Influence of Fibre Architecture on Mechanical Properties of Jute Fibre Reinforced Composites

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SCHOOL OF MATERIALS
Contents

Abstract ............................................................................................................................................. 7

Declaration ......................................................................................................................................... 8

Intellectual Property Statements ....................................................................................................... 9

Acknowledgement ............................................................................................................................. 10

1 Chapter 1: Introduction ..................................................................................................................... 11
   1.1 Composite Materials .................................................................................................................. 11
   1.2 Natural Fibre Composites ......................................................................................................... 11
   1.3 Jute Fibre Reinforced Composites ............................................................................................ 12
   1.4 Aim and Objectives .................................................................................................................... 14

2 Chapter 2: Literature Review .......................................................................................................... 15
   2.1 Composites .................................................................................................................................. 15
   2.2 Types of Composites .................................................................................................................... 16
   2.3 Fibre Reinforced Composites ...................................................................................................... 17
   2.4 Textile Composites ...................................................................................................................... 17
   2.5 Manufacturing of Textile Composites .......................................................................................... 18
   2.6 Textile Preforms .......................................................................................................................... 18
      2.6.1 Preforms Classification ......................................................................................................... 18
   2.7 Matrix ........................................................................................................................................ 20
      2.7.1 Function of Matrix ................................................................................................................ 20
      2.7.2 Types of Resin ....................................................................................................................... 20
      2.7.3 Epoxy Resin .......................................................................................................................... 21
   2.8 Manufacturing of Composites ....................................................................................................... 22
      2.8.1 Vacuum Bagging .................................................................................................................... 23
   2.9 Natural Fibre Composites ............................................................................................................ 25
      2.9.1 Potentiality of Natural Fibre Composites .............................................................................. 25
      2.9.2 Market of Natural Fibre Composites .................................................................................... 26
   2.10 Natural Fibres ............................................................................................................................ 26
      2.10.1 Fibres used in Natural Composites ..................................................................................... 26
3.2.4.1 Calculation of Fibre volume fraction: ........................................... 65
3.2.4.2 Calculation of Fibre weight fraction ............................................ 66
3.2.4.3 Density Test .................................................................................. 67
3.2.4.4 Void Content .................................................................................. 68

4 Chapter 4: Results & Discussion .................................................................. 69
4.1 Properties of Reinforcing Materials ............................................................ 69
  4.1.1 Yarn ................................................................................................. 69
  4.1.2 Woven Fabric ................................................................................... 71
  4.1.3 Non-woven Mat .............................................................................. 73
  4.1.4 Carded Sliver .................................................................................. 74
4.2 Tensile Properties of Composite Laminates ................................................. 75
  4.2.1 Analysis of Tensile Properties of different Composite Laminates ....... 76
  4.2.2 Theoretical Prediction of Tensile Modulus using Rule of Mixture ....... 78
  4.2.3 Comparative Tensile properties for Three Fibre Architectures .......... 81

5 Chapter 5: Conclusion ................................................................................... 86
  5.1 Conclusion ............................................................................................. 86
  5.2 Limitations ............................................................................................ 88
  5.3 Future Work .......................................................................................... 89
Reference ......................................................................................................... 92
Figures

Figure 2-1: Vacuum bagging method of composite manufacturing........................................23
Figure 2-2: Classification of Natural Fibres (Zini and Scandola, 2011).................................26
Figure 2-3: Jute Fibres. ........................................................................................................30
Figure 2-4: Effect of fibre content and orientation on Tensile Modulus (Laranjeira et al., 2006). .................................................................................................................................33
Figure 2-5: Effect of fibre content and orientation on Tensile Strength (Laranjeira et al., 2006). .................................................................................................................................33
Figure 2-6: Influence of testing angle on the tensile strength of weft knit cloth
reinforced composites (de Carvalho et al., 2006). .................................................................34
Figure 2-7: Stress-strain diagram in weft direction (Ahmed and Vijayarangan, 2007).36
Figure 2-8: Stress-strain diagram in warp direction (Ahmed and Vijayarangan, 2007).36
Figure 2-9: Stress vs. axial strain for the tensile test on jute/epoxy in weft and warp
direction (Mir et al., 2010). ..................................................................................................37
Figure 2-10: Tensile strength of composites against jute content in PVC (Khan et al., 2012). .................................................................................................................................38
Figure 2-11: Tensile and bending modulus of jute/gelatin composites (Khan et al., 2010a). .................................................................................................................................39
Figure 2-12: Tensile strength and bending strength of the jute/gelatin composites (Khan et al., 2010a) .................................................................................................................................39
Figure 2-13: Tensile strength as a function of the angle of of testing for the different
composites: (--) as received, (- - -) acetone washed, and (. . .) detergent-washed (Acha et al., 2005). .................................................................................................................................41
Figure 2-14: Variation of tensile strength at different fibre loading (Rahman et al., 2010). .................................................................................................................................42
Figure 2-15: Variation of the Young’s modulus at different fibre loading (Rahman et al., 2010). .................................................................................................................................42
Figure 2-16: Effect of different surface modifications of jute fabrics on tensile properties
of the composites: (A) bleached; (B) detergent washed; (C) dewaxed; (D) alkali treated;
(E) cyanoethylated (Mohanty et al., 2000). ..................................................................................43
Figure 2-17: Variation of tensile strength at different fibre loading showing possible
data trend (Rahman et al., 2008). ..........................................................................................44
Figure 2-18: Effect of NaOH concentration on breaking load of jute fibers (Bera et al., 2010). .................................................................................................................................44
Figure 2-19: Tensile strengths of composites with MAgPP and VTMO treated jute
fibers (Bera et al., 2010). .........................................................................................................45
Figure 2-20: Effect of HEMA on tensile and bending strengths of composites (Khan and
Bhattacharia, 2007). ..................................................................................................................46
Figure 3-1: Jute Woven Fabrics ............................................................................................47
Figure 3-2: Jute Non-woven Mat. .........................................................................................48
Figure 3-3: Woven Fabric inside Non-woven Mat. ..................................................................48
Figure 3-4: Jute Carded Sliver. .............................................................................................48
Figure 3-5: Jute Yarn removed from Woven Fabric.................................50
Figure 3-6: Warp yarn seen in optical microscope under 5.0x optical magnifications...50
Figure 3-7: Fabric specimen for tensile test........................................52
Figure 3-8: Instron Tensile testing machine for yarn and fabric..................52
Figure 3-9: Crimp angle measurement using optical microscope..............53
Figure 3-10: Vacuum Bagging...............................................................57
Figure 3-11: Degassing machine..........................................................58
Figure 3-12: Infusion of vacuum bagged reinforcement..........................59
Figure 3-13: Curing chamber ...............................................................59

**Figure 3-14: Sandblasting machine** ...................................................60
Figure 3-15: Tabing materials attached with test specimen .....................61
Figure 3-16: Vacuum Table .................................................................62
Figure 3-17: Diamond cutter ................................................................63
Figure 3-18: Tensile testing of composite laminates in Instron machine ....64
Figure 3-19: Density measuring machine ..............................................67
Figure 4-1: Weft way crimp angle seen in optical microscope .................71
Figure 4-2: Sliver weight variations.........................................................74
Figure 4-3: Experimental and Predicted modulus of different laminates ....80
Figure 4-4: Tensile modulus (normalized) for different laminates ............82
Figure 4-5: Tensile Strength (normalized) for different laminates ............83
Figure 4-6: Arrangement of fibres in spun yarn.....................................84
Figure 4-7: Arrangements of fibres in non-woven mat ............................84
Figure 4-8: Arrangement of fibres in carded sliver.................................85

**Final Word Count: 15614**
Tables:

Table 2-1: Chemical composition and structural parameters of natural fibres (Williams and Wool, 2000) ................................................................. 27
Table 2-2: Physical properties of some natural and synthetic fibres (Zini and Scandola, 2011). ................................................................. 28
Table 2-3: Comparison of the price of some synthetic and natural fibres (Mir et al., 2010). ................................................................. 29
Table 2-4: Tensile Properties of Jute/Epoxy Composites Jieng et al., (ECCM, 2012) ... 35
Table 2-5: Tensile Properties of JEH(C) for the Optimization Study (Mishra et al., 2000). ................................................................. 35
Table 2-6: Tensile Properties of JEH-50(C) and JEH-50(B) (Mishra et al., 2000) ....... 36
Table 2-7: Tensile and bending properties of PP sheet and the composites (Khan et al., 2010b). ................................................................. 40
Table 3-1: Epoxy Resin ................................................................. 49
Table 3-2: Stacking Sequence of Reinforcing Materials .................................. 55
Table 3-3: Specification of different laminates ............................................. 65
Table 4-1: Yarn properties .................................................................. 69
Table 4-2: Yarn unevenness .................................................................. 69
Table 4-3: Yarn Tensile Properties .......................................................... 70
Table 4-4: Properties of woven fabrics ...................................................... 71
Table 4-5: Tensile properties of woven fabrics ........................................... 72
Table 4-6: Tensile properties of non-woven mats ....................................... 73
Table 4-7: Tensile properties of composite laminates ................................... 76
Table 4-8: Experimental and Predicted modulus of different laminates ......... 80
Table 4-9: Tensile modulus and strength for 20% normalized fibre volume fraction ... 82
ABSTRACT

Jute fibre reinforced epoxy based composites were manufactured by vacuum bagging method using three different jute fibre structures; woven fabric, non-woven mat and carded sliver. The composites were made using different number of layers of reinforcing materials. Then the tensile test on composite laminates was conducted in different directions of composites according to ASTM D 3039 standards. The tensile properties were evaluated as a function of fibre architecture (woven, non-woven and sliver), fibre volume fraction and direction of applied load.

The tensile modulus of woven fabric reinforced composites was found 100% higher (maximum), carded sliver reinforced composites was found 110% higher and non-woven mat reinforced composites was found 53% higher (maximum) than the tensile modulus of pure epoxy resin. There were not any significant influences found in tensile strength for jute fibre reinforcement.

The strengths and modulus of composite laminates also depend on fibre content and tensile properties of reinforcing materials. For woven fabric reinforced composites, maximum strength and modulus observed when tested along weft direction. For non-woven mat reinforced composites, maximum strength was found along Machine direction (MD). In case of woven fabric and non-woven mat reinforced composites, strength and modulus was increased with increase of fibre volume fraction.

For 20% normalized fibre volume fraction, tensile strength and modulus was found maximum for woven fabric reinforced composites tested along weft direction and minimum for non-woven mat reinforced composites; tensile strength and modulus for carded sliver reinforced composites was in between these two.

This relation between fibre architecture and tensile properties of composites is critically analyzed and reported in this research.
DECLARATION

No portion of the work referred to in the dissertation has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.
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Chapter 1: Introduction

1.1 Composite Materials

Composite materials establish themselves as superior and unique in the world of modern engineering materials. Superior specific strength and stiffness, corrosion resistance, high specific modulus made them most attractive and suitable for different high-tech engineering application (Munikenche Gowda et al., 1999). Composite materials already came a long way to replace the conventional materials like wood and metal with its wonder properties. Among different types of composites, fibre reinforced composites are most important one. The technology of fibre reinforced composites has come of age with the advancement in aerospace applications (Mir et al., 2010). Now after meeting the challenge of aerospace sector, it shows the potentiality to cater from domestic to industrial applications.

1.2 Natural Fibre Composites

Fibre reinforced composites made from synthetic fibres are not biodegradable and environment friendly. That is why with the increase of environmental consciousness, they are being criticised. Apart from this, scientists are looking for some cheap reinforcing materials to cut down the high cost of fibre reinforced composite materials (Mir et al., 2010). Natural fibre with biodegradability, environment friendly characteristics and low cost are presenting themselves to serve this purpose; though their strengths are not comparable with high performance fibres as glass, carbon or Kevlar. But, they have fairly good properties to serve in domestic and non-structural purposes.

In fibre reinforced composites, fibres have been reinforced in polymer matrix in different forms and structures. One of the most popular and economical techniques of using the fibre inside a polymer matrix is using “Textile Preforms”. Textile preforms are structures made from fibre strands using different traditional textile technique and machinery. This is the most effective way of handling fibres without any distortions before impregnation in resin. Some of the most popular preforms are woven preforms, knitted preforms, non-woven preforms etc.
Taking advantage of natural fibres (cheap, biodegradable, available) and textile preforms (easy making and cheap); natural fibre composites made, using textile preforms are expected to be a significant addition in the world of composite materials. Thus the idea of this research generated to focus on natural fibre composites from textile preforms.

1.3 Jute Fibre Reinforced Composites

There are different potential natural fibres such as flax, hemp, jute, sisal etc which are being used as reinforcement in fibre reinforced composites. Among all, jute is the cheapest and commercially most available fibre (Islam et al., 2011). This is one of the most important factors for choosing jute fibre as reinforcement, apart from its good mechanical properties and other features. The composites from jute fibre reinforcements are not suitable for high tech applications such as aerospace, but it can serves some other needs as interior parts of automobiles, furniture’s, partitions etc.

There is a long history of jute fibre reinforced composites research. Several important researches have been recognized to characterize jute fibre reinforced composites. Long jute fibre, short jute fibre, jute woven fabric, jute knitted cloth, jute sliver has been used as reinforcement for composites manufacturing in different researches. Along with this, different resin system has also been used by different research groups. These investigations were targeted to find the optimum fibre contents, best reinforcing structures, suitable matrix systems etc for jute fibre reinforced composites. There were few researches which investigate the combination of jute fibres with other natural or synthetic fibres to improve the mechanical properties of reinforced composites.

