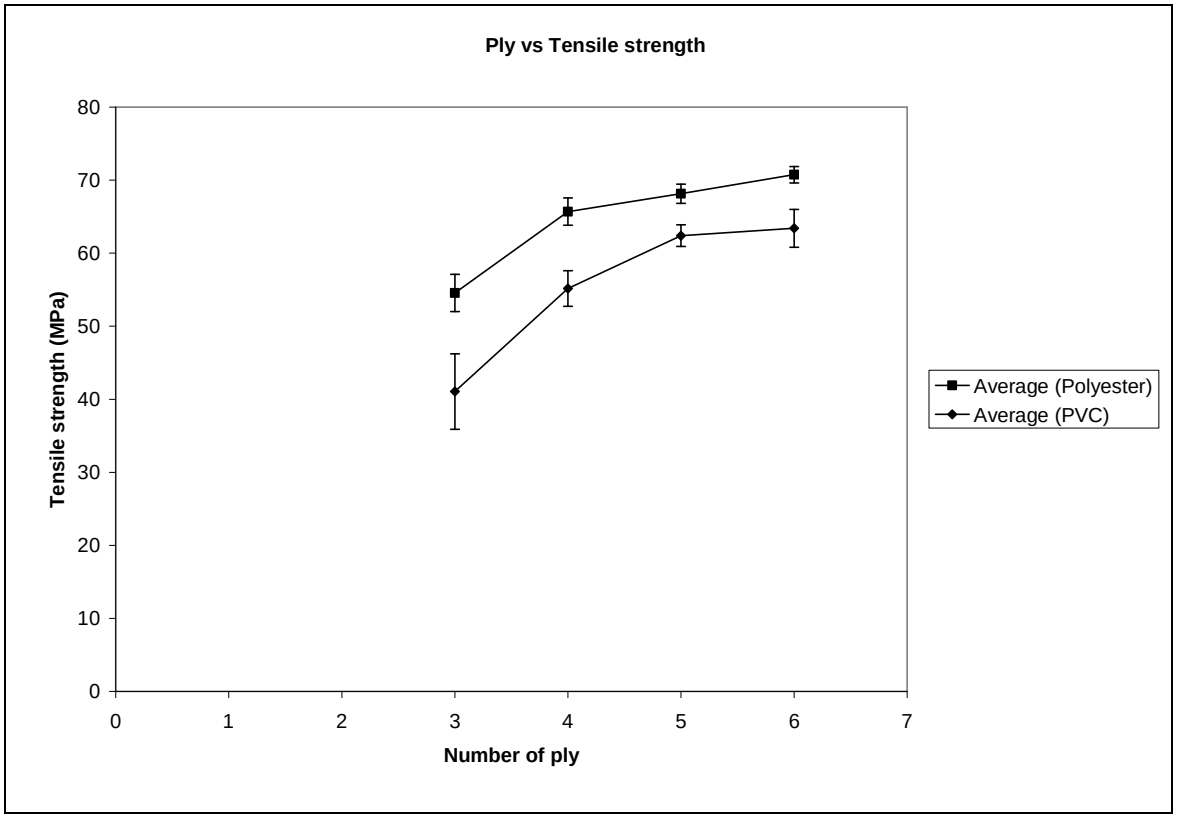


Figure 4.31: Number of ply vs tensile strength for polyester and PVC composites.

Fig. 4.32 shows the variation of the Youngôs modulus at different fiber loading (3, 4, 5 and 6 plies) for both woven jute fabrics polyester and polyvinylchloride composites. The Youngôs modulus increased with fiber loading in accordance with other researchers [67 - 72]. During tensile loading, partially separated micro spaces are created, which obstructs stress propagation between the fiber and matrix [72]. As the fiber load increases, the degree of obstruction increases, which consequently increases the stiffness. The Youngôs modulus for woven jute fabrics reinforced polyester composites found higher in polyester composites compared to PVC composites.

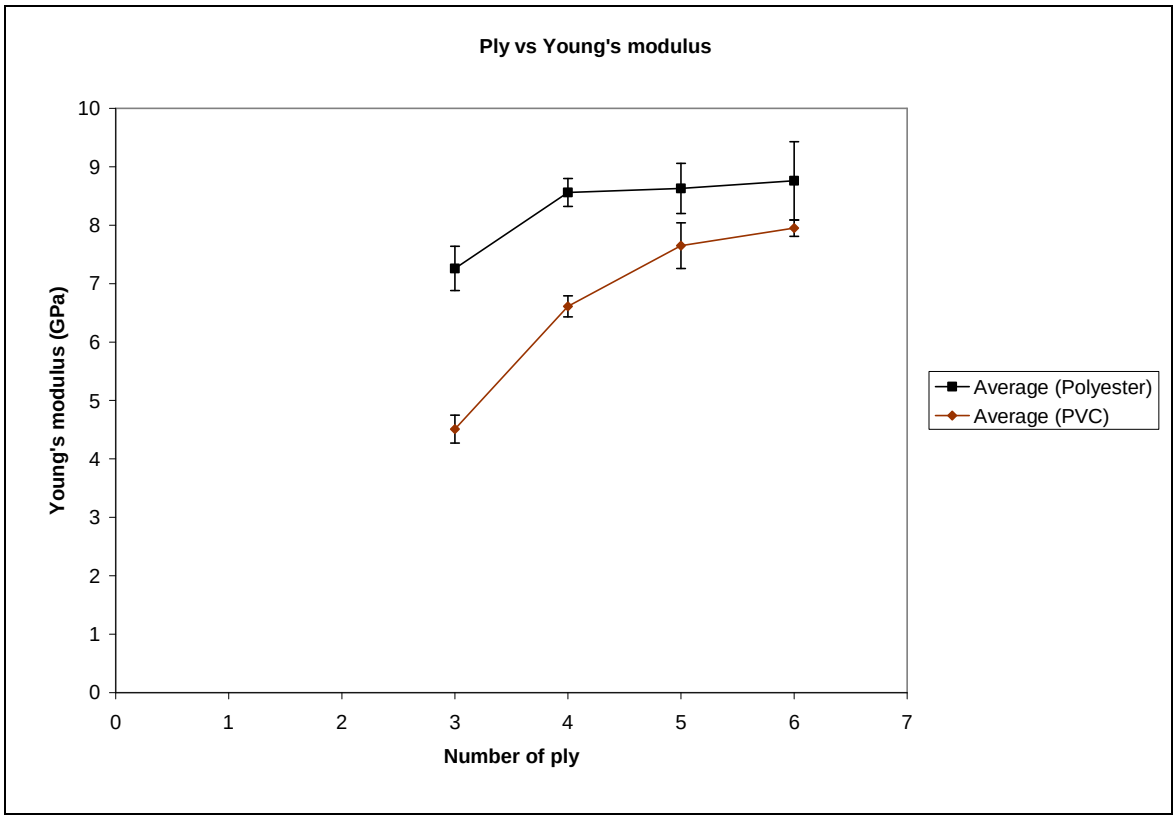


Figure 4.32: Number of ply vs Youngôs modulus for polyester and PVC composites.

Fig. 4.33 shows the strain to failure at different fiber loading (3, 4, 5 and 6 plies) for both woven jute fabrics polyester and polyvinylchloride composites. It is observed that strain to failure increases with increasing fibre loading (no. of plies) for polyester composites, where the strain to failure decreases with increasing fibre loading (no. of plies) for PVC composites. In comparison between polyester and PVC composites, polyester has showed the longer strain to failure. Increasing of the strain to failure of the composites increases the toughness or ductility of the composites.

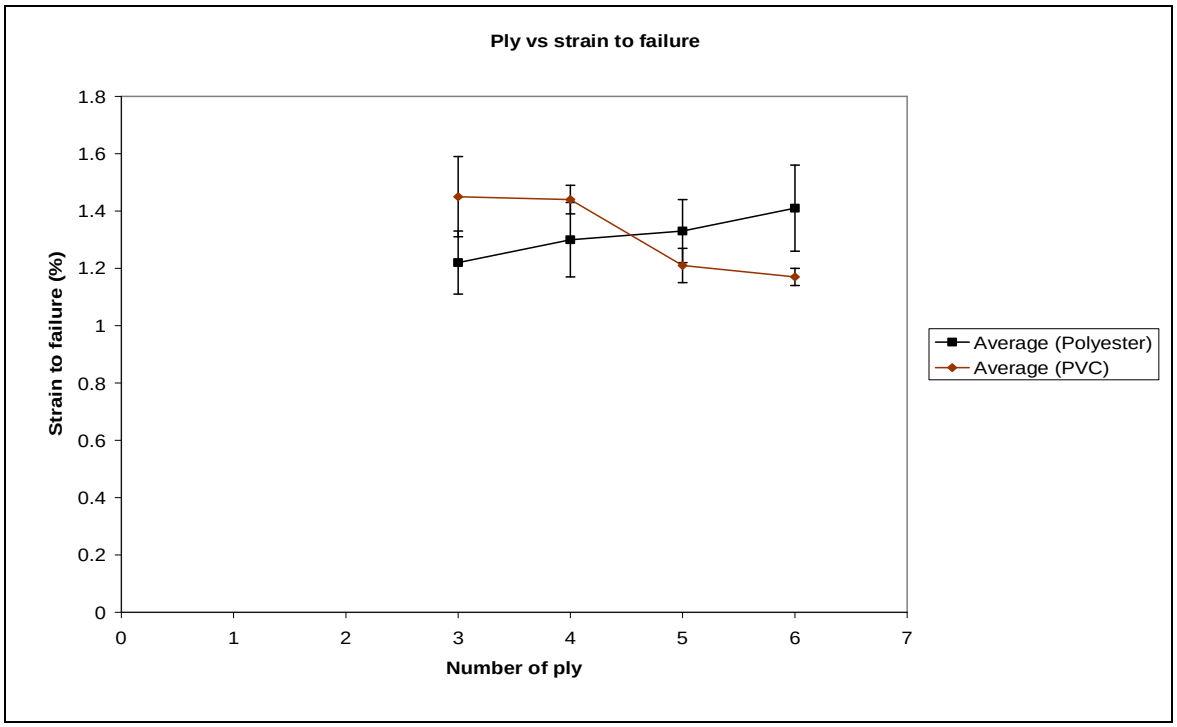


Figure 4.33: Number of ply vs strain to failure for polyester and PVC composites.

The SEM images show in Fig. 4.34 for both woven jute polyester and polyvinylchloride composite. It is clearly observed that the impregnation is good for woven jute polyester composite compare to woven jute PVC composite. So woven jute polyester composite shows good results than woven jute PVC composite. It is also seem from the image that fracture surface of jute polyester is smoother compare to that of jute polyvinylchloride composite. Fibre pull out of jute polyvinylchloride is relatively high than jute polyester composite because of their interfacial bond which is poor in terms of PVC composite.

