KATHMANDU UNIVERSITY

SCHOOL OF ENGINEERING

DEPARTMENT OF MECHANICAL ENGINEERING

PROJECT REPORT

ON

EXPERIMENTAL STUDY OF MECHANICAL BEHAVIOR OF UPCYCLE MATERIAL-BASED COMPOSITE FOR WIND TURBINE BLADE

In Partial Fulfillment of the Requirements for the

Bachelor's Degree in Mechanical Engineering

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Project Evaluation

Experimental study of mechanical behavior of upcycled material-based composite for wind turbine blade

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ABSTRACT

The conventional composite material has negative impact in the environment as they are non-biodegradable and the source of those material is petroleum product. The alternative solution to these materials is natural fiber. The natural fiber rather being used as conventional textile material can be upcycled to structural composite of high-end application. In this project we carried out an experimental study on the mechanical behavior of a composite material made from upcycled natural fiber that can be used as wind turbine blade application. We investigated various natural fiber alternatives and matrix for the composite preparation. Our key finding was that the studied natural fiber alone cannot be used as a structural material for wind turbine blade without prior processing like chemical treatment and use of filler material. There were many challenges we face during the project due to unavailability of the equipment for the mechanical testing. However, we observe specimen with 30% of fiber weight fraction of natural hemp has good mechanical property. This study provides some basic mechanical properties of the composite material as well as limitation one has to face during the experimentation process. This study valuable insight into conduction similar kind of research such as development of sustainable material for engineering application.

Keywords: Natural fiber, upcycling, composite material, wind turbine blade, sustainable material, resin, mechanical properties

LIST OF ABBREVIATION

FRP	Fiber Reinforced Plastics
HAWT	Horizontal Axis Wind Turbines
VAWT	Vertical Axis Wind Turbines
TSR	Tip Speed Ratio
CFRP	Carbon Fiber Reinforced Plastics
RTM	Resin Transfer Molding
VARTM	Vacuum-Assisted Resin Transfer Molding
PLA	Polylactic Acid
PHA	Polyhydroxyalkanoates
NFRP	Natural Fiber-Reinforced Polymer
GFRP	Glass Fiber Reinforced Plastics
ATP	Automated Tape Placement
VI	Vacuum Infusion
TRPC	Textile Fiber Reinforced Composite
UTM	Universal Testing Machine
ASTM	American Society For Testing And Materials
H82	Hemp Composite 80% Matrix 20%Fiber
H73	Hemp Composite 70% Matrix 30%Fiber
FC82	Flax Cotton Composite 80% Matrix 20%Fiber
FC73	Flax Cotton Composite 70% Matrix 30%Fiber
J82	Jute Composite 80% Matrix 20%Fiber
J73	Jute Composite 70% Matrix 30%Fiber
WPD	Wind Power Density
HFRC	Hemp Fiber Reinforced Composite
JFRC	Jute Fiber Reinforced composite
w.m.c	Wood moisture content

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CHAPTER 1 INTRODUCTION

1.1 Background

Global population growth is driving up global energy demand, which has resulted in greater consumption of fossil fuels. As fossil fuel consumption increases, greenhouse gas emissions in nature increase, causing adverse environmental effects such as global warming, melting ice from mountains, ozone layer depletion, acid rain, etc. Due to the progressively increasing concern for the environmental deterioration caused by fossil fuel-based energy sources, renewable sources are nowadays highly focused upon. Among the available renewables, wind energy is nowadays considered the most reliable and cleanest of all renewable energy [1].

Out of 26 million people of Nepal, 75% are benefitted from the access to electricity from various sources. The population getting electricity from national grid is 67% and other are benefitted from other sources such as micro hydro or Solar PV. In rural are only 43% of population have access to the electricity. The remaining large number of people are without access to grid electricity due to the reason such as distance to the grid, remoteness, lack of infrastructure and limited generation capacity [2]. Nepal being very susceptible to the pollution, sustainable energy solution is very important. One such solution could be wind energy where propeller driven turbine converts wind energy into electricity at an efficiency ranging from 60 to 80 % [1]. Wind energy technology is still in its initial experiment phase in Nepal. A wind power system was installed in Kagbeni to generate about 20kW of electrical power (annual energy of 50MWh). By considering commercially viable wind power density (WPD) 300W/m2, there is 6074 sq. km area with the aforesaid 300 or greater than 300 WPD. If 10% of the area is considered as feasible for wind energy production, then the huge amount of power can be generated from the wind. From aforesaid figure,10% of the 6074 sq. km i.e., 607.4 sq. km at the rate of 5 MW per sq. km, 3000 MW of electricity can be generated from wind energy only which is far greater than electricity demand of Nepal [3]. However, the installation cost of the wind turbine is very high and there will be waste management issue for the non-biodegradable component.

To convert the kinetic energy of the wind into mechanical or electrical energy, wind turbines or mills have been established. Most wind turbines consist of three rotor blades that rotate around a horizontal hub and convert the wind energy into mechanical energy. The rotor blades of wind turbines are considered one of the key components of the wind turbine [4]. The components of turbines are changing as the technology improves and evolves. There is a trend toward lighter-weight systems. Lightweight, low-cost materials are especially important in blades and towers [5]. In wind turbine structures a wide range of materials are used. Many factors such as mechanical equipment, fatigue resistance, corrosion resistance, breaking toughness, rigidity, weight, and appearance have impacts on wind turbine materials [6].

The total global production of the fiber reinforced plastics (FRPS) amounts to the 5.9 million tons and the figure is increased to the 8.7 million tons in 2011 [7]. Carbon fibers and glass fibers, which are previously mainly used as reinforced fibers of composite materials, generate a large amount of CO_2 in the manufacturing process and are highly resistant to the environment, so even when discarded after use, carbon fibers and glass fibers are hardly permanently decomposed. Natural fibers not only absorb a large amount of CO_2 in the process of cultivating materials but also have complete biodegradability when made of a composite material combined with biodegradable natural resin and have excellent eco-friendliness because they are completely eco-friendly[8] . The key mechanical parameters, defined by the component function and constraint, are typically stiffness and strength. Material selection, on the basis of these performance indices, is best achieved by plotting the performance indices (which are typically a mathematical

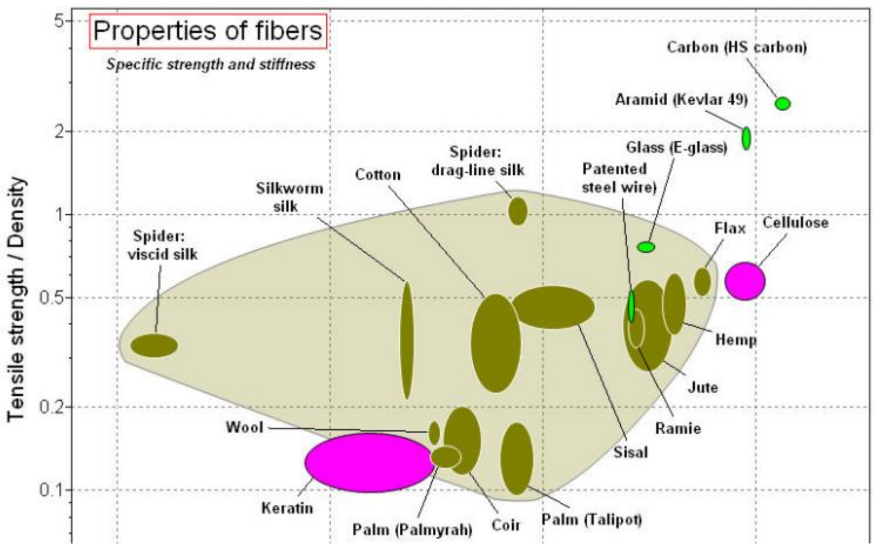


Figure 1: Comparison of natural fiber with synthetic fiber with tensile properties

combination of material properties) on each axis of a materials selection chart, also known as an Ashby plot.

This suggests that exploration of different material composite which is eco-friendly and reduces the impact on the environment should be done. The Ashby plot in Figure 1 compares the specific tensile performance of various natural fibers (from animals and plants) with synthetic fibers [9]. It is observed that several plant fibers, including flax, hemp and jute, have better specific tensile stiffness than E-glass. On the other hand, specific tensile strength of plant fibers is consistently lower than that of synthetic fibers [10].

Similarly, various properties can be screened through Ashby chart, which assist in selection of material. After selecting materials composites is fabricated the project aims to test the composite specimen for various mechanical and physical properties.

1.2 Problem statement

Only 43% of the population in rural Nepal has access to electricity, and there is a shortage of infrastructure that makes it difficult to extend the use of power. Alternatives that are both affordable and sustainable must be investigated to solve this problem. A potential option is wind energy, and wind turbines are a crucial part of this sustainable energy source. Particularly, the wind turbine blade is a crucial structural component that needs to be robust, long-lasting, and lightweight. However, traditional composite materials like glass fiber and carbon fiber composites are expensive and not environmentally friendly. This project focuses on exploring natural fibers, for upcycling them into composite materials suitable for the wind turbine blade. The study aims to investigate mechanical properties of these natural fiber composite.

1.3 Rationale

The need for the sustainable and affordable energy solutions is very significant especially in place like Nepal with the limited infrastructure. Nepal being developing and the citizens residing in rural area do not have access to electricity, and expanding the use of traditional power sources is difficult. With wind turbines playing a crucial role in producing power, wind energy has emerged as a promising alternative. However, the composite materials used to make traditional wind turbine blades are not ecologically friendly and are expensive.

Our project investigates the different natural fibers to upcycle composite materials for wind turbine blades. The study focuses on the mechanical characteristics of composites of natural fiber which have potential use case for the wind turbine blade application and considered as alternative for conventional composites.

Furthermore, our project states the upcycling term in broad way rather than its conventional definition. Upcycling often termed as conversion of the waste product into valuable source, However, our project redefines the term ‘upcycling’ to the conversion of natural fibers, often used for making textile into advance engineering material. The upcycling term in our definition is making more valuable product from the resources that are traditionally used to create simpler products and those products are sustainable environment friendly.

1.4 Objective

- To study different upcycled natural fiber material and identification of the binding material that can be used to make composites
- To fabricate the composite material and experimentally study the mechanical properties of composite specimen.

1.5 Scope

- The project involves the study of the different natural fiber option which is upcycled to make composite.
- The project includes the preparation and testing of the composite for their basic physical and mechanical properties such as water absorption test, tensile strength, impact strength and compressive strength.
- The project aims to provide a foundation for future studies on the design and optimization of NFRP for the wind turbine blade application.

1.6 Limitation

- The material composite will be prepared from only one matrix study will be conducted accordingly in particular condition.
- The mechanical test of the composite was done on specimen rather than the component.

- The project does not incorporate the blade structure design optimization and limited to study of the natural fiber reinforced composite.

CHAPTER 2 LITERATURE REVIEW

2.1 Wind turbine

A wind turbine converts wind energy into electricity. Wind Turbines can be classified as horizontal axis wind turbines (HAWTs) or vertical axis wind turbines (VAWTs). HAWTs are nowadays the preferred turbine design, especially for big-size wind projects, but small-scale VAWTs have been also recently installed in urban areas, as they are characterized by lower noise levels and allow the production of energy also in locations with discontinuous and turbulent winds [11]. Vertical axis wind turbines (VAWTs) are not commercially successful like horizontal axis wind turbines (HAWTs) because of their poor performance and reliability [4]. The principal subsystems as shown in figure 2 which make up the horizontal axis wind turbine are [12]:

- The rotor
- The power trains
- The nacelle structures
- The tower
- The foundation
- The ground equipment station

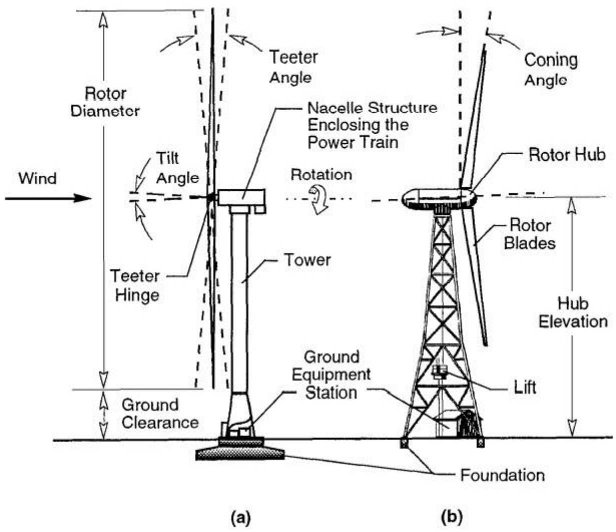


Figure 2: Principle subsystem of horizontal axis wind turbine[12]

2.2 Turbine blade

The Turbine blade is the first element in the chain of functional elements of a wind turbine. Its aerodynamic and dynamic properties, therefore, have a decisive influence on the entire system in many respects. The capability of the blade to convert a maximum proportion of the wind energy flowing through its swept area into mechanical energy is the direct result of its aerodynamic properties which, in turn, largely determine the overall efficiency of the energy conversion in the wind turbine [13]. Blades are designed with a circular root that transitions into an airfoil with the maximum chord occurring at about 25% span [14].

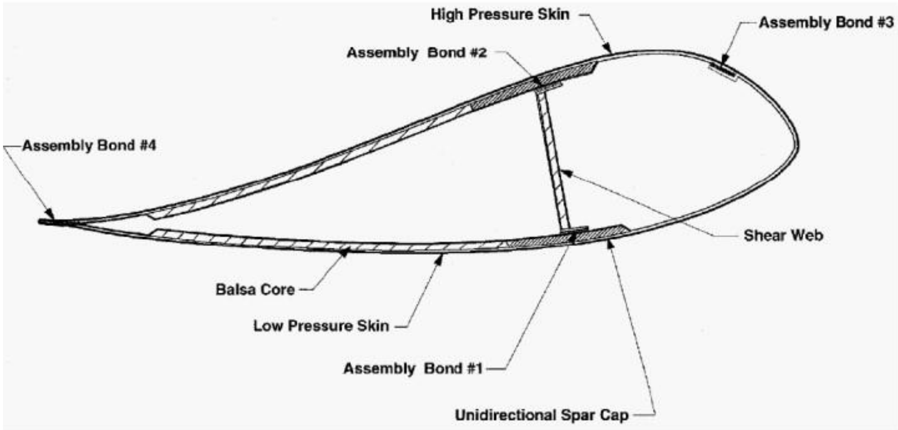


Figure 3: Typical wind turbine blade cross section [14]

The blade internal structure consists of multi-cellular section with a box-spar as shown in Figure 4:

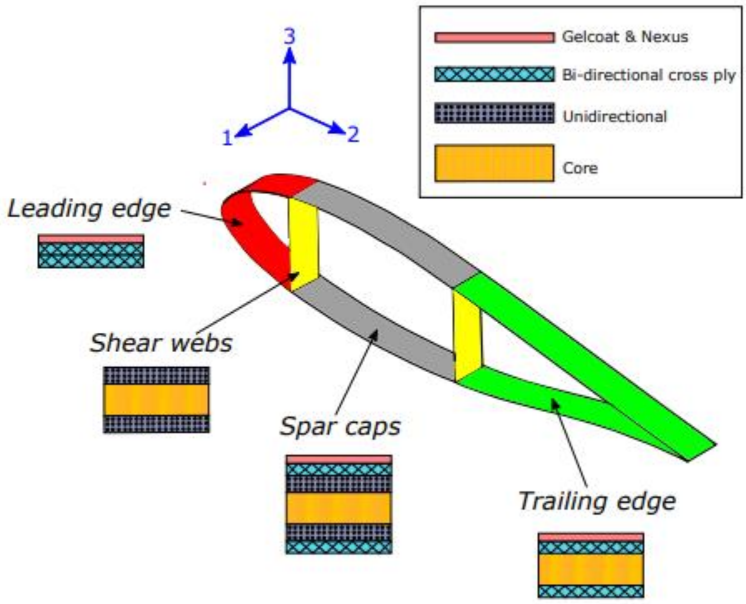


Figure 4: Blade internal structure and material schematic [15]

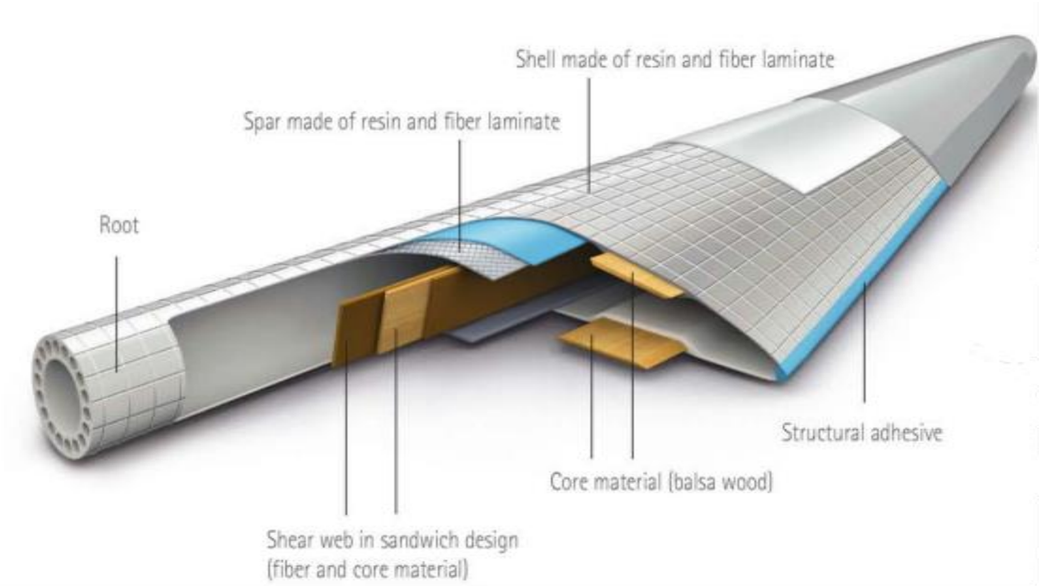


Figure 5: Anatomy of typical wind turbine blade [16]

Internal structure of blade has shear webs which provide the better torsion in comparison to an I-beam and spar cap are place at the either end of the shear web. Balsa wood or polymer foam are the core materials for both the shear web and the shell of the blade the shell itself is composed of resin, fiber laminate, balsa wood core and structural adhesive. The shear web has balsa wood at its core which is sandwiched by two layers of composite material and either end of the shear web has seal cap which comprises of the laminated resin and fiber. The wind turbine blade comprises of about 85% of the composite material and majority of them found within root of the blade and spar caps. [16].

2.3 Upcycling of material

Upcycling is referred as the act of taking something no longer in use and giving it a second life and new function. In doing so, the finished product often becomes more practical, valuable and beautiful than what it previously was. The upcycle of the product in our project sense was different from the actual definition. We have considered upcycling referring it as sustainable solution for the given purpose. It is not about recycling or converting waste in to something valuable. The project is rather about producing advance material from the product which has simple use case traditionally. Natural fiber like hemp, jute, flax, cotton, etc. are used to make textile, however the preliminary study has shown that they possess very good mechanical property to introduce them as advance engineering material. Different natural fiber is studied for the upcycling and the material we chose to experiment is hemp fiber and the property will be compared with jute fiber and glass fiber. So, following literature involves study of the natural fiber.

2.4 Material for turbine blade

Material properties required for the wind turbine blade should have the following properties for the optimal design:

- High strength (to withstand gravity load and even extreme)
- High fatigue resistance and reliability (to make sure the stable functioning for longer duration of the time
- Low weight (to reduce the load on the tower, and the effect of gravitational forces)
- High stiffness (to make sure the stability of the shape and orientation of the blade during the work time, as well as clearance between blade and tower)

The objective of this project is not to study the efficient material rather the study of the material locally available which can be used for the wind turbine blade. In general form stiffness and density gives the merit indices which can be used for the material selection procedure [17]. The mechanical design of the rotor blade corresponds to a beam and merit indices for this case is:

$$M_b = \frac{E^{1/2}}{\rho} \tag{1}$$

Where E is the material stiffness and ρ is the material density [18]. In the figure below, line of the constant is super imposed to give appropriate material for the wind turbine blade.

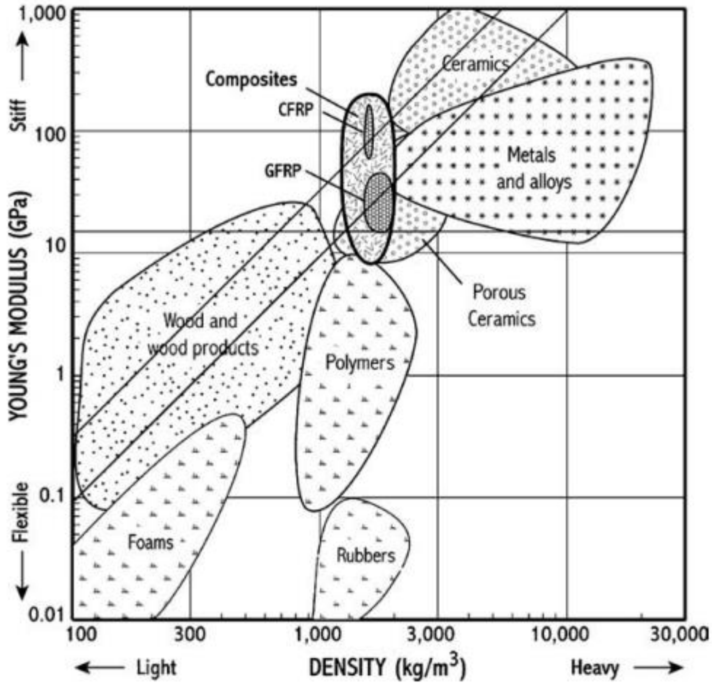


Figure 6: Diagram showing stiffness versus density for all the material [17]

The lower of the two line in the figure 6 indicates the potential candidate material are wood, composite, porous ceramics, ceramics and metal. And the upper line gives the candidate material to be wood, composite and ceramics. Similarly, it is important to consider material fracture toughness and from the reference it is found that the candidate material is woods and composite [17]. In general, wind turbine blades are made up of composite laminates, sandwich core materials, gelcoat film and adhesive joint [19]. They undergo intense loading throughout their service life and are exposed to natural forces depending on their site of deployment where they do not have to concern about wind load only but also to the extreme heat or cold, solar radiation, erosion or even earthquake. However, the study of the loading condition could be very complex for wind turbine blade, the primary study could be done by studying mechanical behavior of the Fiber reinforced plastic (FRP) which is common material for the construction of the wind turbine blade [20]. The material used for the wind turbine blade has certain desire properties like low weight to reduce the gravitational force, high strength to withstand wind force and gravitational force of the blade, high fatigue resistance to withstand the cyclic load, high stiffness to ensure the stability of optimal shape [21]. Generally composite materials are used to fabricate the wind turbine blade and the composite are prepared mostly from the different composition of fibers and polymers [22]. Composite means material having two more distinct constituent materials. Generally automobile industry has introduced large scale use if the composite. Figure 5 below shows the use of composite has been grown steadily through the year 1960 and is projected to continue to increase in future.

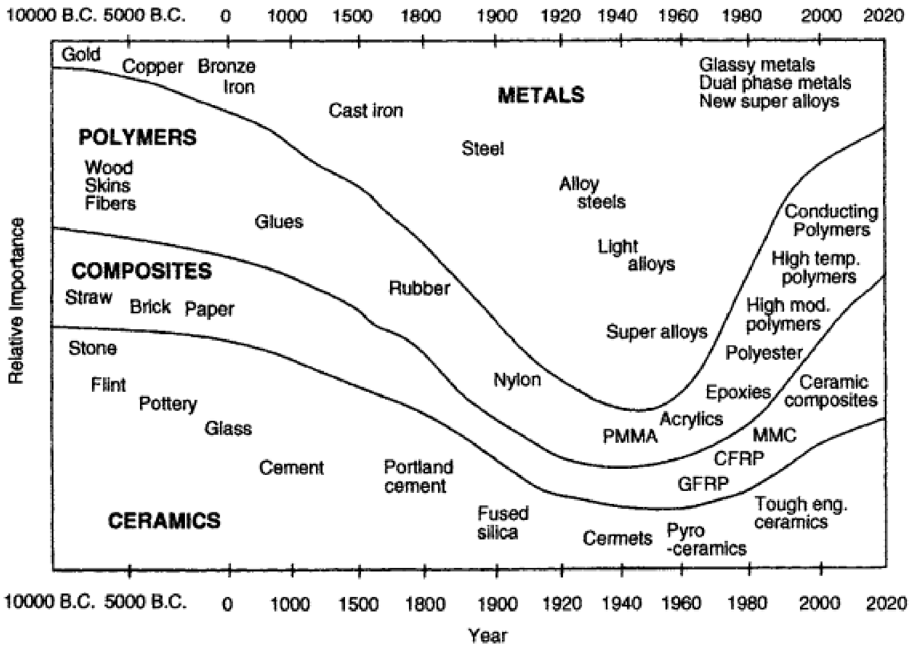


Figure 7: Relative importance of material development through history [23]

Generally composite are arrange in such a way that one or more discontinuous phase is embedded in a continuous phase. The discontinuous phase is termed as reinforcement while the continuous phase is termed as matrix [23]. Composite are classified on the basis of the type of reinforcement used. Composites are classified as:

a) Fibrous composite: The fibrous composites are formed by embedding and binding together fibers by a continuous matrix. Technically they have high strength and stiffness on weight basis the matrix is meant for bonding the fibrous and is to support, protect, and transfer stress among the fibers. The mechanical properties of such composite depend on the degree to which an applied load is transmitted to the fibers by the matrix phase. The matrix is usually of much lower strength, stiffness, and density and is tougher than the fibers. It would not withstand high stresses. The composite, resulting from the combination of fibers and matrix, possesses higher specific stiffness and specific strength and is lighter than conventional engineering material. In general, fiber is the principal load-carrying member, while the surrounding matrix keeps them in the desired location and orientation acts as a load transfer medium between them and protects them from environmental damages due to elevated temperatures and humidity, etc.

The mechanical property typically depends on the stress-strain behavior of the fiber and matrix phases, the phase volume fractions and the direction in which the stress or loads is applied. Furthermore, they are highly anisotropic and depends on direction in which they are measured. The fibers are either continuously aligned, discontinuous and aligned and discontinuous and randomly oriented fiber-reinforced composites.