One of the major limitations of jute fibre reinforced composites is its lower mechanical properties compared to glass or carbon fibre composites. Different fibre treatment such as alkali treatment, oxidization, detergent wash, acetone wash, chemical coating has been applied on jute fibre before using as reinforcement to improve the mechanical performance of composites. Post treatment of composites was also found to be a successful technique to improve the mechanical performance of jute fibre reinforced composites.
Different important aspects of jute fibre reinforced composites are revealed from previous work. The strength and modulus of long and uniformly oriented jute fibre reinforced composites are higher than short and randomly oriented jute fibre reinforced composites (Laranjeira et al., 2006). In a research de Carvalho et al. showed that jute plain weft knitted fabric reinforced composites possess lower strength and modulus than plain woven fabric (de Carvalho et al., 2006). In the case of woven fabric reinforced composites, strength and modulus vary depending on the number of yarn in warp and weft direction (Ahmed and Vijayarangan, 2007). Also fibre loading or fibre volume fraction directly influence the mechanical properties of jute fibre reinforced composites (Khan et al., 2012)

By reviewing previous research on jute fibre reinforced composites, it was clearly understood that there is a strong correlation of composite properties with the arrangement or orientation of reinforcing fibres or preforms; and the preforms properties depend on its fibre architecture and fabrication mode.

After viewing different researches, a limited approach was realized in using different jute fibre structure as reinforcement to find out the best structure in terms of mechanical properties; since the main focuses of previous researches were to improve the mechanical performance of jute fibre reinforced composites.

Jute woven fabrics, non-woven mats or jute carded slivers are the most popular, cheap, and commercially available jute structures. So, their potentiality as reinforcing materials deserved to be investigated. But, no single approach was detected to study the jute fibre reinforced composites fabricated from different jute preforms with same matrix system and same manufacturing parameters, which is very important to understand and to come to a conclusion about the comparative mechanical properties of these preforms. That was why, this research was aiming to study the mechanical properties of jute fibre reinforced composites made from different jute preforms. The study dealt only with tensile properties.
1.4 Aim and Objectives

The aim of this research is to critically analyze the mechanical properties, more precisely the tensile properties of the jute fibre reinforced composites. The composites will be made from different commercially available textile preforms as jute woven fabrics, jute non-woven mats and jute carded sliver by resin infusion. Our aim is to see how the different fibre architecture of different textile preforms influence the mechanical properties of the final composite laminates, when all other conditions like resin system, manufacturing parameters etc remain same.

To meet the intended purpose, the following step will be carried out:

- To check the basic specification of different textile preforms intended for use as reinforcement in composite manufacturing.

- To fabricate composite laminates using commercially available jute woven fabrics with different numbers of layers and different stacking sequences.

- To fabricate composite laminate using commercially available jute non-woven mats with different numbers of layers and different stacking sequences.

- To fabricate composite laminate using commercially available jute carded slivers with different number of layers and different stacking sequences.

- To perform tensile tests on all composite laminates made.

- To critically analyze the tensile test results and find the relationship with fibre architecture.

- To theoretically predict the tensile modulus of composite laminates using rule of mixtures and compare with experimental modulus.
Chapter 2: Literature Review

2.1 Composites

A composite is the combination of two or more materials to form a new material with increased performance. The idea of a composite is particularly relevant with engineering components which may consist of two or more materials combined to give a performance superior to the properties of individual materials. For example, steel coated with a layer of zinc is galvanised steel which combines the strength of steel and corrosion resistance of zinc. Composites are not mandatorily synthetic materials; rather composites are also available in nature. In human the body, many tissues are made of stiff fibres embedded in a lower stiffness matrix which combines high strength with enormous flexibility.

Definitions: When two or more physically distinct and mechanically separable materials mixed in such a way that the dispersion of one material in the other can be done in a controlled manner to achieve optimum properties and the properties achieved are superior compared to the properties of the individual components; then this newly formed material is called composite.

In a composite, the reinforcing material is embedded within a matrix material. The main role of the reinforcing material is to reinforce the strength and stiffness whereas matrix contributes to several other properties of composites. Strong fibres cannot be used alone in composite due to their low sustainability against compressive or transverse loads. That is why matrix is used as binder to hold the fibres together and to provide protection to the fibres against environmental attack.

Before innovation of composite materials; plastics, ceramics and metals were the most popular and available engineering materials. Each of them has some distinct advantage and uniqueness to serve specific engineering purpose; as well as some limitations. But composite materials come with a couple of superior properties over all other engineering materials. Some of the distinctive features of composites materials are (Munikenche Gowda et al., 1999):

1. Superior specific strength
2. Superior specific stiffness
3. Corrosion resistance
4. High specific modulus

2.2 Types of Composites

Based on matrix materials, composites are usually classified in following categories:

**Polymer-matrix composites:** The composites where polymer based resins are used as matrix and various kinds of fibres are used as reinforcing materials are known as polymer-matrix composites. These are also known as fibre-reinforced polymer. They are mainly used in applications that involve maximum 200° C.

**Metal-matrix composites:** The composites where metals like boron/aluminium (B/Al), Graphite/aluminium (Gr/Al) are used as matrix and different kinds of fibres are used as reinforcing materials are known as metal-matrix composites. Usually these composites are used in the automobile industry with application up to 700° C.

**Ceramic-matrix composites:** The composites where ceramic is used as matrix and fibres, which can sustain above 1000° C (such as alumina, zirconium, carbon etc) are used as reinforcing materials are known as ceramic-matrix composites or CMC. They are used in high temperature environment with temperature 1200°C or above. (Derek Hull et al., 1996)

Based on origin of reinforcing materials or matrix system, composites can be classified as follow:

**Synthetic composites:** The composites where not a single constituent (reinforcement or matrix) come readily from renewable resources are known as synthetic composites or man-made composites. For example, carbon, Kevlar etc are used in synthetic composites along with polyester resin.

**Natural composites:** The composites where at least one constituent (reinforcement or matrix) come readily from renewable resources are known as natural composites or bio-
composites. Most common natural fibres are jute, flax, hemp etc that are used as reinforcing material in a natural composite.

**Hybrid composites**: The composites where more than one reinforcement or more than one matrix is used are known as hybrid composites. It can be both natural or synthetic or the combination of both. Most common combination for hybrid composites are flax-glass fibre, jute-glass fibre etc.

The classification of composites can be summarised in the following way (M.E. Tuttle., 2004)

- Depending on constituent materials origin, composites can be both natural and manmade.
- Depending on physical form of the reinforcing materials, composites can be of particulate, whisker, short fibre and continuous fibre reinforced.
- Depending on matrix materials, composites can be of metal matrix composites, ceramic matrix composites, polymer matrix composites.
- Depending on orientation of reinforcing materials, composites can be of unidirectional, bidirectional etc.

### 2.3 Fibre Reinforced Composites

In fibre reinforced composites, fibres (natural or synthetic) are used as reinforcing materials in different forms and architectures. Textile composite is a kind of fibre reinforced composites, where textile fibres are used as fibre reinforcement. The focus of this research will remain limited in textile composites.

### 2.4 Textile Composites

Usually, reinforcing materials are used in a disciplined and oriented manner inside the fibre reinforced composites. There are several different techniques by which reinforcing materials are prepared for composite manufacturing. The composites where textile
techniques are involved for preparing the reinforcing materials for final composite manufacturing are known as Textile Composites.

2.5 Manufacturing of Textile Composites

There are two distinct parts of a textile composites.

1. Dry preform.

2. Resin System.

To manufacture a textile composites, at first fibres are arranged using textile technique in a required manner which are known as dry preforms. Then these preforms are impregnated in a resin system and cured.

2.6 Textile Preforms

Textile dry preforms are simply different traditional textile structures made by using traditional textile processes such as weaving, knitting, braiding, stitching, embroidery etc.

2.6.1 Preforms Classification

Textile Preforms can be classified in following way (P. Potluri., 2002):

Woven preforms: 2D solid: broadcloth

3D solid: angle interlock, orthogonal

3D shell structures

Braided preforms: maypole braiding: flat, tubular

Bi axial, tri axial

3D solid braiding: tubular

cartesian: 2-step, 4-step
Knitted preforms:  
  - weft knitting: standard, inlayed yarns
  - warp knitting: standard, inlayed yarns
  - multiaxial
Stitched preforms  
  - conventional stitching
  - embroidery: standard, inlayed yarns

Among all those different preforms, only the most relevant ones with this research are below:

**Woven Preforms:**

Woven fabrics are traditionally produced on a loom by interlacement of two sets of yarn; warp and weft. A wide variety of woven structure such as plain, twill, satin etc. can be produced by using different interlacement techniques. Different weft insertion technologies are used for producing these woven fabrics as shuttle, rapier, projectile etc.

**Plain Weave:**

Plain-woven fabrics are produced by interlacement of two sets of yarn (warp yarn and weft yarn) in one-up and one-down manner. This is one of the simplest weave patterns possible to make by looms. The main features of plain weaves compared to other 2D weave patterns are:

+ Highest in-plane shear stiffness
+ Highest toughness
+ Higher crimp
- Less stable
- Lowest tensile stiffness
- Low mechanical properties. (P. Potluri., 2002)
Non-woven Preforms:

Usually nonwoven mats are used as nonwoven perform. The most common method of non-woven bonding to make this non-woven mat is needle punching or hydro-entanglement. But, it can be also bonded by adhesive or chemical bonding, thermal bonding and stitch bonding.

Unidirectional Preforms:

Unidirectional preforms, as the name refers; majority of the fibres will run in a single direction only and a small amount of fibre will run in the other direction with the objective of holding these primary fibres. This fibre assembly is uncrimped and straight.

2.7 Matrix

In a composite material, reinforcing fibres remain embedded in the matrix system. For fibre reinforced polymer composites, this matrix system consists of resin polymer and curing agent (known as hardener). The structural properties of the fibre-matrix interface play a vital role in the mechanical and physical properties of composite materials (M.E. Tuttle., 2004).

2.7.1 Function of Matrix

- To provide a physical form to the composites by holding fibres together.
- To distribute the fibres in a predetermined manner in the composites.
- To transmit load to the reinforcing fibres.
- To protect the fibres from environmental attack (M.E. Tuttle., 2004)

2.7.2 Types of Resin

Resins can be broadly classified as follows-
**Thermoplastic Resin:**

Thermoplastic resins derived their strength and stiffness from the inherent properties of the monomer units without being cross-linked (Derek Hull et al., 1996). They soften on heating and harden again on cooling. This softening and hardening can be carried out as desired without any appreciable effect on the materials properties. Nylon, polypropylene, ABS are the typical resins (M.E. Tuttle., 2004).

**Thermosetting Resin:**

Thermosetting polymers form a tightly bound three-dimensional network of polymer chain by non-reversible chemical cross-linking and thus the liquid resins converted into hard and solid. When cured, thermo-sets will not become liquid again on heating; although above glass transition temperature their mechanical properties will significantly change. Phenolic resin, epoxy resin etc are thermosetting resin.

For manufacturing the fibre reinforced composites, Epoxy resin has been used in this research.

### 2.7.3 Epoxy Resin

**Features:**

- Epoxy resin consists of long chain molecular structure carrying two aromatic rings at its centre and two epoxy groups at two ends.

- Epoxy resin can absorb better thermal and mechanical stresses, as it contains two aromatic rings at its centre. This eventually gives good stiffness, toughness and heat resistance properties to epoxy resin.

- Chemical structure of a typical epoxy is shown below:

- Epoxy resins are usually amber or brown in colour.

- Epoxy cured at any temperature 5° C - 150° C based on the curing agent.
• Hardener (usually amine) is used to cure epoxy resin by addition reaction. Amines make bonding with two epoxy sites in two ends of resin and thus form a complex three-dimensional molecular structure.

**Advantages:**

• High mechanical and thermal properties
• High water resistance
• High chemical resistance
• High electrical insulation
• Resistance to environmental degradation
• Low cure shrinkage

**Disadvantages:**

• Critical mixing
• Corrosive handling
• High viscosity
• Expensive

### 2.8 Manufacturing of Composites

There are several different routes of composites manufacturing. Each distinct route has its own speciality and suitability. Some of the most popular manufacturing routes are:

• Spray Lay-up
• Vacuum Bagging
- Filament Winding
- Pultrusion
- Resin Transfer
- Infusion Processes
- Prepreg Moulding
- Low-Temp Prepreg
- Resin Film Infusion
- Wet/Hand Lay-up

2.8.1 Vacuum Bagging

![Diagram of vacuum bagging method of composite manufacturing.](image)

Figure 2-1: Vacuum bagging method of composite manufacturing.

In this process (Figure 3-1), reinforcing materials along with the other manufacturing kits such as release film, peel ply, breather fabric are assembled on a coated mould and the full assembly is sealed by vacuum bagging film. The air inside the bag is extracted by suction pump and thus up to one atmosphere pressure applied to the assembly. When the arrangement is perfectly vacuum bagged, resin is
infused using external pipe by suction pump. Finally the full arrangement is kept in an oven for curing for a certain time and temperature.