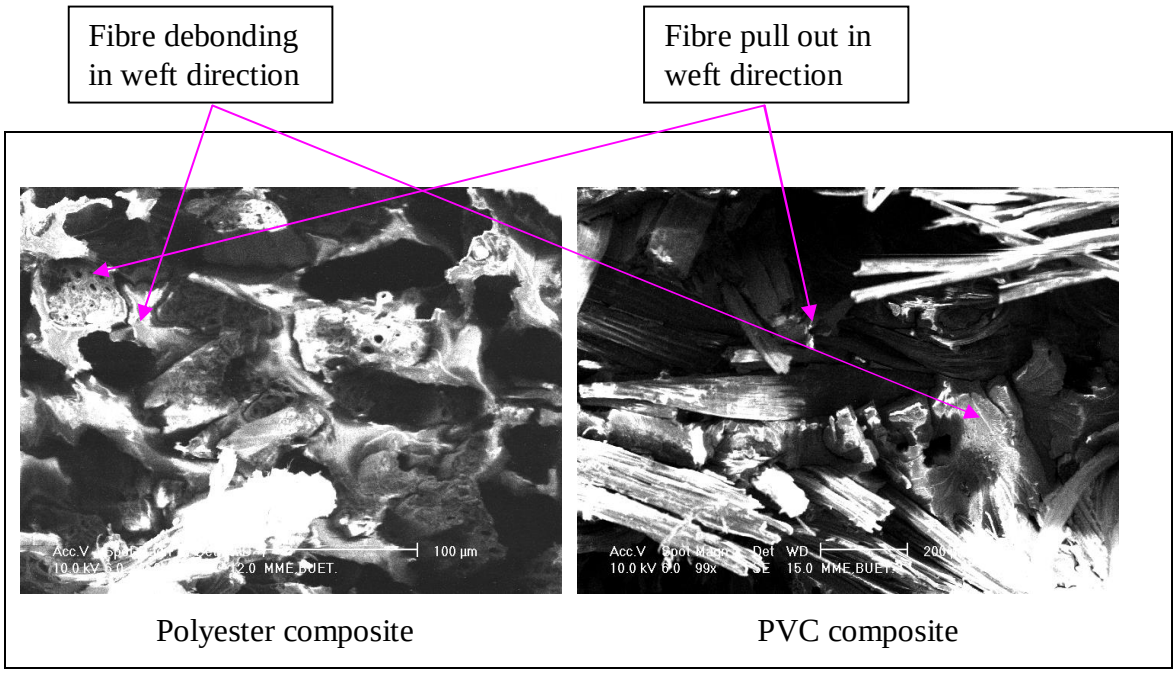


Figure 4.34: SEM micrograph for woven jute polyester and PVC composites after tensile test.

4.5.2 Analysis of tensile properties of woven jute fabrics reinforced polypropylene (PP) composites [Hessian Jute Fabrics]

Table 4.13 shows the tensile properties of woven jute fabrics reinforced polypropylene (PP) composites in different fabric angle.

Table 4.13: Tensile properties of woven jute fabrics polypropylene composites.

Number of ply (woven jute)	Ply orientation	Tensile strength (MPa) ± STD	Young's modulus (GPa) ± STD	Strain to failure (%) ±STD
4	0-45-90-45-0	60.79 ± 1.77	7.24 ± 0.91	1.64 ± 0.20
4	0-90-0	48.57 ± 0.67	6.87 ± 0.61	1.46 ± 0.16

It is clearly observed from the table that ply orientation affects the tensile properties. It is seen that 0-45-90-45-0 angle with fibres have showed the better tensile properties. When the results of 4 ply jute fabrics polypropylene composite are compared with other polymer composites using 4 ply woven jute fabrics it can be found that woven jute epoxy composite have showed the highest tensile strength (~ 69) and jute polypropylene composite showed the lowest value (~ 49) when 0-90-0 fibre orientation was used. In terms of Youngôs modulus all composite shows almost same values. Strain to failure varies between 1.30 to 1.64 % this is also overall the same values.

4.5.3 Analysis of tensile properties of woven jute fabrics reinforced epoxy composites [Hessian Jute Fabrics]

Table 4.14 shows the tensile properties of woven jute fabrics reinforced epoxy composites in different fibre loading

.

Table 4.14: Tensile properties of woven jute fabrics epoxy resin composites.

Number of ply (woven jute)	**Tensile strength (MPa) ± STD**	**Young's modulus (GPa) ± STD**	**Strain to failure (%) ± STD**
4	69.43 ± 2.86	6.14 ± 0.57	1.30 ± 0.04
6	92.38 ± 8.06	8.84 ± 0.48	1.38 ± 0.14

Typical stress-strain curve of woven jute- epoxy composite are shown in Fig. 4.35. In general overall stress-strain behaviour of this specimen is non-linear. Usually a linear behaviour is displayed up to 0.25% strain and the curve is level out at about 1.2% strain. The strain at maximum tensile stress for all types of specimen ranged from 1.2 ï 1.4%. Tensile strength and tensile modulus of this composites ranged from 70 ï 92 MPa and 6-9 GPa respectively. The fibre volume fraction of 4 and 6 ply composites are 22.65 % and 26.66% respectively. It is seen that tensile strength and modulus increases with increasing fibre loading. This is may be due to good interfacial bond between fibre and matrix.

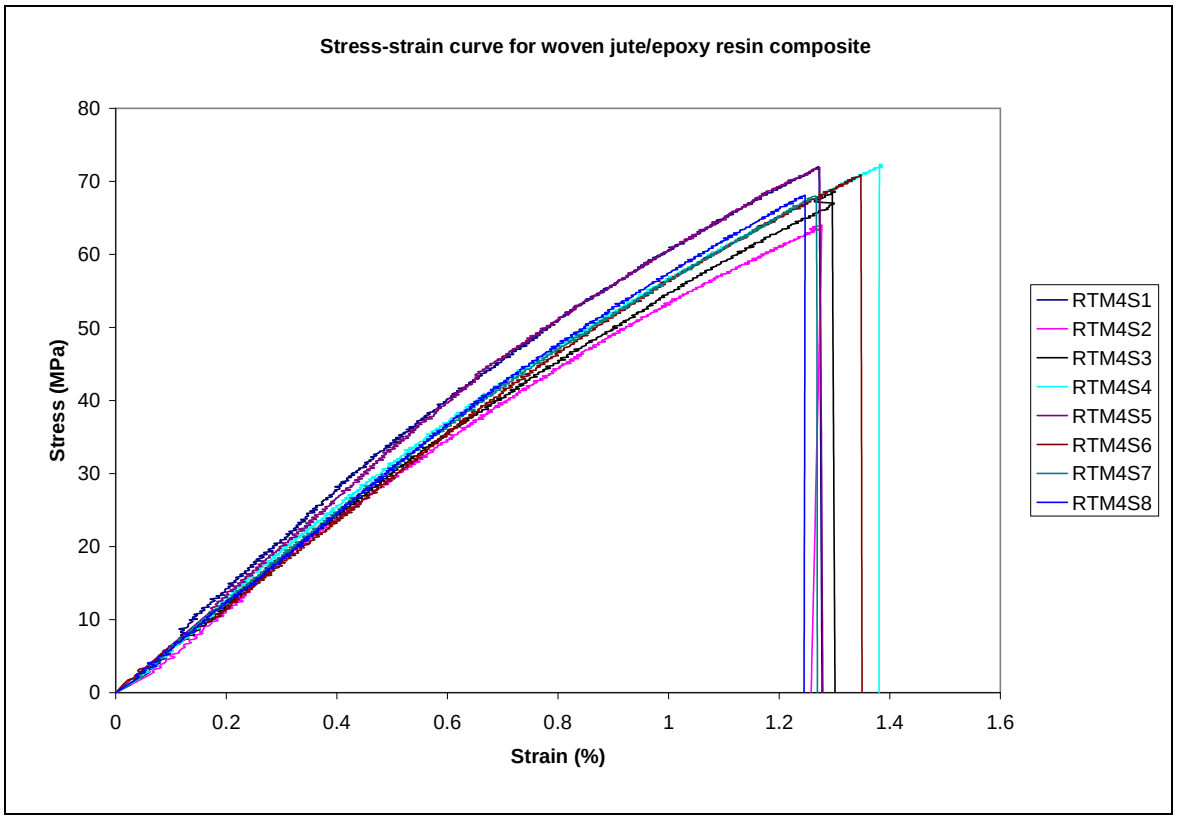


Figure 4.35: Typical stress-strain curve for woven jute-epoxy composites.

4.6 Flexural (3 point bending test) properties of composites

4.6.1 Analysis of flexural properties of UD fibre/epoxy composites (longitudinal distribution of the fibres).

Table 4.15 shows the results for unidirectional jute and bamboo fibre/ epoxy composites. Figs. 4.36 and 4.37 show a typical stress/strain curve for jute/epoxy and bamboo/epoxy composites respectively.

Table 4.15: Flexural properties of unidirectional jute and bamboo fibre composites with longitudinal distribution of fibres.

Fibre	Flexural strength (MPa) ± STD	Flexural modulus (GPa) ± STD	Strain to failure (%)± STD
Jute (52 % by weight)	157.69 ± 18.90	18.13 ± 1.92	2.87 ± 0.29
Bamboo (57 % by weight)	225.81 ± 25.13	18.81 ± 1.32	7.55 ± 0.67

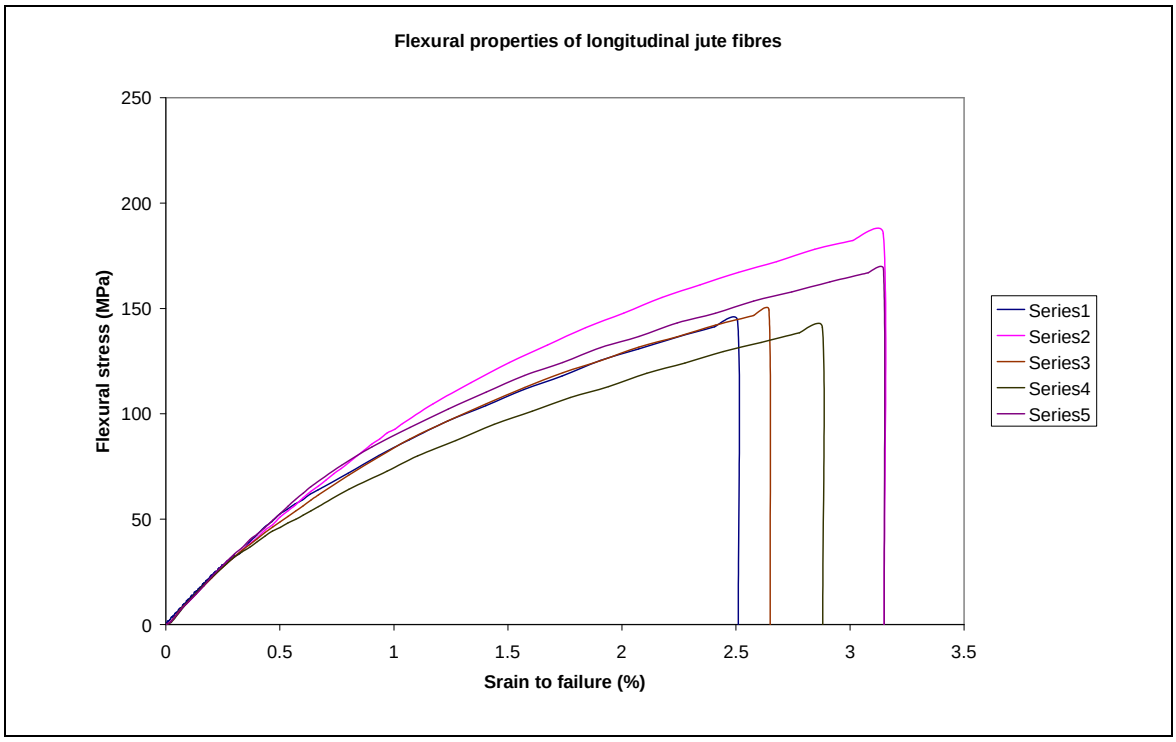


Figure 4.36: Stress/strain curve for flexural longitudinal properties of jute/epoxy composites.