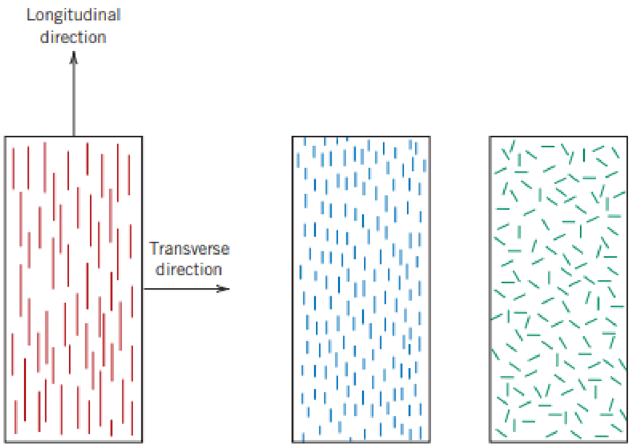


Figure 8: Schematic representation of continuous aligned, discontinuous aligned and randomly oriented fiber-reinforced composite [24]

If we consider the fiber to be totally brittle and the matrix phase to be reasonably ductile, the mechanical uniaxial stress-strain response can be illustrated as follow:

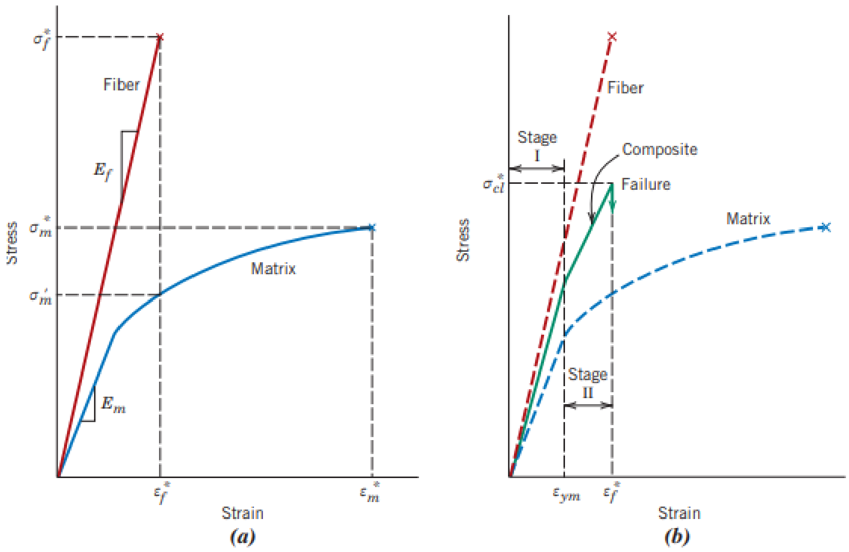


Figure 9: (a) Schematic stress-strain curve for brittle fiber and ductile matrix materials. (b) Schematic stress-strain curve for an aligned fiber-reinforced composite that is exposed to a uniaxial stress applied in the direction of alignment [24].

In the initial stage both fiber and matrix deform elastically and after sometime matrix yield and deform plastically while fiber continue stretch elastically making tensile strength of the fiber significantly higher than the yield strength of matrix. The composite failure begins as the fiber starts to fracture. However, composite failure is not that catastrophic because there is always considerable variation in fatigue strength of brittle material and even fractured fiber are still intact with the matrix [24].

b) Laminated composites: It is the most frequently used composite materials in different industrial application and these types of composites are fabricated by assembling a number of fibrous layer and combining them with a matrix.

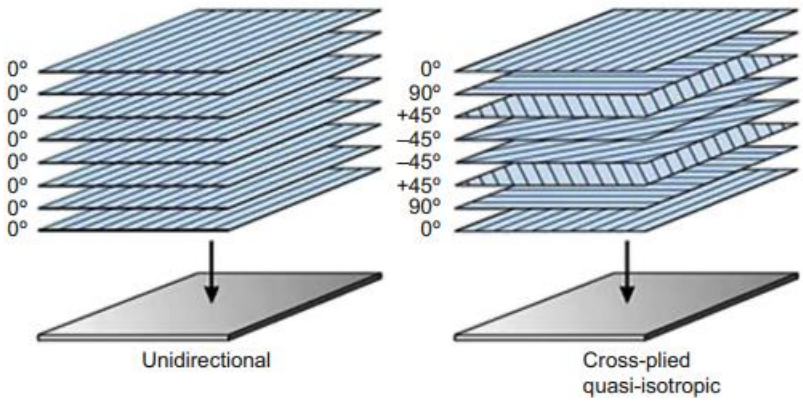


Figure 10: Schematic representation of laminated composites [25]

The fibrous layer can be arranged in various orientation with respect to the axis of composite and they are characterized by high in-plane strength and stiffness. The major failure mode of the composite is delamination [25]. Bonding layers of different materials or the same materials makes laminated composites. Depending upon the ways of fabrication, behavior, or constituent materials of laminates, laminated composites are commonly called bimetal, clad-metals, laminated or safety glass, plastic-based laminates, laminated fibrous or hybrid composites, and sandwiches.

c) Particulate composites: Suspending particles of one or more materials in a matrix of another material produces particulate composites. The particles and matrix can be either metallic or non-metallic. The commonly used particulate composites are concrete, solid rocket propellants, carbides, etc. [26].

Wind turbine blade has sandwich structure consisting of the composite face sheets enclosing sandwich core made up of light-weight material called as balsa wood or polymer foam. The load carrying parts are made up of glass fiber and carbon fiber impregnated with the epoxy resins [27]. The orientation of the research is toward studying different natural fiber which are locally available and experimental study of their mechanical property mechanical property.

2.5 Fiber

Composite materials are made by combining two or more materials to create a new material with improved properties. The materials used in composites are typically a combination of a reinforcing fiber and a matrix, which is a binder that holds the fibers together.

There are many types of fibers that can be used as reinforcement in composite materials, including:

2.5.1 Glass fibers:

The stiffness for the composite is determined by the stiffness of fiber and their volume content. The borosilicate glass which is also called as the E-glass fiber are used as main reinforcement in the composite. By increasing volume content, stiffness, tensile and compression strength increases however the fatigue strength of the composite increases. The glass fiber constitutes of about 75% weight of whole composite [28]. Glass fibers are strong and have a high modulus of elasticity, making them a popular choice for reinforcing composites. They are often used in construction, automotive, and aerospace applications. There are many classes of the glass fiber which are classified on the basis of the physical property which is shown in the figure below:

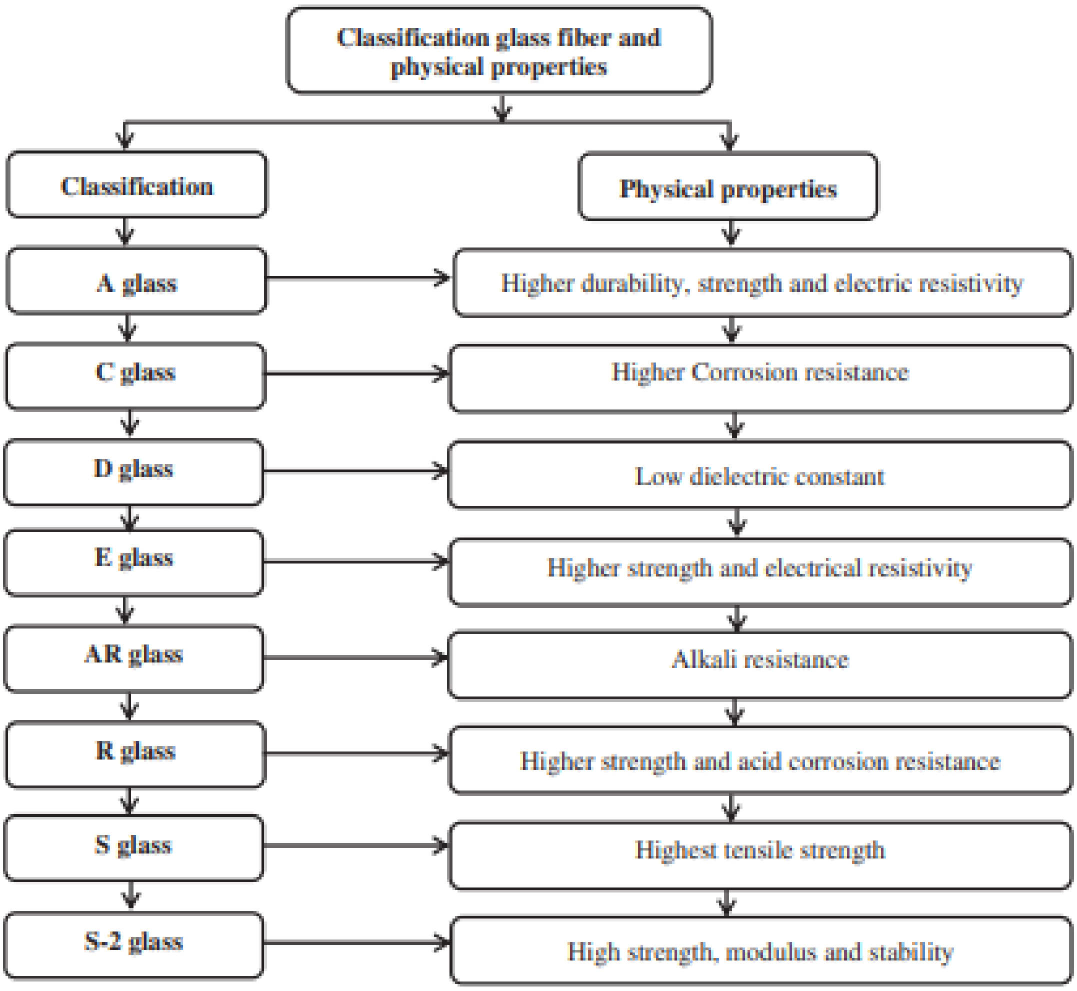


Figure 11: Classification and physical property of the various glass fiber [29]

Typically, E glass are used for the wind turbine blade application due its superior mechanical property as well as it has high electrical resistivity [27]. Following table explains the physical and mechanical properties of the glass fiber:

Table 1: Different mechanical properties of glass fiber [29]

Fiber	**Density(g/cm^3)**	**Tensile strength (GPa)**	**Young's modulus (GPa)**
E-glass	2.58	3.445	72.3
C-glass	2.52	3.310	68.9
A-glass	2.44	3.310	68.9
D-glass	2.11 – 2.14	2.415	51.7
R-glass	2.54	4.135	85.5
S_2-glass	2.46	4.890	86.9
AR glass	2.70	3.241	73.1

Figure 12: Glass Fiber [30]

2.5.2 Carbon fibers:

They are considered as the prominent alternative of the glass fiber. Carbon fibers are extremely strong and lightweight, and they have a high modulus of elasticity. However, they have relatively low damage tolerance, compressive strength and ultimate strain, and are much more expensive than glass fiber. Carbon fiber reinforced composite are sensitive to the fiber misalignment and waviness: even small misalignments lead to the strong reduction of compressive and fatigue strength [28]. They are often used in high-performance applications, such as aerospace, sports equipment, and military equipment.

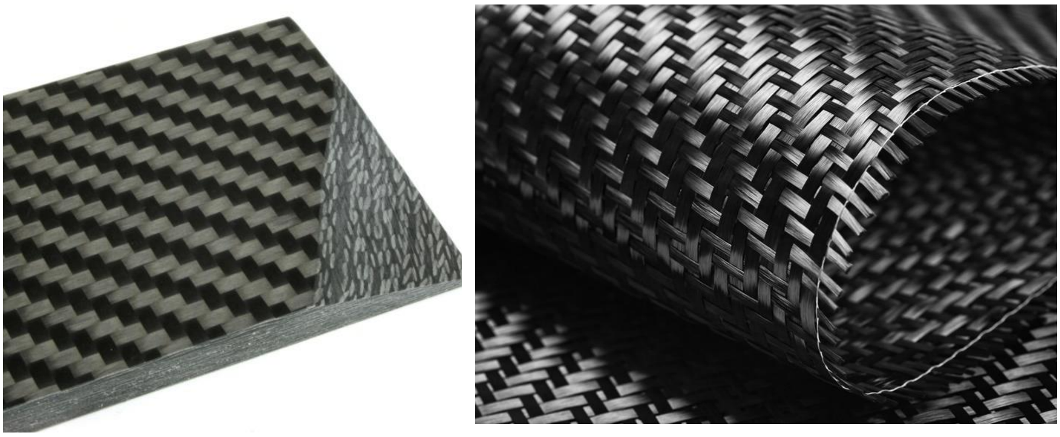


Figure 13: Carbon Fiber [31]

2.5.3 Aramid fibers

Aramid fibers, such as Kevlar, are strong, lightweight, and have a high tensile strength. They are often used in bullet-resistant vests, tires, and ropes.

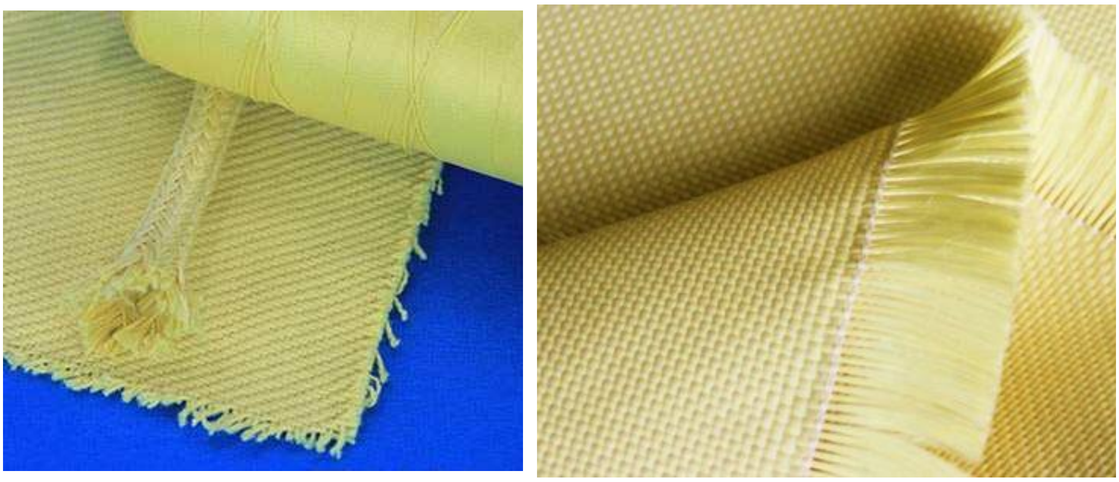


Figure 14: Aramid Fiber [32]

2.5.4 **Basalt fibers**

Basalt fibers are made from molten basalt rock and have high mechanical strength and are tough and damage tolerant. However, they have low compressive strength, low adhesion to resin, absorb moisture, and degrade due to ultraviolet radiation. They are often used in construction, automotive, and aerospace applications.

Figure 15: Basalt Fiber

Stiffness, tensile and compressive strength of the composite increases with increase in the content of the fiber. However increased fiber content to make the composite mechanically dominating will not be suitable as the after 65% of the volume fraction of fiber makes the case for the presence of the dry area and the adhesion of the fiber and matrix would not be appropriate. The mechanical properties of the different synthetic fiber are compared on the following table:

Table 2: Mechanical properties of the synthetic fiber [33],[34]

Material Property	Fiber				
	Aramid	**Carbon**	**Basalt**	**E glass**	**S glass**
Density(g/cc)	1.44	1.81	2.63-3.05	2.54-2.62	1.78
Tensile strength (MPa)	2920	3500-6000	3000-4840	4020-4530	3500-6000
Stiffness (GPa)	70.5	230-600	79.3-110	83-91	230-600
Elongation (%)	3.6	1.5-2.0	5.3-5.6	4.7	5.3-5.6

From above table it is evident that carbon fiber dominates all the aspect of the mechanical properties which makes it noble for the wind turbine application. However, if we consider cost aspect of it, it is expensive than all other kind of the fiber. Because of this reason near rival glass fiber dominates the wind turbine blade industry [28].

2.5.5 Natural fibers:

In engineering material selection of a sustainable product plays huge role. The material mechanical property must be understood before using it for any structural application. One such sustainable solution is us Natural fiber as composite instead of the synthetic fiber. The competitive edge natural fiber provides over synthetic fiber ae their abundance, availability and low cost [35]. Natural fiber composites are used as load bearing structural component due to their advantageous low cost and recyclability compared to the conventional reinforcing materials such as glass fiber and carbon fiber. However, their vulnerability to moisture absorption has been one of the key concerns for these materials regarding their use in structural applications. Many natural fibers have a hollow space, called lumen. At irregular distances, there are nodes dividing the fiber into individual cells. The surface of the natural fibers is rough and uneven which can act as mechanical interlocking and this often can give a good adhesion to the matrix in a composite structure. Natural fibers are mostly constituted of cellulose, a biopolymer of the plant sugar glucose. Other constituents are also present in natural fibers such as hemicelluloses, lignin and waxes [36]. Natural fibers obtained from the different sources like plant, animal, minerals and geological processes can decompose. Unlike the artificial fibers natural fibers do not require additional processing. It is used to fabricate different products like rope, threads, filaments, clothes, etc. There are eight major types of plant fibers: bast fibers (jute, ramie, flax, soybean, hemp, vine, banana, and kenaf), collected from the skin and bast around the plants stem; leaf fibers (abaca, banana, sisal, and pineapple), collected from leaves; seed fibers (cotton, coir, and kapok), collected from seeds and seed cases; grass fibers (corn, wheat, bamboo, barley, and rice); core fibers (corn and wheat stalk), collected from the stalks of the plants; wood pulp [37].

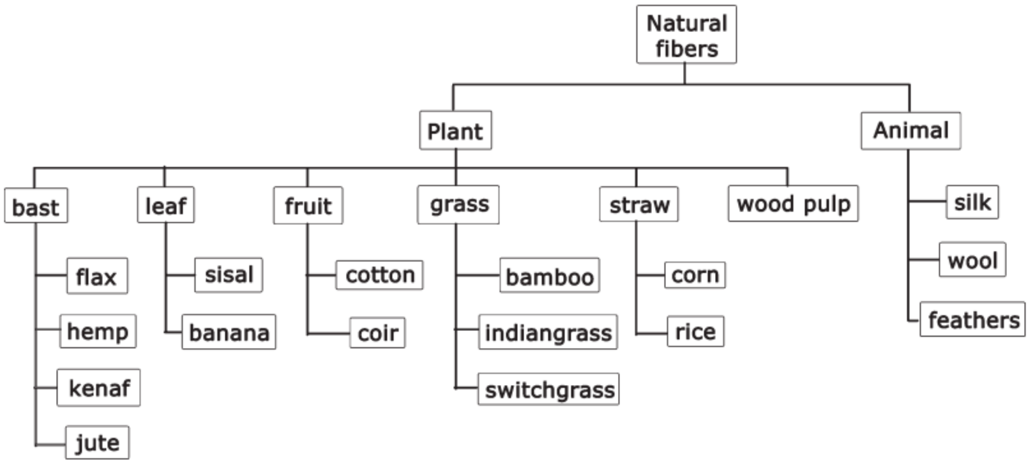


Figure 16: Classification of natural fiber [37]

2.5.5.1 Plant fiber:

Plant fiber has two general classifications in terms of the utilization, primary and secondary. Primary refers to those which are grown for fiber extraction purpose while secondary refers to those where fiber is extracted as by product or the main purpose of planting that plant is not for the fiber extraction. The plant fiber consists of the cellulose, hemicellulose, lignin, pectin and other waxy substance as shown in figure 17:

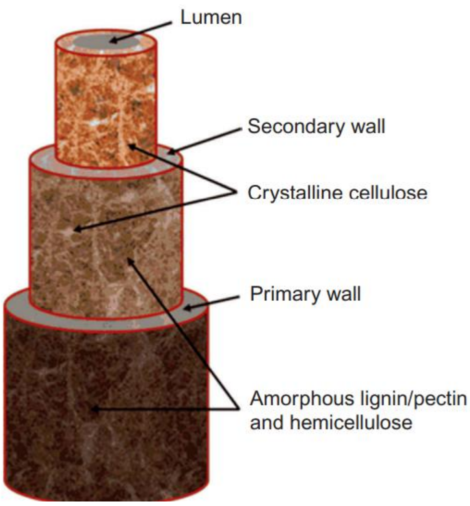


Figure 17: Structure of the plant fiber [38]

The basic chemical structure of the cellulose for all plant-based fiber are similar, however cell geometry of each type of cellulose varies. Cellulose provide strength to the fiber but they have very low thermal resistance which make them highly flammable. Cellulose is linear polymer constituted by several glucose molecules ($C_6H_{10}O_6$) considered as basic monomer and the repeat unit is called cellobiose dimer. The chemical formula for the cellulose is $(C_6H_{10}O_6)_n$, where n is the number of glucose molecule. The number differs from one plant to another. The content of the fiber are hemicellulose and lignin. Hemicellulose is hydrophilic in nature and is soluble in alkali solution [38]. The lignin has hydrophobic characteristics and is totally amorphous. Lignin gives coarse and stiff characteristics to the plant fiber. Lignin is also soluble in alkali. Following figure shows the chemical structures of the cellulose, hemicellulose and lignin respectively.

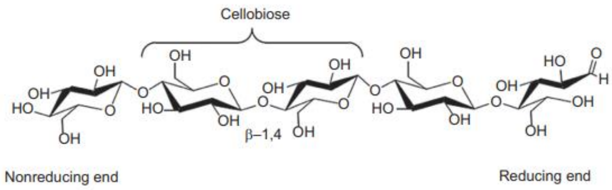


Figure 18: Cellulose chain structure [38]

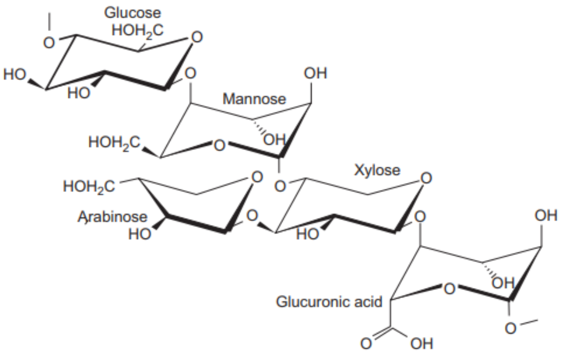


Figure 19: Hemicellulose Structure [39]

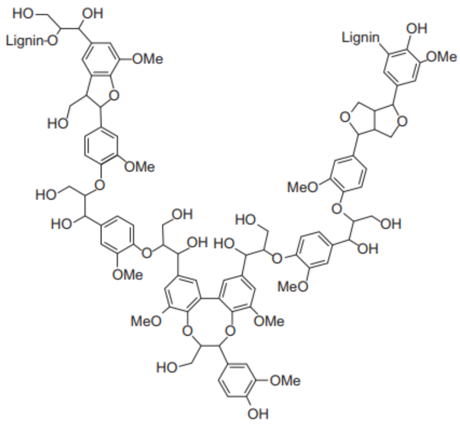


Figure 20: A lignin structure [39]

The table below gives the chemical composition of the different plant fibers:

Table 3: Chemical composition of Natural plant fiber [38]

Fiber	Cellulose (wt%)	Hemicellulose (wt%)	Lignin (wt%)	Waxes (wt%)
Bagasse	55.2	16.8	25.3	-
Bamboo	26-43	30	21-31	-
Flax	71	18.6-20.6	2.2	1.5
Kenaf	72	20.3	9	-
Jute	61-71	14-20	12-13	0.5
Hemp	68	15	10	0.8
Ramie	68.6-76.2	13-16	0.6-0.7	0.3
Abaca	56-63	20-25	7-9	3
Sisal	65	12	9.9	2
Coir	32-43	0.15-0.25	40-45	-
Oil palm	65	-	29	-
Pineapple	81	-	12.7	-
Curaua	73.6	9.9	7.5	-
Wheat straw	38-45	15-31	12-20	-
Rice husk	38-45	19-25	20	14-17
Rice straw	41-57	33	8-19	8-28

From the composition of fiber, we can assume the moisture absorption property as hemicellulose is responsible for the hydrophilic nature of the fiber. It can be observed that fiber like coir, curaua has very low hemicellulose content and will refer to the lower moisture property than other. Similarly, flax, hemp, jute, ramie has similar content of the cellulose [38].

2.5.5.2 Animal fiber:

Unlike plant fiber, animal fiber is composed of proteins [39]. Structurally external sheath of the animal fibers is called as cuticle and have its own architecture. It is formed of four layers: the epicuticle, the a-layer, the exocuticle, and the endocuticle. The cuticle is usually highly abundant in cystine residues, which makes a highly cross-linked structure. The 2.4 nm-long hydrocarbon tail of the acid is oriented to the outside and is supposed to be responsible for the water-repellent behavior of animal fiber surface. The protein by which the fiber is made up of is keratin. It possesses high mechanical strength [40].