**Materials Options:**
Resins: Epoxy and Phenolic resins are mostly used.
Fibres: A variety of fabric can be used.

**Main Advantages:**
Usually laminates with higher fibre content can be made in this process compared to others. This process ensures lower void contents in laminates compared to other process. The high suction force make better resin flow throughout the assembly and give better fibre wet-out. Along with this, the vacuum bag assembly reduces the scope of emission of volatiles chemical during curing, which keeps the manufacturing environment healthy and safe.

**Main Disadvantages:**
The operation of manufacturing requires a highly skilled operator as, proper vacuum bagging, resin mixing, resin degassing, controlling the resin content in laminates is determined by operator skills. The disposal of bagging materials after making the laminates is costly and labour consuming.

**Typical Applications:**
Racing car components, boat components etc
2.9 Natural Fibre Composites

Since the beginning of composite material research, researchers emphasized on synthetic matrices and reinforcements; due to their good mechanical properties and durability. In most modern times with the increase of environmental consciousness, synthetic materials are criticised due to their poor biodegradability. Hence, researchers are trying to innovate environment-friendly composite materials using natural and biodegradable reinforcing fibres such as jute, flax, hemp etc. Moreover fibre reinforced plastics with Glass, Carbon, Kevlar are extremely expensive; therefore their application is limited in aerospace industry. To optimize the cost of raw materials, scientists’ and technologists have been attracted by natural fibres like jute, sisal, coir etc. (Munikenche Gowda et al., 1999). Thus the term “Natural Composite” comes in use and is a popular name in the domain of composite material (Islam et al., 2011).

2.9.1 Potentiality of Natural Fibre Composites

Natural fibre composites have been appreciated due to their different special properties and advantage compared to other materials (Munikenche Gowda et al., 1999) such as:

- Lower weight
- High strength to weight ratio
- Better electrical resistance
- Good thermal and acoustic insulating properties due to hollow & cellular structure of fibre
- Higher resistance to fracture
- Biodegradable
- Cheap and available raw materials

These special features give them the potential for various applications. Though there are certain characteristics which limit their scope and potentiality.
2.9.2 Market of Natural Fibre Composites

To cater for increased environmental concern and the search for an eco-friendly and green material, natural fibre composites might be the best options among all alternatives. Natural fibre composites have wide application in automobiles, household materials, low engineering materials, furniture etc. European automotive industry used 43,000 tonnes of natural fibres as composite reinforcing materials in 2003. In 2010, this raised to 315,000 tonnes, which is 13% of the total amount of fibre used (natural and synthetic fibres) in fibre reinforced composites in European Union (Liu et al., 2007, HOBSON and CARUS, 2011). They also planned to use 95% recyclable materials and 20% green materials in construction of vehicles by 2015 (Binetruy and Boussu, 2010). These data shows the huge potential of natural composites market.

2.10 Natural Fibres

2.10.1 Fibres used in Natural Composites

There are a wide ranges of fibres available from natural resources. Based on the origin fibres can be classified as below (Figure 2-2) (Zini and Scandola, 2011).

![Classification of Natural Fibres](image-url)

**Figure 2-2: Classification of Natural Fibres (Zini and Scandola, 2011).**
The scope of application of these fibres as reinforcing materials depends on properties of particular fibres, commercially available form and ultimate end use of the composite materials made. Usually the following range of fibres are popular as reinforcing materials for composites:

- **Bast Fibres:** Flax, hemp, jute, kenaf, ramie etc are most popular bust fibres used in natural composites.

- **Leaf Fibres:** Sisal, abaca, banana, palm etc are popular leaf fibres used in natural composites.

- **Fruit Fibres:** cotton, coir, kapok etc are well known seed fibre used in natural composites.

### 2.10.2 Chemical Composition

Basically, cellulosic fibres such as jute, flax, hemp etc are used as reinforcement in natural fibre composites due to their good mechanical properties. The percentage of cellulose and other constituents along with micro fibril arrangement plays an important role in determining the properties of a cellulosic fibre as well as composites reinforced by them. Chemical composition of most popular natural fibres, used as reinforcement in fibre reinforced composites are stated here (Table 2-1) (Williams and Wool, 2000):

**Table 2-1: Chemical composition and structural parameters of natural fibres (Williams and Wool, 2000).**

<table>
<thead>
<tr>
<th>Fiber</th>
<th>Cellulose (%)</th>
<th>Hemi-cellulose (%)</th>
<th>Lignin (%)</th>
<th>Extractives (%)</th>
<th>Ash (%)</th>
<th>Pectin (%)</th>
<th>Wax (%)</th>
<th>Microfibril/epitaxial angle (°)</th>
<th>Moisture content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jute</td>
<td>61–71</td>
<td>13.6–20.4</td>
<td>12–13</td>
<td>/</td>
<td>/</td>
<td>0.2</td>
<td>0.5</td>
<td>8.0</td>
<td>12.6</td>
</tr>
<tr>
<td>Flax</td>
<td>71–78</td>
<td>18.6–20.0</td>
<td>2.2</td>
<td>2.3</td>
<td>1.5</td>
<td>2.2</td>
<td>1.7</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Hemp</td>
<td>70.2–74.4</td>
<td>17.9–22.4</td>
<td>3.7–5.7</td>
<td>3.6</td>
<td>2.6</td>
<td>0.9</td>
<td>0.8</td>
<td>6.2</td>
<td>10.8</td>
</tr>
<tr>
<td>Kenaf</td>
<td>53–57</td>
<td>15–19</td>
<td>5.9–9.3</td>
<td>3.2</td>
<td>4.7</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Sisal</td>
<td>67–78</td>
<td>10–14.2</td>
<td>8–11</td>
<td>/</td>
<td>1</td>
<td>10</td>
<td>2.0</td>
<td>20.0</td>
<td>11.0</td>
</tr>
<tr>
<td>Cotton</td>
<td>82.7</td>
<td>5.7</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>0.6</td>
<td>/</td>
<td>/</td>
</tr>
</tbody>
</table>
2.10.3 Mechanical Properties

The mechanical properties of natural fibres are not comparable to synthetic fibres. That is the main reason of why natural fibre composites are not suitable for hi-tech purpose like aerospace application. But they have fairly good properties to serve in different low strength purpose. Mechanical properties of different popular natural and synthetic fibres are stated here (Table 2-2) (Zini and Scandola, 2011):

Table 2-2: Physical properties of some natural and synthetic fibres (Zini and Scandola, 2011).

<table>
<thead>
<tr>
<th>Fiber</th>
<th>Density (g/cm³)</th>
<th>Elongation (%)</th>
<th>Young’s modulus (GPa)</th>
<th>Tensile strength (MPa)</th>
<th>Specific tensile strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-glass</td>
<td>2.5</td>
<td>2.5</td>
<td>70</td>
<td>2000-3500</td>
<td>800-1400</td>
</tr>
<tr>
<td>Aramide</td>
<td>1.4</td>
<td>3.3-3.7</td>
<td>63-67</td>
<td>3000-3150</td>
<td>2140-2250</td>
</tr>
<tr>
<td>Carbon</td>
<td>1.4</td>
<td>1.4-1.8</td>
<td>230-240</td>
<td>4000</td>
<td>2860</td>
</tr>
<tr>
<td>Flax</td>
<td>1.5</td>
<td>1.2-3.2</td>
<td>27-80</td>
<td>345-1500</td>
<td>230-1000</td>
</tr>
<tr>
<td>Cotton</td>
<td>1.5-1.6</td>
<td>3.0-10.0</td>
<td>5.5-12.6</td>
<td>287-800</td>
<td>190-530</td>
</tr>
<tr>
<td>Jute</td>
<td>1.3-1.5</td>
<td>1.5-1.8</td>
<td>10-55</td>
<td>393-800</td>
<td>300-610</td>
</tr>
<tr>
<td>Hemp</td>
<td>1.5</td>
<td>1.6</td>
<td>70</td>
<td>550-900</td>
<td>370-600</td>
</tr>
<tr>
<td>Sisal</td>
<td>1.3-1.5</td>
<td>2.0-2.5</td>
<td>9.4-28</td>
<td>511-635</td>
<td>390-490</td>
</tr>
<tr>
<td>Ramie</td>
<td>1.5</td>
<td>2.0-3.8</td>
<td>44-128</td>
<td>400-938</td>
<td>270-620</td>
</tr>
<tr>
<td>Coir</td>
<td>1.2</td>
<td>15-30</td>
<td>4-6</td>
<td>131-220</td>
<td>110-180</td>
</tr>
<tr>
<td>Soft wood Kraft</td>
<td>1.5</td>
<td>–</td>
<td>40</td>
<td>1000</td>
<td>670</td>
</tr>
<tr>
<td>Chicken feathers</td>
<td>0.89</td>
<td>–</td>
<td>3-10</td>
<td>100-200</td>
<td>112-220</td>
</tr>
<tr>
<td>Silkworm silk</td>
<td>1.3-1.4</td>
<td>15</td>
<td>0.5</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

2.10.4 Price of Natural Fibres

One of the major barrier in wide application of fibre reinforced composites in different engineering and non-engineering purpose is its high cost. A large part of this cost comes from the cost of the raw materials. Hence the price of reinforcing fibres is an important factor. One of the most important reason of why materials scientist all over the world concentrate on natural fibre reinforced composites is, primarily to cut down the cost of raw materials (Mir et al., 2010).:
Table 2-3: Comparison of the price of some synthetic and natural fibres (Mir et al., 2010).

<table>
<thead>
<tr>
<th>Fiber</th>
<th>Carbon</th>
<th>Steel</th>
<th>Glass</th>
<th>Sisal</th>
<th>Jute</th>
<th>Coir</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost (USD $/kg)</td>
<td>200</td>
<td>30</td>
<td>3.25</td>
<td>0.36</td>
<td>0.30</td>
<td>0.25</td>
</tr>
<tr>
<td>Modulus Cost (GPa kg/$)</td>
<td>2.0</td>
<td>6.7</td>
<td>21.5</td>
<td>41.7</td>
<td>43.3</td>
<td>20.0</td>
</tr>
</tbody>
</table>
2.11 Jute Fibres

![Image of Jute Fibres](image)

**Figure 2-3: Jute Fibres.**

Jute is an agricultural fibre (Figure 2-3) grown mainly in South Asia (Bangladesh, India, Nepal, Myanmar etc). It is the cheapest among all natural fibre. Along with this, it is commercially available in any form required. (Islam et al., 2011). Traditionally, it is used mainly as bags, packaging materials, handicrafts, carpet backing cloths etc. There are lot of different types of jute grown around the world.

From the raw Jute division of the Indian Jute Institute Research Association, approximately one thousand varieties of jute have been identified. (Munikenche Gowda et al., 1999).
2.11.1 Constituents of Jute Fibre

The main constituents of jute fibre are (Islam et al., 2011):

α - cellulose

Hemi-cellulose

Lignin

Fats and waxes

Inorganic matters

Nitrogenous matters

Traces of pigments like β-carotene and xanthophylls

**Cellulose:**

Cellulose of jute fibre is highly crystalline and it constitutes the main building materials of its ultimate cells. Degree of polymerization (DP) of jute is reported to be one of the lowest among the vegetable fibres, which is around 1150.

**Hemi cellulose:**

Hemi cellulose is a chain molecular substance, having a relativity short chain length (DP not more than 150) and being mainly composed of pentsans, hexosans and uronic acid.

**Lignin:**

Lignin is a complex polymer which functions as the structural materials in jute. The structural unit of lignin are aromatic alcohols with a phenyl propane backbone, such-as p-coumaryl alcohol etc. lignin from all sources contains similar types of functional groups such as hydroxyl, methoxy, dioxyethylene, complex etc. which increase the fibre strength and also reduce the flexibility and extension of the fibre.
2.11.2 Speciality of Jute Fibres

The following characteristics make jute fibre an attractive choice for natural fibre reinforced composites (Munikenche Gowda et al., 1999):

- Eco-friendly
- Non-toxic
- Non-health hazardous
- Specific gravity 1.5 g/cc, where glass 2.5
- Low cost
- Easily available
- Biodegradable
- Moderate moisture regain

2.11.3 Limitation of Jute Fibres

Being a natural fibre, jute has some distinct characteristics which limit its suitability as reinforcing materials in fibre reinforced composites. Some of those are stated below (Munikenche Gowda et al., 1999) and (Acha et al., 2005):

- Cross-section is highly non-uniform
- Physical and mechanical properties are highly inconsistent depending on different factors as origin, growth condition and fibre extraction technique.
- Coarseness
- Low extensibility
- Moderate wash shrinkage
- Limited maximum processing temperature
- Susceptible to microbial attack
- Poor crease recovery
2.12 Review of Previous Researches

Jute fibres have been used as reinforcing materials in different forms and structures for polymer matrix composites for a long time. The reinforcing effect and mechanical properties of composites have been investigated by different group of researchers.

Laranjeira et al. (Laranjeira et al., 2006) investigated the influences of fibre orientation on the mechanical properties of unsaturated polyester/jute composites. They prepared composites from uniformly distributed long jute fibre (200 mm) and randomly oriented short jute fibre (10 mm) using compression moulding technique. The tensile properties for uniformly distributed long jute fibre composites were found to be higher (tested along fibre length) compared with randomly oriented short jute fibre composites.