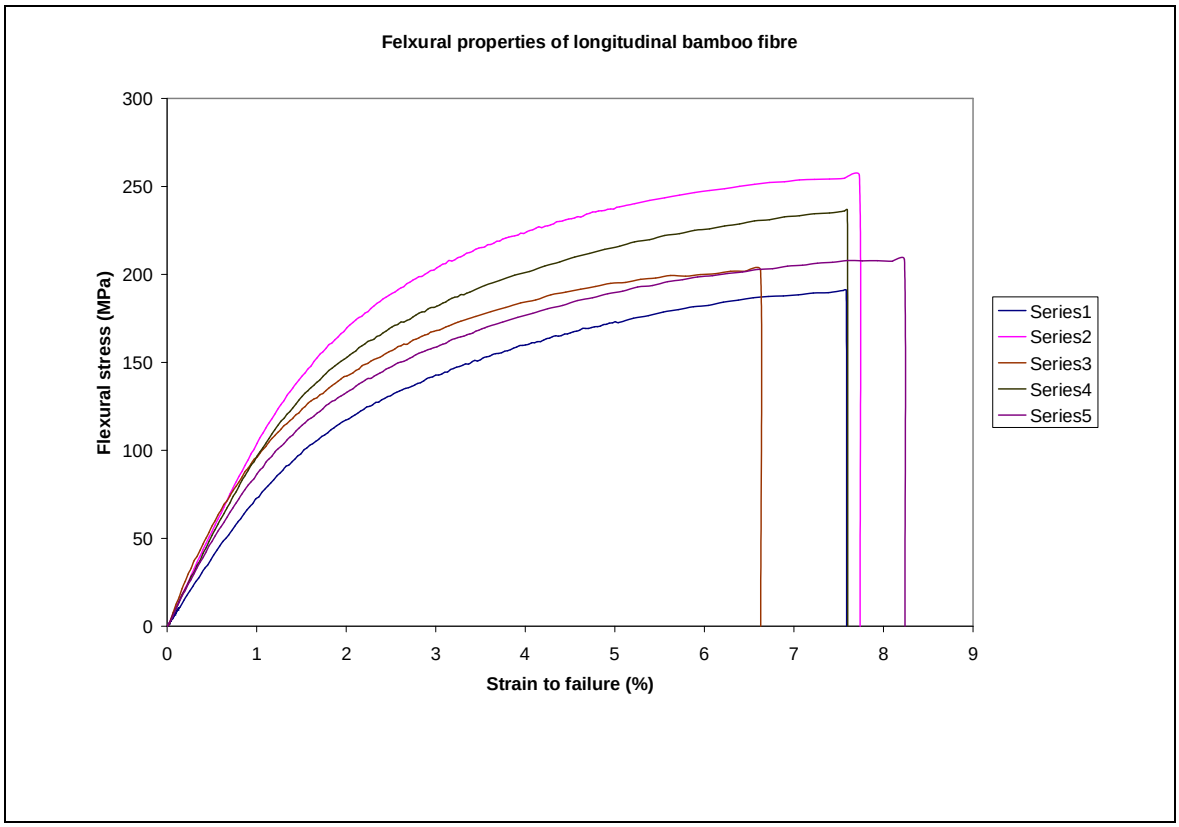


Figure 4.37: Stress/strain curve for flexural longitudinal properties of bamboo/epoxy composites.

Three point bending tests (3PBT) were first carried out in the fibre direction to evaluate the performance with thermoset resin. In this study, jute and bamboo fibres reinforced epoxy have taken into account.

As shown in Table 4.15, flexural modulus and strain to failure are almost same for both jute and bamboo fibres. The flexural strength is the highest for bamboo fibres compared to jute fibres. This may be due to difference between the extraction processes of two fibres. As described in chapter 3, bamboo fibre have extracted by steam explosion method where jute fibre extracted through mechanical process. Apparently the mechanical extraction process gives fibres with rough surface and little amount of lignin.

Stress-strain curves (Figs. 4.36 and 4.37) show the first linear part of the curve at a very small strain. This is due to manual preparation of composite. The alignment of the fibres was not perfect. The non perfect alignment of the fibres in the matrix causes the non linearity. This can be avoiding by using some special technique like drum winder which allows a perfect alignment of the fibres.

When the experimental results are compared with theoretical results (using the rule of mixture which mentioned in equation 4.06 and 4.07), it can be observed that experimental stress is lower (157.69 MPa and 225.81 MPa for jute and bamboo fibre respectively) than theoretical ones in concern of both jute and bamboo fibres. In the case of flexural modulus for both fibres (18.13 GPa and 18.81 GPa for jute and bamboo fibre respectively), however, it is much closed to theoretical results which is 16.40 and 21.53 GPa for jute and bamboo fibre respectively. Jute fibre shows bit larger value than theory but bamboo shows bit smaller value. Strain to failure of jute and bamboo fibre shows all most same value.

$$E_C = E_f(V_f) + E_m(V_m) \qquad \text{(Equation 4.07)}$$

For jute fibre:

E_C = 28.80 (0.52) + 2.97 (0.48)

E_C = 16.41 GPa

For bamboo fibre:

E_C = 35.52 (0.57) + 2.97 (0.43)

E_C = 21.53 GPa

The crack profile of the flexure specimen of UD jute and bamboo fibres from SEM images are shown in Fig. 4.38. It is clearly observed from micrographs that the fibre has been broken in the middle bottom portion of the specimen. Closer looks towards the fracture surface shows that the fracture slide parallel to the load direction for jute fibres while perpendicular to the load direction for bamboo fibres.

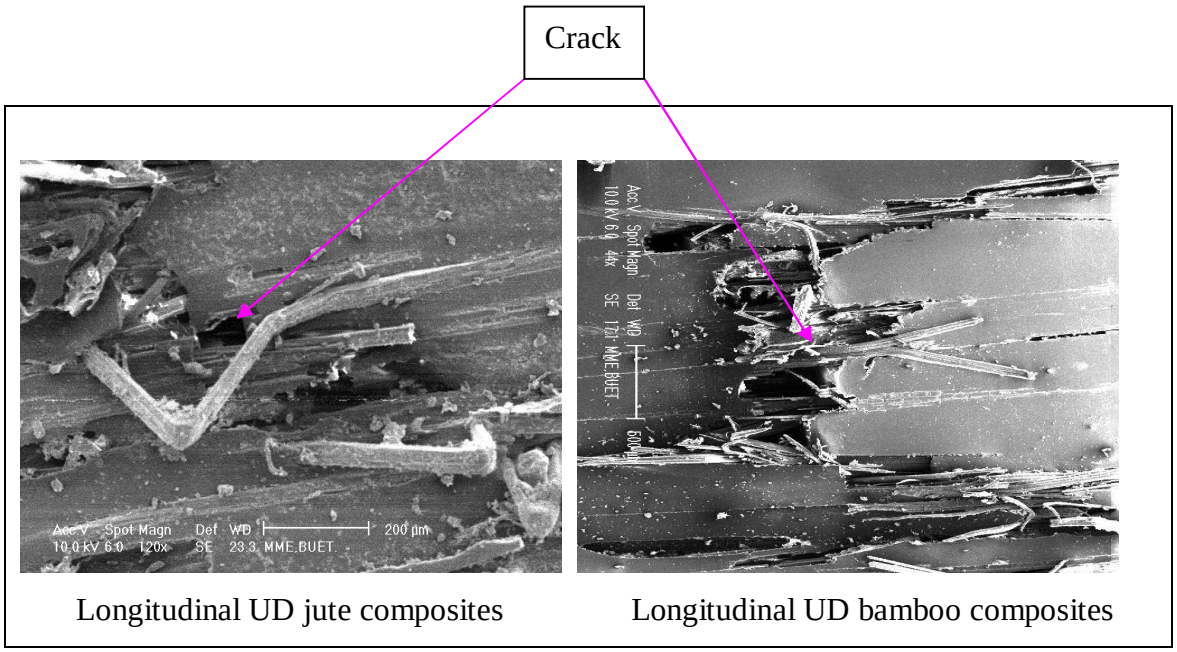


Figure 4.38: SEM micrograph of unidirectional jute and bamboo fibre reinforced epoxy composites after 3 point bending test with longitudinal distribution.

4.6.2 Analysis of flexural properties of UD fibre/epoxy composites (transversal distribution of the fibres)

Table 4.16 shows the results for unidirectional jute and bamboo fibre/ epoxy composites for transversal distribution of fibres.

Table 4.16: Flexural properties of unidirectional jute and bamboo fibre composites with transverse distribution of fibres.

Fibre	**Flexural strength (MPa) ± STD**	**Flexural modulus (GPa) ± STD**	**Strain to failure (%)± STD**
Jute (52 % by weight)	25.7 ± 2.17	2.73 ± 0.28	2.17 ± 0.48
Bamboo (57 % by weight)	11.89 ± 3.87	2.01 ± 0.11	1.46 ± 0.33

In this work, jute and bamboo fibre/epoxy composites reached flexural strength of 25.7 MPa and 11.89 MPa for jute and bamboo fibre composite accordingly. In comparison between jute and bamboo fibres, jute fibre shows almost two times higher than that of bamboo fibres in terms of transversal flexural stress. For flexural modulus jute fibre also shows better result compared to bamboo fibre. This is because of their interfacial bonding, where jute fibre have more compact structure and have broader surface area compared to bamboo fibre which diameter has almost 8/9 times larger than jute fibres. In transverse composite, it is matrix driven phenomenon. The transverse 3 point bending test provides a direct estimation of interface strength.

Nevertheless, results of UD jute and bamboo fibre/ epoxy composites in comparison with other natural fibre reinforced thermoplastics, these composite with a thermoset resin (epoxy) presented the best performance in terms of flexural stiffness. This is explicable since generally, thermoset resins have low viscosity and requires lower processing temperature than thermoplastic resins; these two factors clearly benefit the creation of a good fibre/matrix interface. Concerning transverse properties, the inclusion fibres reduces strength of the resin as it happens with epoxy resin matrix. This indicates that the interface is the weakest link.

SEM micrographs are shown in Fig. 4.39, where the broken area of the composite is clearly seen with transversal distribution of fibres. It is observed that fibre could not take

any stress during 3 point bending test. Because the fibres are aligned with the parallel direction of bending load.

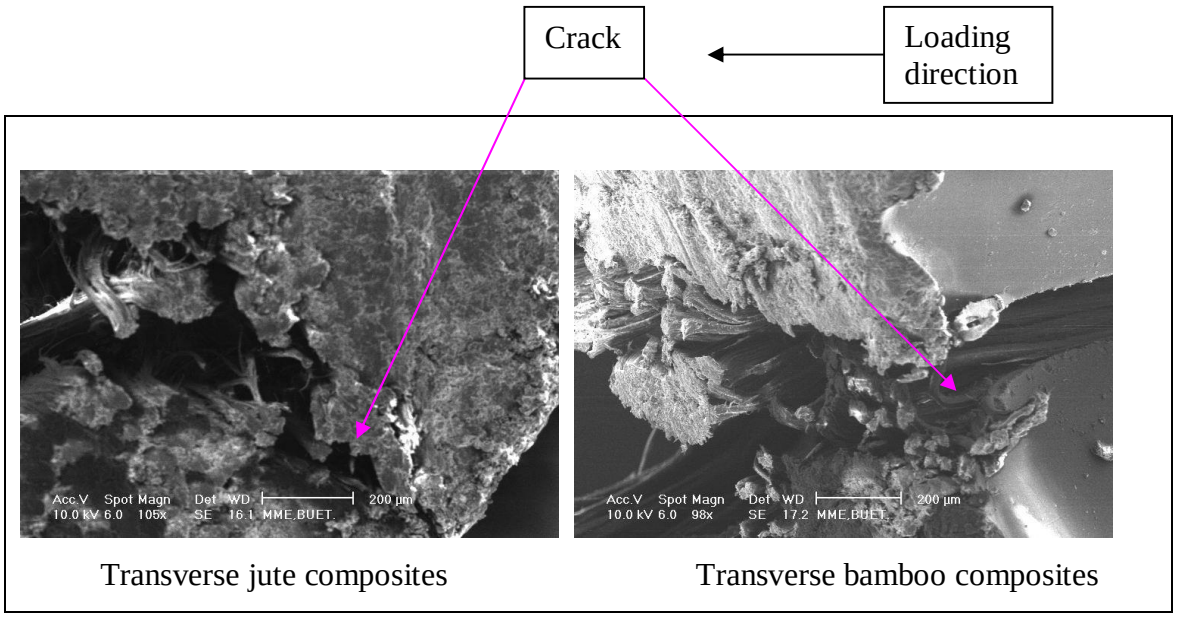


Figure 4.39: SEM micrograph of unidirectional jute and bamboo fibre reinforced epoxy composites after 3 point bending test with transversal distribution.