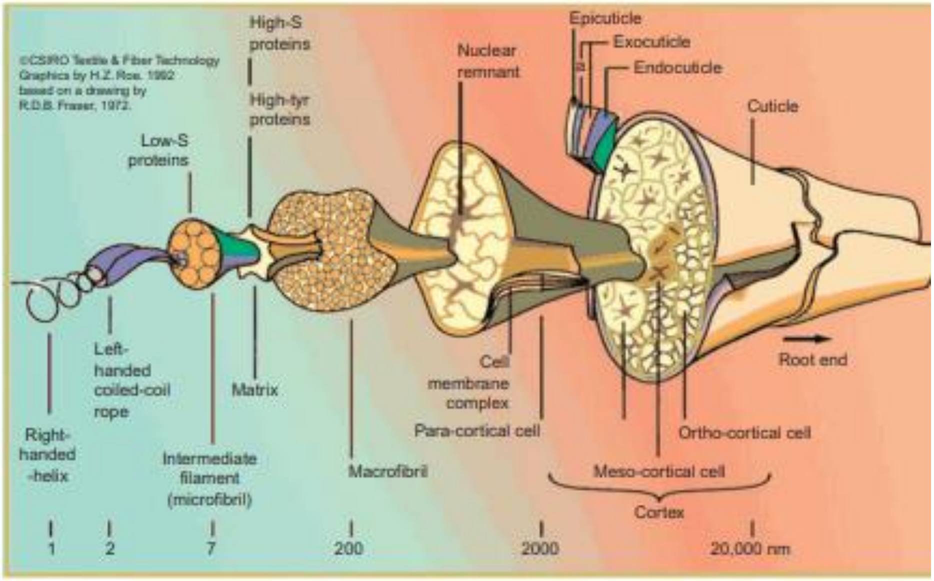


Figure 21: Cross-section diagrams of wool fiber at progressive magnification [39]

Following table shows major sources of natural fibers and main properties:

Table 4: Major sources of natural fibers and main properties [41]

Group	Fiber	Source	Fiber length (mm)	Main properties
Bast (plant fibers)	Flax	Linum Usitatissimum	Up to 900	Rapid absorption and desorption of water
	Jute	Corchorus capsularis (*white jute*), Corchorus olitorius (*tossa jute*)]	Up to 4000	Low thermal conductivity, moderate moisture regains, high insulation, high anti-static properties
	Kenaf	Hibiscus	6	Excellent durability
	Hemp	Cannabis	Up to 4000	Heat conducting, good dying, good ultraviolet-light blocking, natural anti- bacterial properties
	Ramie	(Boehmeria nivea)	Up to 1900	Rapid absorption and desorption of water, low elasticity, easy dying
Leaf (plant fibers)	Abaca	Abaca plant (*Musa textilis*)	Up to 3000	High mechanical strength, buoyancy,
	Pina	Pineapple leaf (*Ananas magdalenae*)	Up to 200	Resistant to salt water, wear resistant
	Sisal	Agave (*Agave sisalana*)	Up to 1000	Coarse, hard, durable, strong, and stretchable, not easily absorb moisture, resistant to saltwater deterioration, with a fine surface that accepts a wide range of dyes
	Raffia	Raffia palm (*Raphia ruffia*)	Up to 1500	Rough

Seed (plant fibers)	Coir	Coconut (*Cocos nucifera*)	Up to 350	High concentration of lignin, high strength, less flexibility than cotton, unsuitability for dyeing, good resistance to salt water damage and microbial action
	Cotton	Shrub (*Gossypium*)	100–650	Rapid moisture absorption, high tensile
	Kapok	Pentandra tree (*Ceiba pentandra*)	20–32	Fluffy
Grass (plant fibers)	Bamboo	Grass pulp (*Bambusoideae*)	Up to 90	Excellent durability, high stability, good
Core (plant fibers)	Cornstalk	Maize	Up to 3000	Lightweight, strong
Wood pulp (plant fiber)	Modal	Beech tree (Fagus)	–	Lightweight, soft, wear resistant
Animal fibers	Silk	Chinese mulberry silkworm	Up to 1500	Good absorbency, low conductivity, easy dying finish
	Byssus	Saltwater clam	–	Lightweight
	Chiengora	Dog hair	25	Lightweight, fluffy
	Qiviut	Muskoxen	50–80	Soft, does not shrink
	Yak	Yak	16	Heavy, warm
	Rabbit	Rabbits	–	Soft
	Wool	Sheep	Up to 152	Good thermal and acoustic insulation, high deformability, high durability
	Feather	Chicken, birds	3–13	Lightweight, good thermal and acoustic insulation
	Lambswool	Lambs	Up to 50	Soft, warm, elastic

	Cashmere wool	Indian cashmere goat	Up to 390	Soft
	Mohair wool	North African angora goat	Up to 115	Durable, resilient, holding dyes well
	Camel hair	Arabian dromedary and Northeast Asian Bactrian camels	Up to 125	Warm, lightweight
	Alpaca	South America camels	Up to 150	Soft, warm
	Angora wool	Angora rabbit	–	Soft, good blending with other fibers
Mineral-based fibers	Asbestos cloth	Asbestos	12–300	Fire resistant, lightweight
	Glass	Mixed silicates	–	Fire resistant

Figure 22: Natural Fiber

Figure1 shows the comparison of the specific tensile property which makes it clear that fiber like flax, hemp and jute have desirable property for wind turbine among blade mechanical properties of the fiber through Ashby chart which help in sorting the material from huge database [9].

Plant fiber is a term for the single cell that provide mechanical stability to the plant. When plant fibers are fully developed, their intracellular organelle starts to degenerate resulting in fibers having internal cavity lumen which helps in the transport of the water and nutrient [42].

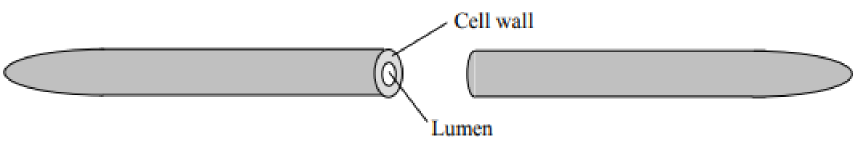


Figure 23: Drawing of a plant fiber [42]

In natural fiber aspect ratio plays very important role in determining the mechanical property of the fiber. The table below gives the mean dimension of various fiber and their aspect ratio.

Table 5: Mean dimension and aspect ratio of various plant fiber [42]

Plant	**Fiber type**	**Dimension**		**Aspect ratio**
		Length (mm)	Diameter(μm)	
Hemp	Bast	25 (5-25)	25(10-51)	1000
Flax		33 (9-70)	19 (5-38)	1750
Jute		2 (2-5)	20(10-25)	100
Ramie		120 (60-250)	50(11-80)	2400
Sisal	Leaf	3 (1-8)	20(8-41)	150
Cotton	Seed	18 (10-40)	20 (8-34)	900
Wheat	Stem	1.4	15	90

The figure below depicts the aspect ratio of the different fiber in visual form:

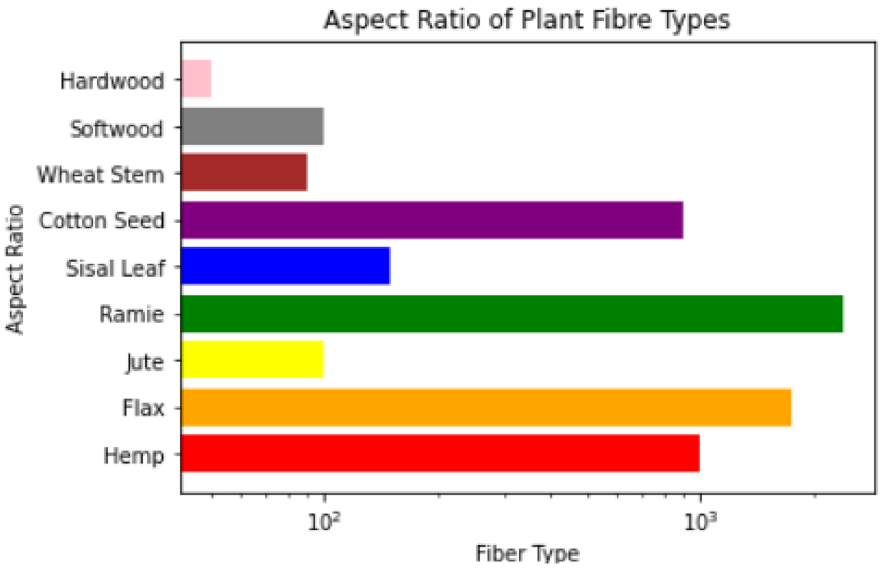


Figure 24: Aspect ratio of the different fiber [42]

In the table 3 the physio-mechanical properties of the different plant fibers are compared and it is observed that the tensile properties are in the following order: bast fiber > leaf fibers > seed fibers. Only bast fiber have tensile stiffness and tensile properties (absolute and specific) are comparable to the E-glass.

Table 6: Tensile properties of different natural fiber [43]

Fiber		Density [gcm^{-3}]	Tensile modulus [GPa]	Specific tensile modulus [GPa/gcm^{-3}]	Tensile strength (MPa)	Specific tensile strength [MPa/gcm^{-3}]	Failure strain [%]
Blast	Flax	1.45-1.55	28-100	19-65	343-1035	237-668	2.7-3.2
	Hemp	1.45-1.55	32-60	22-39	310-900	214-581	1.3-2.1
	Jute	1.35-1.45	25-55	19-38	393-773	291-533	1.4-3.1
Leaf	Sisal	1.40-1.45	9-28	6-19	347-700	248-483	2.0-2.9
	Pineapple	1.44-1.56	6-42	4-27	170-727	118-466	0.8-1.6
	Banana	1.30-1.35	8-32	6-24	503-790	387-585	3.0-10.0
Seed	Cotton	1.50-1.60	5-13	3-8	287-597	191-373	6.0-8.0
	Coir	1.10-1.20	4-6	3-5	131-175	119-146	15-30
	Oil palm	0.70-1.55	3-4	2-4	248	160-354	25.0
other	Bamboo	0.60-1.10	11-30	18-27	140-230	210-233	1.3
	Wood pulp	1.30-1.50	40	26-31	1000	667-769	4.4
	E-glass	2.55	78.5	31	1956	767	2.5

2.6 Matrix

In composite materials, the matrix is the continuous, solid phase that surrounds and supports the dispersed, discrete phase, known as the reinforcement. The matrix can be a polymer, metal, ceramic, or a combination of these materials. The reinforcement is typically a fiber, such as a carbon fiber or glass fiber, that is added to the matrix to improve the overall properties of the composite [44].

Composite materials are used in a variety of applications because they can offer a combination of properties that cannot be achieved with a single material. For example, fiber reinforced polymer composites are used in the construction of aircraft and automobiles because they offer high strength and stiffness, as well as low weight [45]. Metal matrix composites are used in the aerospace and defense industries because they offer high strength and stiffness at high temperatures [46].

The properties of a composite material depend on the properties of the matrix and the reinforcement, as well as the way in which they are combined. The matrix plays a key role in determining the overall properties of the composite, as it determines how the reinforcement is distributed throughout the material and how it is held in place. The matrix also provides the main load-bearing capacity of the composite and helps to protect the reinforcement from damage.

A matrix is used in composite to hold the reinforcing material together by surface connection. The main responsibilities of the matrix are the environmental tolerance, surface appearance, and durability of the composite. As the matrix is stressed, it transfers the external load uniformly to the fibers, and it is applied to resist the propagation of cracks and damage. Following diagram shows the classification of polymeric matrices used in green based on their degradability.

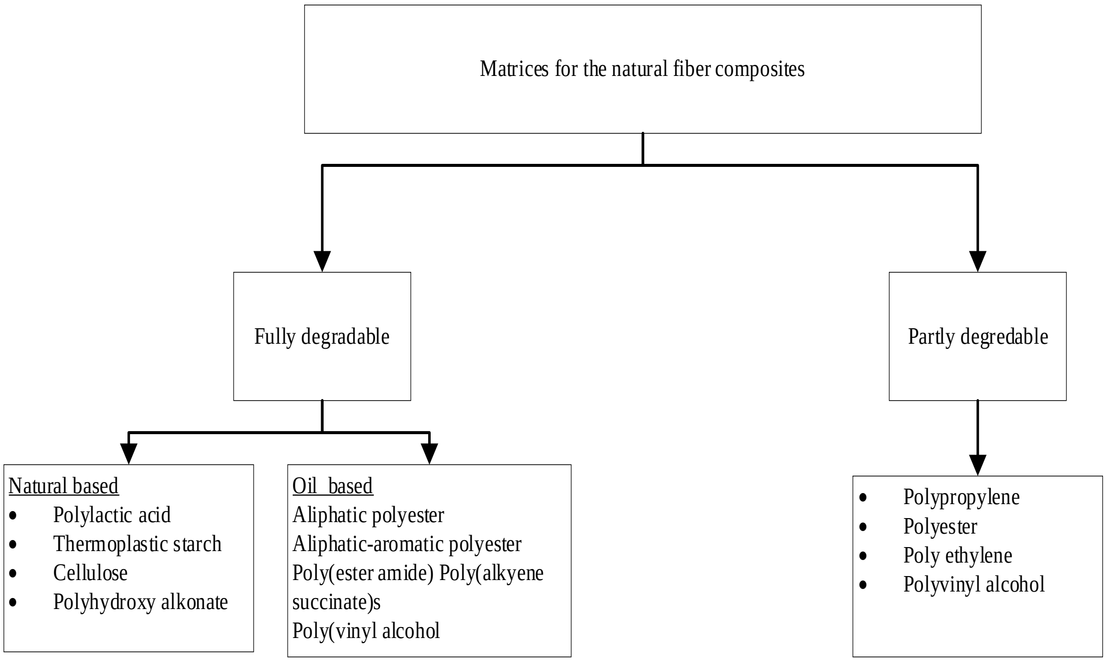


Figure 25: Matrix used for fibers

Bio-based resins are polymers that are fully or partially obtained from renewable resources. Bio based polymers can be produced from plants (e.g., starch and cellulose) or through the polymerization of plant-based sugars and oils [e.g., polylactic acid (PLA), polyethylene terephthalate, and polypropylene 4. Based on the physical properties, there are three types of bio-based polymers: fully bio-based and biodegradable, e.g., Polyhydroxyalkanoates (PHA) and starch, partially bio-based and biodegradable, e.g., cellulose and PLA, and partially bio-based and non-biodegradable, e.g., bio-polyethylene terephthalate, bio-polyethylene, and bio polypropylene. Similarly, there are Petro-chemical based resin which are derived from petroleum, which is obtained from fossil fuels like coal and natural gas. There are two types of the petrochemical based resin one of which is thermoset and another one is thermoplastic.

Thermoset: They are infusible insoluble material that are cured by heat or a catalyst and cannot be melted or replaced by heating. They have covalent bonds between the polymer chains, this type of resin has a higher modulus, improved creep resistance than thermoplastic resins. They are brittle at room temperature and shows low fracture toughness.

Thermoplastic: They are based on polymers that can be shaped in hot viscous state and could be solidified by cooling. They are solid at room temperature and can be reformed and reshaped when heated without chemical reaction. Thermoplastic resin has higher impact resistance, higher damage tolerance and higher processing temperature and pressure than thermoset resin [41].

2.7 Composite

A composite material is a material that is made up of two or more different materials with distinct physical and chemical properties. The materials are combined in such a way that they form a new material with improved properties over those of the individual components. Composite materials are used in a variety of applications because they can offer a combination of properties that cannot be achieved with a single material. There are two main types of composite materials: fiber-reinforced composites and particle-reinforced composites. In fiber-reinforced composites, the reinforcement is in the form of fibers, such as carbon fibers or glass fibers, that are embedded in a matrix, which is typically a polymer. The fibers provide the main load-bearing capacity of the composite and help to improve its strength and stiffness. In particle-reinforced composites, the reinforcement is in the form of particles, such as ceramics or metals, that are dispersed throughout a matrix. The particles provide the main load bearing capacity of the composite and help to improve its wear resistance and thermal stability. Composite materials are used in a wide range of applications, including the aerospace and defense industries, the automotive industry, the construction industry, and the sports and leisure industry. They are often used because they can offer a combination of high strength, stiffness, and low weight, as well as good fatigue resistance, corrosion resistance, and impact resistance.

Glass, carbon or aramid fiber-reinforced polymer (GFRP, CFRP, AFRP) composites are replaced many metallic components in the various manufacturing sectors. These are used as main material for the reinforcement because they have good mechanical property [47]. The table below gives the mechanical property of the GFRP, CFRP and AFRP:

Table 7: Mechanical properties of GFRP, CFRP, AFRP [47]

Mechanical Properties	**GFRP**	**CFRP**	**AFRP**
Density (kg/m^3)	1250-2500	1500-2100	1250-1450
Tensile Strength (GPa)	0.483-4.58	0.6-3.9	1.7-3.6
Young Modulus	35-86	37-784	41-175
Elongation at break (%)	1.2-5	0.5-1.8	1.4-4.4

The figure below gives the stress – strain curves for unidirectional composites with standard fiber reinforcements:

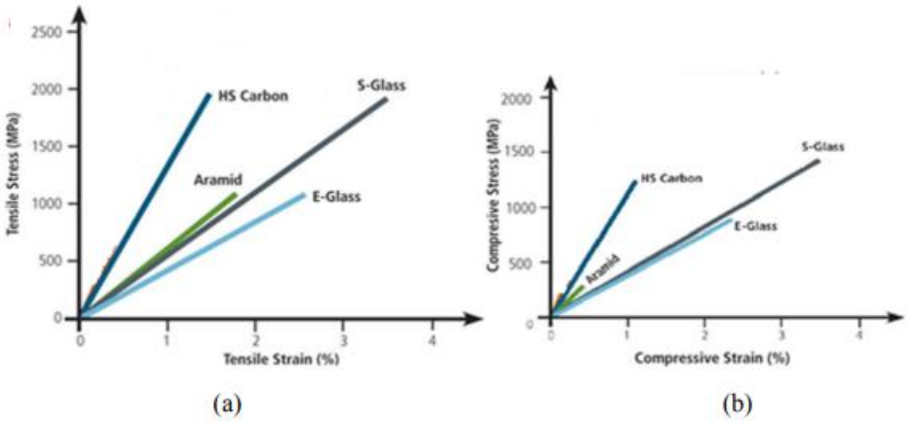


Figure 26: Stress-strain curves for UD composite with standard fiber reinforcement [48]

It is clearly evident that carbon fiber has high mechanical property in comparison to the other synthetic fiber. However, all these fibers possess property that is required for the wind turbine blade application. But, the using of these materials is not considered as suitable for the environment, because these materials are greatly dependent on petroleum-based resources which are depleting rapidly. Due to the many environmental issues, the researchers and technologist has shifted on the utilization of natural biodegradable materials. Due to this fact, the use of natural fiber-reinforced polymer (NFRP) composites is multiplying at a very fast pace. Recently, NFRP composites have been used for automotive parts because of their excellent mechanical properties and lightweight characteristics. In addition, NFRP composites showing certain advantages those cannot be obtained by synthetic fiber-reinforced composites which include low density, low cost, non-abrasive properties, biodegradability and renewable nature. Natural fibers such as flax, hemp, sisal, kenaf, bagasse, banana, jute, abaca and bamboo are easily available and low processing cost. Mostly glass and carbon fiber-reinforced plastics (i.e., GFRP and CFRP, respectively) are used for the production of large-scale wind turbine rotor blades. The uses of glass and carbon fiber are not attractive to the rotor blade manufacturers, because the cost of these materials is high and the use of these materials causes environmental hazards. These attribute makes the essence of alternative which cause less environmental impact. The project is all about the study of the natural fiber composite for the wind turbine blade. We consider wind turbine as renewable source of energy and clean energy source but the fact is that the material like carbon fiber and glass fiber is non-bio degradable and there is huge waste management problem. So, natural fiber can be useful if they can be used to develop such turbine blade. Plant fibers offer many economical, technical and ecological advantages over synthetic fibers in reinforcing polymer composites. Due to the relative abundance, low cost of raw material, low density, high specific properties, and positive environmental profile of plant fibers like flax, hemp, bamboo and jute; they have been marketed as prospective substitutes to traditional composite reinforcements, specifically E-glass. Natural fibers and their composites have a great opportunity for development and market capture [49]**.** Along with the natural fiber, wood epoxy laminate is also used for making of wind turbine rotor blade. According to the National Research Council's Report on wind turbine rotor materials technology, the wood/epoxy composite has following basic property:

Table 8: Static strength of wood/epoxy laminate[50]

Test direction	Type of test	Max stress at 8% w.m.c (MPa)	Max stress at 12% w.m.c (MPa)
Longitudinal	Compression	62.05	49.64
Longitudinal	Tension	68.95	64.81

The table gives the basic mechanical property of the wood/epoxy laminate and also shows how water absorption affect the mechanical property [50]. In the different research paper research has been done on the NFRP and experimentally investigated their property. The disadvantage of the natural fiber composite includes poor matrix interfacial bonding, poor wettability and moisture absorption. Also, the NFRP composite have low damage tolerance and to overcome this limitation Textile fiber reinforced composite (TRPC) has been developed. The research interest has been focused toward the TRPC because of their high damage tolerance, high delamination and impact resistance. In TRPC, fiber have been formed into the textile form – woven, knitted or braided. The TRPC are significant where weight reduction plays very important role such as aerospace, energy structure, automobile industry, etc . The table below compares the different textile structure on the basis different characteristics:

Table 9: Comparison of textile structure based on characteristics [51]

Properties	Woven	Warp-knitted	Weft-knitted	Braided	Non-woven
Stiffness	High	Mid-low	Low	Mid-low	Varies
Flexibility	Low	Mid-High	High	Mid-low	Low
Resilience	Mid-low	Mid-high	High	Mid-High	Low
Impact resistance	Mid	Mid-High	High	Mid-High	Low
Rate of production	Mid	High	High	High	Very High
Cost of production	Mid	Low	Low	Low	Low

From above table 11 we can conclude that the woven, braided and knitted fabric have good mechanical property than the non-woven fabric [51]. This is the reason the study of the natural fiber composite is mostly done on woven fabrics. Ratim et al. have studied the effect of the woven and Non-woven fiber of Kenaf on the composite where they found out woven structure have better mechanical property than unwoven fabric [52]. The figure below depicts the structural differences between nonwoven and woven fabric.

Figure 27: The structural difference between nonwoven and woven fabrics

Since, the mechanical property of the NFRP can be upgraded by weaving and knitting the fiber so for wind turbine blade application such fabric can be used for composite preparation. The table below gives the typical blade material properties of the E-glass polymer composites:

Table 10: Typical blade material property [48]

Properties	Property	Units	E-glass/polyester composite property
Physical	Fiber volume fraction	%	42.8
	Density	g/cm^3	1.79
Tensile	Composite specific stiffness	GPa/ g.cm^{-3}	20.6
	Composite specific strength	MPa/g.cm-^{3}	461
	Composite failure strain	%	1.90

Darshil et al. has conducted the research for the possibility of flax fiber for the small wind turbine blade. The flax fiber and glass fiber are compared and suggested the flax as structural replacement of wind turbine blade [53]. John et al. has examined the mechanical property of bamboo-poplar epoxy laminate which is being developed for the wind turbine blade. The uniaxial tensile test of the composite was found to be 175 MPa to 191 MPa and similarly modulus was found to be 20 GPa [54].

2.8 Chemical treatment of Natural fiber

Natural fiber is first treated with the chemical to make the composite less hydrophilic. One of such process is alkalization. The natural fiber consists of lignin, pectin, waxy materials, and natural oils which covers the outside layer of the fiber cell wall. The alkaline treatment alters the cellulose in the plant fibers by cleaning the surface and the process called alkalization. It can be done by treating natural fiber with the NaOH [55]. Alkalization was found to change the surface topography of fiber bundles and the diameter decrease with increased concentration and decreased at higher NaOH concentrations. It was also found that the tensile strength and stiffness increased with increase in the concentration of NaOH up to a limit. Tensile strength and Young's modulus increased with decrease in cellulose content, while crystalline cellulose decreased slightly but with improved crystalline packing order resulting in increased mechanical properties. Similar observations were elucidated by the crystallinity index. Alkalized hemp fiber bundles were found to exhibit a similar specific stiffness to steel, E-glass, and Kevlar 29 fibers. The improvement in mechanical properties of alkali treated hemp fiber bundles confirmed their use as reinforcement. Study shows the 22% NaOH solution on hemp fibers changes the flexural strength was increased by 45% and flexural modulus was increased by 100% following the treatment [56]. Other method employed for the chemical treatment are Saline treatment, acetylation treatment, peroxide treatment, etc. The chemical treatments of the natural fibers mainly enhance the properties of the fiber by modifying their microstructure along with improvement in wettability, surface morphology, chemical groups and tensile strength of the fibers. The chemical treatment of the fiber improved the interfacial adhesion between the fiber surface and polymer matrix thereby the thermomechanical properties of the composites. The chemical treatment on ramie fibers has shown that the treatment of fibers with alkaline or saline or the combined treatment results in the improvement of the tensile strength. The chemical treatment is one of the important techniques used to reduce the hydrophilic nature of the natural fibers also it improves the adhesion with the matrix. The structural and morphological changes can be observed with the treatment of the fibers, and this is mainly due to the removal of non-cellulosic substances from the natural fibers. The significant improvements of the properties of the composites are reported after different chemical treatments along with the increase in the thermal stability of the composites reinforced with natural fiber [35].

2.9 Manufacturing process of composite

Composite materials are produced using several manufacturing processes, each with its own distinct advantages and limitations. The selection of a manufacturing process for composites is influenced by factors such as the size and shape of the part, the quantity required, the type of reinforcement and matrix materials employed, and the cost. Manufacturing processes for composites can generally be categorized as either open processes (including hand lay-up, spray lay-up, automatic tape placement, and filament winding) or closed mold processes (such as resin transfer molding, vacuum infusion, and autoclave processing) [57].

2.9.1 Open mold processes

2.9.1.1 Wet Hand Lay Up

One of the simplest and most cost-effective methods for producing composites is the hand lay-up technique. This process involves spraying a release gel onto the mold surface to prevent the polymer from sticking, followed by the placement of woven or chopped strand mats. A thermosetting polymer in liquid form, along with a curing agent, is then poured onto the surface of the mat and evenly spread with a brush. Additional layers of mat and polymer are added and rolled to remove excess polymer and trapped air until the required number of layers are achieved. After curing, the mold is opened, and the composite part is removed for further processing. While this method requires minimal infrastructure and is easy to perform, it may not be suitable for high-volume production or for achieving a high-volume fraction of reinforcement [58].

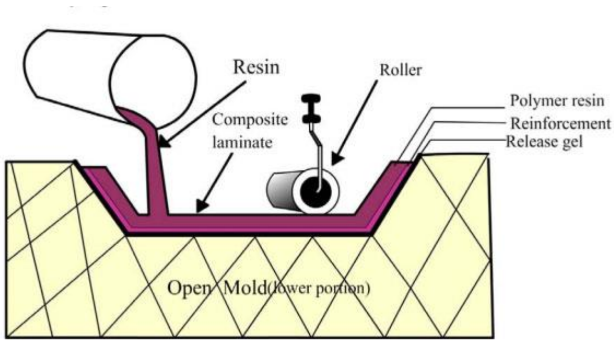


Figure 28: Schematic of Wet Hand Lay Up [59]

Although this process is the earliest manufacturing method for composites, it is still widely used in marine industry because of its simplicity and low cost. However, the major drawbacks of this process can be listed as follows:

1. High labor cost
2. High emissions of styrene to the environment
3. Low surface quality and dimensional tolerances
4. Low mechanical properties because of low fiber volume fraction [58]

2.9.1.2 Spray Lay-Up

The spray-up process is a simple and low-cost method for producing composite parts, and is an extension of the hand lay-up technique. It involves spraying pressurized resin and reinforcement in the form of chopped fibers onto a mold surface, and then rolling the laminate to compact the chop and remove trapped air. The process can use simple tooling, and allows for on-site fabrication with no size limitations. However, the process is highly operator-dependent and can result in low mechanical properties due to low fiber volume fraction. Overall, the spray-up process is a viable option for producing low to medium volume composite parts with relatively simple geometries [60].