The graphs demonstrate some clear idea about the relationship among the tensile properties of composites and reinforcing fibre length and orientations (Figure 2-4 & Figure 2-5). Though short and randomly distributed fibres exhibit lower tensile properties, but still it proves its potentiality in bringing reinforcing effect in a polymer matrix.

In a research De Carvalho deals with jute plain woven fabric and plain weft knitted fabric (de Carvalho et al., 2006). They studied the mechanical behaviour of jute fibre reinforced composites made from plain woven fabric and plain weft knitted fabric. They
used compression moulding technique for composites fabrication and achieved fibre weight fraction 16-48 wt% and 26-38 wt% with knit and woven fabrics respectively.

They reported that fibre incorporation was not able to bring any reinforcing effect in the case of knit fabrics and a weak fibre-matrix interface developed. The scanning electron microscopic analysis confirms the development of weak fibre-matrix interfaces (De Albuquerque et al., 2000). Due to this weak interface, stress transfer from matrix to the fibre was not adequate. That is why the tensile properties of this composite did not significantly change with fibre orientation and fibre content, with respect to the tensile load direction (Figure 2-6).

Knit fabrics exhibit uneven distribution of the fibre along the plane of the fabric, which has been reported as the reason for the weak fibre-matrix interface development.

Better tensile properties have been reported in case of woven fabric reinforced composites. With the increase of fibre weight fraction, strength improved, which demonstrate the better reinforcing capability of woven fabric than the weft knit fabrics.

In most recent times, jute 3D fabric was also used as reinforcing materials in fibre reinforced composites. Jieng et al., (ECCM, 2012) studied the mechanical properties of 2D and 3D jute fabric reinforced epoxy composites. They made composites by the hot pressing method using pure (10% alkali solution treated) and washed jute fibres, in 2D fabric and 3D orthogonal fabric form. They tested tensile properties according to ASTM 3039 and the following results were achieved:
Table 2-4: Tensile Properties of Jute/Epoxy Composites Jieng et al., (ECCM, 2012).

<table>
<thead>
<tr>
<th>Materials</th>
<th>Modulus (MPa)</th>
<th>Break Stress (MPa)</th>
<th>Strain at Break (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy</td>
<td>2449.43</td>
<td>64.37</td>
<td>4.86</td>
</tr>
<tr>
<td>2D/Epoxy</td>
<td>3099.91</td>
<td>62.56</td>
<td>2.64</td>
</tr>
<tr>
<td>3D/Epoxy</td>
<td>2822.73</td>
<td>34.06</td>
<td>1.33</td>
</tr>
</tbody>
</table>

The modulus of 2D jute/epoxy and 3D jute/epoxy were found to be 26.6% and 15.2% higher than pure epoxy specimens. 2D jute/epoxy composites found better in tensile strength but weak in tensile deformation; whereas resistance to tensile elongation was improved by 3D jute fabric reinforcement.

A research has been carried out by Mishra et al. (Mishra et al., 2000) on jute sliver reinforced epoxy composites. The composites were fabricated by compression moulding technique using untreated (named controlled = C) and bleached (B) jute sliver as reinforcement. Different fibre loading percentages were used in different composites. The Properties of three composites JEH-40, JEH-50 and JEH-57 were reported (where JEH = jute epoxy hot curing and 40, 50 & 70 are different fibre loading percentage.)

Table 2-5: Tensile Properties of JEH(C) for the Optimization Study (Mishra et al., 2000).

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Specification</th>
<th>Ultimate strength (MPa)</th>
<th>Ultimate strain (%)</th>
<th>Toughness (MPa)</th>
<th>Tensile energy absorption (N/mm)</th>
<th>Tensile modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JEH-40</td>
<td>Average</td>
<td>139.8</td>
<td>7.316</td>
<td>3.731</td>
<td>10.099</td>
<td>2826</td>
</tr>
<tr>
<td></td>
<td>Standard deviation</td>
<td>4.594</td>
<td>0.694</td>
<td>0.319</td>
<td>1.275</td>
<td>146</td>
</tr>
<tr>
<td>JEH-50</td>
<td>Average</td>
<td>148.3</td>
<td>6.393</td>
<td>3.969</td>
<td>10.743</td>
<td>3184</td>
</tr>
<tr>
<td></td>
<td>Standard deviation</td>
<td>6.944</td>
<td>0.928</td>
<td>0.347</td>
<td>1.354</td>
<td>620</td>
</tr>
<tr>
<td>JEH-57</td>
<td>Average</td>
<td>145.355</td>
<td>5.978</td>
<td>3.770</td>
<td>10.206</td>
<td>3060</td>
</tr>
<tr>
<td></td>
<td>Standard deviation</td>
<td>4.062</td>
<td>0.919</td>
<td>0.330</td>
<td>2.083</td>
<td>185</td>
</tr>
</tbody>
</table>

For 50% fibre loading, the tensile modulus was maximum. Beyond 50%, tensile modulus decreased with the increase of fibre loading%. According to the researchers, this is due to poor wetting of jute fibre by resin above 50% fibre content.
They made composites using untreated jute sliver “JEH-50 (C)” and bleached jute sliver “JEH-50(B)” in 50% fibre content (considering this as the optimized fibre assembly). The tensile properties achieved are shown below:

Table 2-6: Tensile Properties of JEH-50(C) and JEH-50(B) (Mishra et al., 2000).

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Specification</th>
<th>Ultimate strength (MPa)</th>
<th>Ultimate strain (%)</th>
<th>Toughness (MPa)</th>
<th>Tensile energy absorption (N/mm)</th>
<th>Tensile modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JEH-50(C)</td>
<td>Average</td>
<td>148.3</td>
<td>6.292</td>
<td>3.969</td>
<td>10.743</td>
<td>3184</td>
</tr>
<tr>
<td></td>
<td>Standard deviation</td>
<td>6.944</td>
<td>0.928</td>
<td>0.347</td>
<td>1.354</td>
<td>620</td>
</tr>
<tr>
<td>JEH-50(B)</td>
<td>Average</td>
<td>131.085</td>
<td>7.412</td>
<td>4.150</td>
<td>11.683</td>
<td>2348</td>
</tr>
<tr>
<td></td>
<td>Standard deviation</td>
<td>23.863</td>
<td>0.904</td>
<td>0.564</td>
<td>2.186</td>
<td>261</td>
</tr>
</tbody>
</table>

The tensile strength for bleached sliver composite is lower than untreated sliver composite. During bleaching jute fibres lose lignin (the cementing material) by delignification, thus the tensile strength of jute fibres decrease and subsequently tensile strength for bleached sliver reinforced composites decrease.

Researchers used jute fibres with different resin system and the mechanical and other properties of those composites were investigated. Ahmed and Vijayarangan (Ahmed and Vijayarangan, 2007) characterized woven jute-fabric reinforced isothalic polyester composites. They have used plain weave jute fabric (22 warp yarn of 310 Tex and 12 weft yarn of 280 Tex) as a reinforcement to make composites by the compression moulding technique. The composite laminates has been tested according to ASTM D 3039 in both warp and weft direction.

![Figure 2-7: Stress-strain diagram in weft direction (Ahmed and Vijayarangan, 2007).](image1)

![Figure 2-8: Stress-strain diagram in warp direction (Ahmed and Vijayarangan, 2007).](image2)
The average tensile strength achieved was 80.19 MPa and 40.50 MPa for warp and weft direction respectively (Figure 2-7 & Figure 2-8). There was a higher number of yarn in warp direction than weft, which offers greater resistance to crack propagation in warp direction. Thus we understand how the factors of a woven fabric directly influence the tensile properties of fabric reinforced composites.

(Mir et al., 2010) studied the mechanical properties of Jute/Epoxy composite laminates. The composite was prepared with jute woven fabric using infusion process. The laminates were tensile tested both in warp and weft direction. The strength observed in warp and weft direction is 43 MPa and 61 MPa respectively (Figure 2-9).

![Figure 2-9: Stress vs. axial strain for the tensile test on jute/epoxy in weft and warp direction (Mir et al., 2010).](image)

The variation of yarn diameter and mode of weaving was reported as the primary reason of this difference in strength. Also there were more number of yarns in weft direction than warp; what gave higher strength in weft direction.

An almost similar observation was found in the case of untreated jute fabric reinforced polyester composites (Munikenche Gowda et al., 1999). The study reported the variation of number of warp and weft yarns as the reason of strength variation between warp and weft direction of composites laminate.
Khan et al. (Khan et al., 2012) made composites by reinforcing jute hessian cloths in polyvinyl chloride using compression moulding technique.

![Tensile strength of composites against jute content in PVC](image)

Figure 2-10: Tensile strength of composites against jute content in PVC (Khan et al., 2012).

They showed that composites with 40% jute fibres demonstrate the best performance due to maximum fibre orientation and most uniform stress transfer from continuous polymer matrix to the dispersed fibre phase. At low fibre level, composites shows poor mechanical properties due to poor fibre population and lower load transfer. Again at high fibre level (more than 40%), poor mechanical properties were observed due to non-uniform stress transfer and high fibre agglomeration within the matrix (Figure 2-10). Similar observations were reported in the case of jute woven fabric reinforced gelatine composites (Khan et al., 2010a). They showed that, tensile strength decreases with the increase of fibre loading after a certain limit (50 wt%)
This is an important paper which demonstrates, how the properties of a composite laminate vary with the variation of amount of reinforcing fibre inside it, in case of jute fibre reinforced composites. It also shows the optimum fibre loading to achieve best tensile properties from a jute fibre reinforced composites.

Jute fibre reinforced composites have a couple of important features such as higher specific strength, low cost, biodegradability etc. But at the same time, they have some limitations. The strength and modulus of jute fibre reinforced composites is not comparable with glass or carbon fibre reinforced composites.

Khan et al. (Khan et al., 2010b) made a comparative study between jute and E-glass fibre-reinforced polypropylene composites. They fabricated composites from jute hessian cloth and E-glass fibre (woven roving) in hot pressing method and tensile and bending properties were investigated.
Table 2-7: Tensile and bending properties of PP sheet and the composites (Khan et al., 2010b).

<table>
<thead>
<tr>
<th>Material</th>
<th>Tensile properties</th>
<th>Bending properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Strength (MPa)</td>
<td>Modulus (GPa)</td>
</tr>
<tr>
<td>PP</td>
<td>21 ± 2</td>
<td>0.53 ± 0.14</td>
</tr>
<tr>
<td>Jute fiber/PP composite</td>
<td>48 ± 2.4</td>
<td>2.50 ± 0.20</td>
</tr>
<tr>
<td>E-glass fiber/PP composite</td>
<td>85 ± 3.5</td>
<td>7.00 ± 0.10</td>
</tr>
</tbody>
</table>

The tensile strength and modulus for E-glass fibre composites were found to be 77% and 180% higher than jute fibre composites respectively. It was also noticed that E-glass fibre composites achieved 52% and 166% higher bending strength and modulus than jute fibre composites. Due to this lower strength of jute fibre reinforced composites, since the beginning of jute fibre composite research; researchers were trying to improve the strength as well as other mechanical properties of jute fibre composites in different ways.

Acha et al. (Acha et al., 2005) fabricated jute fibre reinforced composites using as-received jute, acetone washed jute and detergent washed jute fabrics in compression moulding process. Tensile tests were carried out on composites laminates and results reported and the effect of the modification and the orientation of jute fabric on tensile properties of composites were observed.

They performed tensile tests in different direction of the composites. The highest values are observed in the composite samples with fibres oriented at 0° because of the alignment of the half of the fibre with the applied force direction.
The modulus achieved when tested in the 45° direction is 30% less than the modulus in the principal direction (0°) (Figure 2-13). In case of bidirectional composites, the modulus in the principal direction was reported as lower than the corresponding one for unidirectional composites. The reason behind this is only one half of the fibre ran in each direction. Along with this, crimp of the warp and weft yarn in the interlacement point makes the fibre packing less efficient in the woven structure; which reduces the modulus of woven composites compared to any unidirectional composites. Due to all these factors, usually the modulus of bidirectional composites is around one third of unidirectional composites, when both the composites made from same reinforcing materials (Farebrother and Raymond, 1977).

Rahman et al. (Rahman et al., 2010) tried to improve the tensile properties of jute fibre reinforced polypropylene composites. They made composites using a single extruder and an injection moulding machine. As reinforcement, raw jute fibre and sodium periodate treated jute fibre were used. Jute fibre reinforced composites were post treated in urea solution.

Figure 2-13: Tensile strength as a function of the angle of testing for the different composites: (--) as received, (---) acetone washed, and (....) detergent-washed (Acha et al., 2005).
The improvement in tensile properties was observed in case of oxidized jute fibres. Due to post treatment, tensile strength increased by 14-20% compared to untreated raw jute fibre reinforced composites and increased by 11-15% compared to untreated oxidized jute fibre composites

(Mohanty et al., 2000) studied the influence of chemical surface modification on the properties of jute fibre reinforced polyester amide composites. They did bleaching, dewaxing, alkali treatment and cyanoethylation of jute fabrics. They made composites by compression moulding using different layers of fabrics and resin films. The tensile strength and bending strength of composites were measured following DIN 53455 and DIN 53452.
They found that the maximum tensile strength was from alkali treated jute fabrics and maximum bending strength was from cyanoethylated jute fabrics. The properties achieved from alkali treated and cyanoethylated fabrics are better than detergent washed, dewaxed and bleached jute fabrics (Figure 2-14). According to them, alkali treatment removes natural and artificial impurities from fibre surfaces; thus increasing fibre surface adhesive characteristics by making it rough. They also mentioned that alkali treatment improves the fibre-matrix bonding by increasing the sites for mechanical interlocking. The mechanical properties improved in the case of cyanoethylated fabrics, as the β-cyanoethyl group make a bond with the polymer matrix, thus improving fibre-matrix interface.