4.6.3 Results and discussion of water absorption test of woven jute fabrics polyester and polyvinylchloride (PVC) composites

Water absorption and specific gravity of lignocellulosic fibre composites are important characteristics that determine end use applications of these materials [73]. Water absorption could lead to a decrease in some of the properties and needs to be considered when selected for applications. It is difficult to eliminate entirely the absorption of moisture from the composites without using expensive surface barriers on the composite surface. Water absorption in linicellulosic based composites can lead to build up of moisture in the fibre cell wall as well as in the fibre-matrix interface region. Among the components of natural fibres, hemicellulose is mainly responsible for fibre moisture absorption. Moisture build up in the cell wall could result in fibre swelling and concerns on the dimension stability cannot be ignored [73].

Cellulose, hemicellulose and lignin contains hydroxyl group. Hydroxyl group forms hydrogen bond with water molecule. As a result, natural fibres tend to absorption moisture. Results of water absorption obtained in present study are shown in Fig. 4.40 for woven jute fabrics polyester composites, while Fig. 4.41 shows water absorption of woven jute fabric polyvinylchloride (PVC) composites. It is observed that water absorption of jute fibre polyester composite increased and PVC composites decreased with increasing fibre loading (number of ply in this case). This is may be because of hydrophobic PVC polymers acted as barriers and prevent direct contact between jute fibre and water. It also can be observed that water absorption rate was high in the initial stage of testing, then the rate became low and finally the absorption curve flattens out. The figure also shows that with an increase of time water absorption increased for respective plies of composite. When compare the water absorption results between woven jute fabrics reinforced polyester and polypropylene (PVC) composites, it can be observed that jute absorbed little bit higher water when polyester was used as matrix after a certain period.

Table 4.17: Water absorption test data for woven jute/polyester composite.

Composite (Fibre weight fraction %)	**Absorption after 1.5 hour (%) ±STD**	**Absorption after 24 hour (%) ±STD**	**Absorption after 48 hour (%) ±STD**	**Absorption after 96 hour (%) ±STD**	**Absorption after 168 hour (%) ±STD**	**Absorption after 216 hour (%) ±STD**	**Absorption after 576 hour (%) ±STD**
3 ply (29.41)	1.35±0.3	7.49±0.3	9.83±0.3	10.4±0.3	10.46±.3	10.47±.3	10.84±.4
4 ply (30.67)	1.42±0.1	6.29±0.3	8.84±0.4	10.13±.4	10.42±.4	10.52±.4	10.87±.4
5 ply (30.90)	1.17±0.3	5.98±0.9	8.01±0.7	9.95±0.4	10.44±.1	10.49±.1	10.90±.2
6 ply (31.71)	0.96±0.2	5.32±0.3	7.67±0.4	9.80±0.3	10.49±.3	10.62±.2	11.14±.4

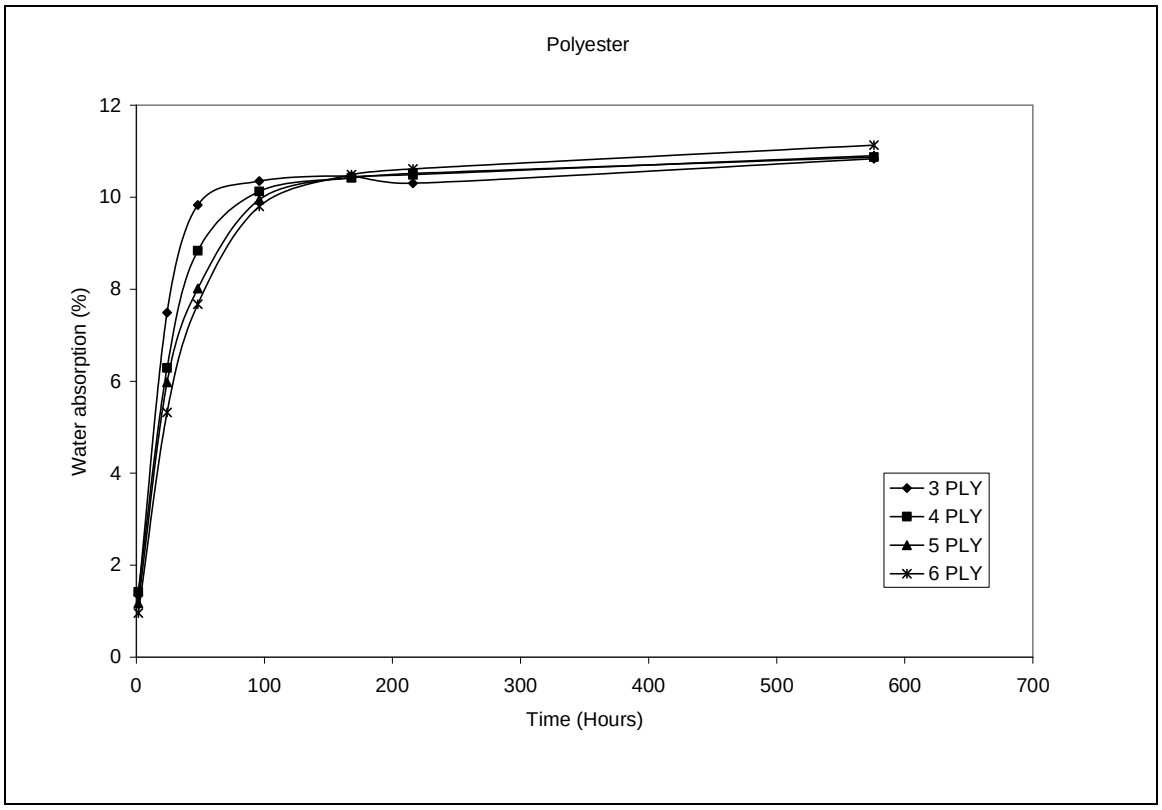


Figure 4.40: Water absorption of woven jute fabrics polyester composites.

Table 4.18: Water absorption test data for woven jute/polyvinylchloride (PVC) composite.

Composite (Fibre weight faction %)	Absorption after 1.5 hour (%) ±STD	Absorption after 24 hour (%) ±STD	Absorption after 48 hour (%) ±STD	Absorption after 96 hour (%) ±STD	Absorption after 168 hour (%) ±STD	Absorption after 216 hour (%) ±STD	Absorption after 576 hour (%) ±STD
3 ply (21.60)	4.22±0.9	7.65±0.6	8.67±0.5	9.08±0.5	9.59±0.3	9.86±0.2	10.6±0.4
4 ply (22.88)	0.87±0.2	3.71±0.3	5.11±0.4	5.95±0.7	6.20±0.2	6.38±0.3	7.14±0.5
5 ply (25.80)	0.44±0.1	2.33±0.2	3.26±0.2	4.04±0.4	4.86±0.2	5.12±0.3	6.05±0.3
6 ply (29.24)	0.33±0.1	2.22±0.1	3.13±0.1	3.81±0.1	4.78±0.1	5.03±0.1	5.83±0.1

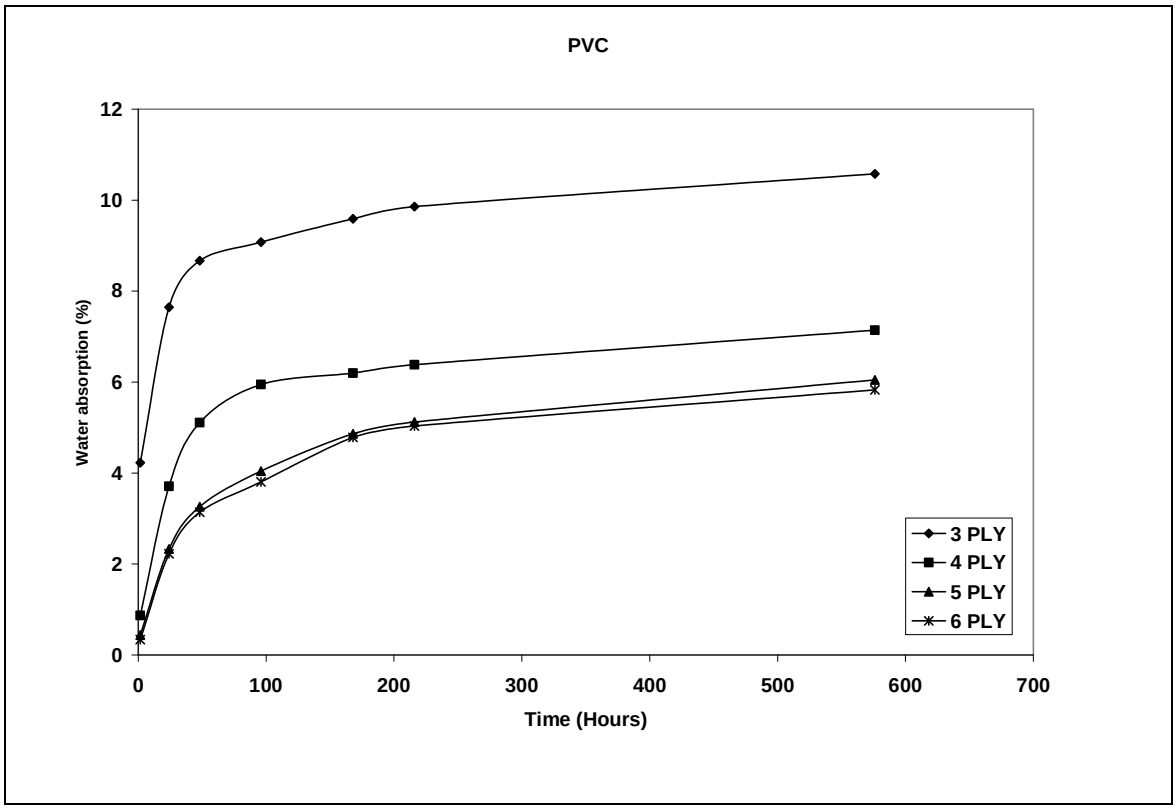


Figure 4.41: Water absorption of woven jute fabrics PVC composites.

4.6.4 Analysis of flexural properties of woven jute polyester and polyvinylchloride (PVC) composites

Results on flexure properties of woven jute fabrics reinforced polyester and PVC composites before and after water absorption test are shown in Tables 4.19 - 4.22 respectively for flexure strength, flexural modulus, strain to failure and Interlaminar Shear Stress (ILSS).

Table 4.19: Flexural strength of woven jute fabrics polyester and polyvinylchloride (PVC) composites before and after water absorption.

Number of ply (woven jute)	Flexural strength of polyester before water absorption (MPa) ± STD	Flexural strength of polyester composites after water absorption (MPa) ± STD	Flexural strength of PVC composites before water absorption (MPa) ±STD	Flexural strength of PVC composites after water absorption(MPa) ± STD
3	72.08 ± 10.93	42.80 ± 4.44	44.84 ± 5.01	35.61 ± 1.77
4	95.23 ± 8.45	49.91 ± 5.79	76.24 ± 4.42	48.67 ± 9.17
5	86.93 ± 4.03	50.55 ± 1.95	74.88 ± 6.85	50.21 ± 7.58
6	82.84 ± 10.28	51.56 ± 2.06	72.02 ± 7.53	53.36 ± 5.19

Table 4.20: Flexural modulus of woven jute fabrics polyester and polyvinylchloride (PVC) composites before and after water absorption.

Number of ply (woven jute)	Flexural modulus of polyester composites before water absorption (GPa) ± STD	Flexural modulus of polyester composites after water absorption (GPa) ± STD	Flexural modulus of PVC composites before water absorption (GPa) ±STD	Flexural modulus of PVC composites after water absorption (GPa) ± STD
3	4.22 ± 0.56	1.00 ± 0.13	2.00 ± 0.57	1.31 ± 0.09
4	6.76 ± 0.59	2.01 ± 0.30	4.80 ± 0.51	1.95 ± 0.14
5	6.40 ± 0.49	2.65 ± 0.48	5.64 ± 0.48	2.59 ± 0.25
6	6.28 ± 0.70	2.91 ± 0.26	5.92 ± 0.25	3.09 ± 0.28

Table 4.21: Strain to failure of woven jute fabrics polyester composites before and after water absorption.