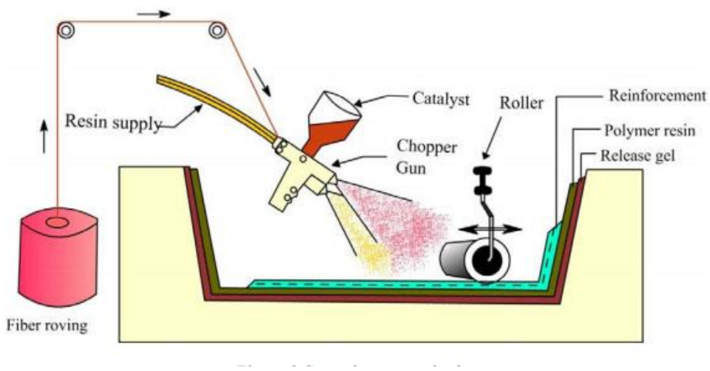


Figure 29: Schematic of Spray Lay-Up

2.9.1.3 Automated Tape Placement (ATP)

Automated Tape Placement (ATP) is a manufacturing technique used in various industries, including automotive and aircraft, for creating precisely contoured continuous filament structures with high rigidity. This technique involves using unidirectional, continuous thermoplastic filaments that are partially pre-impregnated with adhesive resin and rolled onto a reel. The system's feed unit draws the tape from the roll, and a robot places it on the work platform or semi-finished component in the required position. The tape is heated with a laser, which melts the adhesive and increases its grip, enabling automated fiber placement to create complex structures [57], [61] .

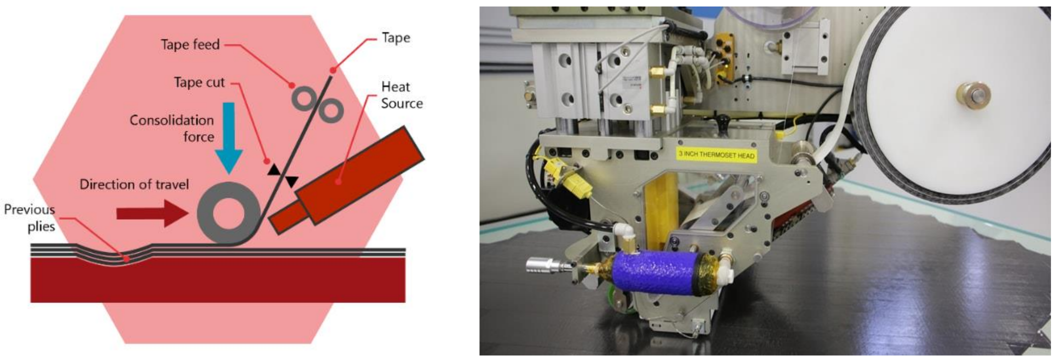


Figure 30: Automated Tape Placement (ATP) [62]

Other advantages of ATP can be listed as:

1. Low labor cost
2. Low material waste
3. High part quality

However, it has some disadvantages listed as:

1. High equipment cost

2. Limited part geometry and size
3. Long process time

2.9.1.4 Filament Winding

Filament winding is a versatile and precise manufacturing process that produces high-strength, lightweight composite structures with a wide range of applications. It is particularly well-suited for producing pressure vessels, aerospace components, golf clubs, military armaments, and other products where strength and durability are critical. The process involves cross-weaving continuous roving of carbon fiber, fiberglass or aramid fiber, and embedding them in a resin matrix, resulting in optimized products that can be modeled, prototyped, and manufactured at almost any scale. Although it has some limitations and challenges, such as high capital and equipment costs and limitations in producing large, complex shapes, the benefits of filament winding make it a valuable and widely used manufacturing process in many industries [57].

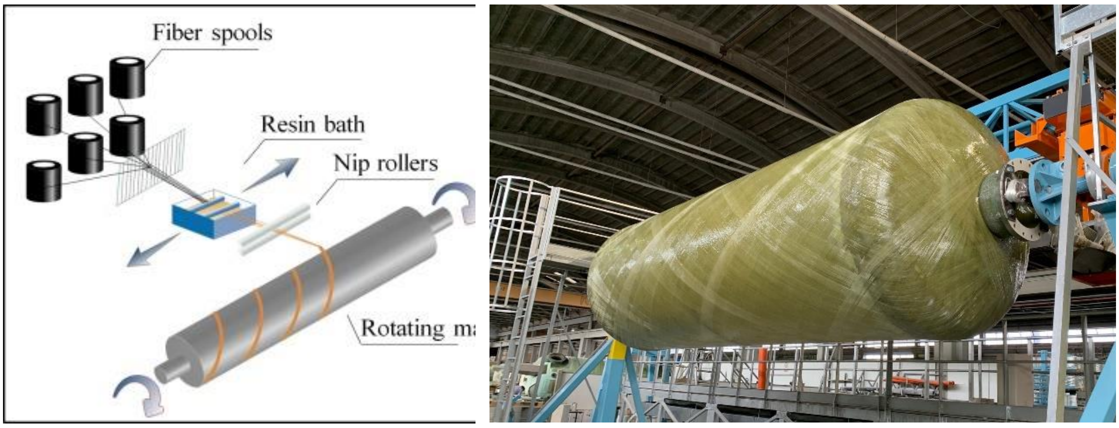


Figure 31: Filament Winding [63]

However, as with any manufacturing process, there are also drawbacks to filament winding. The high capital and equipment costs can make it less accessible for smaller businesses, and the process can be complex and time-consuming, requiring skilled operators and engineers to design and oversee the production. Additionally, while the resulting structures can be incredibly strong and lightweight, the complexity of the process means that it may not be suitable for producing large, complex shapes, which may require other methods such as hand lay-up or injection molding. Despite these challenges, filament winding remains a popular and effective method for producing high-quality, high-performance composite structures.

2.9.2 <u>Closed Mold Processes</u>

2.9.2.1 Vacuum Infusion (VI)

Vacuum Infusion is a widely used process for manufacturing large and complex-shaped composite parts with a low molding cost. The process involves stacking layers of fabric on a lower mold and placing an upper mold in the form of a flexible vacuum bag over the fabric layers. The vacuum is used to compress the fabric layers and apply pressure to the resin to help it flow through the fabric layers, resulting in a high-strength composite part. However, the use of a flexible vacuum bag as an upper mold leads to major drawbacks, including long mold filling time and the potential formation of dry spots or voids due to the limited resin driving pressure.

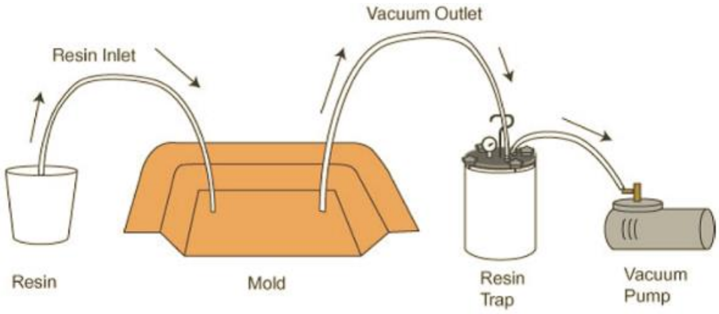


Figure 32: Vacuum Infusion[64]

Despite these drawbacks, the Vacuum Infusion process is still a popular choice in the manufacturing of composite parts, particularly for large-scale applications. Improvements in equipment and material technology have helped to reduce the occurrence of dry spots and voids, and the process can be optimized to achieve high-quality composite parts. Overall, the Vacuum Infusion process remains a cost-effective and reliable method for producing large and complex-shaped composite parts with excellent strength and durability[64].

2.9.2.2 Resin Transfer Molding (RTM)

In Resin Transfer Molding (RTM), fabric layers are cut and placed inside the lower half of a rigid mold. In contrast to the Vacuum Infusion process, the rigid mold serves as the upper mold in RTM. The fabric layers are compressed until they reach the desired thickness by enclosing them between the lower and upper molds. A resin is then injected into the mold with positive pressure to impregnate the fabric layers. After the resin has flowed through the fabric layers and reached the vent, the injection is stopped by closing the inlet valve. Once the composite part has reached its green strength, it is ready to be removed from the mold.

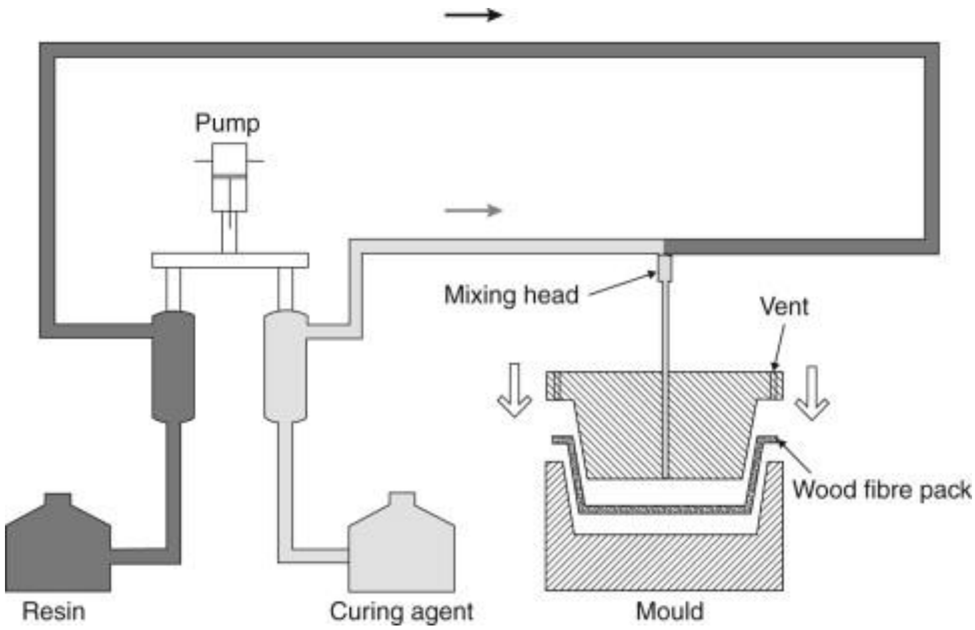


Figure 33: Resin Transfer Molding (RTM) [65]

One disadvantage of using rigid upper and lower molds is that it can be more expensive and not suitable for producing large scale parts compared to the VI process. However, this process has the advantage of being able to create composite parts with excellent mechanical properties and surface quality [65].

2.9.2.3 Autoclave Molding

An autoclave is a large pressure vessel that has the ability to heat up. Autoclave molding is a common method used in the aerospace industry to manufacture advanced composite materials. In the first stage of the autoclave process, uncured resin-impregnated fabric (called prepreg) is cut into the desired dimensions, stacked, and placed on the lower mold half. This step is often done by hand, but using ATP (automated tape placement) can be advantageous. After the fabric is placed, a peel ply, breather, and vacuum bag are placed on top of the fabric in sequence. The next stage involves applying vacuum inside the mold to remove any air and sealing any leaks. The mold is then placed inside the autoclave, where temperature is applied to initiate the curing cycle and solidify the resin, and external pressure is applied to consolidate the fabric layers [59].

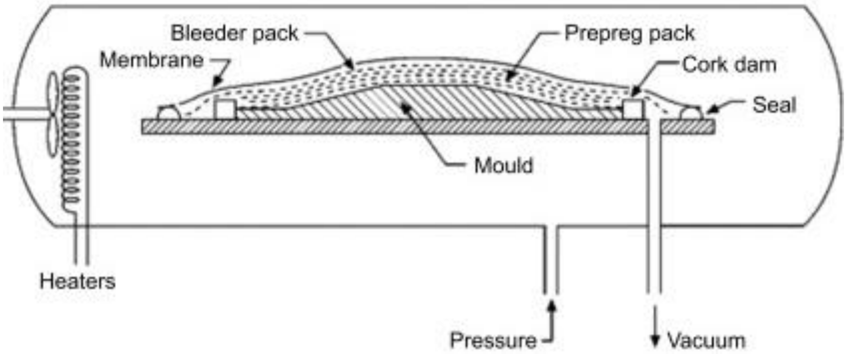


Figure 34: Autoclave Molding [66]

The main advantages of autoclave molding are listed as:

1. Capability to manufacture parts with high mechanical properties
2. Low potential to form dry-spots in the part compared to VI and RTM

However, the main drawbacks of this process are:

1. High equipment cost because of the initial investment of an autoclave
2. Part size is limited to the size of the autoclave

2.10 Properties and testing method of natural fiber reinforced composite

In design process of wind turbine blades, tests on three level is done in material in order to check the accuracy of the computational design models to estimate the load bearing capacity. To certify for the wind turbine blade, coupon and full-scale test are enough. The figure below shows the level of the test done:

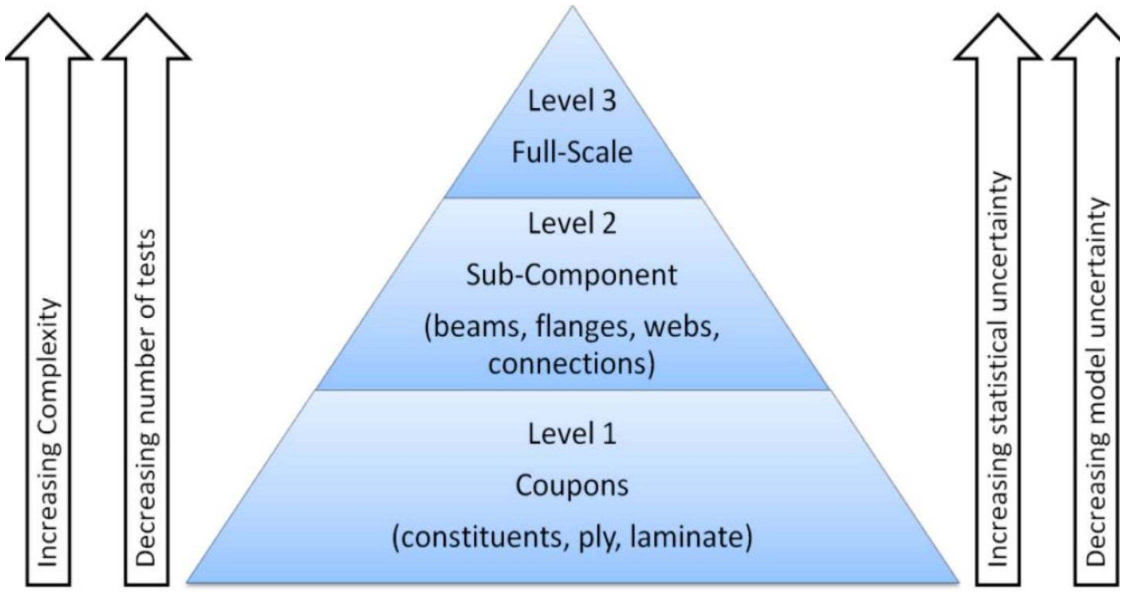


Figure 35: Levels of test for assessing load bearing capacity of wind turbine blade [28]

At coupon level, small test specimens with the basic material are tested in order to determine the material property for determining the ultimate and tensile strength. Similarly, for the sub-component level parts like beams, flanges are tested and Full-scale level testing is done according to the IEC 61400-23 standard [28]. The scope of project is to determine basic property of the coupon. The fatigue strength test is also out of the scope as there is lack of standard equipment is not available in the university premise. The material requirement for the blade is high strength, high stiffness, high fatigue strength and low weight. The main testing that should be done for the composite are:

a) Tensile test
b) Flexural test
c) Compressive test
d) Impact test

2.10.1 <u>Tensile test</u>

Tensile strength is defined as the resistance of a material to applied force. Tensile strength is defined as the resistance of a material to an applied force. There are different ASTM methods for testing the tensile strength of polymer samples. ASTM D638 is recommended for testing discontinuous, randomly arranged polymer composites, whereas ASTM D3039 is applied for well-oriented, highly tensile modulus polymer composites, ASTM D882 is used to determine the tensile strength of thin plastic sheets. From the study it has been found that the unidirectional orientation of the fiber has great tensile property than the other kind of orientation [67].

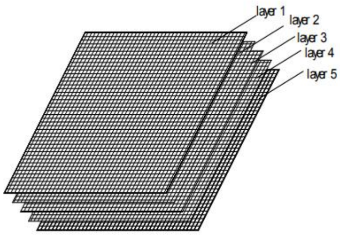


Figure 36: Multiaxial direction reinforcement 0/90 degree

By controlling the volume fraction between fiber and matrix we can alter the properties to meet the specific design requirement. Following figure 25 shows the uniaxial reinforced fiber composite material and the stress on the composite is carried by the fibers and the matrix.

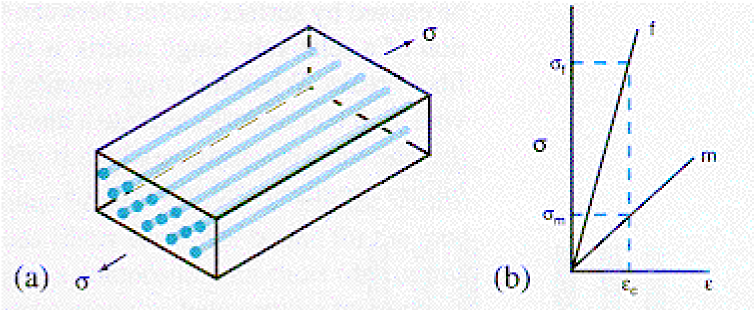


Figure 37: Stress strain diagram for fiber and composite

For analytical purposes, a plot of stress(σ) vs strain(ε) is constructed during a tensile test. The unit for the tensile strength is measured in N/m^2 or Pa. Mathematically it is expressed as:

$$\sigma = \frac{F}{A} \tag{2}$$

$$\varepsilon = \frac{L - L_0}{A} \tag{3}$$

Where F refers to the force and A refers to the Area. Similarly, Tensile modulus is calculated by taking slope of the graph. Also, can be calculated using[68]:

$$E = \frac{\sigma}{\varepsilon} \tag{4}$$

2.10.2 <u>Flexural testing</u>

It is used to measure the force required to bend a beam under three-point loading condition determine the stiffness of materials by measuring the force required to bend material. Three-point loading is generally applicable to both rigid and semi rigid materials, resins and laminated fiber composite materials [68]. If a beam is simply supported at the ends and loaded at center, beam concave toward the center which is called as deflection of beam. In flexural test, maximum stress and maximum strain are calculated for the increment of load and results are plotted in the stress-strain diagram. The convex surface undergoes tensile stress while concave surface undergoes tension compression.

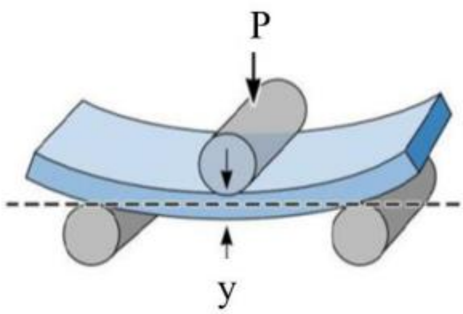


Figure 38: Three-point bending test of beam[69]

Flexural strength can be obtained by using following formula [69]:

$$\sigma_f = F * S \tag{5}$$

$$\sigma_f = \frac{3\,PS}{2bt^2} \tag{6}$$

Where,

σ_f = flexural strength (N/m^2), P = Load at the fracture point, b = width, t = thickness

The standard for the three-point bending test for reinforced and unreinforced polymer composites is ASTM D790. Commonly used dimension of the ASTM D790 is 150 * 12.7 * 3.5 mm. The thickness can vary around [70].

2.10.3 Charpy Impact test

It is used to determine the material response to suddenly applied stress. The impact test explicitly used for evaluating the toughness, brittleness, notch sensitivity and impact strength to resist high-rate loading. For the Charpy impact test specimen typically has v-notch as shown in the figure 43:

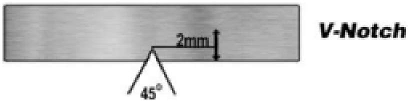


Figure 39: V notch for the Charpy impact test [68]

The standard dimension for the Charpy impact test is 55mmX10mmX10mm [68]. The Charpy impact test is based on the change in potential energy (p.e.). In a typical Charpy impact test, the specimen is held in a fixture and notched to create a pre-determined area of weakness. A pendulum hammer is then released from a specific height to strike the specimen, causing it to fracture. The energy absorbed by the specimen during fracture is measured by the amount of swing of the pendulum after the impact. The results of the Charpy impact test can be used to assess the impact toughness of a material, and to determine its suitability for specific applications. A high energy absorption value indicates that a material is able to resist impact loads and is therefore suitable for use in applications where impact resistance is important [71]. From the dial we can find the energy absorbed by the material and measuring the cross-sectional area below the v-notch we can find the toughness.

$$Impact\ energy = \frac{Energy\ absorbed}{cross\ sectional\ area} \tag{7}$$

2.10.4 <u>Compression test</u>

For the compression test, the specimen can be prepared in block shaped. The ASTM D695 can be utilized to prepare specimen to perform the compressive test. The standard dimension of the specimen is 25.4mmX12.7mmX12.7mm [70].

2.10.5 <u>Water absorption test</u>

In this test composite specimen of ASTM standard D570 is placed in the water for 36 hours and the percentage of water absorption is calculated according to given equation [68]:

$$Water\ absorption(\%) = \frac{(W_n - W_d)}{W_d} * 100 \tag{8}$$

Where, W_n is the weight of the composite sample after immersion and W_d is the weight of composites samples after immersion.

2.10.6 Deviation in Results

By using the standard deviation formula, the variation in results for various specimens during the experiment can be assessed. In order to evaluate the consistency and dependability of the experimental data, this formula provides a measure of how much the findings deviate from the mean value.

$$\sigma = \sqrt{\frac{\sum(xi - \mu)^2}{N}} \tag{9}$$

σ = Standard Deviation

N = Number of Specimen

xi = each value of the specimen

μ = Mean

CHAPTER 3 METHODOLOGY

3.1 Study design

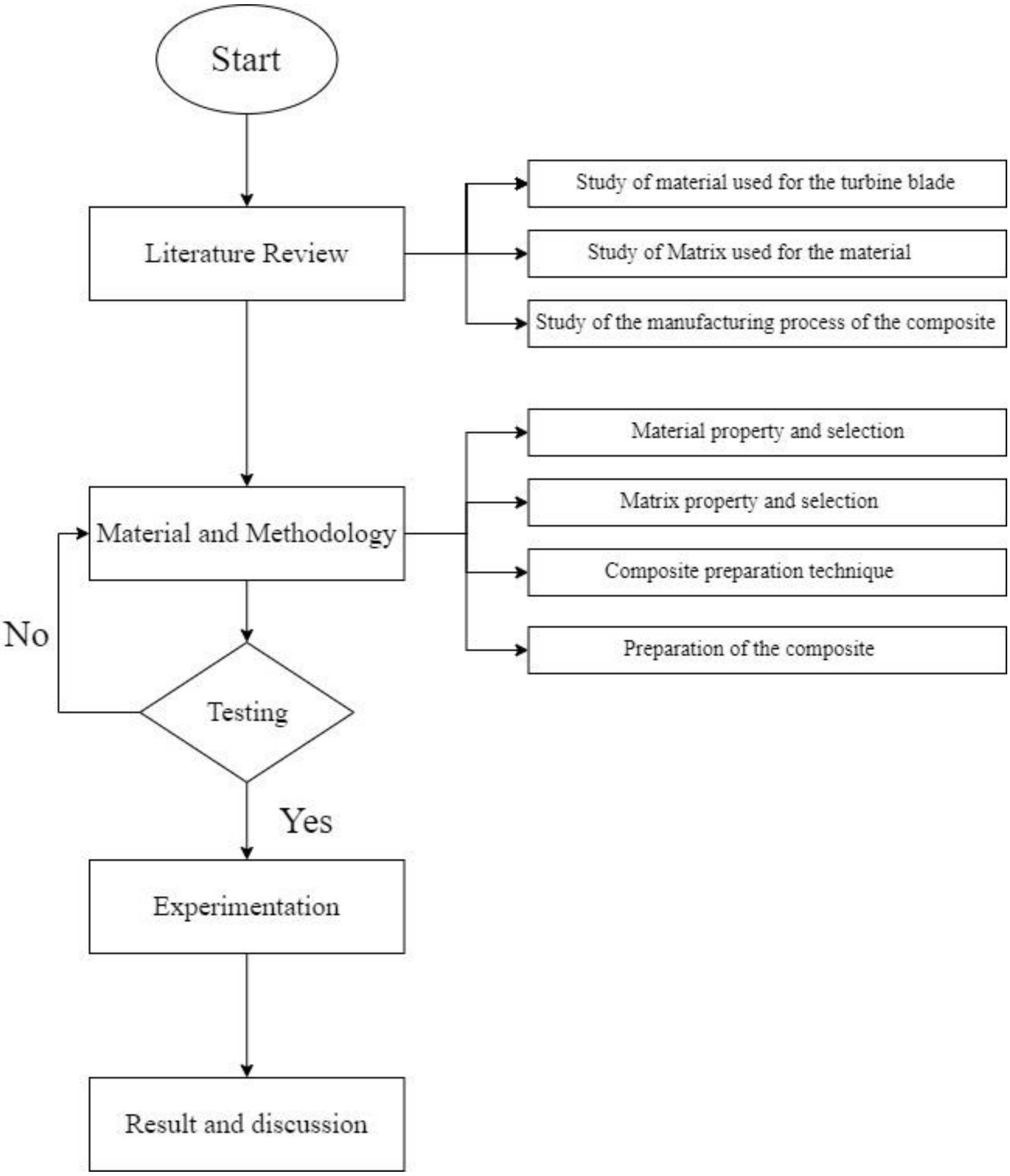


Figure 40: Study Design

The study has a structured flow, which starts with an extensive literature review to select natural fibers, matrix, and a manufacturing process. After literature stud, research was followed by experimental testing, result analysis, and a discussion of findings. The study is concluded with the discussion on result and provide insights into the performance of the fabricated composite material.

3.2 Conceptual framework

The wind turbine blades are critical component of wind energy system but the material involves to make composite has adverse impact on environment. The natural fiber locally available could have mechanical characteristic to develop wind turbine blade. The research involves study of different natural fiber and resin. The natural fiber is considered to be upcycled after they are developed into engineering material. Based on the study, few natural fibers are selected for experimental purpose. The composite is fabricated using the wet hand layup process. After preparing composite, they are visually inspected for adequate composition of fiber and matrix. Once the adequate composition is achieved, the mold is prepared for fabricating specimen for conducting mechanical property tests: tensile strength, compressive strength, impact strength and water absorption property. After fabricating specimens' experiments were conducted and the results were analyzed and interpreted to determine basic mechanical property of the composite material. Based on the findings, conclusion was drawn regarding the potential of material to be alternative for small wind turbine blade applications.