Rahman et al. (Rahman et al., 2008) tried to improve the mechanical properties of jute fibre reinforced composites by post treatment. They fabricated composites by injection moulding from raw jute and oxidized; afterwards they treated the composites with urotropine. For all the three cases after a certain fibre content, tensile strength decrease with fibre loading.
The tensile strength for urotropine treated composites is significantly higher than raw and oxidized fibre composites. It increases by 14-20% over raw jute fibre and 8-15% over oxidized jute fibres (Figure 2-15).

Bera et al. (Bera et al., 2010) studied the interfacial properties of jute fibre-PP composites. They made composites from jute fibres and polypropylene in compression moulding technique. They treated jute fibre by NaOH and after that by maleic anhydride grafted PP (MAgPP) and vinyl trimethoxy silane (VTMO). They tested the tensile properties of composites according to ASTM 3039 D.

They treated jute fibre with NaOH to remove surface wax, pectin and other organic compounds. There was a 6.13% improvement in tensile strength of jute fibre with 4%
NaOH treatment and beyond 4% concentration, strength reduced. So, 4% was found as the optimum concentration of NaOH to remove wax, pectin and others (Figure 2-16).

![Tensile strengths of composites with MAgPP and VTMO treated jute fibers](image)

**Figure 2-17: Tensile strengths of composites with MAgPP and VTMO treated jute fibers (Bera et al., 2010).**

In the case of MAgPP treated jute fibre composites, the tensile strength increased with the concentration of MAgPP and achieved maximum tensile strength at 15% concentrations. In the case of VTMO treated jute fibre composites, the tensile strength has found to be maximum at 10% concentrations of VTMO and remain stable (Figure 2-17). So, they conclude that MAGPP performed as better coupling agent for jute fibre than VTMO.

Khan and Bhattacharia (Khan and Bhattacharia, 2007) studied the effect of the coupling agent on jute fibre reinforced composites. They fabricated composites from jute fibre (raw and 2-hydroxyethyl methacrylate, HEMA treated) and vinyl ester in compression moulding technique.
They showed that composites made from HEMA treated fibres exhibit higher tensile and bending strength compared to non-treated one (Figure 2-18). According to them, HEMA treatment brings considerable changes in morphology and topography of fibre surface. Due to this, there occurs improved contact between fibre and polymer matrix.

Figure 2-18: Effect of HEMA on tensile and bending strengths of composites (Khan and Bhattacharia, 2007).
Chapter 3: Materials & Methodology

This chapter gives the details of the procedure of reinforcing materials characterization and subsequently the manufacturing procedure of composite laminates for this research. It also explains all testing procedures and necessary calculations.

3.1 Materials

3.1.1 Reinforcing Materials

100% Jute fibre in three different architectures were used in this research as reinforcing materials. Jute woven fabrics, non-woven mats & carded slivers have been received from Janata Jute Mills, Bangladesh. These materials were directly used as reinforcement during manufacturing of composites.

Woven Fabric:

Jute 1×1 plain weave fabric (Figure 3-1) was used as reinforcement for composite manufacturing. Usually, before weaving some commercially available surface coating is applied to the fibres to facilitate weaving procedure. In this research, the effect of that coating is ignored (if any).

Figure 3-1: Jute Woven Fabrics
Non-Woven Mat:

100% Jute needle-punched non-woven mat was used as reinforcing materials in this research. The manufacturer used a woven mesh with EPI × PPI = 3 × 3 inside the non-woven mat during manufacturing (Figure 3-3).

Carded Sliver:

In this research, 100% Jute carded sliver (Figure 3-4) was used as reinforcing material. The sliver used here was withdrawn from the spinning line of jute yarn just after carding.

3.1.2 Matrix System

Epoxy resin, sourced from Huntsman Ltd. (Table 3-1) was used as the matrix system in this research. Hardener ARADUR 3486 was used as curing agent. The properties of the resin are listed below (Huntsman Data Sheet):
### Table 3-1: Epoxy Resin

<table>
<thead>
<tr>
<th>Technical Name</th>
<th>ARALDITE LY564</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>1.1 g/cm³ (approx.)</td>
</tr>
<tr>
<td>Curing Condition</td>
<td>80° C for 8 hrs.</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>70 MPa (curing at 80° C for 8 hrs.)</td>
</tr>
<tr>
<td>Tensile Modulus</td>
<td>2.8 GPa (curing at 80° C for 8 hrs.)</td>
</tr>
</tbody>
</table>

### 3.2 Methodology

#### 3.2.1 Characterization of Reinforcing Materials

In this research composites made from different types of fibre assembly. Each type of fibre assembly has different characteristics when used as reinforcement. That is why; at first characterization of each type of fibre assembly is important.

**3.2.1.1 Fibre:**

*Fibre Orientations*

A yarn was removed from the woven fabric and placed on the glass plate of optical microscope (Model name: Projectina). Then the fibre orientations were observed using macro 2.0 x magnifications. Different places of the yarn were observed and a representative part of yarn was reported here.

A small strip was cut from non-woven mat and carded sliver randomly. Then they were placed on glass plate in a way, that their surface was facing to the lens of the optical microscope. Thus the fibre orientations were observed using macro 2.0x magnifications. Different places on the surface were observed and a representative part is reported here.

**3.2.1.2 Carded Sliver**

*Linear Density:*

Carded sliver liner density was measured according to BS 947:1970. Five samples were measured and the average linear density was reported.
3.2.1.3 Yarn

From woven fabric, warp and weft yarn was separated (Figure 3-5). The following parameters of both sets of yarn have been checked.

![Figure 3-5: Jute Yarn removed from Woven Fabric.](image)

**Diameter:**

The yarn was observed under an optical microscope (Model: Projectina) using 5.0x optical zoom. The diameter was measured in different parts of the yarn from the optical image (Figure 3-6). The diameter was measured for both warp and weft yarn. Several yarns were checked and an average reported.

![Figure 3-6: Warp yarn seen in optical microscope under 5.0x optical magnifications.](image)
**Count:**

Both the warp and weft yarn count was measured according to BS 947:1970. Five different samples were measured and the average count for both yarns was reported.

**Twist per Inch (TPI):**

The amount of twist per unit length for both the warp and weft yarn was measured using a Shirley twist tester. The amount of twist in 10 cm length of yarn was measured and then converted to twist per inch. Ten yarn samples were tested for both warp and weft and an average reported.

**Twist Angle:**

Warp and weft yarns were placed on the glass plate of an optical microscope and observed using macro 2.0x optical magnifications. The twist angle of warp and weft yarn was measured and an average reported here.

In this research, TPI is referred to show the relation of strength with amount of twist in a fibre strands and Twist angle is referred to show the relation of strength with fibre orientations.

**Tensile Strength:**

The tensile strength of warp and weft yarn was measured according to BS 2865:1984 in an Instron machine. Five samples were tested for both warp and weft yarn and an average is reported.

### 3.2.1.4 Woven Fabric

**Ends and Picks:**

The ends/inch & picks/inch was counted according to BS EN 1049-2:1994, Method B. As yarns used in fabric were visible and fabric the structure was quite loose, so it was easy to count them using needle. That is why Method B of this standard was found most suitable for this purpose.

**Fabric Weight:**
Fabric weight in grams per square meter was measured according to BS EN 12127:1998. Here GSM cutter was used as the cutting device and five samples from different places of the fabric were cut. Then fabric weight was taken using an electronic balance and an average was reported.

**Tensile Strength:**

The Tensile Strength of woven fabric was measured according to BS EN ISO 13934-2:1994. The strength was measured for different directions of fabric. Here, the specimen gauge length was 200 mm, width 50 mm (Figure 3-7). Machine loading is pneumatic and cross-head speed was 100 mm/min.

![Figure 3-7: Fabric specimen for tensile test](image1)

![Figure 3-8: Instron Tensile testing machine for yarn and fabric.](image2)
**Fabric Thickness:**

Fabric thickness was measured in millimetre using a thickness gauge under a pressure foot of 8.0 cm diameter and pressure of 1000 g. Ten measurements were taken and an average was reported.

**Crimp Angle:**

![Crimp angle measurement using optical microscope.](image)

Figure 3-9: Crimp angle measurement using optical microscope.

Fabric specimens in warp way and weft way were set in microscope glass plate. Crimp angle was measured using optical microscope [Model name: Projectina] under 1.0x magnification (Figure 3-9).

### 3.2.1.5 Non-woven Mat

**Area Density:**

Fabric weight in grams per square metre was measured using BS EN 12127:1998. Here GSM cutter was used as a cutting device and five samples from different place of fabric were tested and results reported.

**Thickness:**

Mat thickness was measured in millimetre using thickness gauge under a pressure foot of 8.0 cm diameter and pressure of 1000 g. Ten measurements were taken and an average was reported.
**Tensile Strength:**

The Tensile Strength of non-woven fabric was measured using BS EN ISO 9073-18:2008. Strength was measured in different direction. The gauge length used was 200mm and cross head speed used was 100mm/min.

### 3.2.2 Composite Fabrication

The process of composites manufacturing is described in different stages here:

#### 3.2.2.1 Stage 1: Preparation of Reinforcements

Three different types of structure were prepared individually for use as reinforcement in composites manufacturing. Their preparation procedure is below:

**Chemical Content of Fibres:**

The structures have been used as received; without any further physical and chemical treatment. There might have been a little percentage of wax or chemical coating on yarn which has been used prior to weaving to avoid any yarn breakage during weaving. During jute fibre processing, jute batch oil is used to soften the fibre. So, there might have been a little amount of jute batch oil in the fibre. The effect of these chemicals in this research is ignored.

**Shaping of Reinforcing Materials:**

The dimension of the mould plate used for composite manufacturing was 50 cm × 25 cm. Another steel plate (28 cm × 18 cm) was used on top of the reinforcing material to avoid any structural waviness after vacuum bagging, especially for the nonwoven structure which is highly variable on surface. The woven fabrics, non-woven mats and slivers all were cut in 28 cm × 18 cm dimensions to fit the available top plate dimension.

**Preconditioning:**

Jute fibre is a hygroscopic fibre. The moisture regain is around 11.5%. So, the fibre can hold quite a large amount of water in it. In the fibre-matrix interface this water acts like a separating agent. Moreover, during for curing process of making fibre-reinforced composites, voids appear in the matrix due to evaporation of water (Acha et al., 2005).
That is why, before making composite panels performs are heated in a pre-heated oven for 1hr at 105° C temperature (Islam et al., 2011).

**3.2.2.2 Stage 2: Preparation of Mould Plate**

The mould used for making laminates was made of steel with 50 cm × 25 cm dimension. The mould was cleaned by acetone first and then subsequently by mould cleaner (commercial name: Sika Mould Cleaner). Then the mould was coated by mould releasing agent (commercial name: LOCTITE 700NC Frekote) for three times with ten minutes interval between each coating. The purpose of applying this releasing agent was to make sure that the laminate will be separated from mould conveniently after curing.

**3.2.2.3 Stage 3: Stacking of Reinforcement**

The way of arranging the different layers of reinforcing material in a laminate is known as the stacking sequence (Table 3-2).

**Table 3-2: Stacking Sequence of Reinforcing Materials**

<table>
<thead>
<tr>
<th>Stacking Sequence</th>
<th>2 layer</th>
<th>3 layer</th>
<th>4 layer</th>
<th>9 layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Woven fabric</td>
<td></td>
<td></td>
<td>0° direction</td>
<td>0° direction</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0° direction</td>
<td>0° direction</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0° direction</td>
<td>0° direction</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0° direction</td>
<td>0° direction</td>
</tr>
<tr>
<td>Non-woven mat</td>
<td>0° direction</td>
<td>0° direction</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carded sliver</td>
<td></td>
<td></td>
<td>0° direction</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0° direction</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0° direction</td>
<td></td>
</tr>
</tbody>
</table>
**Woven Fabric:**

Two different types of laminates were made with woven fabric reinforcement; one using 4 layer of fabric and another using 9 layer of fabric. In both case, different layers of woven fabric were placed in same direction that is 0° direction.

**Non-woven Mat:**

Two different types of laminates were made with non-woven mats reinforcement; one using 1 layer of fabric and another using 2 layer of fabric. In both case, different layers of non-woven mats were placed in same direction that is 0° direction.

**Carded Sliver:**

Carded silver was cut along length direction and then three different slivers were placed one above other for making laminates.

### 3.2.2.4 Stage 4: Vacuum Bagging (Figure 3-10)

A layer of nylon release fabric was placed on the coated mould. Then reinforcing materials were placed on this in a predetermined stacking sequence. On top of the reinforcing materials another layer of release fabric, then a layer of peel ply, a layer of mesh and on top most surface another steel plate of 28 cm × 18 cm were placed.

**Release fabric:** The purpose of the release fabric on both sides of the reinforcing materials is to make both sides identical.

**Mesh Fabric:** Mesh fabric helps in proper flow of resin during infusion.

**Peel Ply:** Peel ply just separates the release fabric and mesh fabric from being attached.

**Top Plate:** The purpose of top plate was to make the laminate surface free of waviness, especially in the case of non-woven mats.