Number of ply (woven jute)	Strain to failure before water absorption (%) ± STD	Strain to failure after water absorption (%) ± STD
3	5.02 ± 0.37	12.66 ± 0.96
4	4.59 ± 0.28	10.89 ± 0.79
5	4.58 ± 0.33	10.78 ± 1.06
6	4.52 ± 0.37	10.61 ± 1.03

Table 4.22: Interlaminar shear stress (ILSS) of woven jute fabrics polyvinyl (PVC) composites before and after water absorption.

Number of ply (woven jute)	ILSS before water absorption (N/mm^2) ±STD	ILSS after water absorption (N/mm^2) ± STD
3	1.48 ± 0.23	1.11 ± 0.05
4	2.38 ± 0.14	1.52 ± 0.28
5	2.30 ± 0.21	1.57 ± 0.24
6	2.22 ± 0.23	1.67 ± 0.16

Fig. 4.42 shows the flexural strength of woven jute fabrics reinforced polyester and PVC composites before and after water absorption. Both jute fabrics polyester and PVC composites show better properties before water absorption in terms of flexural strength. In comparison between polyester and PVC composites, polyester composite shows better strength for both polyester and PVC composite before water absorption. Considering among all number of ply, 4 ply have showed the largest value. This is because 4 ply shows a good mechanical interlocking. After fibre loading from 4 ply flexural strength decreases slowly with increasing fibre loading for both polyester and PVC composites before water absorption. After water absorption, however, less flexural strength shows for both polyester and PVC composites. This is due to water weaken the

interfacial bonding between fibre and matrix. It also can be observed that flexural strength increases smoothly with increasing fibre loading. Flexural strength of PVC composite with 6 ply shows bit higher than that of polyester composites. Because incase of PVC water absorption tendency much lower that polyester composites which mentioned on next article in this thesis paper.

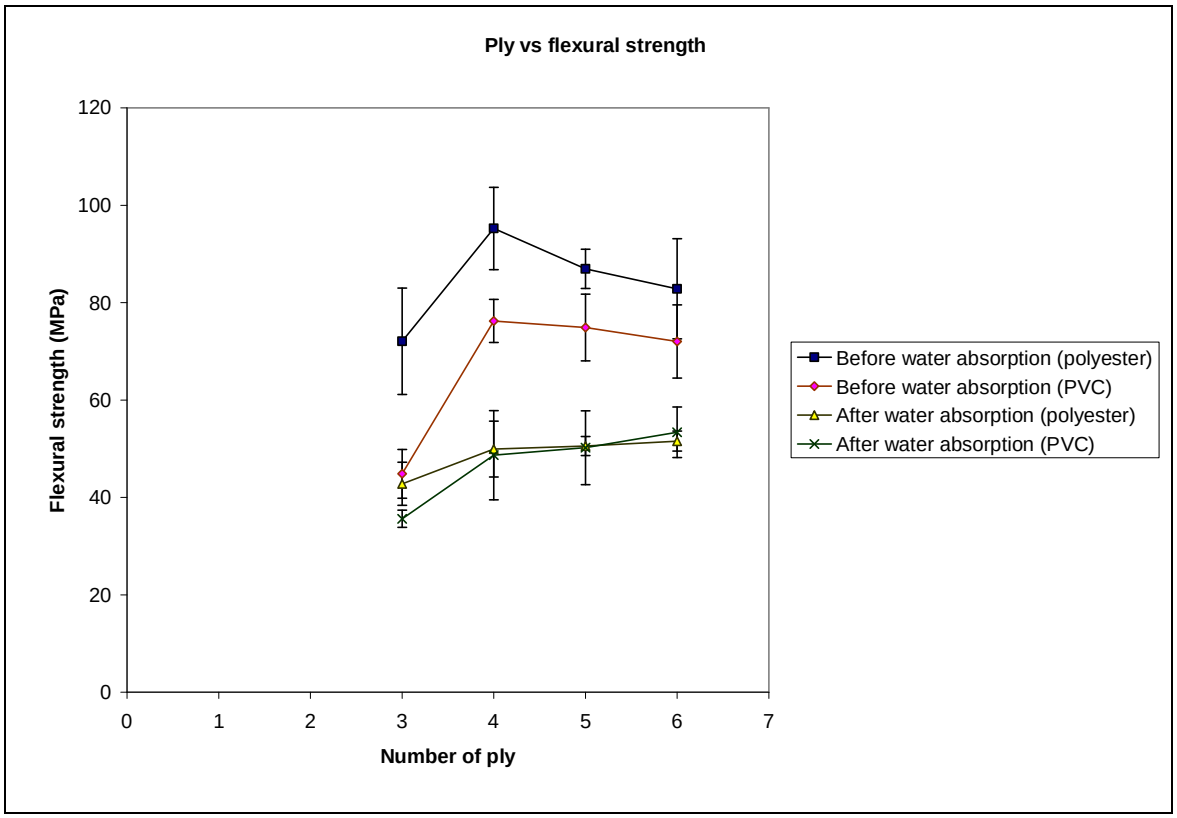


Figure 4.42: Number of ply vs flexural strength for polyester and PVC composites before and after water absorption.

Fig. 4.43 shows the flexural modulus of woven jute fabrics reinforced polyester and polyvinylchloride before and after water absorption. It seems that polyester shows better results compared to PVC composite before water absorption. In case of polyester 4 ply of woven jute fabrics shows the highest value, then the modulus decreases with increasing number of ply. PVC composite, however, the modulus increases with increasing the number of ply and 6 ply shows the highest value. The better compatibility

may arise from the opening of glucoside ring of cellulose molecules. It is quite logical to expect that better entanglement is possible from the open chain large molecule than cycle molecule. The flexural modulus decreases in both cases for the polyester and polyvinylchloride composites after water absorption. But the trend line increases with increasing number of ply. In this case both polyester and PVC composites show almost the same results.

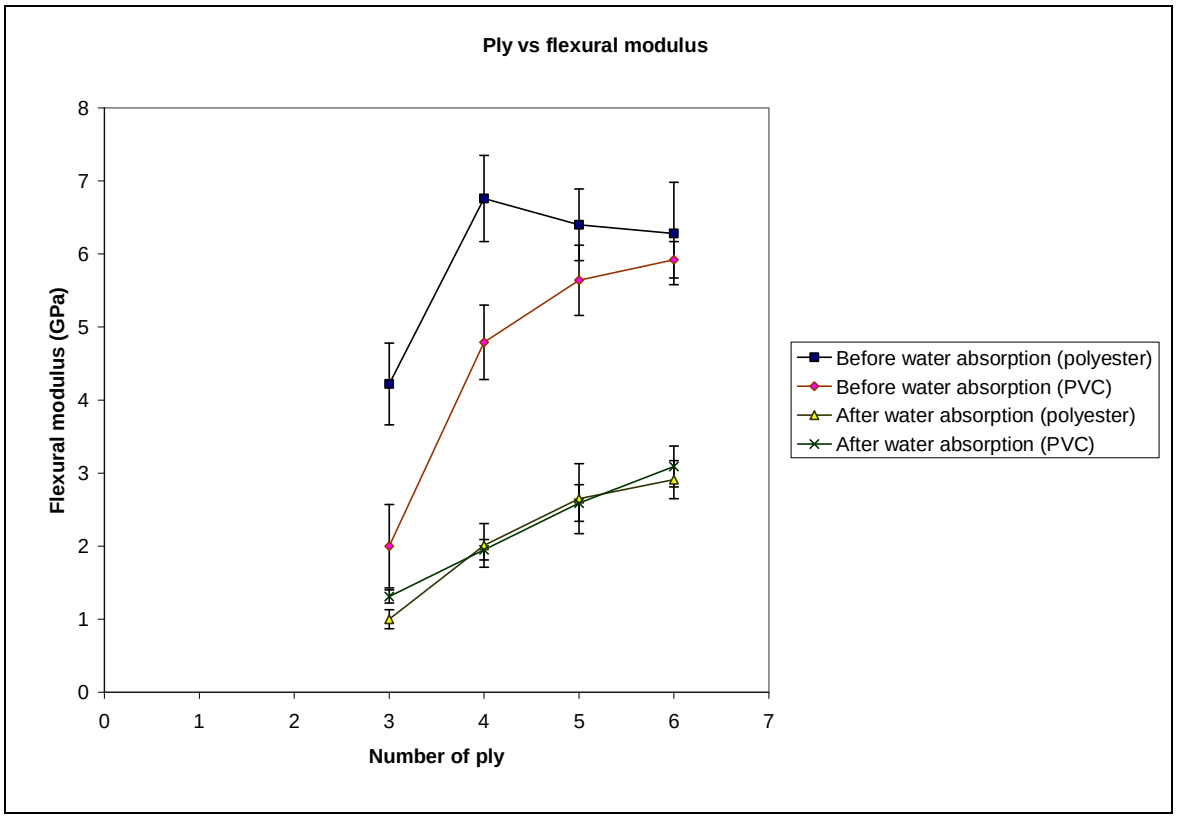


Figure 4.43: Number of ply vs flexural modulus for polyester and PVC composites before and after water absorption.

Fig. 4.44 shows strain to failure of polyester composites before and after water absorption. It is observed that strain to failure decreases with increasing the number of ply in composites. The strain to failure showed the same behavior after water absorption as mentioned above. Strain to failure after water absorption is higher for a fix ply

composite. It is found from the literature that strain to failure increases with decreasing its strength [74].

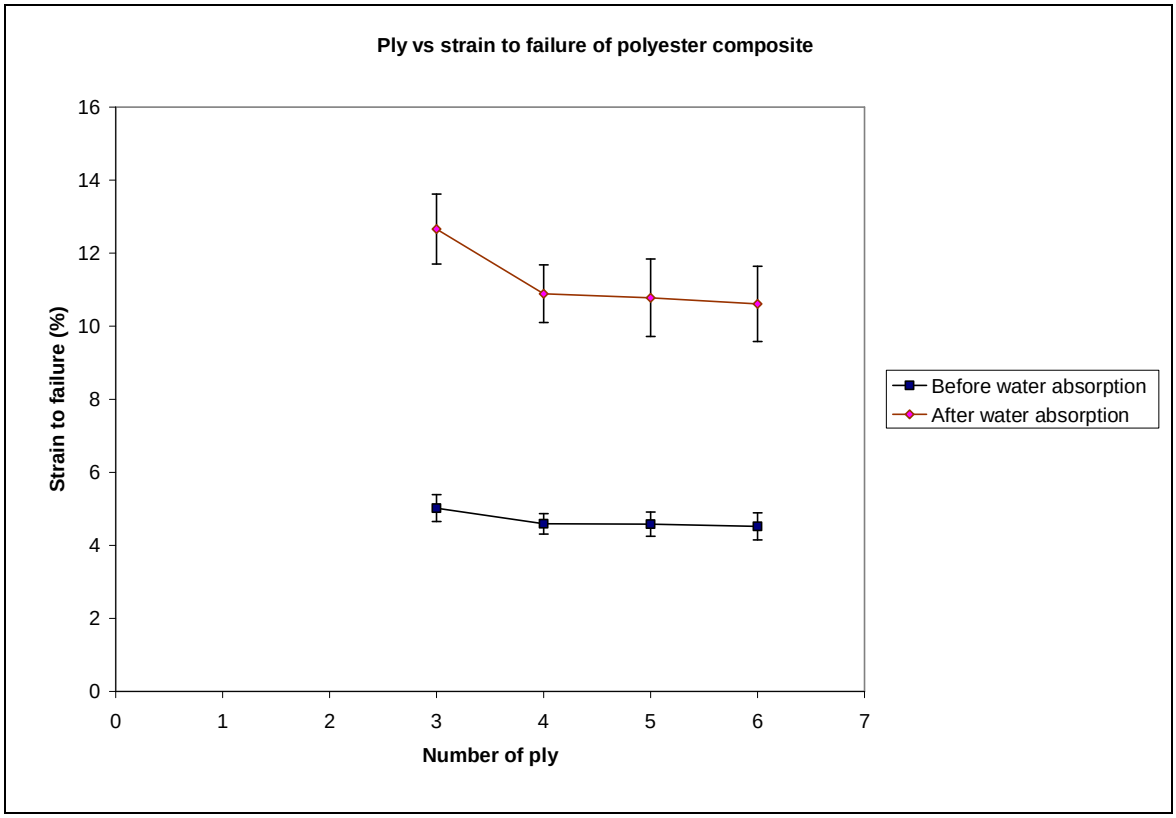


Figure 4.44: Number of ply vs strain to failure for polyester composites before and after water absorption.