3.3 Fiber selection

Among three sources of the natural fiber, plant fibers contain cellulose as their main structural component, while animal fibers mainly consist of protein. Mineral-based natural fibers, such as asbestos, have health hazard associated with it and are not taken into consideration. Plant fibers tend to have higher strength and stiffness than animal fibers, with the exception of silk, which can have high strength but is relatively expensive and less readily available. Plant fibers are therefore more suitable for use in structural composites [49].

For the material selection process, it is evident people utilized different matrix and objective function. Objective function includes desired property. We have utilized the Ashby chart for the basic material to be studied then used objective function for the creating matrix table.

The figure below compares the natural fiber material on basis of basic mechanical property tensile strength and tensile modulus:

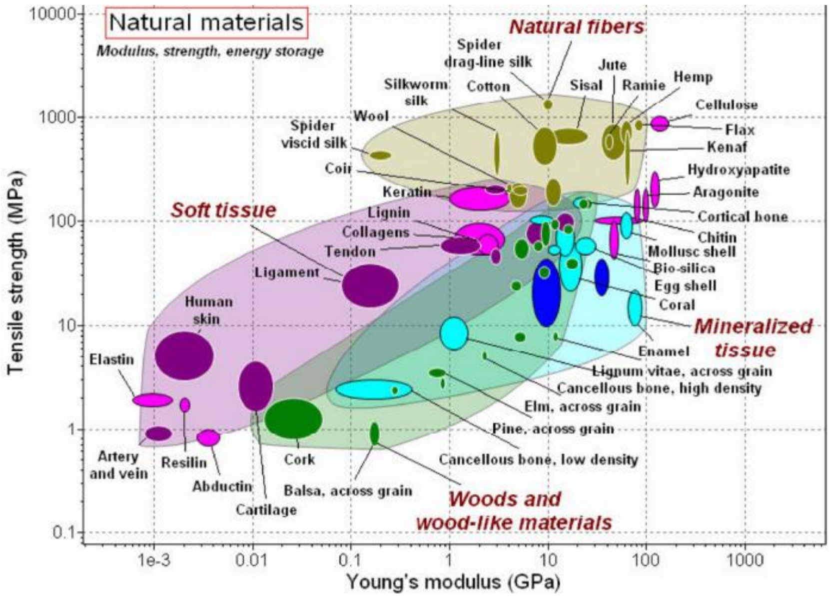


Figure 41: Ashby chart for the Natural fiber with comparison basis of tensile strength and young's modulus [43]

The above chart shows the natural fiber has dominating property than the fiber obtained from minerals and wood like material. Also, hemp, flax and jute has very good property which can be taken to consideration for the natural fiber reinforced composite material (NFRC). Here is the ash by chart to screen the different types of plant fiber:

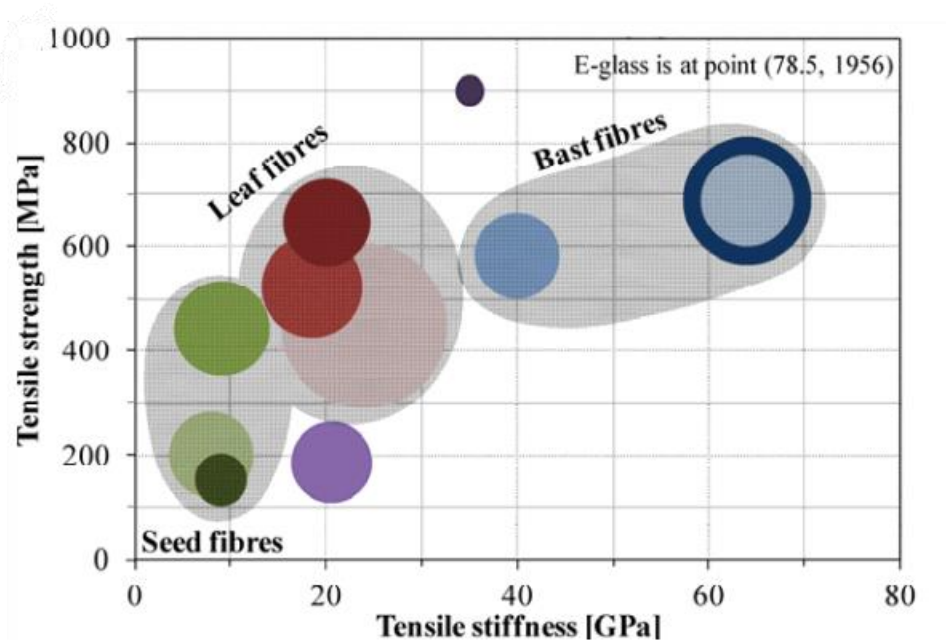


Figure 42: Material selection chart for the various natural fiber [43]

This chart can be utilized to compare the property of different classification of natural fiber. From the different table and comparison chart above we consider flax, hemp, jute and bamboo for the material selection basis. We went to the market and asked different supplier for the following fiber and from there we utilized the decision matrix for the availability of the material. Decision matrix for the material is created on the weightage basis. There are the following desirable properties which are looked upon such as:

- Mechanical property
- Moisture absorption property
- Availability
- Cost

The property which have negative impact are given reciprocal rating. The objective function is:

$$F = 2M + W + 2A + C \tag{10}$$

Where, M is mechanical property and W is moisture absorption, A is availability and C is Cost. There are 3 ranking in the high, moderate and each having score 3,2 and 1 respectively. Here, the matrix table generated for the different kind of the fiber and we selected the material fiber on the basis of rating:

Table 11: Decision matrix table for the fiber

Fiber	**Mechanical property (Weightage = 2)**	**Moisture absorption property (Weightage – 1)**	**Availability (Weightage-3)**	**Cost (Weightage – 1)**	**Score**
Flax	High (3)	Low (1)	Moderate (2)	Moderate (1/2)	13.5
Hemp	High (3)	Low (1)	High (3)	Moderate (1/2)	16.4
Jute	Medium (2)	Moderate (1/2)	High (3)	Low (1/3)	14.33
Bamboo	low (1)	Moderate (1/2)	Moderate (2)	Moderate (1/2)	9

The weightage for the availability is given high priority which will aid us in complete the project in the meantime. The hemp fiber has more score in it and jute comes second. We have considered to do experimentation on the Jute and hemp fiber for our purpose.

3.4 Matrix selection

The table below compares different type of matrix and gives the basis for the selection of matrix.

Following table compare different types of resin on their strength and weakness:

Table 12: Different types of resin and their strength and weakness

Resin type	Resin name	Advantage	Disadvantage
Bio-Based resin	Starch	• Fully biodegradable • Low cost	• Brittle • Difficult to produce • Water sensitive
	PLA	• High modulus and strength • Non-toxic	• Brittle • Relatively poor impact strength • Low thermal degradation temperature
	PHA	• High molecular weight • Fully biodegradable	• Relative low decomposition temperature • Low stability • Brittle • Low deformability • More expensive than other bio-based polymer
Petrochemical based thermoplastic resin	Polyethylene	• High ductility and impact strength • Good fatigue resistance • Lightweight • Low moisture absorption	• Poor weathering resistance • Flammable • High thermal expansion
	Polypropylene	• High temperature resistance • High dielectric resistance	• Difficult to process • Comparatively expensive and limited availability

		• Excellent chemical resistance	
	Polystyrene	• Good chemical resistance • Resistance to stress cracking • Very low moisture absorption	• Flammable • Low impact resistance • Brittle
Petrochemical based thermosetting plastic	Epoxy	• High thermal and mechanical properties • High water resistance • Low curing shrinkage • Long working time availability • Easily available	• Difficult to process
	Polyester	• Long working time availability • Easy to use • Low cost	• High curing shrinkage • Limited range of working times • Moderate mechanical properties

Following table gives the overview of the mechanical properties of the different polymer which is used as matrix [72]:

Table 13: Mechanical properties of different type of polymer

Polymers	Density (g/cm3)	Tensile strength (MPa)	Tensile modulus (GPa)	Elongation (%)	Impact strength (J/m)	Water absorption (%)
Thermoplastic polymers						
Polyester	1.3–1.4	55–60	2.1–2.8	1.5	1064	-
Polycarbonate	1.2	55–70	2.1–3.5	200	50	0.1
Polyethylene	0.9–1.0	20–35	0.7–1.4	350	1064	-
Polypropylene	0.899–0.920	26–41.4	0.95–1.77	15–700	21.4–267	0.01-0.02
Low density polyethylene	0.910–0.925	40–78	0.055–0.38	90–800	>854	<0.015
High density polyethylene	0.94–0.96	14.5–38	0.4–1.5	2–130	26.7–1068	0.01-0.2
Polystyrene	10.4–1.06	25–69	4–5	1–2.5	1.1	0.03-0.10
Polylactic acid	1.21	45	2.8	3	235.83	-
Thermoset polymers						
Epoxy	1.2–1.4	50–110	2.5–5.0	1–6	0.3	0.1-0.4
Phenolic	1.2–1.4	35–60	2.7–4.1	–	–	1.1
Polyester	1.1–1.4	35–95	1.6–4.1	2	0.15–3.2	0.1-0.3
Vinyl ester	1.2–1.4	69–83	3.1–3.8	4–7	2.5	0.1

However, epoxy resins are widely used in the manufacturing of wind turbine blade. It is used to reinforce the glass fiber and natural fiber both. They are widely used cross-linked polymers that offer significant physical, mechanical, and offer high-performance composite. Epoxy-based composite materials are widely utilized in load-bearing applications, such as automotive, aerospace, construction, oil and gas, and marine, due to their superior mechanical qualities, high specific strength, super adhesiveness, and strong resistance to heat and solvents [73]. Bio-based epoxy resin is widely used in the natural fiber reinforcement and the epoxy resin will be utilized in the study of the performance of the composite and turbine blade made from the same composite.

3.5 Experimental Details

3.5.1 <u>Material</u>

3.5.1.1 Fiber

The natural fiber used to study were hemp and jute. The hemp fiber and jute are obtained from locally grown Cannabis sativa and Corchorus olitrus respectively. The fibers are bought in the form of fabric (woven mat) having biaxial orientation from Sunshine Hemp Pvt ltd. Another fabric having combination of Flax and cotton is bought. In this study, flax and cotton fabric were used as reference materials to compare with the mechanical behavior of jute and hemp fiber reinforced composite. The primary goal of this research was to examine the mechanical characteristics of composites reinforced using jute and hemp fibers. Before performing the experiments on the jute and hemp fiber specimens, flax and cotton fabric samples were utilized as control samples to make sure that any mistakes or inconsistencies in the experimental setup would be found and fixed. This approach allowed us to ensure the accuracy and reliability of our results while minimizing the potential risk of experimental errors. The fabric is cut in the square size having dimension 10 * 10 cm and following are specification observed:

Table 14: Properties of the fiber

Fibers	Weight (g)	Mesh size (mm)	No of fibers in warp direction	No of fiber in weft direction
Hemp	4.60	0.28	66	54
Jute	3.45	0.76	43	39
Flax Cotton	3.77	0.18	55	48

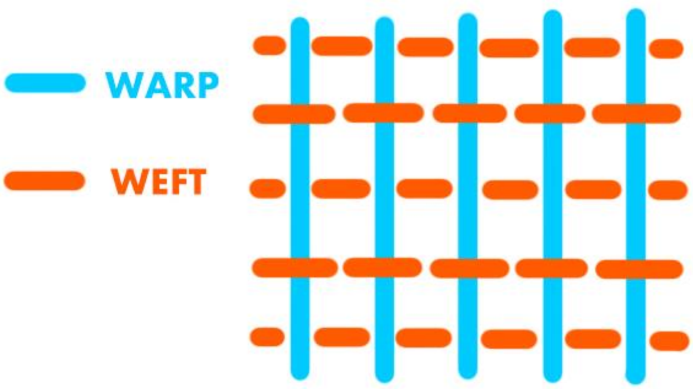
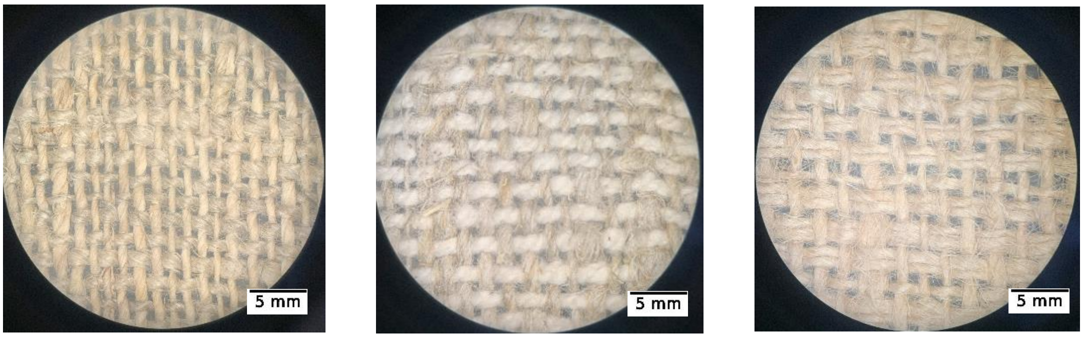


Figure 43: Figure showing warp and weft direction of the fabric mat



a b c

Figure 44: 7x zoomed Fibers a) Hemp, b) Flaxcotton, c) Jute

3.5.1.2 Resin

A thermosetting epoxy resin (318A-7T) of the brand Sparko was used as matrix material for the composite. The resin was mixed with hardener (318B-7T) in ratio of 3:1 by volume and 100:33 by weight. They are bought from the authorized distributor of the Sparko adhesive Champak and Chirag International. The curing time of the epoxy resin was 24 hours at 25º C. Following are the property of the resin by manufacturer:

<u>Properties before hardening:</u>

Table 15: Properties of the resin before hardening

Part	318A-7T	318B-7T
Color	Transparent	Transparent
Specific gravity	1.15	0.97
Viscosity (25º C)	2000-4000CPS	50max CPS
Mixing ratio	A:B = 100:33 (weight ratio)	
Hardening condition	At 25º C 24-48 hrs (100g)	
Usable time	120 min 25º C (100g)	

<u>Properties after hardening:</u>

Table 16:Properties of resin after hardening

Hardness, shore D	<86
Flexural strength, Kg/mm^2	28
Thermal conductivity, W/M.K	1.36
Withstand high temperature, ºC	80
Moisture absorption	<0.15
Compressive strength, Kg/mm^2	8.4

The density of the resin after mixing was 1.105 g/cm^3.

Figure 45: Epoxy resin with Hardener

3.5.1.3 Fabrication equipment

For the fabrication, mold was prepared which is made up of wood and to give specific thickness and to separate the compartment for different fiber, foam was used as shown in the figure 44. In the wood platform stationary plastic paper was used and candle wax is used over the plastic so that epoxy does not get attached with the wood.

Figure 46: Mold for the fabrication of the composite

Equipment used for the fabrication: During the fabrication process of the composite weighing machine, scissor, painting brush, electric tape, double tape, abrasive paper, cello tape, painting knife, beakers, sand paper and hand cutter were used.

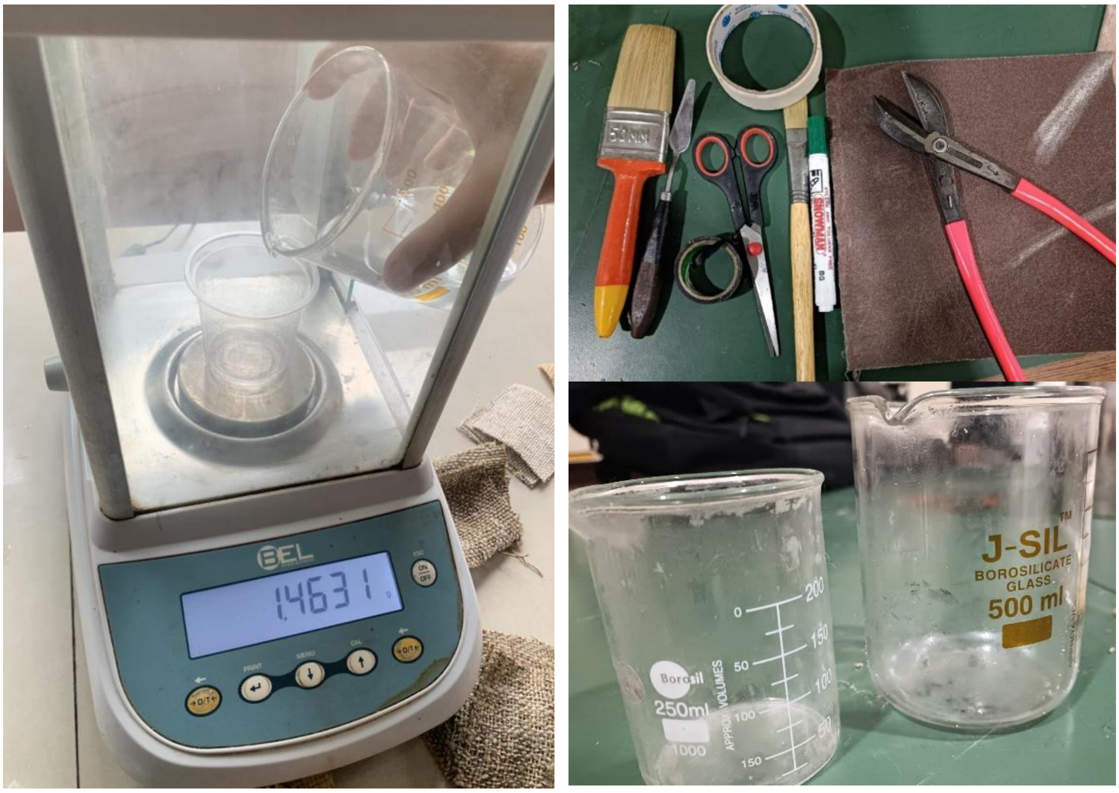


Figure 47: Equipment’s used during experiment

3.5.1.4 Testing equipment

Tensile tests were conducted using an Ultimate Tensile Testing Machine (AIMIL) available at the Institute of Engineering, Thapathali Campus. Charpy impact tests, compression tests, and water absorbability tests were conducted using equipment available at Kathmandu University. To evaluate the wettability of the composites, tap water was utilized. All tests were conducted at room temperature. Although we have tried to prepare specimen in accordance with the ASTM standards for the accuracy and reproducibility of the result, we acknowledge the error happened during the specimen preparation process. For the microscopic view of the specimen, stereo zoom microscope was used.

3.5.1.5 Specimen composition and dimension

To investigate the effect of fiber and resin composition on the mechanical properties of the composite, specimens were prepared with varying compositions of hemp and jute fibers and epoxy resin, including 20/80, 30/70, 40/60, 50/50, and 60/40 fiber to resin weight ratios. The composite with the 50/50 and 60/40 of fiber to weight ratio do not show the proper adhesion between the laminate. The 10/90 ratio of fiber to weight was not included in this study due to the limited amount of resin available and our expectation, based on literature, that it would not exhibit significant mechanical properties compared to the 20/80 and 30/70 ratio. ASTM D3039, ASTM D790, ASTM D695, ASTM D570 standard were used for the tensile, flexural, compression, water absorption test respectively.

3.5.2 Fabrication process of the composite

The composite specimens were prepared by using a hand layup technique. Here is the step-wise description of the fabrication process for the preparation of the composite specimen:

1. Preparation of the mold: First two wooden plank having dimension 30m X 30m size were cut. The foam was then affixed on to the wood for different compartment for different specimen. For the tensile, Charpy, flexural and compression test specimen mold of 270*90*4 mm, 55*45*10 mm, 250*50*5 mm, 30*50*15mm respectively were prepared. A stationary plastic paper was laid on top of the wooden board to prevent the specimens from adhering to the mold. Candle wax was melted and rubbed onto the surface of the plastic paper to further prevent the resin from adhering to it. This was accomplished by rubbing the candle wax with friction, which dispersed it uniformly across the plastic paper's surface. By preparing the mold in this way, it was possible to ensure that the composite specimens would be of uniform size and shape. Foam was used to make compartments for the various specimens, which made efficient use of the available space by enabling the fabrication of numerous specimens at once. Finally, the combination of the plastic paper and candle wax served to keep the resin from adhering to the mold.

Figure 48: Cutting wood to create mold for composite fabrication

2. Preparing the fiber:
   - To get rid of moisture, fabric was dried outside in the sun.

- Fabric was marked with the help of marker for specific specimen size.
- For the specimen standard, fibers were divided into pieces of the proper size.
- Cutting was done with some accuracy.
- Each piece was inspected to make sure specimen met with required shape and size

Figure 49: Marking and cutting fiber

3. Weighing the fiber and resin:
    - First the hemp, jute, flax cotton was coded as HAB, JAB, FCAB respectively where A gives the weight fraction of resin and B gives weight fraction of the fiber.
    - The hemp, jute and flax cotton were weighed on the weighing balance which could weigh up to 250 gm with the accuracy ±0.1 gm.
    - The resin is also weighed on the beaker according to the requirement of the composition. For example, if the specimen H82 has to be prepared, weight fraction of 80% were calculated and weighed in weighing balance. Then the hardener is weighed in such a way ratio of resin to hardener is 100:33.

Figure 50: Weighing the matrix and fiber for the composite

4. Preparation of resin:
   - The epoxy resin and hardener were weighed and mixed and stirred thoroughly for 2-4 minute to get homogenous mixture.
5. Applying resin:
   - The mixed resin was applied to the fibers using brush to ensure uniform distribution of the resin.
   - The fiber was then laid out in the mold in layer to achieve required thickness.
   - After each layer resin was applied and small amount of pressure is applied over the fiber paint knife.

Figure 51: Applying Resin to Fabric Layers for Composite Formation

6. Molding the composite:
   - Plastic with candle wax rubbed on it was placed over the layer of fiber.

- Foam layer was placed over the plastic layer.
- Wooden board was placed over the foam layer for support.
- Load of 11.2 kg was applied to compress the layers and form the composite material.

Figure 52: Applying load to the laminated composite

7. Cutting the Specimen to Standard size: After leaving composite for 48 hrs. They are cut into the pieces according to standard size using hand cutter. Sand paper was used to smooth finishes to edges.

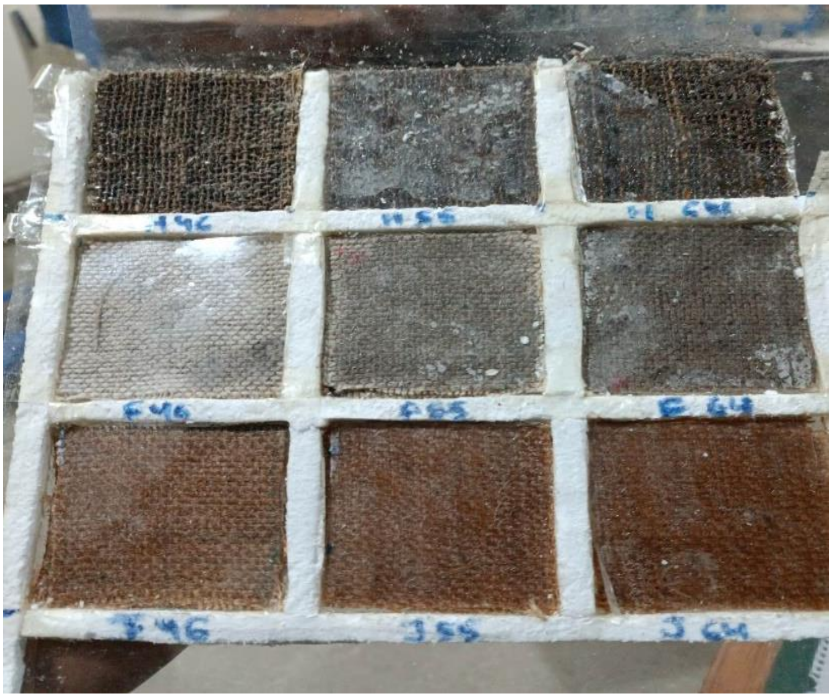


Figure 53: Composite Specimen

Figure 54: Cutting specimen to standard size

The density of the composite after curing was:

Composite type	Density
H82	1.174
H73	1.025
FC82	0.998
J82	0.931
J73	0.938

3.5.3 Experimental setup

3.5.3.1 Microscopic setup

During the study, a Raical stereo zoom microscope was used to get high-resolution pictures of the recycled materials and composites. This cutting-edge microscope featured a digital camera that was designed to take clear pictures of the materials and a maximum magnification of 45x.

To ensure that the samples were in focus and that the photographs were of the highest caliber, the microscope was carefully positioned. To capture all of the features and subtleties of the materials, many pictures of each sample were taken at various magnifications. After the photos were gathered, they were examined with cutting-edge software to precisely quantify the dimensions of the composites and upcycled materials. Following these measurements, the properties of the materials were ascertained in order to compare them to theoretical values.

Figure 55: Experimental Setup for microscopic study

In general, the study's microscopic setup was essential because it gave researchers a clear, accurate perspective of the materials under investigation. By applying this state-of-the-art technology, researchers were able to gather insightful knowledge about the composition and characteristics of the recycled materials and composites, advancing our knowledge of the prospective uses of these materials in wind turbine blade design.

3.5.3.2 Tensile test

It was done in the UTM called as AIM having loading accuracy as high as ± 1% of the indicating value. It did not have extensometer to calculate transverse strain rate as well as young's modulus and Poisson's ratio. The specimen was prepared according to ASTM D3039 where the size is about 250 * 25*3.2 ±2 mm. For the gripping sandpaper was wrapped around.

Figure 56: UTM machine used for the tensile test

c

Figure 57: specimen before and after (tensile test)

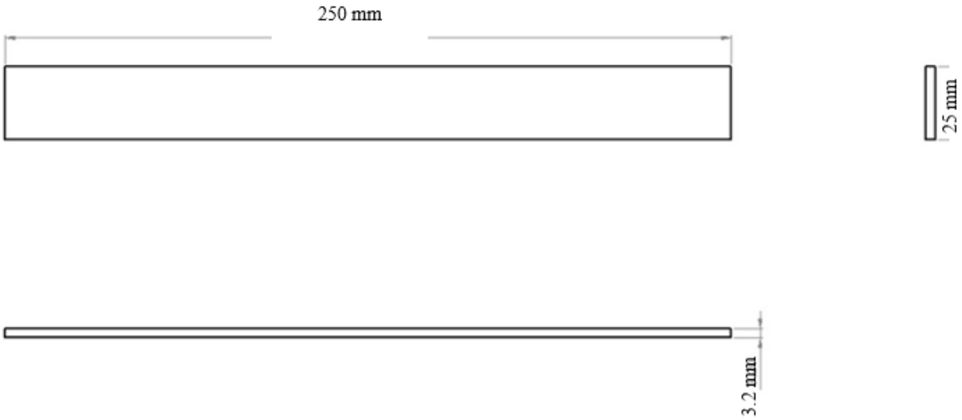


Figure 58: Tensile test specimen schematic

3.5.3.3 Charpy Impact test

The specimen was prepared of size 55*10*10 mm. The specimen was placed horizontally onto the support anvils of the Charpy impact testing machine. The pendulum was released from height of 64 inch to strike specimen at the center. The impact energy was repeated three times to obtain an average value.