**Inlet, outlet and spiral tube:** On two ends of the mould, the inlet & outlet pipe was set up along with spiral tube (helps in resin flow).

**Plastic film and Tacky tape:** The full arrangement was covered with a plastic film and all the edge was sealed by tacky tape.
**Vacuum Drawing:** The outlet pipe was connected with vacuum pump to draw air from this arrangement, when the inlet remains sealed.

**Pressure gauge:** A pressure gauge was used to check the air leakage in the full assembly. If the full assembly is air sealed, then it is ready for resin infusion.

![Vacuum Bagging](image)

**Figure 3-10: Vacuum Bagging**

### 3.2.2.5 Stage 5: Resin Formulation

**Resin Mixing:**

Epoxy resin “ARALDITE LY564” and hardener “ARADUR 3486” of Huntsman was used in resin infusion. For making 100 g of matrix for infusion, 66 g of resin and 34 g of hardener was weighed and mixed together. Then the mixture was stirred gently until it mixed well.
Resin Degassing:

The mixture was then placed in the degassing machine (Figure 3-11) for an hour. This machine sucked all the air bubbles from the mixture. Thus the resin became air bubble free and this helps to make the final laminate void free.

3.2.2.6 Stage 6: Infusion

For resin infusion, the outlet pipe of the vacuum bagged mould was connected to a suction pump, when inlet pipe was inserted into resin mixture. Controlling of the resin flow inside the moulding arrangement is important to ensure that all the fibres were wetted properly. When the infusion was completed, inlet and outlet were sealed with D-clamp. Then the mould assemble becomes ready for curing (Figure 3-12).
3.2.2.7 Stage 7: Curing

After infusion, the sealed mould assembly was placed inside a curing chamber (Figure 3-13). The curing time was 8hrs and temperature was 80° C. The programme was set to raise temperature from room temperature to 80° C, was an hour.

Figure 3-12: Infusion of vacuum bagged reinforcement

Figure 3-13: Curing chamber.
3.2.2.8 Stage 8: Removing cured laminate from oven and separation of manufacturing kits

After curing, the oven was allowed to cool. Then the mould assembly was removed from the curing chamber and manufacturing tools were carefully removed from the laminate. Thus the desired laminate was parallel.

3.2.3 Tensile Test of Composite Laminates

The tensile properties of composite laminates were tested according to ASTM D 3039. The tensile test specimens were prepared and test carried out in following way:

3.2.3.1 Test Specimen Preparation

Stage 1: Sand Blasting:

For attaching the tabs, composite laminates were sandblasted (projection of sand particle) using pressure gun with high air pressure (Figure 3-14). This made the laminate surface rough which assists in the proper adhesion of tabs with laminates.

Figure 3-14: Sandblasting machine
Stage 2: Tabs Attachment:

Tabs were needed to be bonded with the composite laminate for effective introduction of force to the laminate during tensile test (Figure 3-15). According to ASTM D 3039, tabs are recommended for unidirectional laminates or strongly unidirectional dominated laminates. So, tabs were needed for sliver laminates. As this work involves the comparative study, that is why to avoid any variation among laminates tabs were used in all laminates.

A mixture was made from commercial glue and hardener. This mixture was used to attach tabs to the laminates. Then laminates were placed in the vacuum table (Figure 3-16) and kept overnight. This vacuum pressure helps the tabs to attach with laminates. The tabs used here was of 1.5 mm thickness.
Stage 3: Cutting of Specimens:

The following is the specification, mentioned in the standards for tensile test:

Specimen length – 250 mm

Specimen width – 25 mm

Specimen thickness – As made. (Standard recommends 10 mm thickness; but in this research, different composite laminates were made with different thickness. So, thickness recommendation was not followed exactly)

Tensile specimens according to above dimensions were cut using diamond saw (Figure 3-17) with sufficient allowance for finishing. Emery paper was used for finishing of the samples to achieve final dimensions. After cutting, specimens were dried to remove water from the diamond cutter.
Stage 4: Measurement of Specimens:

The width and thickness of every individual test specimens were measured before testing. Width was measured using digital callipers in three different positions and an average was taken. The thickness was measured using a digital micrometer in three different positions and an average was taken.

3.2.3.2 Test of Specimens

Tensile tests were carried out using Universal Instron Tensile Testing Machine “Model: INSTRON-5569” (Figure 3-18).

Test Parameters: Tests have been carried out at 2 mm/min cross-head speed using 50kN load cell. The specimens gauge length was 150 mm and 25 mm. An extensometer with gauge length 50 mm was used for strain measurement.
Figure 3-18: Tensile testing of composite laminates in Instron machine
3.2.3.3 Laminate Specifications

The following table specifies different laminates made from three different structures, along with tensile test direction (Table 3-3):

Table 3-3: Specification of different laminates

<table>
<thead>
<tr>
<th>Type of Reinforcement</th>
<th>Number of Layers</th>
<th>Specimen ID</th>
<th>Laminates Test Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Woven Fabric</td>
<td>4 layer</td>
<td>W1</td>
<td>Along warp</td>
</tr>
<tr>
<td></td>
<td>4 layer</td>
<td>W2</td>
<td>Along weft</td>
</tr>
<tr>
<td></td>
<td>9 layer</td>
<td>W3</td>
<td>Along warp</td>
</tr>
<tr>
<td></td>
<td>9 layer</td>
<td>W4</td>
<td>Along weft</td>
</tr>
<tr>
<td>Non-woven Mat</td>
<td>1 layer</td>
<td>N1</td>
<td>Along MD</td>
</tr>
<tr>
<td></td>
<td>1 layer</td>
<td>N2</td>
<td>Along CD</td>
</tr>
<tr>
<td></td>
<td>2 layer</td>
<td>N3</td>
<td>Along MD</td>
</tr>
<tr>
<td></td>
<td>2 layer</td>
<td>N4</td>
<td>Along CD</td>
</tr>
<tr>
<td>Carded Sliver</td>
<td>3 layer</td>
<td>S</td>
<td>Longitudinal direction</td>
</tr>
</tbody>
</table>

Here the running direction or the length direction of non-woven mats is termed as “Along Machine Direction (MD)” and the direction perpendicular to MD is termed as “Cross Direction (CD)”.

3.2.4 Other Tests for Composites

3.2.4.1 Calculation of Fibre volume fraction:

Fibre volume fraction can be defined as, \( V_f = \frac{v_f}{v_c} \), where

\( v_f = \) volume of fibre, \( v_c = \) volume of composite

Now,
\( v_f = \) volume of fibre, \( v_c = \) volume of composite, \( v_m = \) volume of matrix,

\( V_f = \) Fibre volume fraction, \( V_m = \) Matrix volume fraction

We know,

\[ v_c = v_f + v_m \]

Or, \( \frac{v_c}{v_c} = \frac{v_f}{v_c} + \frac{v_m}{v_c} \)

Or, \( 1 = V_f + V_m \)

We know,

Fibre volume fraction, \( V_f = \frac{v_f}{v_c} \)

Matrix volume fraction, \( V_m = \frac{v_m}{v_c} \)

Now,

\( m_f = \) mass of fibre in the composite, \( \rho_f = \) density of fibre

\( m_c = \) mass of composite, \( \rho_c = \) density of composite

So,

\[ V_f = \frac{m_f/\rho_f}{m_c/\rho_c} \]  \hspace{1cm} (5-1)

And, \( V_m = 1 - V_f \) \hspace{1cm} (5-2)

Using this above formula (1) and (2), fibre volume fraction of laminates was measured from fibre mass, fibre density and composite mass, composite density. Fibre weight was measured after drying; composite weight was measured after curing. Fibre density is known from literature and composite density was measured.

### 3.2.4.2 Calculation of Fibre weight fraction

Fibre weight fraction can be defined as, \( W_f = \frac{w_f}{w_c} \) \hspace{1cm} (5-3)

where

\( w_f = \) weight of dry fibre, \( w_c = \) weight of composite laminates
Fibre weight was measured after drying and just before using them as reinforcement. Composite laminate weight was measured after curing.

3.2.4.3 Density Test

Laminates were cut into 1 cm × 1 cm size for measuring density. Then specimens were oven dried to remove moisture from them. Using density measuring machine (Figure 3-19), density was measured directly. This machine is composed of an electric balance which can measure weight of a specimen in air and in water and from these data’s; machine can automatically calculate density of any specimen. For each type of laminates, five specimens were tested and an average was taken.

![Figure 3-19: Density measuring machine](image)
3.2.4.4 Void Content

Here, the composites are manufactured by the vacuum bagging method, which ensures the production of almost void free laminates; so, void content is ignored in fibre volume fraction calculation.
Chapter 4: Results & Discussion

4.1 Properties of Reinforcing Materials

4.1.1 Yarn

The test result of different parameters of warp and weft yarns are shown below (Table 4-1):

<table>
<thead>
<tr>
<th></th>
<th>Diameter, mm</th>
<th>Count, Tex</th>
<th>Twist per inch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warp Yarn</td>
<td>0.098 ± 0.02</td>
<td>175 ± 3</td>
<td>4.5 ± 0.5</td>
</tr>
<tr>
<td>Weft Yarn</td>
<td>0.122 ± 0.02</td>
<td>190 ± 2</td>
<td>5.5 ± 0.5</td>
</tr>
</tbody>
</table>

During measurement of warp and weft yarn count, the high weight variations of jute yarn were observed. To investigate this issue, the weight of 36 different warp and weft yarns, each with 30 cm length was measured and a summary of processed data is reported here (Table 4-2):

<table>
<thead>
<tr>
<th></th>
<th>Weight, g</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Warp Yarn</td>
</tr>
<tr>
<td>Mean</td>
<td>0.053</td>
</tr>
<tr>
<td>Max</td>
<td>0.079</td>
</tr>
<tr>
<td>Min</td>
<td>0.031</td>
</tr>
<tr>
<td>S.D</td>
<td>0.01</td>
</tr>
<tr>
<td>C.V. %</td>
<td>18</td>
</tr>
</tbody>
</table>

The co-efficient of variation (CV %) for warp yarn and weft yarn weight is 17.86% and 16.18% respectively, which reveals the high weight variation characteristics for both the yarns.

Yarn tensile properties were checked and results achieved are reported here (Table 4-3):
### Table 4-3: Yarn Tensile Properties

#### Warp Yarn

<table>
<thead>
<tr>
<th>Sample</th>
<th>Maximum Load, cN</th>
<th>Breaking Extension, mm</th>
<th>Elongation at break, %</th>
<th>Tenacity, cN/tex</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1800</td>
<td>6.72</td>
<td>2.69</td>
<td>463.42</td>
</tr>
<tr>
<td>2</td>
<td>2181</td>
<td>8.89</td>
<td>3.56</td>
<td>564.33</td>
</tr>
<tr>
<td>3</td>
<td>2694</td>
<td>9.69</td>
<td>3.88</td>
<td>586.97</td>
</tr>
<tr>
<td>4</td>
<td>1298</td>
<td>7.62</td>
<td>3.05</td>
<td>356.56</td>
</tr>
<tr>
<td>5</td>
<td>2118</td>
<td>8.50</td>
<td>3.40</td>
<td>485.99</td>
</tr>
<tr>
<td>6</td>
<td>2059</td>
<td>7.15</td>
<td>2.86</td>
<td>569.75</td>
</tr>
<tr>
<td>7</td>
<td>2605</td>
<td>7.90</td>
<td>3.16</td>
<td>789.27</td>
</tr>
<tr>
<td>8</td>
<td>2660</td>
<td>9.20</td>
<td>3.68</td>
<td>517.15</td>
</tr>
<tr>
<td>9</td>
<td>1472</td>
<td>5.30</td>
<td>2.12</td>
<td>400.86</td>
</tr>
<tr>
<td>10</td>
<td>2560</td>
<td>9.63</td>
<td>3.85</td>
<td>532.07</td>
</tr>
<tr>
<td>AVG</td>
<td>2144</td>
<td>8.06</td>
<td>3.22</td>
<td>526 ± 118</td>
</tr>
<tr>
<td>CV%</td>
<td></td>
<td></td>
<td></td>
<td>22</td>
</tr>
</tbody>
</table>

#### Weft Yarn

<table>
<thead>
<tr>
<th>Sample</th>
<th>Maximum Load, cN</th>
<th>Breaking Extension, mm</th>
<th>Elongation at break, %</th>
<th>Tenacity, cN/tex</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3047</td>
<td>7.55</td>
<td>3.02</td>
<td>596.65</td>
</tr>
<tr>
<td>2</td>
<td>2411</td>
<td>6.32</td>
<td>2.52</td>
<td>588.52</td>
</tr>
<tr>
<td>3</td>
<td>3340</td>
<td>8.90</td>
<td>3.56</td>
<td>601.48</td>
</tr>
<tr>
<td>4</td>
<td>2689</td>
<td>7.20</td>
<td>2.88</td>
<td>569.07</td>
</tr>
<tr>
<td>5</td>
<td>2655</td>
<td>7.19</td>
<td>2.88</td>
<td>606.24</td>
</tr>
<tr>
<td>6</td>
<td>3687</td>
<td>9.67</td>
<td>3.87</td>
<td>689.45</td>
</tr>
<tr>
<td>7</td>
<td>2454</td>
<td>6.80</td>
<td>2.72</td>
<td>568.53</td>
</tr>
<tr>
<td>8</td>
<td>3179</td>
<td>7.90</td>
<td>3.16</td>
<td>632.34</td>
</tr>
<tr>
<td>9</td>
<td>1464</td>
<td>5.80</td>
<td>2.32</td>
<td>434.05</td>
</tr>
<tr>
<td>10</td>
<td>2721</td>
<td>6.72</td>
<td>2.69</td>
<td>669.36</td>
</tr>
<tr>
<td>AVG</td>
<td>2764</td>
<td>7.41</td>
<td>2.96</td>
<td>595 ± 69</td>
</tr>
<tr>
<td>CV%</td>
<td></td>
<td></td>
<td></td>
<td>12</td>
</tr>
</tbody>
</table>
From Table 4-3: Yarn Tensile Properties it is seen that weft yarn can sustain more load than warp yarn before breaking under tension. Also the weft yarn modulus is higher than warp yarn. The reason that can explain this higher strength phenomenon is the higher count of weft yarn. Also, weft yarn diameter is higher than warp yarn diameter. These factors all together help weft yarn to achieve higher strength than warp yarn. Due to this higher tensile strength, higher diameter and higher twist per inch compared to warp yarn; the weft yarn Elongation at break % is less than warp yarn.