Fig. 4.45 shows interlaminar shear strength (ILSS) for woven jute fabrics polyvinylchloride (PVC) composites. It can be observed that ILSS increases with increasing number of ply in composites from 3 ply to 4 ply. After it decreases with increasing ply in composites. The majority of past studies have involved processing voids introduced by entrapment of air during resin impregnation, while John et. al. [75] have described the voids present in an acid-cured phenolic matrix are much smaller and thus were referred to as micro voids. Wisnom et. al. [76] reported the results of study of ILSS reduction by voids in composites and characterized two types of voids, descrete larger voids and small distributed voids. The larger voids act as crack initiation sites

under a shear stress, whereas increase in stress due to the reduction in net cross-section was the main factor in shear failure in composites with small distributed voids. However, in order to raise ILSS achievable, the degree of microvoids is necessary. A significant decrease in ILSS after water exposure was observed in Fig. 4.45 for the entire PVC composite studied. 3 ply showed the smallest decreased. It is clearly observed that the short exposure to water can lead significant loss of ILSS.

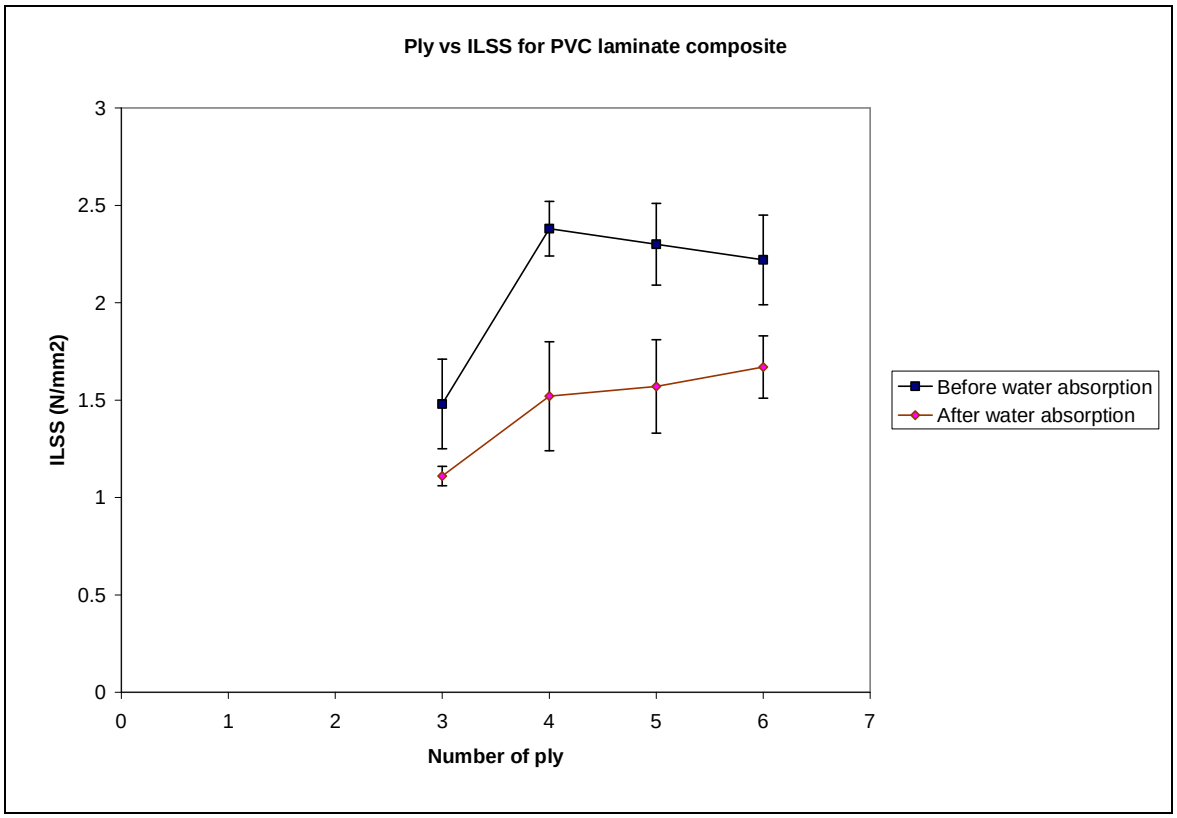


Figure 4.45: Number of ply vs interlaminar shear strength (ILSS) for PVC composites before and after water absorption.

Fig. 4.46 shows the SEM micrograph of woven jute polyester and polyvinylchloride composite. It is seem that the woven jute fabrics polyester and polyvinylchloride composite specimen were all observed to fail at the fibres located at the bottom surface, directly below the loading roller. It is also observed woven jute polyester composite breakage in a brittle manner.

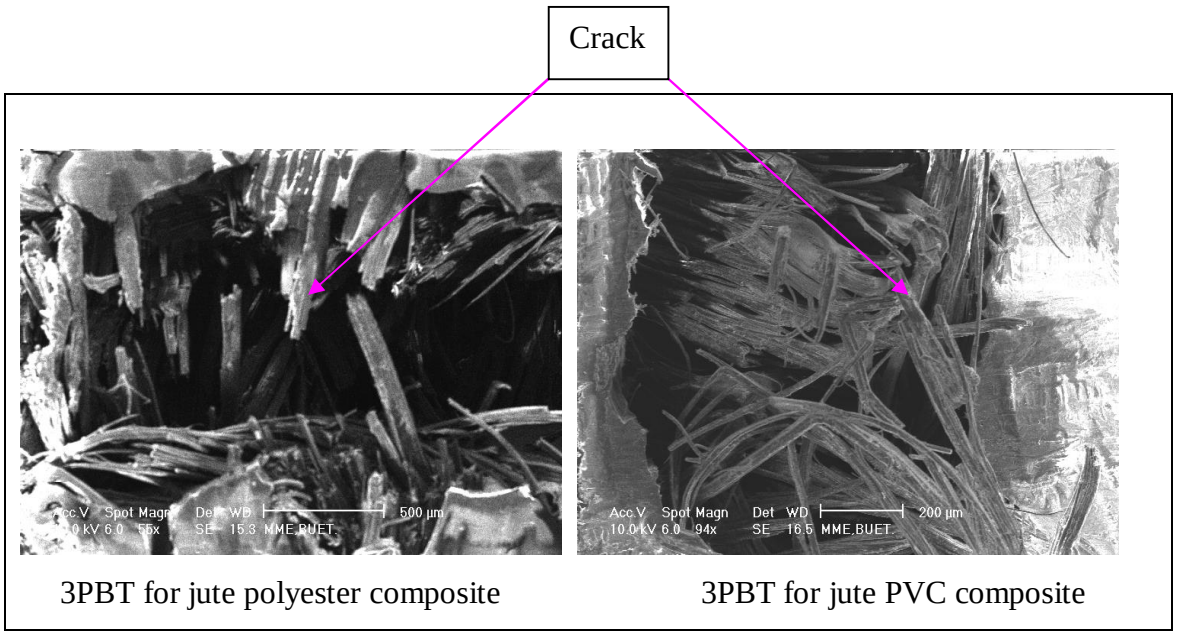


Figure 4.46: SEM micrograph of woven jute polyester and polyvinylchloride composite after 3 point bending test.

4.7 Analysis of impact properties of composites

The impact strength of jute fabrics polyester and PVC composites before and after water absorption are shown in Fig. 4.47 and Table 4.23 respectively. It is apparent from the result presented in this figure and table that values of impact strength of jute-polyester are significantly more than that of jute-PVC composites. These may be due to mechanical entanglement between the fibre and polymer matrix.

The impact performance of fibre-reinforced composites depends on many factors including the nature of the constituent, fibre/matrix interface, the construction and geometry of the composite and test conditions [77]. The impact failure of a composite occurs by factors like matrix fracture, fibre/matrix debonding and fibre pull out. Even though, fibre pull out is found to be an important energy dissipation mechanism in fibre reinforced composites [77]. The applied load transferred by shear to fibres may exceed the fibre/matrix interfacial bond strength and debonding occurs. When the stress level

exceeds the fibre strength, fibre fracture occurs. The fractured fibres may be pulled out of the matrix, which involves energy dissipation [78].

It has been reported that high fiber content increases the probability of fiber agglomeration which results in regions of stress concentration requiring less energy for crack propagation [79]. As presented in Fig. 4.47, impact strength increases with increasing number of fabrics ply for jute-polyester composites (fibre volume fraction is also increases). In the case of PVC composites, however, the situation is the same, with increasing the number of ply impact strength also increases. This result suggests that the fiber was capable of absorbing energy because of strong interfacial bonding between the fiber and matrix. Another factor of impact failure of composite is fiber pull out. With increase in fiber loading, bigger force is required to pull out the fibers. This consequently increased the impact strength.

Table 4.23: Impact strength of woven jute fabrics polyester and PVC composites before and after water absorption.

Number of ply	Impact strength of	Impact strength of polyester after	Impact strength of PVC before water	Impact strength of PVC after water

	polyester before water absorption (kJ/m^2) ± STD	**water absorption (kJ/m^2) ± STD**	**absorption (kJ/m^2) ± STD**	**absorption (kJ/m^2) ± STD**
3	9.39 ± 1.02	9.34 ± 0.55	9.08 ± 1.15	8.92 ± 0.96
4	11.59 ± 1.23	10.15 ± 0.83	10.00 ± 1.47	9.74 ± 1.31
5	12.77 ± 0.72	12.32 ± 0.89	10.64 ± 0.58	9.68 ± 0.89
6	13.14 ± 0.52	12.87 ± 0.82	11.37 ± 0.36	9.94 ± 0.69

After water absorption the trend line is the same. Impact strength increases with increasing number of ply in both composites. For jute-polyester composite impact strength is appearing little bit lower than that of before water absorption. These is due to water weaken the fibre-matrix adhesion. So it has broken easily compare to before water absorption. In the case of jute-PVC composite the impact strength also decreases after water absorption. This value is almost fixed from three ply to six ply.