Figure 59: Charpy impact testing specimen

Figure 60: Charpy impact testing Machine Setup

3.5.3.4 Compressive strength test

The specimen was prepared according to the ASTM D 695 having dimension 25.4*12.7*12.7 mm. The test was done in compressive strength testing machine named as ENKAY DIGIMAX – 109.

Figure 61: Charpy impact testing specimen

Figure 62: Compressive strength testing of the composite

3.5.3.5 Water absorbability Test

To conduct the water absorbability test, specimens of each material were cut into pieces measuring 20x15x4 mm. Three pieces were used for each material. The specimens were then placed inside plastic containers filled with water and left to soak for a duration of 36 hours. The purpose of this test was to observe the degree of water absorption of the specimens.

Figure 63: Water absorbability test

CHAPTER 4 RESULT AND DISCUSSION

4.1 Initial observation of the composite

The composite of the flax + cotton, hemp and jute was prepared first with following resin to fiber weight ratio 40/60, 50/50, 60/40, 70/30 and 80/20. Initial observation of the weight ratio of the 40/60, 50/50 did not exhibit desirable adhesion of laminate and for the flax and cotton even the combination of the 60/40 weight ratio donot show the proper adhesion between the laminate indicating that these composition are unsuitable for the composite preparation. The figure below depict the specimen having improper adhesion:

Figure 64: Composite specimen with improper adhesion

Even with the composition of 60/40 of resin to weight ratio there were void with in the composite referring fiber require greater amount of matrix. The figure below gives observation of the void in the surface of the jute fiber reinforced composite (JFRC):

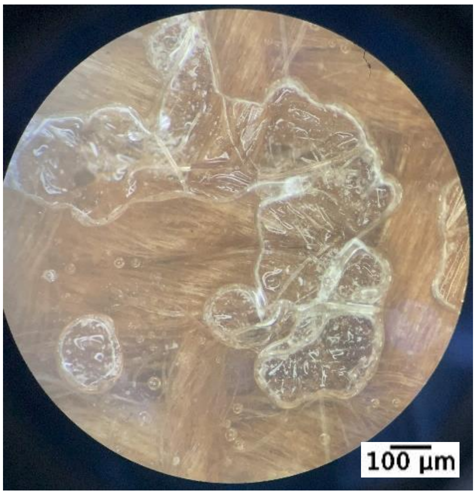


Figure 65: JFRC of 60/40 ratio having surface defect

For the Flax and cotton fiber reinforced composite (FCRC) only composition having 80/20 was prepared as we were only using it as a reference. The composite of HFRC and JFRC with 70/30 and 80/20 ratio have air trapped within the composite as depicted in the figure below:

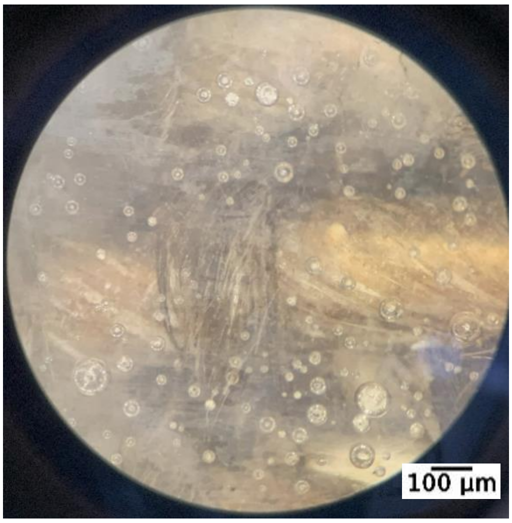


Figure 66: HFRC of 80/20 ratio having air trapped within the composite

4.2 Water absorption test of the composite

For the water absorption test, composite material was paced into the water at room temperature 24ºC for 36 hours. After 36 hours the state of the different composite is as depicted by bar diagram:

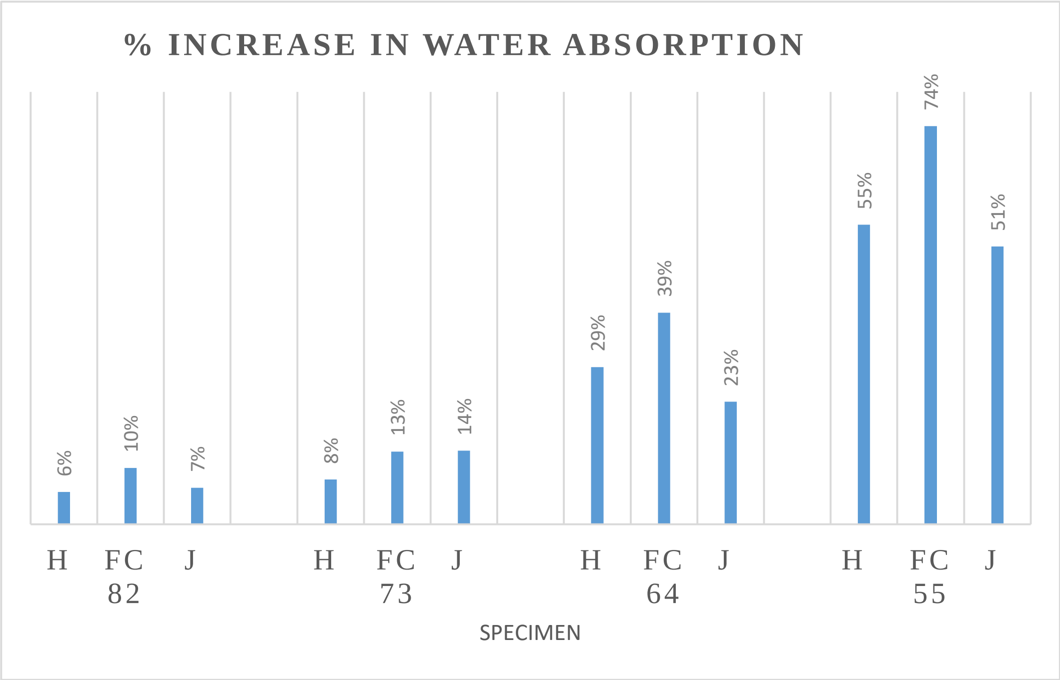


Figure 67: Water absorption % of different specimen

The water absorption test determines the ability of the composite material to resist moisture or water penetration and retention, which can lead to the degradation of mechanical properties and structural integrity. Water absorption tests was conducted on the different specimen to assess their water resistance properties. The results showed that the 80/20 hemp fiber composite had the least amount of water absorption while jute-glass fiber composite showed low water absorption in the 64 and 55 compositions compared to the hemp composite. 55% fiber composition have highest water absorption which indicates that a higher proportion of fibers in the composite matrix leads to increased water absorption. No chemical treatment was applied to any of the specimens, and the water absorption rates could potentially be lowered by treating specimen with chemical like alkali base. The water absorption test also showed that 70/30 and 80/20 composition of epoxy and fiber is optimum for the composite preparation as after 70/30 composition water absorption % was rapid. The figure 68 shows how moisture is absorbed inside the composite. H55 shows the improper amount of matrix and has absorbed more amount of water and FC73 have void in it which makes the specimen to absorb more water.

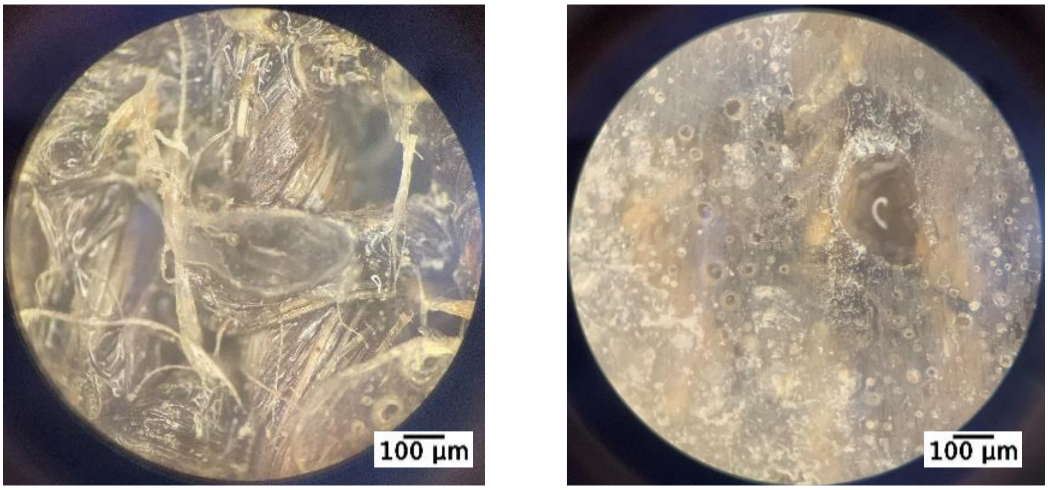


Figure 68: H55 and FC73 after water absorption test

4.3 Tensile Test

Tensile test for each specimen were done on the calibrated UTM machine with the standard size and for the gripping part sand paper was used. The result of the tensile test experiment is compared in the chart below:

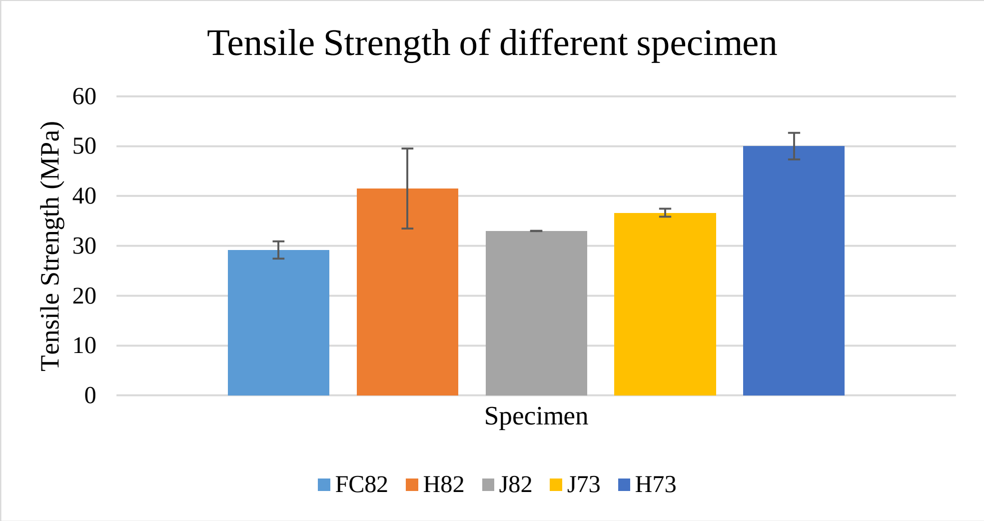


Figure 69: Tensile strength of different specimen

From above table and figure it can be observed that hemp has better mechanical property than the jute in both the 80/20 and 70/30 composition. Some data were missing because the property of those data was not saved after the test has been conducted. Those missing data were replaced by taking average of the two previous data of specimen. The jute fiber composite does not have yield strength which means it does not undergo plastic deformation and shows brittle property. The HFRC H70/30 has average Ultimate Tensile strength of 50 MPa which is quite similar to the data observed from the literature by carlos et al. [74]. The average value of tensile strength and standard deviation of each data are presented below:

Table 17: Average tensile strength and standard deviation of the observed data

Specimen	**Average Tensile strength (MPa)**	**Standard deviation**
FC82	29.18	1.74
H82	41.50	8.04
J82	32.96	0.03
J73	36.63	0.8
H73	50	2.64

There is less deviation J82, J73, FC82 because the missing data were replaced by the average value. As a whole this data represents 70/30 combination of epoxy and fiber possess better mechanical property than other combination and can be considered as appropriate mixture combination for the future trial of Natural fiber composite. There could be little bit of error in the data because repetition of the experiment was not adequate. The graph below gives the curve of tensile load and displacement of H73 composite:

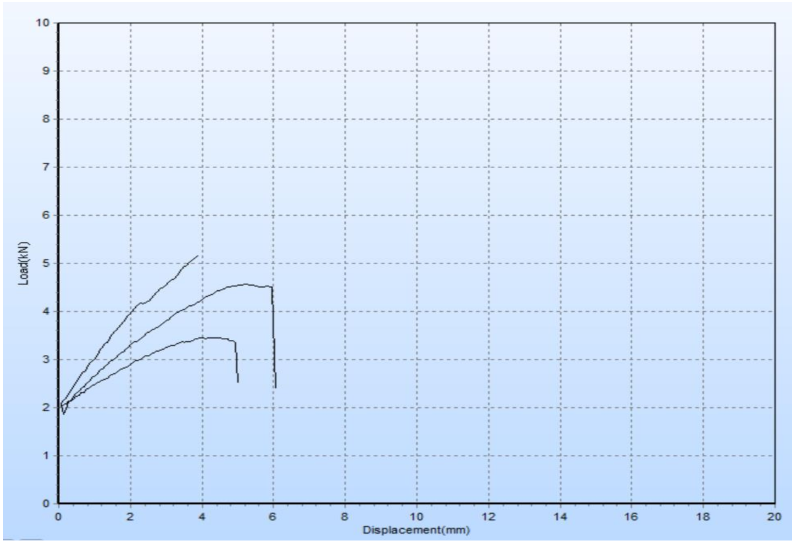


Figure 70:Load vs displacement graph of H73 composite

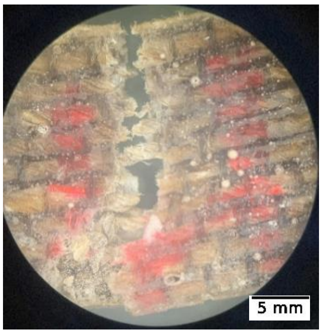


Figure 71: Figure showing delamination of the composite

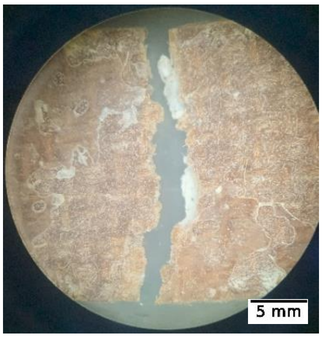


Figure 72: Breaking of the fabric and matrix

Figure 73: Fiber breakage and Fiber pulling out from the composite

The failure mode like pulling out of the fiber shows the improper adhesion between matrix and fiber. This failure mode affects in the tensile property of the composite. This problem can be solved by using filler material which increases the adhesion between the matrix and fiber.

4.4 Compression Test

The compression test was performed in Digital Compression Testing Machine: EM-500, manufactured by Enkay Enterprise. To obtain a comprehensive understanding of the compressive properties of each material grade, three samples were tested for each of the H82, J82, FC82, H73, J73, and FC73 composite specimens. The test gave the value of experimental buckling load and compressive strength across the cross-section of those given specimens.

Table 18: Average Ultimate load and standard deviation of the observed data:

Specimen	**Ultimate load (KN)**	**Standard Deviation**
H82	8.633333333	1.721433511
H73	8.556666667	0.824398771
F82	6.533333333	0.461880215
F73	7.666666667	1.607275127
J82	7.666666667	0.2081666
J73	5.4	1.637070554

Table 19: Average Compressive strength and standard deviation of the observed data:

Specimen	**Compressive strength (N/mm^2)**	**Standard Deviation**
H82	56.14810961	11.19558735
H73	55.64949705	5.361594506
F82	42.49046133	3.003903585
F73	49.86125564	10.45314208
J82	48.56052723	1.353841048
J73	35.11966701	10.64692088

The results show that H82 and H73 composite specimens have the highest compressive strength and ultimate load values, followed by J82 and FC82 specimens. J73 and FC73 specimens have the lowest values in both compressive strength and ultimate load. The standard deviations for the values are relatively small, indicating good consistency and repeatability in the test results as shown in the figure 74 and 75. The compressive strength vs. material and ultimate load vs. material diagrams, which show the average values and standard deviation for each material grade, provide a visual representation of the test results. The results obtained cannot be considered as absolute, since the specimen were experimented which is prone to human error. The compressive strength machine was not calibrated as well and there was somewhat error in surface of the specimen causing premature buckling. These diagrams can be useful in comparing the performance of different material grades and identifying trends or patterns in the data. The standard deviation bars on the diagrams indicate the amount of deviation from the mean value for each material grade, providing an indication of the degree of variability in the test results.

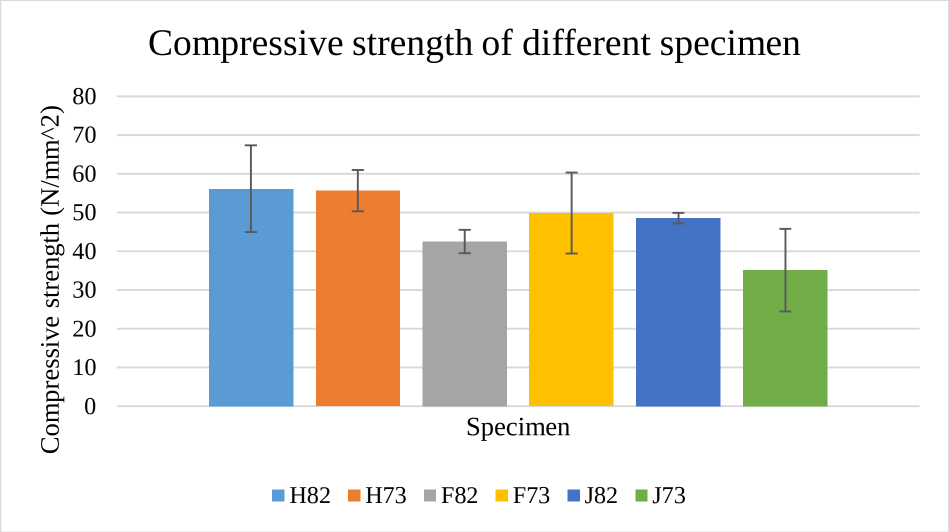


Figure 74: Compressive strength of different specimen

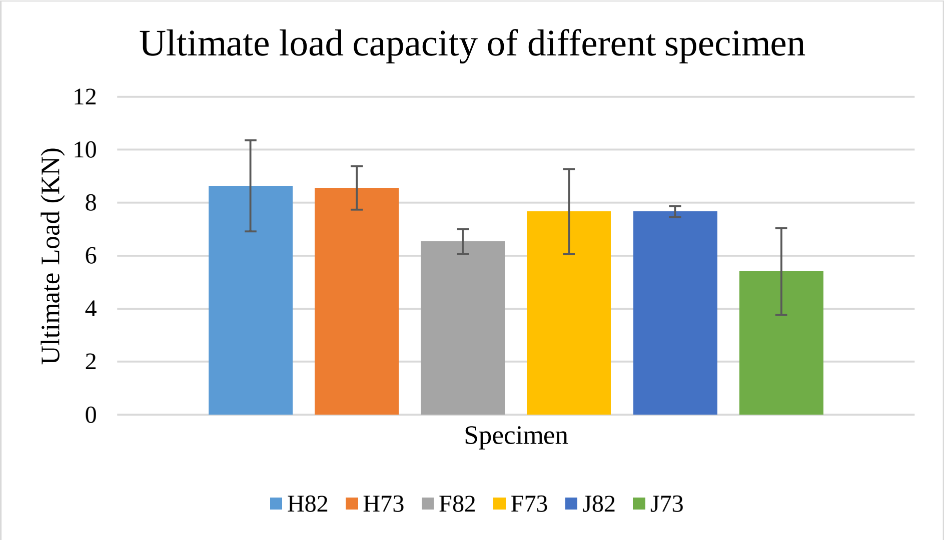


Figure 75: Ultimate load capacity of different specimen

The microscopic image was obtained using trinocular stereo zoom microscope each of those specimens had same failure methods i.e. buckling. Buckling is a failure mode that occurs when a slender structural member, such as a column or beam, is subjected to compressive loads beyond its critical buckling load. In the case of composite specimens, buckling was occurred due to the weak interfacial bonding between the fiber and matrix, or due to the geometric imperfections in the specimen, such as waviness or curvature.

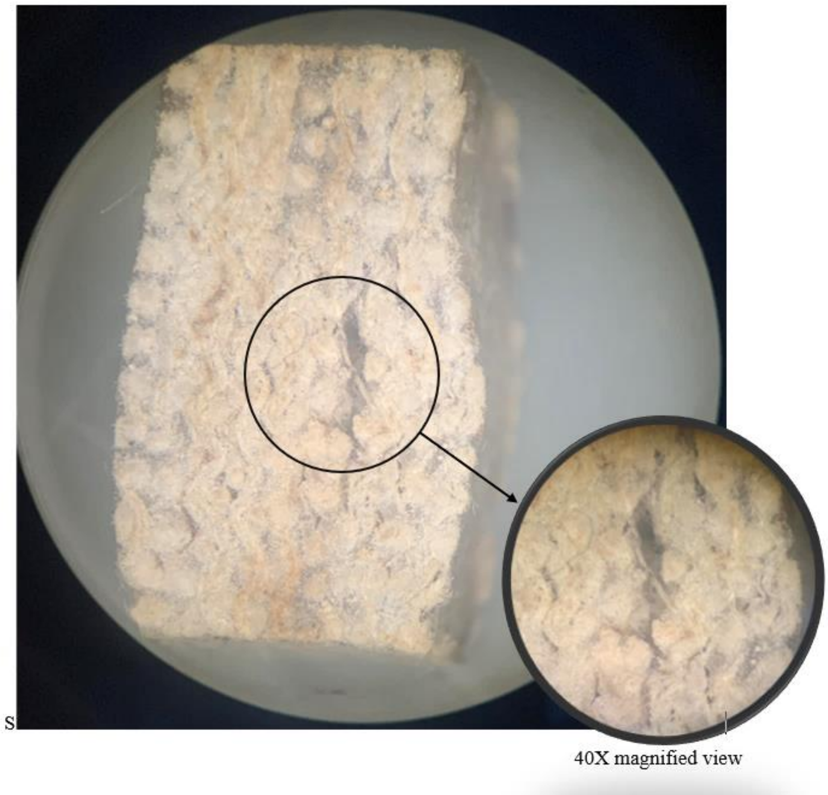


Figure 76: 7x magnified view of FC82 specimen showing delamination due to buckling

The figure 76 shows 40x magnified view of buckling with in FC82 at the center. The images of the FC82 specimen showed a distinct buckling pattern in the center of the specimen, where the deformation was concentrated. Under the microscope, it was observed that the delamination occurred at the interface between the flax-cotton fiber and the matrix. The interface was weakened due to improper bonding or weak adhesive, which caused the layers to separate when the specimen was subjected to compressive load. The delamination appeared as a thin white line that was visible under the microscope.

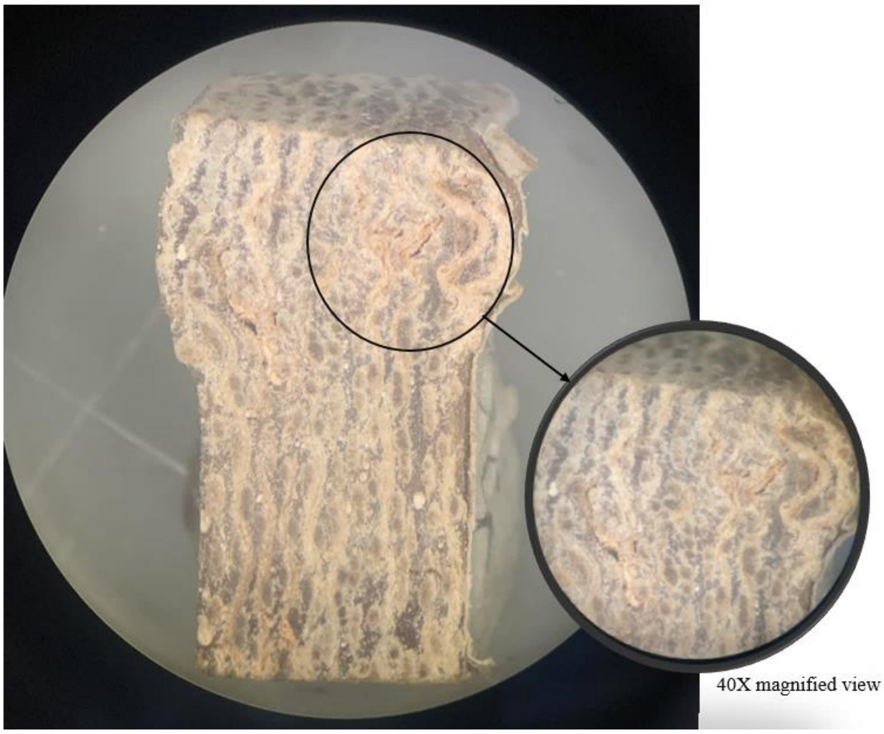


Figure 77: 7x magnified view of J73 specimen showing buckling at the top

Under microscopic analysis, it was observed that the buckling in the J73 specimen as shown in figure 77, occurred due to the bending of the fibers at the top of the sample. The fibers were subjected to compressive stress, causing them to bend and eventually buckle. This was likely due to the fact that the top of the sample was not supported adequately, causing it to bend and leading to premature failure.

These observations indicate that the compressive strength values reported earlier for the specimens are not the true material strength but rather the strength of the material at the point of experimental buckling. Buckling is a mode of failure that significantly reduces the load-carrying capacity of a structure and leads to premature failure. Therefore, to accurately measure the compressive strength of composite materials, it is crucial to prevent buckling by using proper testing techniques and supports.