4.1.2 Woven Fabric

The different parameters of woven fabrics were checked and reported below (Table 4-4):

**Table 4-4: Properties of woven fabrics**

<table>
<thead>
<tr>
<th>Woven Fabric Properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ends per inch (EPI)</td>
<td>15 ± 1</td>
</tr>
<tr>
<td>Picks per inch (PPI)</td>
<td>15 ± 1</td>
</tr>
<tr>
<td>Weight, g/m²</td>
<td>245 ± 5</td>
</tr>
<tr>
<td>Thickness, mm</td>
<td>1 ± 0.1</td>
</tr>
<tr>
<td>Crimp Angle, degree</td>
<td></td>
</tr>
<tr>
<td>Warp way</td>
<td>22 ± 0.7</td>
</tr>
<tr>
<td>Weft way</td>
<td>22 ± 0.1</td>
</tr>
</tbody>
</table>

Figure 4-1: Weft way crimp angle seen in optical microscope
The tensile strength of woven fabrics were tested in both warp and weft direction. The results are reported here (Table 4-5).

**Table 4-5: Tensile properties of woven fabrics**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Maximum Load, N</th>
<th>Breaking Extension, mm</th>
<th>Elongation at break, %</th>
<th>Tensile Strength, MPa</th>
<th>Tensile Modulus, GPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>568.1</td>
<td>15.23</td>
<td>7.62</td>
<td>10.32</td>
<td>0.335</td>
</tr>
<tr>
<td>2</td>
<td>393.8</td>
<td>16.83</td>
<td>8.42</td>
<td>7.16</td>
<td>0.189</td>
</tr>
<tr>
<td>3</td>
<td>517.0</td>
<td>13.38</td>
<td>6.69</td>
<td>9.40</td>
<td>0.318</td>
</tr>
<tr>
<td>4</td>
<td>502.6</td>
<td>14.02</td>
<td>7.01</td>
<td>9.13</td>
<td>0.295</td>
</tr>
<tr>
<td>5</td>
<td>595.2</td>
<td>13.03</td>
<td>6.52</td>
<td>10.82</td>
<td>0.329</td>
</tr>
<tr>
<td>AVG</td>
<td>515.3</td>
<td>14.50</td>
<td>7.20</td>
<td>9 ± 1</td>
<td>0.3 ± 0.1</td>
</tr>
<tr>
<td>CV%</td>
<td></td>
<td></td>
<td></td>
<td>15%</td>
<td>20%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample</th>
<th>Maximum Load, N</th>
<th>Breaking Extension</th>
<th>Elongation at break, %</th>
<th>Tensile Strength, MPa</th>
<th>Tensile Modulus, GPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>590.6</td>
<td>8.17</td>
<td>4.09</td>
<td>10.73</td>
<td>0.451</td>
</tr>
<tr>
<td>2</td>
<td>687.0</td>
<td>7.88</td>
<td>3.94</td>
<td>12.49</td>
<td>0.483</td>
</tr>
<tr>
<td>3</td>
<td>724.8</td>
<td>8.31</td>
<td>4.16</td>
<td>13.17</td>
<td>0.467</td>
</tr>
<tr>
<td>4</td>
<td>572.6</td>
<td>8.99</td>
<td>4.49</td>
<td>10.41</td>
<td>0.411</td>
</tr>
<tr>
<td>5</td>
<td>643.2</td>
<td>10.02</td>
<td>5.01</td>
<td>11.69</td>
<td>0.420</td>
</tr>
<tr>
<td>AVG</td>
<td>643.6</td>
<td>8.7</td>
<td>4.30</td>
<td>12 ± 1</td>
<td>0.4 ± 0.1</td>
</tr>
<tr>
<td>CV%</td>
<td></td>
<td></td>
<td></td>
<td>9.0</td>
<td>7.0</td>
</tr>
</tbody>
</table>

Woven fabric can sustain higher tensile load when it is tested along the weft way than the warp way. Also the modulus is higher in weft direction. This can be explained by higher tensile strength and modulus of weft yarn. As the EPI & PPI is the same but the tensile strength of weft yarn is higher; so the fabric tensile strength is higher in weft direction than warp.
When the woven fabric is tested in the weft direction, the breaking extension as well as the elongation at break % is lower than when tested in warp direction. This was also due to the higher count, twist and tensile strength of weft yarn compared to warp yarn.

### 4.1.3 Non-woven Mat

The weight of non-woven mats used here as reinforcement is 567.4 g/m² and thickness is 5.38 mm.

The tensile strength of non-woven mats was tested in both machine direction (MD) and cross direction (CD). The results reported here (Table 4-6).

**Table 4-6: Tensile properties of non-woven mats**

<table>
<thead>
<tr>
<th>Non-woven mat tested along MD</th>
<th>Sample</th>
<th>Maximum Load, N</th>
<th>Breaking Extension, mm</th>
<th>Elongation at break, %</th>
<th>Tensile Strength, MPa</th>
<th>Tensile Modulus, GPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>198.0</td>
<td>7.50</td>
<td>3.8</td>
<td>0.59</td>
<td>0.0312</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>164.8</td>
<td>14.5</td>
<td>7.2</td>
<td>0.49</td>
<td>0.0263</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>226.9</td>
<td>7.70</td>
<td>3.9</td>
<td>0.68</td>
<td>0.0333</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>176.1</td>
<td>15.2</td>
<td>7.6</td>
<td>0.52</td>
<td>0.0261</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>123.6</td>
<td>8.70</td>
<td>4.3</td>
<td>0.37</td>
<td>0.0229</td>
<td></td>
</tr>
<tr>
<td>AVG</td>
<td>177.9</td>
<td>10.7</td>
<td>5.4</td>
<td>0.53 ± 0.1</td>
<td>0.0280 ± 0.1</td>
<td></td>
</tr>
<tr>
<td>CV%</td>
<td></td>
<td></td>
<td></td>
<td>22</td>
<td>15</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Non-woven mat tested along CD</th>
<th>Sample</th>
<th>Maximum Load, N</th>
<th>Breaking Extension, mm</th>
<th>Elongation at break, %</th>
<th>Tensile Strength, MPa</th>
<th>Tensile Modulus, GPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>70.73</td>
<td>10.05</td>
<td>5.03</td>
<td>0.21</td>
<td>0.011</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>91.40</td>
<td>9.02</td>
<td>4.51</td>
<td>0.27</td>
<td>0.016</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>125.50</td>
<td>9.80</td>
<td>4.90</td>
<td>0.37</td>
<td>0.021</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>100.93</td>
<td>9.52</td>
<td>4.76</td>
<td>0.30</td>
<td>0.014</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>96.64</td>
<td>9.99</td>
<td>4.99</td>
<td>0.29</td>
<td>0.014</td>
<td></td>
</tr>
<tr>
<td>AVG</td>
<td>97.04</td>
<td>9.68</td>
<td>4.84</td>
<td>0.28 ± 0.1</td>
<td>0.015 ± 0.1</td>
<td></td>
</tr>
<tr>
<td>CV%</td>
<td></td>
<td></td>
<td></td>
<td>20</td>
<td>23</td>
<td></td>
</tr>
</tbody>
</table>
The above table shows that, the non-woven mat can sustain higher load when tested along machine direction (MD). Also the modulus is higher along MD. The reason for this is not clearly understood. This might be due to the higher strength of inside yarn (from woven mesh) along MD than CD or comparatively higher amount of fibre might be oriented along MD than CD. The average elongation at break % is seen to be higher along MD than CD. But, along CD Eb % is consistently around 5. In the case of MD, there are two extreme values which are considered as experimental error. Ignoring these extremes, the average Eb% along MD is 4. This can be explained by higher strength of inside yarn along MD or higher amount of fibre orientation along MD.

4.1.4 Carded Sliver

The count of sliver used here is 46 KTex. During measuring of the sliver count, the high weight variation of jute slivers was observed. To investigate the details, the weight of 10 different slivers, each with 18 cm length, was measured. Here this weight variation is showed in graph:

![Figure 4-2: Sliver weight variations](image)

The standard deviation and CV% of weight of 10 slivers was observed to be 1.86 and 22.68
4.2 Tensile Properties of Composite Laminates

Composite laminates were made from three different jute structures and termed as W (woven fabric reinforced composites), N (non-woven mat reinforced composites) and S (carded sliver reinforced composites). The tensile properties of composite laminates were tested according to ASTM D 3039 and the results achieved are reported below. Along with the tensile properties, fibre volume fraction, weight fraction and laminate thickness are also reported (Table 4-7).
Table 4-7: Tensile properties of composite laminates

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Laminates Thickness (mm)</th>
<th>Fibre weight fraction (%)</th>
<th>Fibre volume fraction (%)</th>
<th>Tensile Strength, MPa</th>
<th>Tensile Modulus, GPa</th>
<th>Elongation at break %</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>2.9 ± 0.1</td>
<td>27.43 ± 0.1</td>
<td>24.0 ± 0.1</td>
<td>3.42 ± 0.2</td>
<td>7.9 ± 0.5</td>
<td></td>
</tr>
<tr>
<td>W2</td>
<td>2.8 ± 0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>71 ± 4</td>
<td>4.7 ± 0.3</td>
<td>6.8 ± 0.5</td>
</tr>
<tr>
<td>W3</td>
<td>5.5 ± 0.1</td>
<td>31 ± 0.8</td>
<td>26 ± 0.9</td>
<td>62 ± 2</td>
<td>4.45 ± 0.1</td>
<td>9.95 ± 0.7</td>
</tr>
<tr>
<td>W4</td>
<td>5.6 ± 0.1</td>
<td>0.1</td>
<td>78 ± 4</td>
<td>5.6 ± 0.2</td>
<td>7.9 ± 0.7</td>
<td></td>
</tr>
<tr>
<td>N1</td>
<td>2.74 ± 0.1</td>
<td>27.25 ± 0.1</td>
<td>23.84 ± 0.1</td>
<td>52 ± 1</td>
<td>4.14 ± 0.2</td>
<td>5.5 ± 0.5</td>
</tr>
<tr>
<td>N2</td>
<td>2.39 ± 0.2</td>
<td>0.1</td>
<td>49 ± 2</td>
<td>3.73 ± 0.2</td>
<td>5.68 ± 0.4</td>
<td></td>
</tr>
<tr>
<td>N3</td>
<td>5.2 ± 0.1</td>
<td>16.13 ± 0.1</td>
<td>25.43 ± 0.1</td>
<td>54 ± 2</td>
<td>4.3 ± 0.1</td>
<td>5.2 ± 0.3</td>
</tr>
<tr>
<td>N4</td>
<td>5 ± 0.3</td>
<td>0.1</td>
<td>51 ± 4</td>
<td>4 ± 0.1</td>
<td>5.5 ± 0.5</td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>5.25 ± 0.2</td>
<td>23.73 ± 0.1</td>
<td>17 ± 0.2</td>
<td>78 ± 5</td>
<td>5.9 ± 0.7</td>
<td>8.1 ± 0.8</td>
</tr>
</tbody>
</table>

4.2.1 Analysis of Tensile Properties of different Composite Laminates

The tensile strength and modulus of woven fabric reinforced laminates was observed to be higher when tested along the weft direction. This can be explained by higher fabric strength and modulus along weft direction, which comes from higher count, twist and diameter of weft yarn compared to warp yarn.
Due to the same reason, (higher tensile strength and modulus of the dry mat) the laminates strength and modulus is higher when tested along MD than CD.

In the case of woven fabric reinforcement, when the number of reinforcing fabric layer increased from four to nine; the tensile strength and modulus increased in both warp and weft direction. This is due to the increase of fibre volume fraction from four layer reinforcement to nine layer reinforcement. The fibre strength and modulus (20 GPa) is higher than the resin strength and modulus (2.8 GPa); that is why with the increase of fibre volume fraction, the laminates strength and modulus increased.

Due to the above same reason tensile strength and modulus increased from one layer to two layer reinforced laminates, in case of non-woven mat reinforced composites.

Elongation at break (Eb) % was found to be higher along the warp direction than weft, which can be explained by comparatively higher Eb% of warp way fabric than weft way.