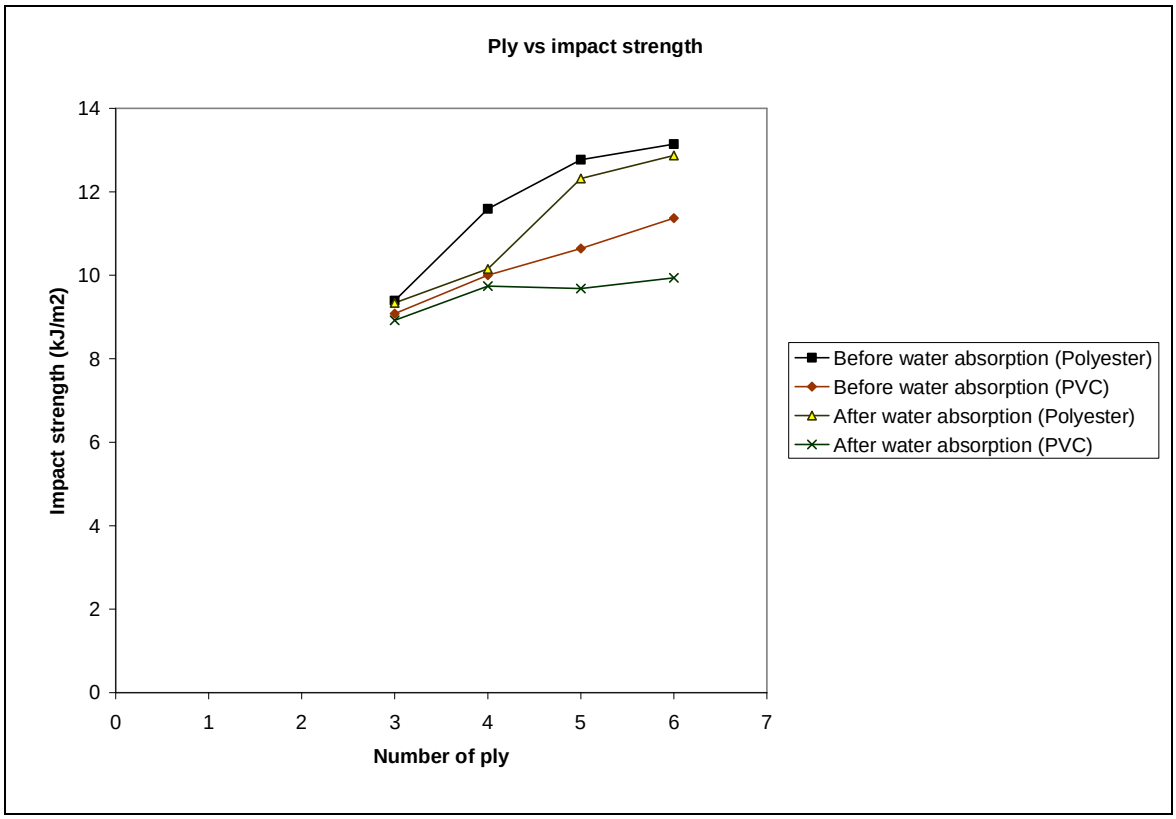


Figure 4.47: Ply vs impact strength curves for woven jute fabrics polyester and polyvinylchloride (PVC) composites before and after water absorption.

Fig. 4.48 shows the fracture surface of woven jute polyester and polyvinylchloride composites. It is observed that tendency of fibre pull out is higher in the case of polyester composite than that of PVC composite. Because the interfacial bonding between jute fibre and polyester is better than jute PVC composite.

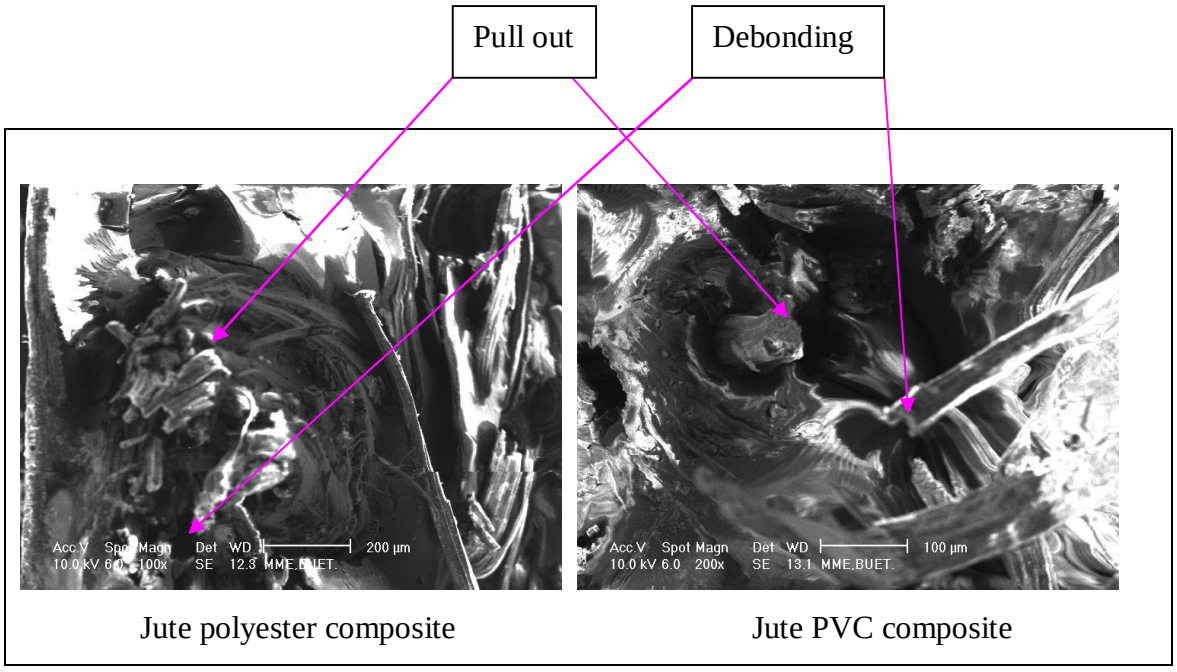


Figure 4.48: SEM image of fracture surface of woven jute fabrics polyester and polyvinylchloride composite after impact test.

4.8 Analysis of Thermo Gravimetric Analysis (TGA)

Derivative curves for jute, bamboo, brown coir and white coir fibres are shown in Figs. 4.49 - 4.52 respectively. It can be observed that all the fibre looks similar to each other. Absorbed water showed the change in the peak before approximately 100^0C for every fibre. At 190^0C bamboo fibre released more moisture in comparison to other fibres. It might be caused by increase in the surface area of the fibre increased. As a result, it is easier to evaporation of moisture at lower temperature. Among all the fibres jute showed bit higher than others and it was 256^0C and white coir showed the lowest value (245^0C). All the fibre showed decomposition in the temperature range of 240 ï 260^0C.

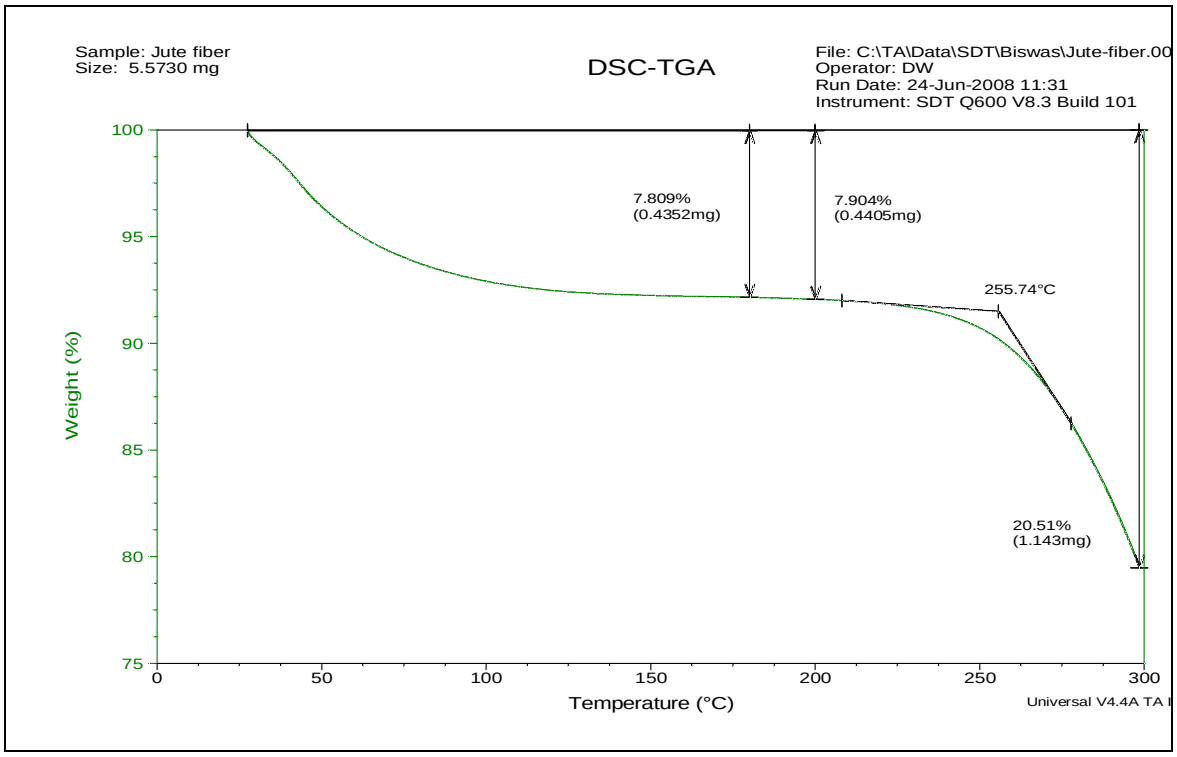


Figure 4.49: Thermo Gravimetric Analysis (TGA) of jute fibre.

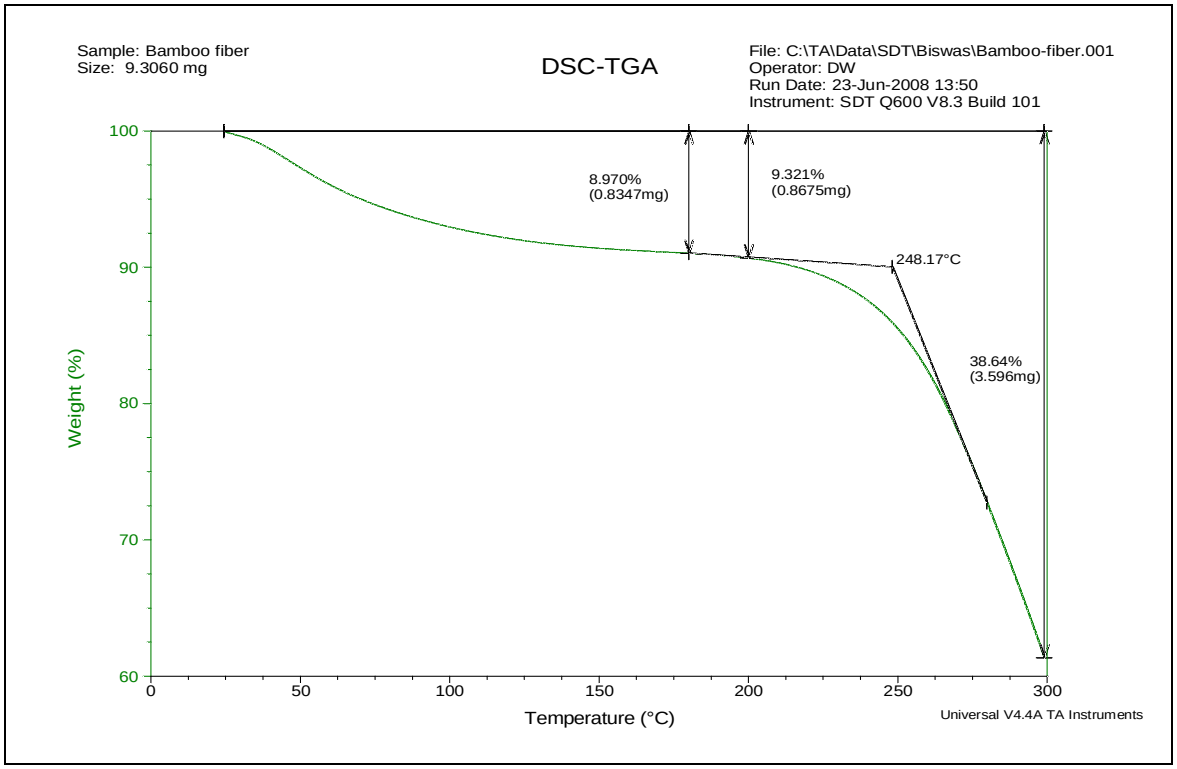


Figure 4.50: Thermo Gravimetric Analysis (TGA) of bamboo fibre.