4.5 Charpy impact test

The impact test was performed on Charpy impact test machine. The result of the impact energy and toughness for all the specimens are depicted below:

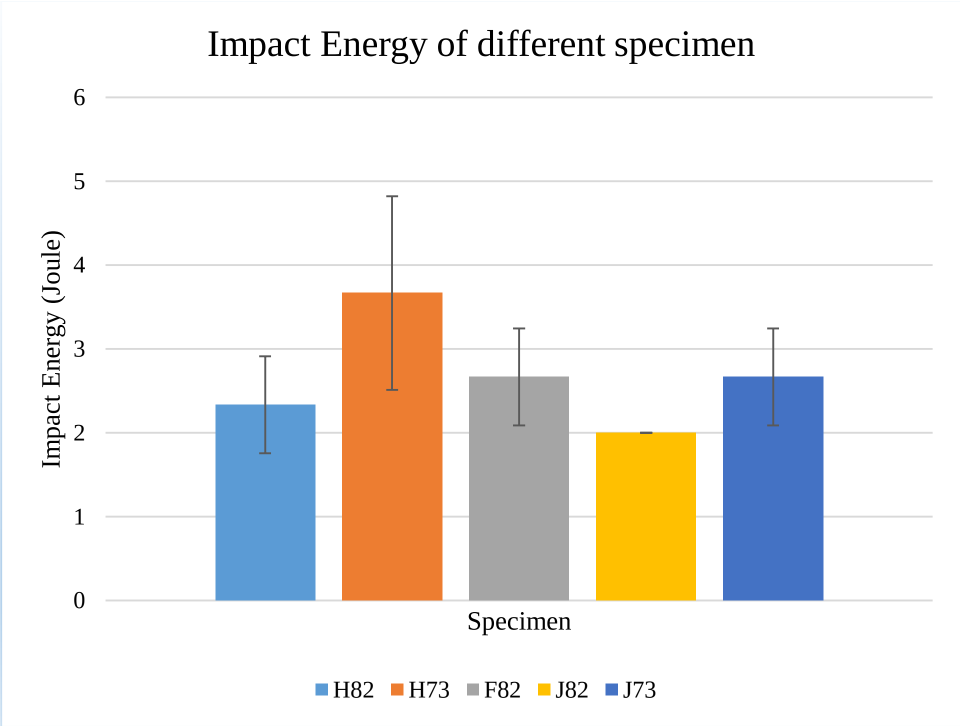


Figure 78: Impact Energy of different specimen

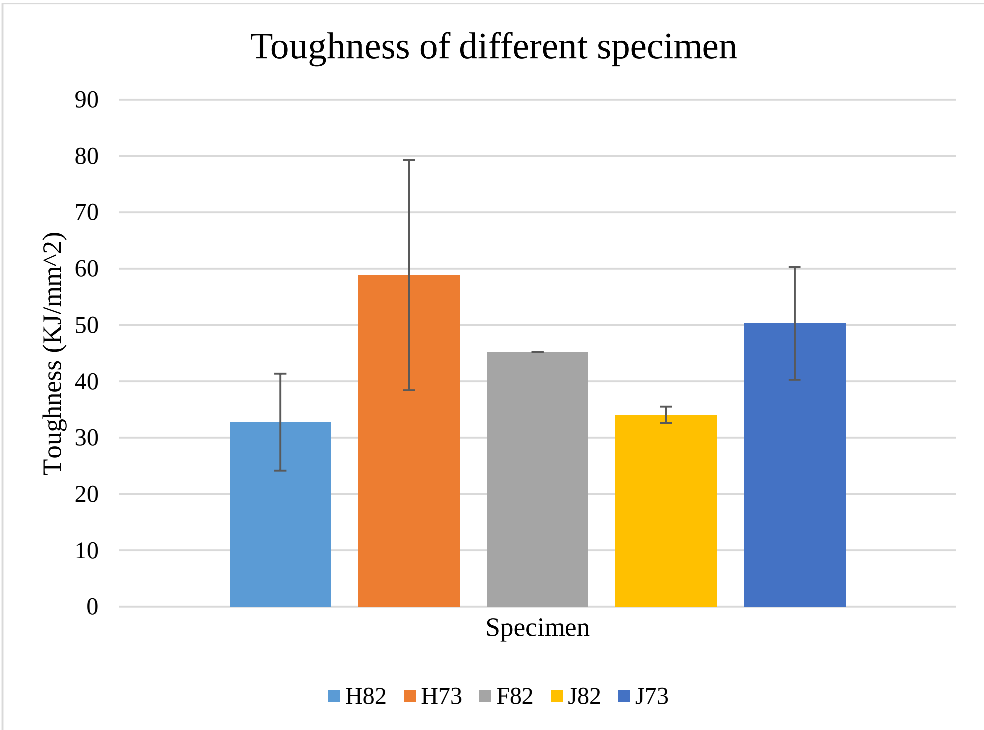


Figure 79: Toughness of different specimen

The impact energy and toughness values of the different specimen are presented in bar diagrams above. Each bar represents a different material, displaying its mean value with error bars to indicate standard deviation. When comparing the two diagrams, some materials have similar impact energy and toughness values, while others show significant differences. Material H73 has a toughness value much higher than its impact energy value, implying its ability to absorb energy before fracturing.

Table 20: Average impact load and standard deviation of the observed data:

Specimen	**Impact energy (Joule)**	**Standard Deviation**
H82	2.333333333	0.577350269
H73	3.666666667	1.154700538
F82	2.666666667	0.577350269
J82	2	0
J73	2.666666667	0.577350269

Table 21: Average Toughness and standard deviation of the observed data:

Specimen	**Toughness (kJ/mm^2)**	**Standard Deviation**
H82	32.7405008	8.618413206
H73	58.86588619	20.46321916
F82	45.22840344	0
J82	34.05311195	1.429452221
J73	50.28401943	10.00813053

On other hand, material J82 has a relatively low toughness value but moderate impact energy value, indicating its susceptibility to fracture under high stress. So, the observation shows that H73 is tougher material than others.

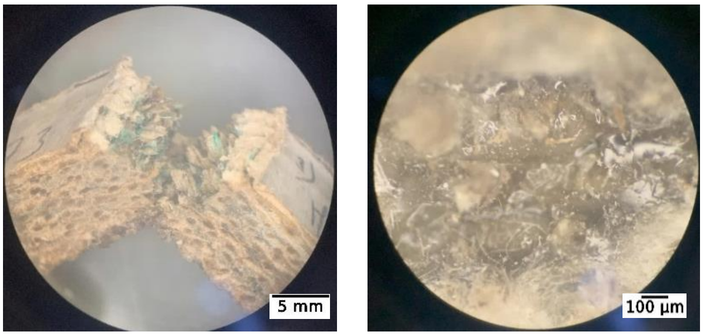


Figure 80: H73 Charpy impact test specimen

The failure modes occurred in above specimens where generally due to fiber fractures, matrix cracking, delamination and fiber pullout. Figure 80, clearly shows that the fractures matrix cracking and fiber pullout of the specimen H73. In the photo, you can see the fracture surface of the specimen, which has a distinctive V-shaped notch that is created before the test.

4.6 Limitation of the experimental study

- Due to the unavailability of standard testing equipment within the University premise, test was conducted with substandard procedure.
- The limited amount of the resin and fiber for the experimentation imposed a limitation on the number of specimen available for repetition.
- The data obtained from the most of the testing equipment was manually observed which makes place for the human error.
- The lack of a fixture for the flexural test at the designated testing facility halt our experiment of flexural test.
- The specimen thickness varied after the curing for different specimen which may affect the reproducibility of the experiment.

CHAPTER 5 GANTT CHART AND BUDGET EXPENDITURE

5.1 Gantt Chart

Table 22: Gantt Chart

	1st Semester																								2nd Semester																			
Task	Jul				Aug				Sept				Oct				Nom				Dec				Jan				Feb				Mar				April				May			
Week No	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Literature Review	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		
Lab visit		■														■						■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		
Proposal defense				■																																								
Design													■	■	■																													
Market Survey									■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■												
Mid-Term Presentation																									■																			
Fabrication																																			■	■	■	■	■	■				
Testing and modification																																						■	■	■	■	■		
Experimentation																																							■	■	■	■		
Data/result analysis																																									■	■		
Final presentation																																											■	

INDEX	
■	Work Completed
	Work to be done

5.2 Budget Expenditure

Table 23: Project budget expenditure

Material	Quantity	Cost per unit (Rs)	Total (Rs)
Resin/Hardener	4 liters	2000	8000
Hemp Fiber	2meter	650	1300
Flax Fiber	2meter	600	1200
Jute Fiber	2meter	350	700
PLA	500gm	3650	3650
Miscellaneous			1500
Total			**16350**

Above table breakdown the budget expenditure of the project. Almost 50% of the budget is spent on resin and hardener while the fiber and PLA consumes similar amount of expenditure. The miscellaneous cost includes the cost of printing document, travelling expenditure and other equipment such as stationary plastic, painting brush, etc.

CHAPTER 6 CONCLUSION

The upcycling natural fiber for the structural application is one of the best approaches to create advance engineering material. The experimental study on the mechanical behavior of upcycled natural fiber composite material, shows the promising mechanical properties despite facing some challenges during fabrication process. From our observation, we observed that the fiber weight fraction should be less than 40% to achieve adequate adhesion, and fiber weight fraction of 30% has shown good mechanical property. Similarly, composite specimen with 60% fiber fraction by weight have showed high moisture absorption rate. To avoid absorption, it has been suggested from the literature to use chemical treatment. This can be future recommendation to investigate the effect of chemical treatment on the absorption of moisture. We have also found that HFRC has better mechanical property than JFRC. Hemp fiber tops the chart in all tensile, compressive and Impact property. So, for the wind turbine blade which is subjected to dynamic load of wind and gravity, hemp fiber can be considered as potential alternative. However, maximum tensile strength found to 52 MPa which fell short of the 100 MPa benchmark. From the literature bamboo poplar composite have tensile strength more than 170 MPa. material. Similarly, if we compare the H73 and H82 composite with the wood/epoxy laminate in literature, the mechanical property of hemp composite is slightly less than that of wood/epoxy laminate. This makes our specimen inferior to another natural option let alone glass fiber. It is not early to conclude that hemp fiber is essentially not suitable for the wind turbine blade application because the mechanical property can be increased by choosing other resin alternative and chemically treating the fabrication of the composite in controlled environment can improve the mechanical property. Hemp can also be used in hybrid mode with the glass fiber to enhance mechanical property.

The project incorporates with many challenges faced during our project due to the unavailability of testing equipment. However, this study serves as a pilot for future research at our university and provide valuable insight in conducting similar kind of research. Also, we recommend the future research to conduct full-scale testing of specimen to accurately identify material property of the composite and to perform structural analysis of the wind blade in analytic software after adding material property. Overall, this project contributes to the study on sustainable material for engineering application.

CHAPTER 7 CHALLENGES AND RECOMMENDATION

7.1 Challenges

- The major challenge we faced during the project was the lack of material testing equipment for the composite within the university premises which led to the need to outsource certain tests to external laboratories. Even the laboratories do not have material testing facility for the composite material which is calibrated.
- The next challenge was the limited number of natural fiber materials in market, which require extensive sourcing effort.
- The resin available in the market were limited. Initially we have thought about using bio epoxy resin and we could not find the vendor which will provide that resin. And the resin available were of certain mixing ratio only. So, there was limited choice of the resin for the experimentation.
- The lack of inter disciplinary cooperation and coordination between departments, which resulted delays and added administrative burden.
- Additionally, the goal of our project was to construct a miniature wind turbine blade and test it in various wind environments. We were unable to achieve this objective, however, due to time restrictions and the requirement to examine the natural fiber composite materials property.

7.2 Future work and Recommendation

- In the future, it would be better to study other natural fiber which are locally available and disregarded like banmaara ghaas, elephant grass, etc. for their use case whether in turbine blade application or structure application.
- Composite study can be done in future with other resin such as vinyl ester, PLA, biopolymer, etc.
- Additionally, further research could be conducted to optimize the manufacturing process of the composite material and explore their potential applications in other industry.
- It would be useful to explore the feasibility of setting up of basic material testing facility on university to reduce the need for outsourcing and enable more comprehensive testing.

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ANNEXES

ANNEX 1:

1. Calculation of the fiber and matrix weight for the composite for compressive test.

Specima n	fiber content	fiber wt	matrix wt	resin wt	hardener wt	ratio
FC82Cp	0.2	5.94	23.76	17.86466165	5.895338346	3.030303
FC73Cp	0.3	6.2	14.46666667	10.87719298	3.589473684	3.030303
J82Cp	0.2	6.01	24.04	18.07518797	5.96481203	3.030303
J73Cp	0.3	6.32	14.74666667	11.0877193	3.658947368	3.030303
H82Cp	0.2	7.24	28.96	21.77443609	7.18556391	3.030303
H73Cp	0.3	6.94	16.19333333	12.1754386	4.017894737	3.030303

Mold Size: LxBxH = 30mm*45mm*15mm

2. Calculation of the fiber and matrix weight for the composite for Charpy Impact Test.

speci men	percentage of fiber	fiber weight	matrix weight	Resin weight	Hardene r wt	ratio
H73I	0.3	9.48	22.12	16.63157895	5.488421053	3.03030303
H82I	0.2	10.76	43.04	32.36090226	10.67909774	3.03030303
FC73I	0.3	9.03	21.07	15.84210526	5.227894737	3.03030303
FC82I	0.2	9.2	36.8	27.66917293	9.130827068	3.03030303
J73I	0.3	9.49	22.14333333	16.64912281	5.494210526	3.03030303
J82I	0.2	9.77	39.08	29.38345865	9.696541353	3.03030303

Mold Size: LxBxH = 60mm*45mm*15mm

3. Calculation of the fiber and matrix weight for the composite for Tensile Test.

speci men	**percentage of fiber**	**fiber weight**	**matrix weight**	**Resin weight**	**Hardene r wt**	**ratio**
H73T	0.2	26	104	78.19548 872	25.80451 128	3.03030 303
J73T	0.3	16.75	39.083333 33	29.38596 491	9.697368 421	3.03030 303
F73T	0.3	19.5	45.5	34.21052 632	11.28947 368	3.03030 303
H82t	0.2	25.41	101.64	76.42105 263	25.21894 737	3.03030 303
J82T	0.2	17.52	70.08	52.69172 932	17.38827 068	3.03030 303
F82T	0.2	19.3	77.2	58.04511 278	19.15488 722	3.03030 303

Mold Size: LxBxH = 270*90*10

ANNEX 2:

1. Data from Charpy Impact Test

Material	Standard	Impact energy (Joule)	Toughness (KJ/mm^2)	Fiber Layers	L*B*H (mm)	Weight (g)
H 82 (1)	ASTM D256	2	27.19312558	8	54.85*8.48*11.35	5.72
H 82 (2)		2	28.3589793		54.80*8.28*11.23	5.51
H 82 (3)		3	42.66939751		52.37*8.2*11.34	5.3
H 73 (1)		3	47.12157838		55.56*7.715*11.14	5.16
H 73 (2)		5	82.49463785		54.61*7.5*11.02	5.07
H 73 (3)		3	46.98144233		51.4*7.5*11.61	4.73
F 82 (1)		3	45.22840344	9	53.23*8.03*11	5.06
F 82 (2)		2	36.18894247		52.46*7.35*10.33	4.35
F 82 (3)		3	47.53981459		52.09*8.01*10.5	4.66
J 82 (1)		2	32.42962771	10	52.66*7.20*11.86	4.73
J 82 (2)		2	35.12284214		53.48*7.13*11.10	4.46
J 82 (3)		2	34.606866		53.95*7.16*11.2	4.62
J 73 (1)		3	57.23443223		51.10*6.68*11.2	3.92
J 73 (2)		3	54.80453051		54.42*6.76*11.5	4.01
J 73 (3)		2	38.81309554		53.22*6.54*11.35	3.85

2. Data from Compression Test

Material	**Standard**	**load (KN)**	**Compressive strength (N/mm^2)**
H 82 (1)	ASTM D256	7.9	51.37877211
H 82 (2)		7.4	48.12695109
H 82 (3)		10.6	68.93860562
H 73 (1)		8.7	56.58168574
H 73 (2)		7.67	49.88293444
H 73 (3)		9.3	60.48387097
F 82 (1)		6.8	44.22476587
F 82 (2)		6.8	44.22476587
F 82 (3)		6	39.02185224
F 73 (1)		9.5	61.78459938
F 73 (2)		7	45.52549428
F 73 (3)		6.5	42.27367326
J 82 (1)		7.4	48.12695109
J 82 (2)		7.7	50.0780437
J 82 (3)		7.3	47.47658689
J 73 (1)		4	26.01456816
J 73 (2)		7.2	46.82622268
J 73 (3)		5	32.5182102

3. Data from Water Absorbability Test

Material	Dimensions (L*B*H)	initial weight (gram)	after 36 hrs (grams)	increase in percentage
H 82 (1)	19*15*4.8	1.59	1.69	6%
H 82 (2)	19.8*15.8*5	1.84	1.94	5%
H 82 (3)	18*15*5	1.59	1.69	6%
H 73 (1)	18*16.8*5.3	1.61	1.76	9%
H 73 (2)	19*17*4.5	1.66	1.79	8%
H 73 (3)	18.2*16.8*4	1.43	1.54	8%
H 64 (1)	20*16*4.3	1.08	1.35	25%
H 64 (2)	20*16.7*4.2	1.07	1.4	31%
H 64 (3)	18.9*15*5	1.18	1.55	31%
H 55 (1)	20*15*5.3	1.07	1.62	51%
H 55 (2)	20*15*5	1.08	1.67	55%
H 55 (3)	19*16*5	1.13	1.81	60%
H 46 (1)	20.6*15.2*4.9	1.03	1.76	71%
H 46 (2)	20*15.5*5	1	1.77	77%
H 46 (3)	20*15*4.7	0.89	1.59	79%
FC 82 (1)	20*15*4.5	1.4	1.55	11%
FC 82 (2)	20*15*4.3	1.3	1.45	12%
FC 82 (3)	20*15*4.8	1.44	1.57	9%
FC 73 (1)	20*15*3.9	1.25	1.43	14%
FC 73 (2)	20*15*4.1	1.24	1.42	15%
FC 73 (3)	20*15*4	1.31	1.46	11%
FC 64 (1)	20*16*4	0.91	1.29	42%
FC 64 (2)	19.7*15.6*3.6	0.92	1.24	35%

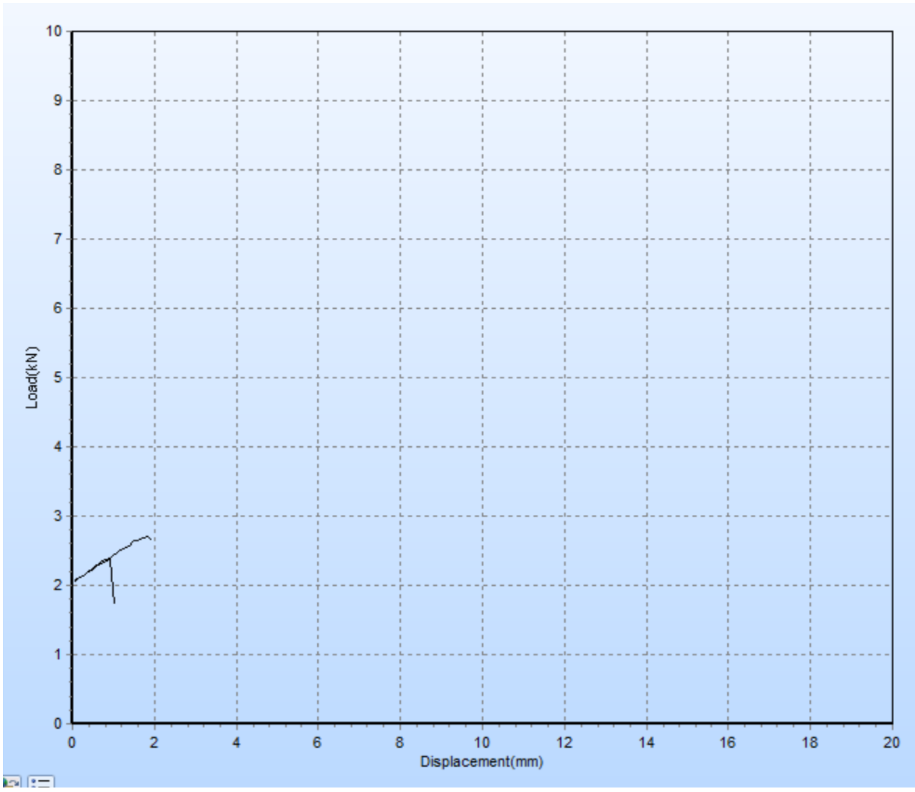
FC 64 (3)	20*15*3.8	0.88	1.24	41%
FC 55 (1)	20*15*4	0.72	1.28	78%
FC 55 (2)	20*15*3.8	0.81	1.36	68%
FC 55 (3)	20*15.7*3.6	0.81	1.42	75%
FC 46 (1)	Not properly binded			
FC 46 (2)				
FC 46 (3)				
J 82 (1)	20*15*4	1.59	1.71	8%
J 82 (2)	20*15*4.8	1.47	1.55	5%
J 82 (3)	20*15*4.5	1.5	1.61	7%
J 73 (1)	19*16*4	1.13	1.33	18%
J 73 (2)	18.5*16.5*4	1.3	1.43	10%
J 73 (3)	19*16*3.8	1.22	1.38	13%
J 64 (1)	20*15*3	0.79	1.03	30%
J 64 (2)	20*15*4	0.87	1.04	20%
J 64 (3)	20*15*5	0.94	1.11	18%
J 55 (1)	20*16*3.8	0.69	1.09	58%
J 55 (2)	20*15.5*3.2	0.64	0.98	53%
J 55 (3)	20*15*3.3	0.65	0.93	43%
J 46 (1)	21*16*3	0.66	1.07	62%
J 46 (2)	21*15*3	0.62	1.05	69%
J 46 (3)	21*15*3	0.59	1.01	71%

4. Data from Tensile Test

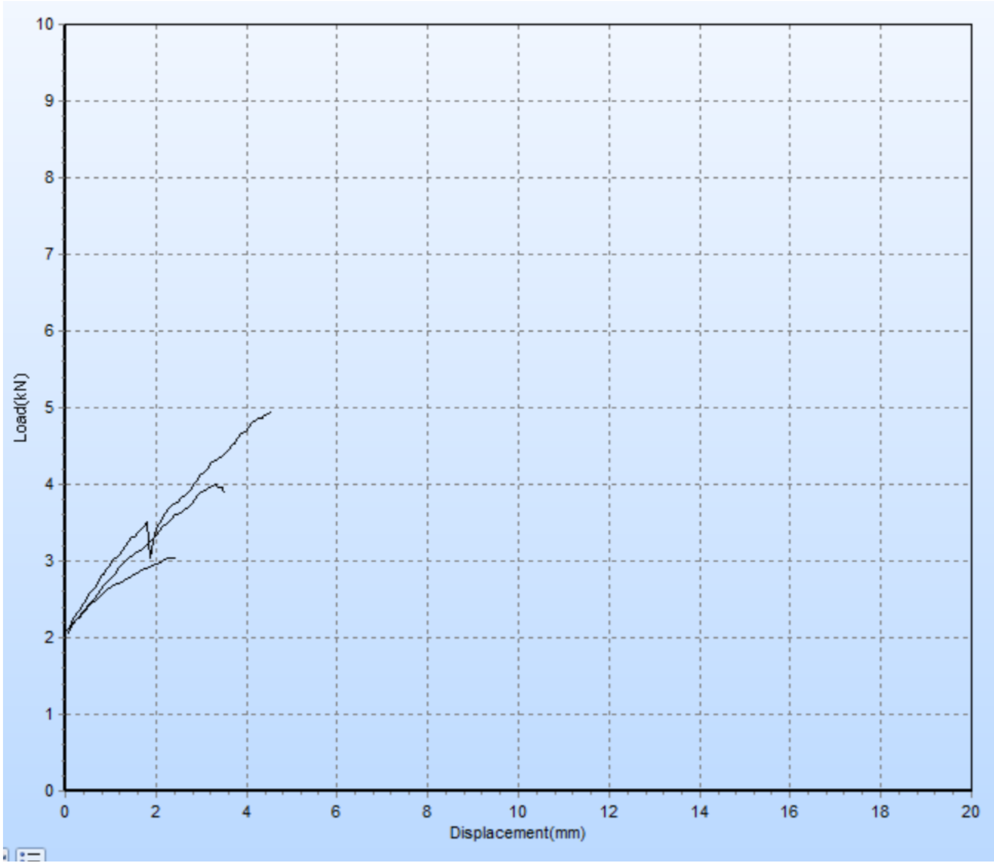
Specima n	fiber content	fiber wt	matrix wt	resin wt	hardener wt	ratio
FC82Cp	0.2	5.94	23.76	17.8646616 5	5.89533834 6	3.03030 3
FC73Cp	0.3	6.2	14.4666666 7	10.8771929 8	3.58947368 4	3.03030 3
J82Cp	0.2	6.01	24.04	18.0751879 7	5.96481203	3.03030 3
J73Cp	0.3	6.32	14.7466666 7	11.0877193	3.65894736 8	3.03030 3
H82Cp	0.2	7.24	28.96	21.7744360 9	7.18556391	3.03030 3
H73Cp	0.3	6.94	16.1933333 3	12.1754386	4.01789473 7	3.03030 3

Date:
2080/01/25

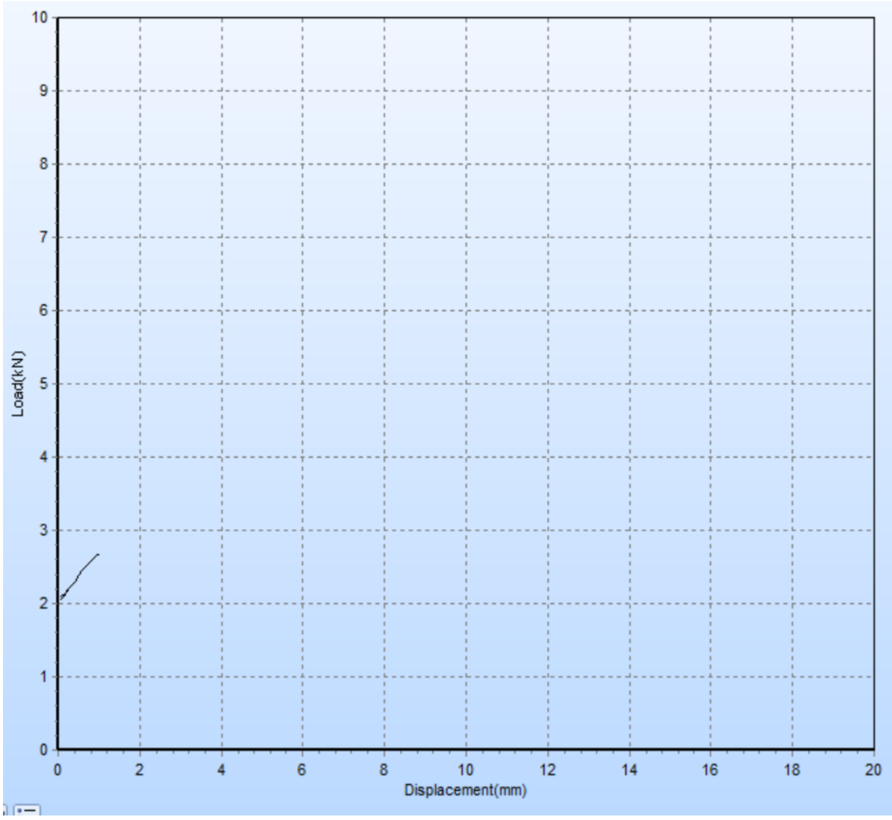
							Tested Date:		1/25/2080
								Machine: U.T.M.	
Sample No.	Sample Type	Thickness (mm)	Width (mm)	Area (mm²)	Yield Load (KN)	Yield Strength (MPa)	Ultimate Load (KN)	Ultimate Strength (MPa)	Remarks
1-2	FC82	3.53	24	84.72	2.51	29.63	2.66	31.40	
1-3	FC82	3.37	25.9	87.28	0	0.00	2.37	27.15	