Due to the same reason, Eb% is higher in CD than MD in case of non-woven mat reinforced composites.

The Eb % increased from 4 layer fabric reinforcement to 9 layer reinforcement in both warp and weft direction. The most potential reason of this is:

- Eb % of both warp and weft way fabric is higher than Eb % of resin and
- Fibre volume fraction is increased from 4 layer fabric reinforced laminates to 9 layers.

For non-woven mat reinforced composites, due to the same reason Eb% increased with increase of number of reinforcing layers from one to two
4.2.2 Theoretical Prediction of Tensile Modulus using Rule of Mixture

According to the Rule of Mixture,

\[
\text{Composite Modulus} = (\text{Fibre modulus} \times \text{Fibre volume fraction}) + ((\text{Resin modulus} \times (1 - \text{Fibre volume fraction}))
\]

**Modulus:**

Jute fibre Modulus = 20 GPa (Ahmed and Vijayarangan, 2007)

Epoxy resin Modulus = 2.8 GPa (Huntsman Data Sheet)

**Fibre Volume Fraction:**

Woven fabric reinforced composites:

Woven fabric reinforced composites are bidirectional, one half of the fibre runs in warp direction and another half in weft direction. That is why, when they were tested along warp or weft direction, only one half of the fibre contribute to the strength or modulus.

Now, weft yarn count (190 Tex) is around 8.0% higher than warp yarn count (175 Tex). So, the fibre volume fraction will be 8.0% higher in weft direction than warp. On a total fibre volume fraction, the contribution of weft yarn will be 54% (50 +8/2) and warp yarn will be 46% (50 – 8/2).

Now,

Fibre volume fraction along warp for laminate W1 = \(24.0 \times 46/100 = 11.04\)

Fibre volume fraction along weft for laminate W2 =\(24.0 \times 54/100 = 12.96\)

Fibre volume fraction along warp for laminate W3 =\(26.45 \times 46/100 = 12.2\)

Fibre volume fraction along weft for laminate W4 =\(26.45 \times 54/100 = 14.3\)
Non-woven mat reinforced composites:

Fibres are randomly distributed in non-woven mats. When non-woven mat reinforced composites were tested in Machine direction (MD); not all the fibres contributed in strength or modulus, rather only the fibres aligned along MD contributed. The same happened in the case of the Cross direction (CD). So, by resolving the contribution of all fibres for strength and modulus along MD and CD, we can assume that the amount of fibre along MD and CD is equal and that is half of the total amount of fibres. So, on a total fibre volume fraction, the contribution of fibre along MD will be 50% and CD will be 50%.

Now,

Fibre volume fraction along MD for laminate N1 = 23.84 × 50/100 = 11.92
Fibre volume fraction along CD for laminate N2 = 23.84 × 50/100 = 11.92
Fibre volume fraction along MD for laminate N3 = 25.43 × 50/100 = 12.71
Fibre volume fraction along CD for laminate N4 = 25.43 × 50/100 = 12.71

Sliver reinforced composites:

Sliver reinforced composites were tested along the longitudinal direction and almost all the fibres were aligned with test direction. So, the contribution of longitudinal fibre was assumed to be 100% on total fibre volume fraction here, as there is no fibre in the transverse direction.

Fibre volume fraction along longitudinal direction for laminate S = 17.0

Modulus Calculations:

According to rule of mixture,

Modulus for laminate N1 = 20 × 0.1104 + 2.8 × (1-0.1104) = 4.7

Thus, the modulus was calculated for rest of the types of laminates (Table 4-8).
Table 4-8: Experimental and Predicted modulus of different laminates.

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Experimental Modulus, GPa</th>
<th>Predicted Modulus, GPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>3.42</td>
<td>4.70</td>
</tr>
<tr>
<td>W2</td>
<td>4.70</td>
<td>5.03</td>
</tr>
<tr>
<td>W3</td>
<td>4.45</td>
<td>4.90</td>
</tr>
<tr>
<td>W4</td>
<td>5.60</td>
<td>5.26</td>
</tr>
<tr>
<td>N1</td>
<td>4.14</td>
<td>4.85</td>
</tr>
<tr>
<td>N2</td>
<td>3.73</td>
<td>4.85</td>
</tr>
<tr>
<td>N3</td>
<td>4.30</td>
<td>4.98</td>
</tr>
<tr>
<td>N4</td>
<td>4.00</td>
<td>4.98</td>
</tr>
<tr>
<td>S</td>
<td>5.90</td>
<td>5.72</td>
</tr>
</tbody>
</table>

Figure 4-3: Experimental and Predicted modulus of different laminates.

Here (Figure 4-3), the predicted values of modulus and experimental values of modulus are close, which ensure that manufacturing and testing of composite laminates were
correct. There were some variations between predicted modulus and experimental modulus. The followings might be potential reason for this:

- During calculation of the modulus from experimental values, void contents were not considered.
- Jute fibres are highly inconsistent. So, variations in fibre modulus are expected.
- Fibre modulus (20 GPa) used for modulus prediction is from literature; but for the fibres used in this research, modulus might be different.
- Resin modulus (2.8 GPa) used for modulus prediction is from company technical data; but for the resin used in this research, modulus might be different.

4.2.3 Comparative Tensile properties for Three Fibre Architectures

For comparison of three different fibre architectures woven, non-woven and sliver; the tensile strength and modulus of each laminate were calculated for 20% normalized fibre volume fraction.

**Calculations:**

Normalized tensile strength for W1 = \(55.6 \times \frac{20}{11.04} = 100.72\)

Normalized tensile modulus for W1 = \(3.42 \times \frac{20}{11.04} = 6.20\)

Thus tensile strength and modulus calculated for each laminate (Table 4-9).
Table 4-9: Tensile modulus and strength for 20% normalized fibre volume fraction.

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Tensile Modulus for 20% normalized fibre volume fraction</th>
<th>Tensile Strength for 20% normalized fibre volume fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>6.2 ± 0.2</td>
<td>100 ± 2</td>
</tr>
<tr>
<td>W2</td>
<td>7 ± 0.3</td>
<td>110 ± 4</td>
</tr>
<tr>
<td>W3</td>
<td>6.64 ± 0.1</td>
<td>102 ± 2</td>
</tr>
<tr>
<td>W4</td>
<td>7.83 ± 0.2</td>
<td>109 ± 4</td>
</tr>
<tr>
<td>N1</td>
<td>6.95 ± 0.2</td>
<td>87 ± 1</td>
</tr>
<tr>
<td>N2</td>
<td>6.26 ± 0.2</td>
<td>82 ± 2</td>
</tr>
<tr>
<td>N3</td>
<td>6.77 ± 0.1</td>
<td>85 ± 2</td>
</tr>
<tr>
<td>N4</td>
<td>6.29 ± 0.1</td>
<td>81 ± 4</td>
</tr>
<tr>
<td>S</td>
<td>6.94 ± 0.7</td>
<td>92 ± 5</td>
</tr>
</tbody>
</table>

Figure 4-4: Tensile modulus (normalized) for different laminates.
Figure 4-5: Tensile Strength (normalized) for different laminates.

From the above figures (Figure 4-4 & Figure 4-5) it is seen that, the tensile strength and modulus of composite laminates were dependent on reinforcement structures (woven, non-woven or sliver) and test directions.

Better tensile strengths were achieved for woven fabric reinforced composites than non-woven mat and carded sliver reinforced composites. The tensile strengths of non-woven mat reinforced composites were lowest and carded sliver reinforced composites were in between these two.

The highest modulus achieved was for woven fabric reinforced composites when tested along weft direction and the lowest modulus for non-woven mat reinforced composites; sliver reinforced composites were in between. For non-woven mat reinforced composites N1, modulus is little higher than modulus of sliver reinforced composites, which was considered as experimental error.

During normalization, it was assumed that 50% of the fibres oriented along MD and 50% along CD in non-woven mat; for carded sliver 100% fibres were assumed to be oriented along longitudinal direction. Though, in practical fibres are not exactly oriented as assumed. As a result the normalized modulus for non-woven and sliver reinforced composites were a bit over estimated. This might be a potential reason for the lower
modulus of woven fabric reinforced composites (when tested along the direction warp) compared to non-woven and carded sliver reinforced composite

Figure 4-6: Arrangement of fibres in spun yarn.

Woven fabric is the assembly of numbers of parallel and interlaced spun yarn. In spun yarn, fibres remain in the twisted state (Figure 4-6). The insertion of twist on this fibre assembly increases the strength of the fibre assembly. Thus spun yarn becomes stronger than other non-twisted or parallel fibre assembly. Ignoring the percentage of crimp that woven fabrics possess, a woven fabric is comparable to a yarn unidirectional structure. That can be reported as a significant reason for the highest strength and modulus of woven fabric reinforced composites compared to other composites.

Figure 4-7: Arrangements of fibres in non-woven mat.
In the non-woven mat, short fibres remain randomly oriented and locally interlaced (Figure 4-7). These fibres are not twisted and not regularly oriented. Also due to shorter fibre length and fibres discontinuity, when non-woven mat was reinforced into a polymer matrix; stress transfer from matrix to fibre was not uniform. This could be a probable reason of lowest strength and modulus of non-woven mat reinforced composites compared to woven fabric reinforced composites and carded sliver reinforced composites.

Carded sliver is the assembly of parallel long fibres (Figure 4-8). These fibres are not twisted or interlaced. No additional force, except fibre cohesion force acts here to keep the fibres all together. That is why this fibres strands are not as strong as twisted fibre strands. Carded sliver when reinforced in polymer matrix, a uniform stress transfer from matrix to fibre occurred due to longer length of fibre and continuity of fibre. These are the most probable factors for which the strength and modulus of carded sliver reinforced composites is lower than woven fabric reinforced composites but higher than other one.
Chapter 5: Conclusion

5.1 Conclusion

The influences of fibre architecture on the tensile properties of jute fibre reinforced epoxy based composites were studied in this research. From the results achieved and analysis, the following points can be concluded:

- All three different structure, jute woven fabrics, non-woven mats and carded slivers became able to bring reinforcing effect in polymer matrix. Though the extent of reinforcement in polymer matrix dependent on reinforcing materials structure (woven, non-woven or sliver).
- The tensile modulus (TM) of woven fabric reinforced composites (5.6 GPa) was found to be 100% higher (maximum) than pure epoxy resin (2.8 GPa).
- The tensile modulus of carded sliver reinforced composites (5.9 GPa) was found to be 110% higher (maximum) than pure epoxy resin.
- The tensile modulus of non-woven mat reinforced composites (4.3 GPa) was found to be 53% higher than pure epoxy resin.
- There were not any significant improvements found in tensile strength (TS) for jute fibre reinforcement.
- The fibre content influenced the tensile properties of composite laminates. For both woven fabric and non-woven mat reinforced composites, TS and TM increased with the increase of fibre volume fraction.
- The tensile properties of composite laminates directly depend on the tensile properties of reinforcing materials.
- The TS and TM of woven fabric was higher when tested along weft direction; similarly TS and TM of composite laminates was also found to be higher when tested along weft direction than warp.
- The TS and TM of non-woven mat was higher when tested along MD than CD; similarly TS and TM of composite laminates was also found higher when tested along MD than CD.
- The theoretical assumption of tensile modulus using the rule of mixture and experimental tensile modulus were found to be closer; which ensures the correctness of manufacturing and testing of composite laminates.
• For 20% normalized fibre volume fraction, the tensile strength and modulus was found to be a maximum for woven fabric reinforced composites tested along the weft and minimum for non-woven mat reinforced composites; the tensile strength and modulus for carded sliver reinforced composites found in between this two.

• For 20% normalized fibre volume fraction, the tensile strength and modulus was dependent of test directions.
5.2 Limitations

The study of fibre matrix interface using Scanning electron microscope was important to understand the variations of strength among different types of composites. But, it was not done due to time limitations.

The study of the fracture surface of composite laminates was essential to understand about the fracture mechanism of different composites and the way of fibre pulling out from the polymer matrix. This was also not carried out due to limited time.

Optical microscope was used to study the fibre orientations in different structure and microscopic photos were directly considered as evidence of fibre orientations. But it would be more rational to analyze the image using an image analysis software and then to decide on fibre orientations, which was not done due to limited time.

To clearly understand the mechanical properties of jute fibre reinforced composites, investigations on some other mechanical properties were essential especially flexural strength, impact strength etc. But due to limitations of time these studies were not being carried out.

It would have been better to repeat all test to cross check the accuracy of laboratory work. But this was not possible due to limited time period.
5.3 Future Work

This research is only a part of a complete mechanical study of jute fibre reinforced composites for different fibre architectures. There are scopes for further work to make this study complete.

More composite laminates can be made using different number of reinforcement layers, different stacking sequences and need to be analyzed. Thus it will be possible to find out the optimum fibre content in polymer matrix for each type of reinforcement. Also, laminates can be tested in some more directions to have comprehensive idea on the relation between tensile properties and test directions.

Flexural properties, impact properties, shear properties etc. should be investigated to have a complete idea about the mechanical properties of jute fibre reinforced composites. Along with this, water up take, biodegradability, fire retardancy etc. can be studied for complete characterization of jute fibre reinforced composites from these three different reinforcements.

A theoretical model can be established for predicting the mechanical properties jute fibre reinforced composites for different fibre architecture and different fibre volume fraction.