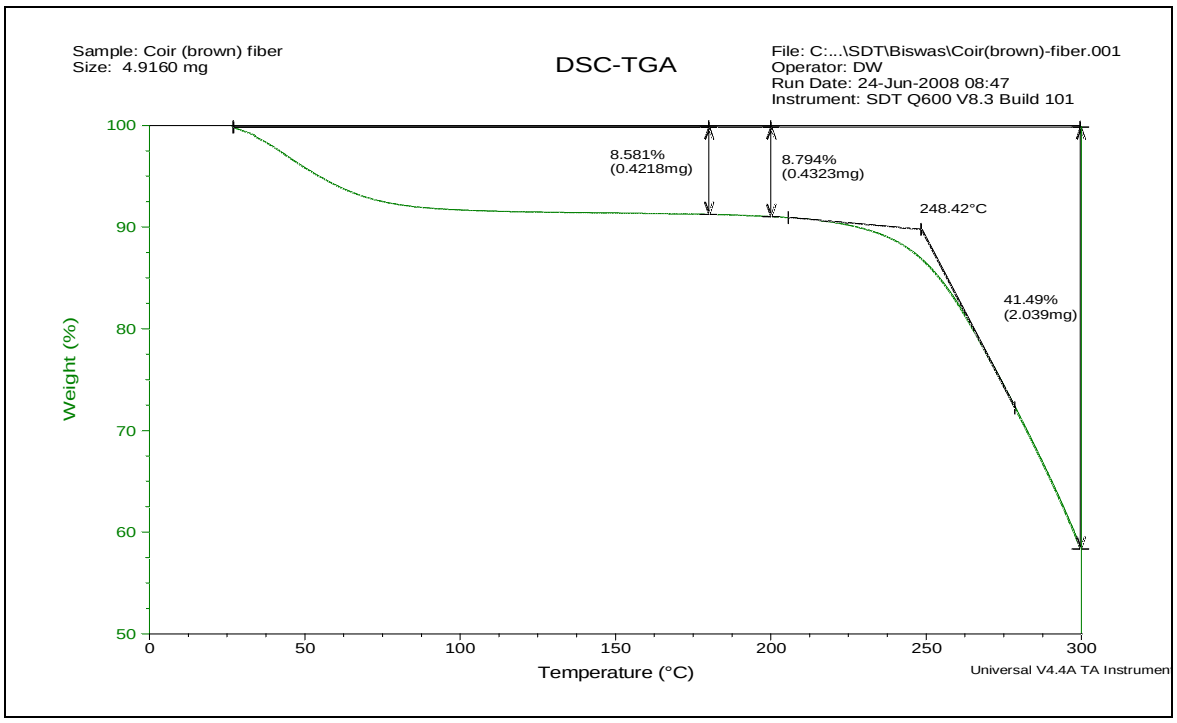


Figure 4.51: Thermo Gravimetric Analysis (TGA) of brown coir fibre.

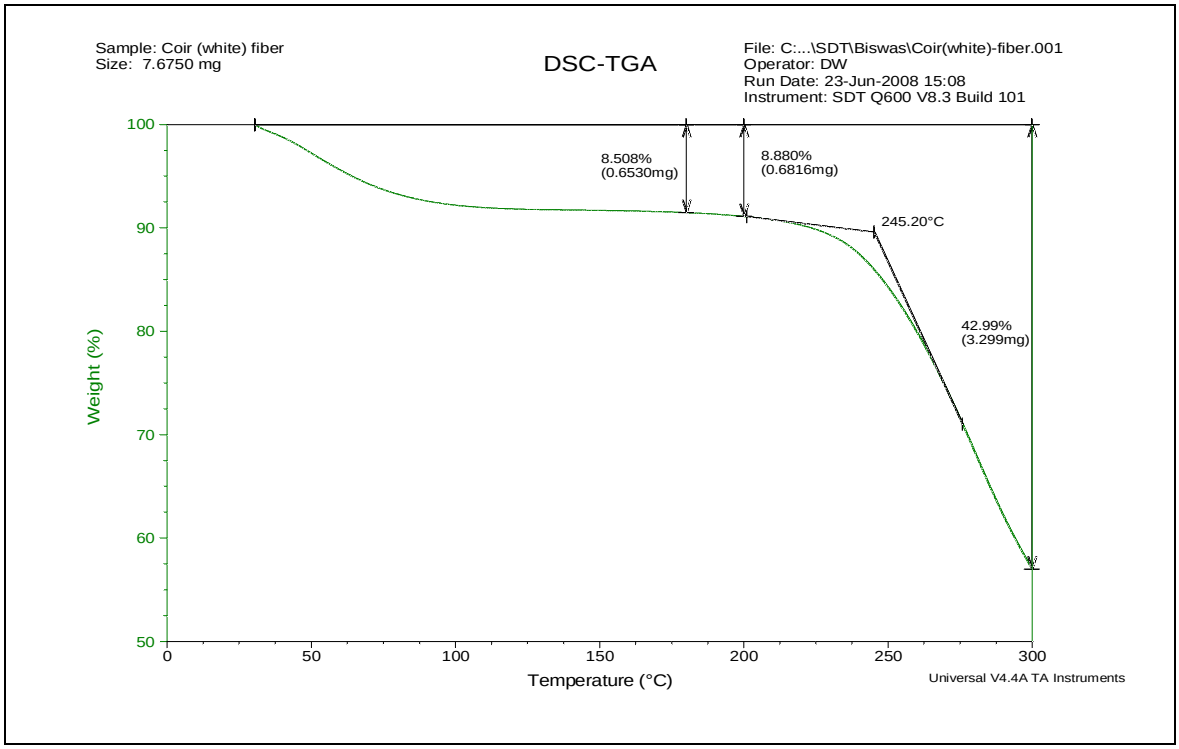


Figure 4.52: Thermo Gravimetric Analysis (TGA) of white coir fibre.

During processing of epoxy composites, jute fibres are exposed to high temperature often combined with trapped air, which might cause thermal degradation. If serious degradation of all the natural fibres occurs at the melt processing temperature, the mechanical reinforcement effect of the fibre can be decreased, with the side effects of discolouration and unpleasant odour of the composites. Therefore, thermal gravimetric analysis was used to determine the high temperature degradation behaviour of the composites as well as their components under air and nitrogen atmospheres.

Chapter 5
CONCLUSIONS

5.1 Conclusions

In the present study, tensile testing of single jute, bamboo, brown coir and white coir fibers was carried out by varying span length. Surface morphology was also observed by using Environmental Scanning Electron Microscope (ESEM). Subsequently, unidirectional and woven jute fabrics composite were manufactured and tensile, flexural (both longitudinal and transversal directional tests were conducted for UD composites) and impact properties of the composites were determined. Based on the experimental results, the following can be concluded:

- The Youngôs modulus increased when span length increased. This is because machine displacement (denoted by Ŭ) is used for the modulus determination. So at longer gauge lengths, the relative effect of slippage in the clamps will be smaller. Tensile strength and strain to failure decreased with an increase in the span length. This is due to more flaws in longer span length fibres that make the probability of failure larger.

- The results of present study also reveal that accurate results of natural fibers can be successfully found by using newly developed analytical equations. It is observed that with an increase in the span length, machine displacement (Ŭ) also decreased. Among jute, bamboo and coir fibers, bamboo fiber had the highest Youngôs modulus values.

- SEM images of tensile test fracture surface show that cracks started from the defect point (flaws) and propagated through the flaws under tensile load. The surface of jute fiber was smoother, while bamboo and coir fibers were a bit rough.

- Void free unidirectional composites were made by using vacuum technique. The analytical results showed good agreement with the experimental results. Bamboo fibre

UD composite showed good results in terms of tensile strength, while jute fibre showed better values in terms of Youngôs modulus.

ÿ Bamboo fibre composite showed good flexure strength in longitudinal distribution while jute fibre composite showed the good flexural strength in transverse fibre distribution when compare each other. This is because the interfacial bonding was better for jute/epoxy composite compared to bamboo fibre.

ÿ SEM image conformed that fibre distribution was not aligned uniformly for both bamboo and jute fibre UD composites and in case of jute fibre composites some fibre had broken during processing.

ÿ Tensile strength and Youngôs modulus increased with increasing fibre loading for both woven jute fabrics polyester and polyvinylchloride composites. Strain to failure increased with increasing fibre loading for woven jute fabrics polyester composites. However, the case is reverse for the jute fabrics polyvinylchloride composites. Again strain to failure decreased with increasing fibre loading.

ÿ In general, woven jute fabrics composite made from polyvinylchloride (PVC) showed the highest resistance to water absorption for highest fibre loading. In case of polyester composite the situation is reverse. However, the lowest resistance to water absorption was shown for highest fibre loading.

ÿ Flexural strength for both jute polyester and polyvinylchloride composites were the highest for four ply. After that with an increase in the number of woven jute fabrics ply, flexural strength decreased. Strength decreased after water absorption for both polyester and polyvinylchloride composites. Flexural modulus for polyvinylchloride increased with increasing fibre loading, where as the composite made by using four ply jute fabrics showed the highest value for polyester composite. This modulus also decreased after water absorption with the respective fibre loading. Strain to failure increased in a

large scale after water absorption for polyester composite. With increasing fibre loading, ILSS increases up to a certain limit then decreased before and after water absorption for PVC composite.

y Impact strength for both polyester and polyvinylchloride composite increased with increasing fibre loading. This strength decreased a bit for respective fibre loading after water absorption.

y Thermo Gravimetric Analysis (TGA) was carried out to compare the thermal properties. Jute fibre showed good thermal behavior compare to bamboo fibre and coir fibres. SEM images of tensile failure surface indicate that fibres were pulled out from the composite. SEM images also conform that there was a good interlocking between jute and polyester composite compared to jute-PVC composite interlocking.

5.2 Future works

y Incorporation of higher percentage of fiber could be achieved through modern mechanical device.

y The hybrid approach of blending glass mat with woven jute fabric in epoxy matrix composite can be a viable approach for enhancing the mechanical properties and dimensional stability of jute epoxy composite.

y It could be possible to incorporate foam in woven jute fabric and polymer using twin screw extruder. Produced composites might show good physical properties such as light in weight.

y Modified composites may be used in automobile (door panel, dash board cover etc.) and household (false ceiling, table top, partition etc.) sector as moderate load bearing structures.

LIST OF PUBLICATIONS

■ ***Subhankar Biswas***, Qumrul Ahsan, Ignaas Verpoest, Mahbub Hasan. **"Effect of span length on the tensile properties of natural fibers"**. Proceedings of conference on Advanced Materials Processing Technology by International Islamic University Malaysia (IIUM), 2009. ID no. 169.

■ Nele Defoirdt, ***Subhankar Biswas***, Linde De Vrieze, Le Quan Ngoc Tran, Joris Van Acker, Qumrul Ahsan, Larissa Gorbatikh, Aart Van Vuure, Ignaas Verpoest. **"Assessment of the tensile properties of coir, bamboo and jute fibre"**. Composite Part-A 41 (2010), pp 588-595. doi:10.1016/j.compositesa.2010.01.005.

■ ***Subhankar Biswas***, Rashnal Hossain, Qumrul Ahsan, Mahbub Hasan, Aart Van Vuure, Ignaas Verpoest. **"Study on physico-mechanical properties of woven jute fabric reinforced polymer composites"**. Proceedings in 3rd International Conference on Structure, Processing and Properties of Materials by Bangladesh University of Engineering and Technology (BUET), Bangladesh, 2010. Ref. ID no. E4.

■ ***Subhankar Biswas***, Rashnal Hossain, Qumrul Ahsan, Mahbub Hasan, Aart Van Vuure, Ignaas Verpoest. **"Study on Physico-Mechanical Properties of Jute, Bamboo and Coir Fiber"**. To be submited to the Journal on ǒComposites Part A-Applied Science and Manufacturingô

■ ***Subhankar Biswas***, Qumrul Ahsan, Aart Van Vuure, Ignaas Verpoest, Mahbub Hasan. **"Study on Mechanical Properties of Jute and Bamboo Fibre UD Composites"**. To be submited to the Journal on ǒComposites Part A-Applied Science and Manufacturingô

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