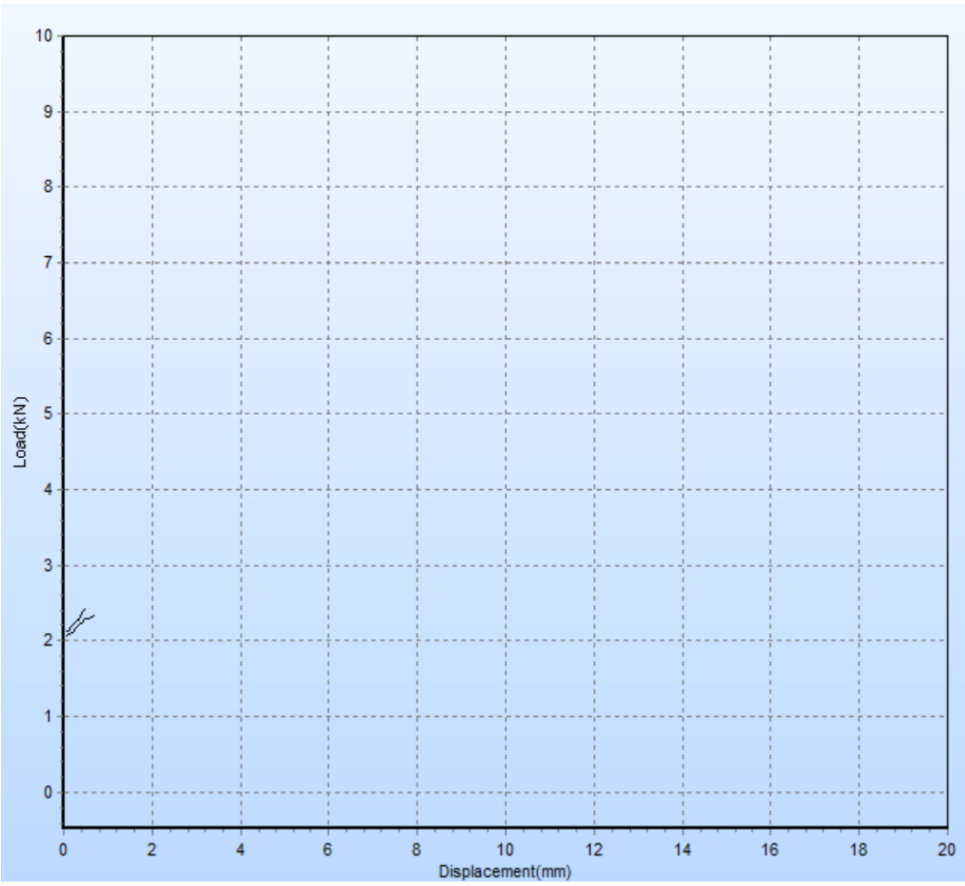
2-1	H82	3.68	24.25	89.24	3.09	34.63	3.95	44.26	
2-2	H82	3.84	25.9	99.46	3.47	34.89	4.94	49.67	
2-3	H82	3.84	25.23	96.88	2.67	27.56	2.96	30.55	



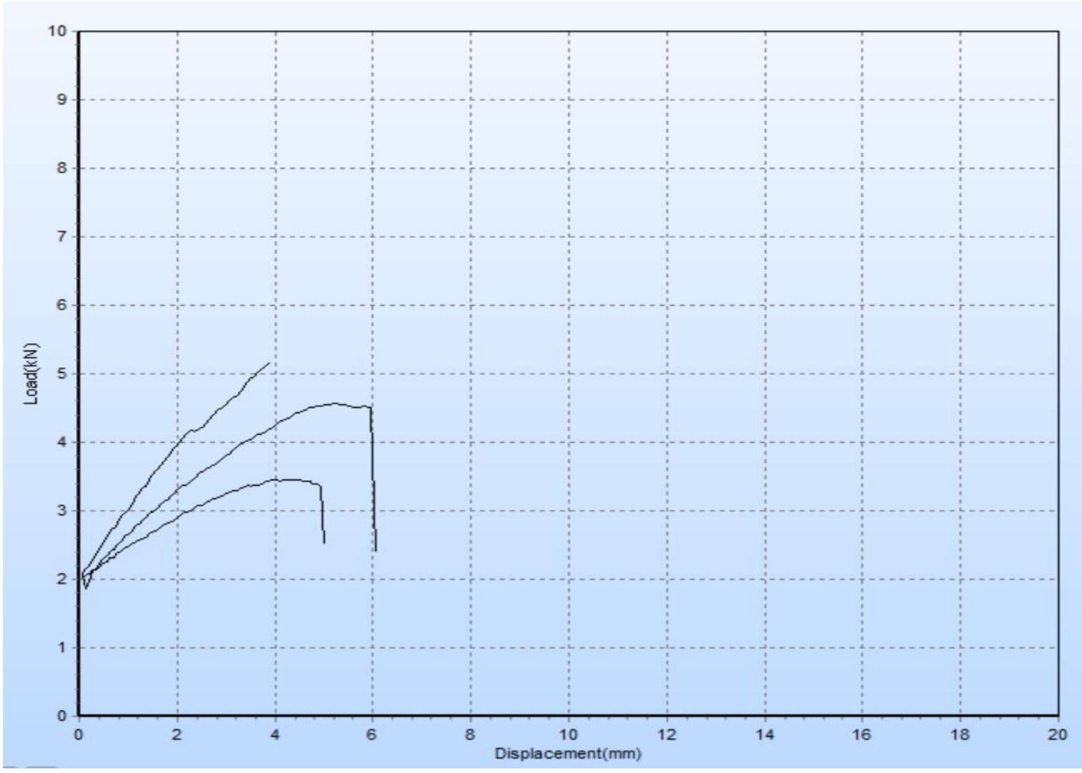
3-2	J82	3.25	24.86	80.80	0	0.00	2.66	32.92	
3-3	J82	2.80	24.5	68.60	0	0.00	2.27	33.09	



4-1	J73	2.36	26.7	63.01	0	0.00	2.37	37.61	
4-3	J73	2.50	25.46	63.65	0	0.00	2.27	35.66	



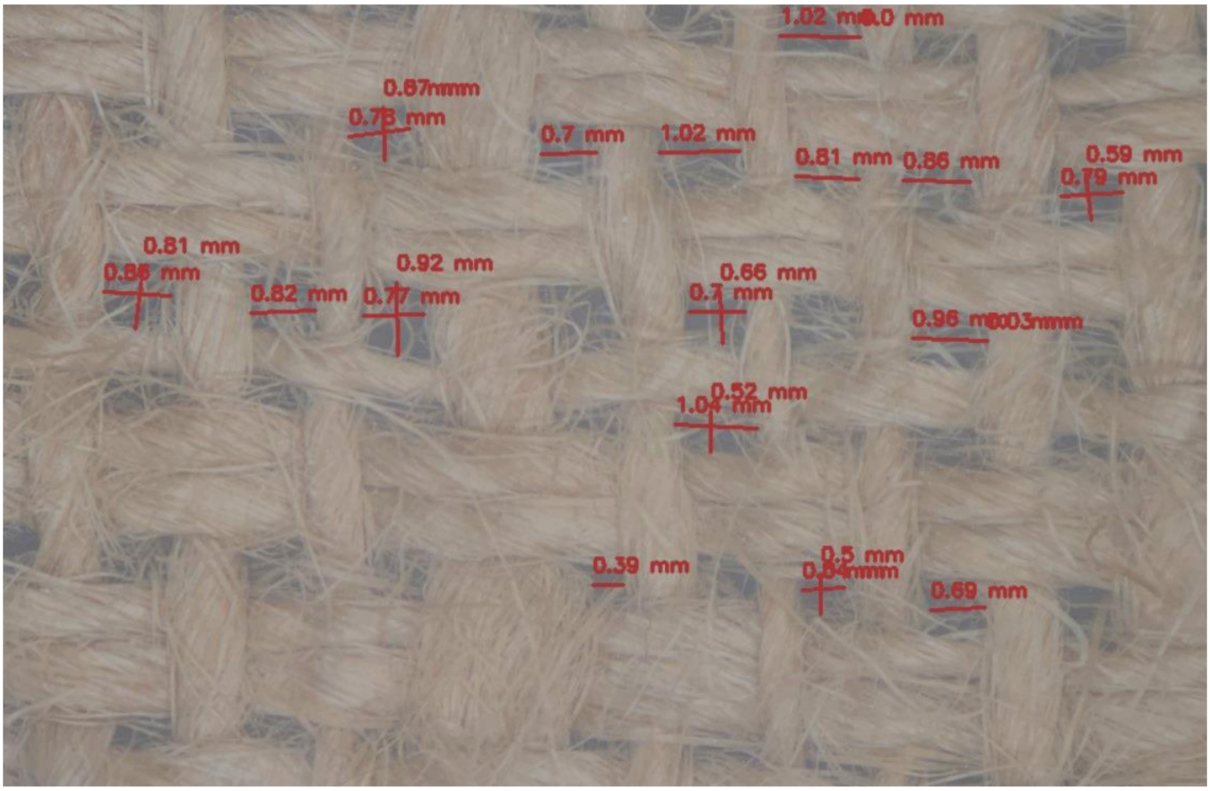
5-1	H73	3.80	25.03	95.11	3.62	38.06	4.54	47.73	
5-2	H73	3.82	24.86	94.97	4.17	43.91	5.03	52.97	
5-3	H73	3.62	20.25	73.31	2.83	38.61	3.45	47.06	

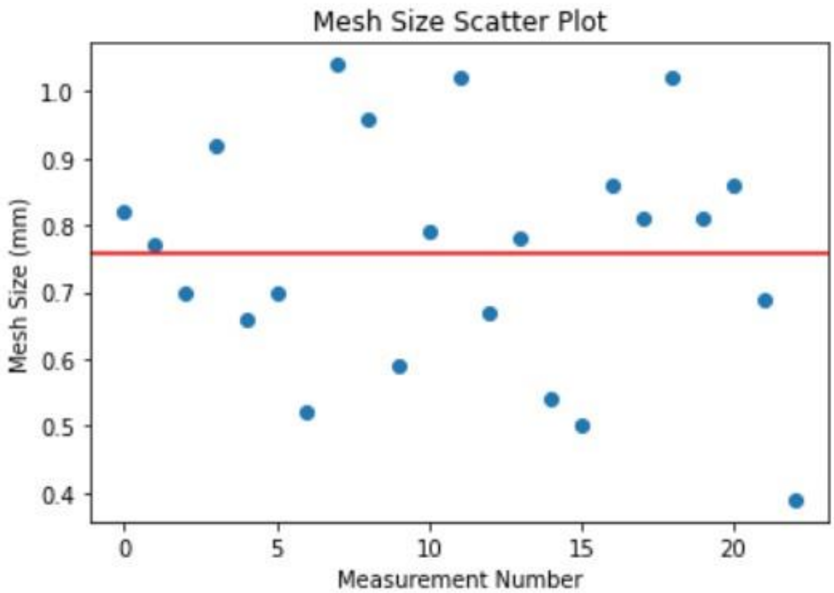


ANNEX 3:

Mesh size calculations using image processing in Jupyter Notebook

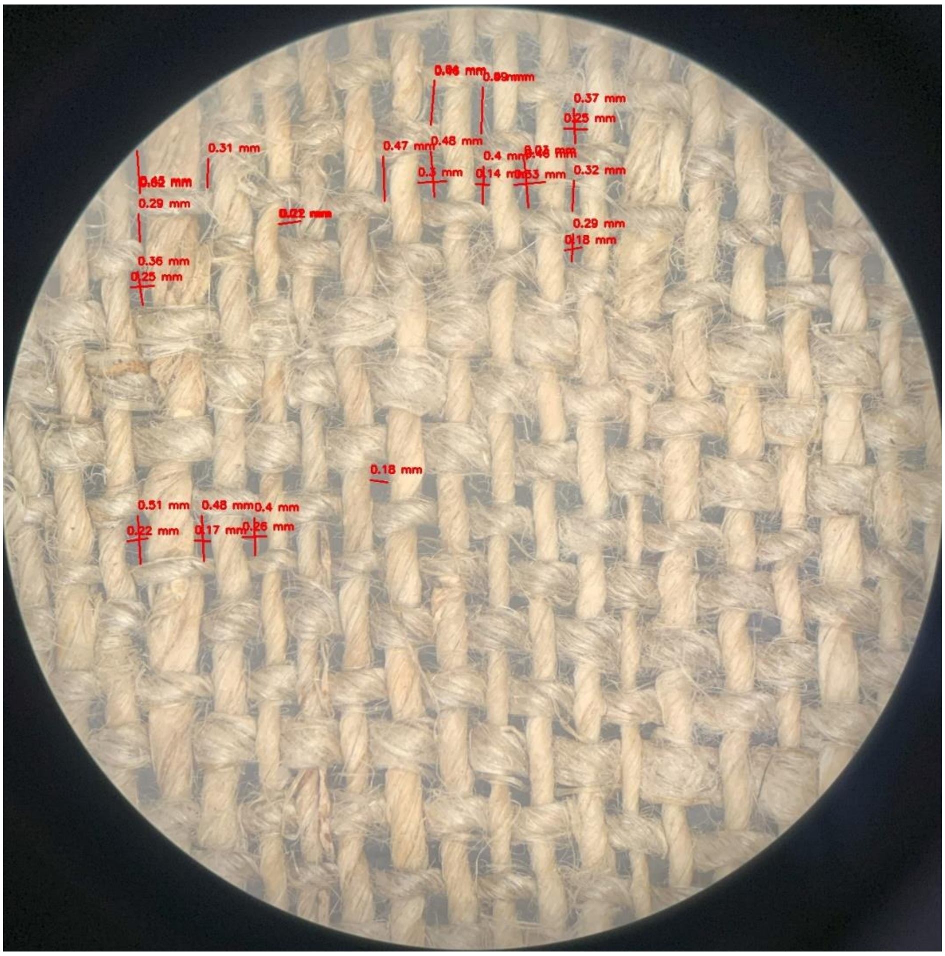
1. Jute

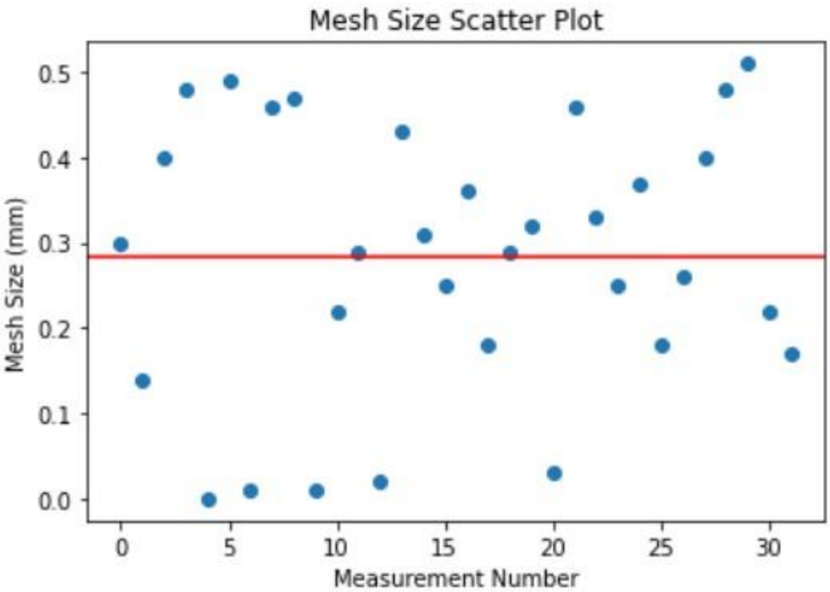





```
Mean: 0.76 mm
Standard Deviation: 0.17 mm
```

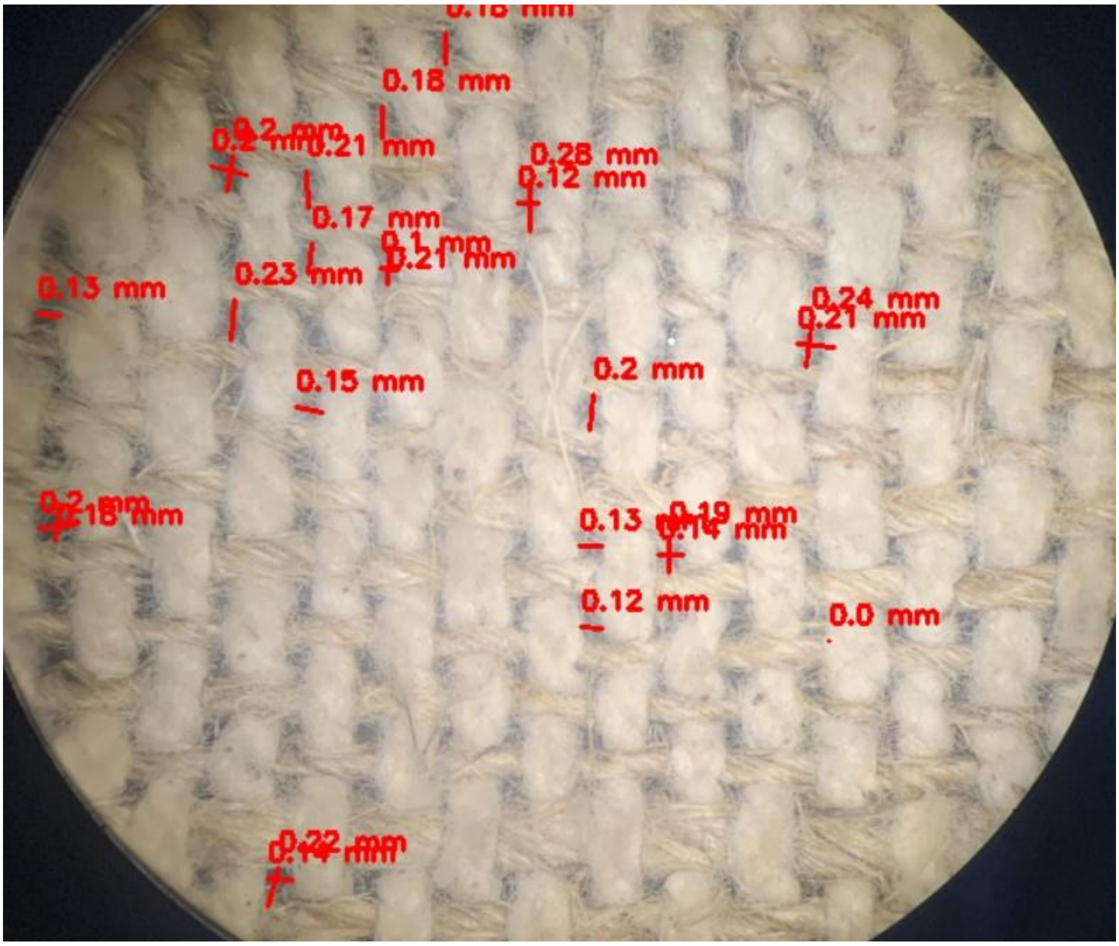
2. Hemp

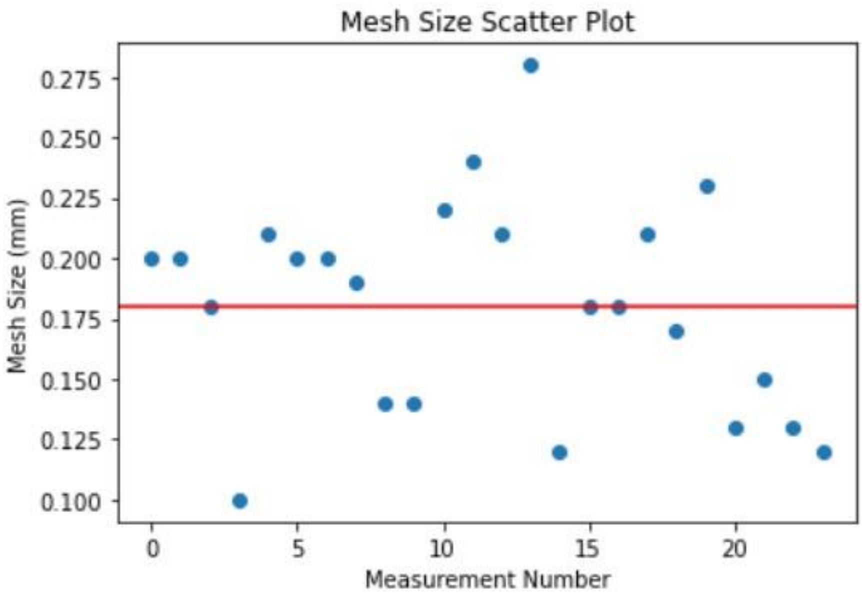





```
Mean: 0.28 mm
Standard Deviation: 0.15 mm
```

3. Flax



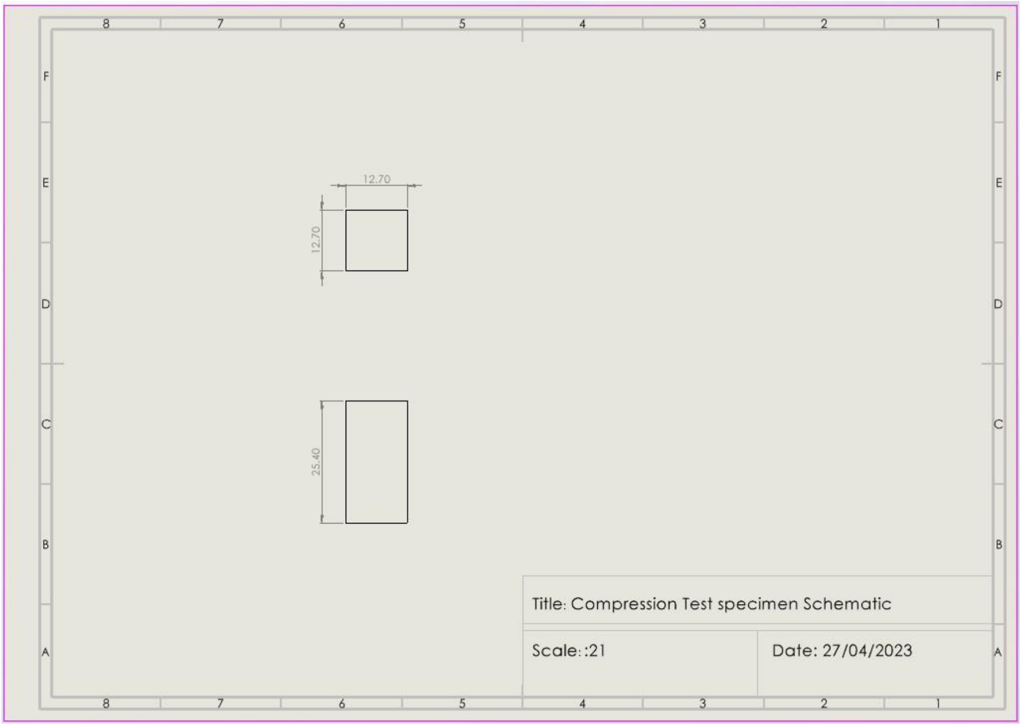



```
Mean: 0.18 mm
Standard Deviation: 0.04 mm
```

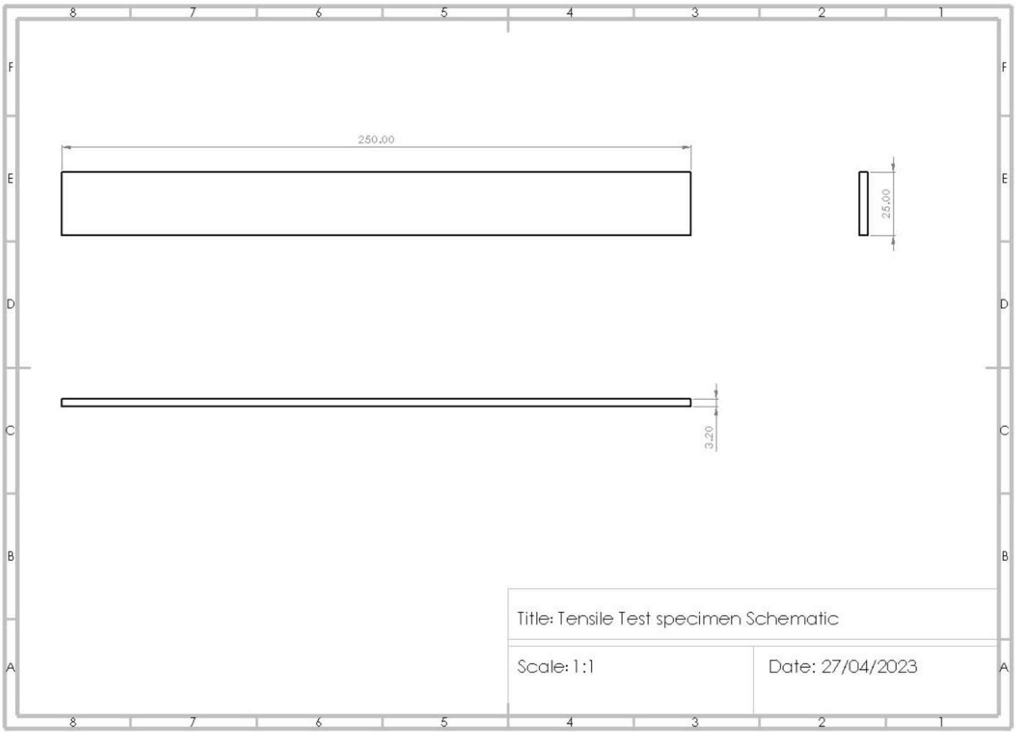
ANNEX 4:

Dimensions of the Specimens

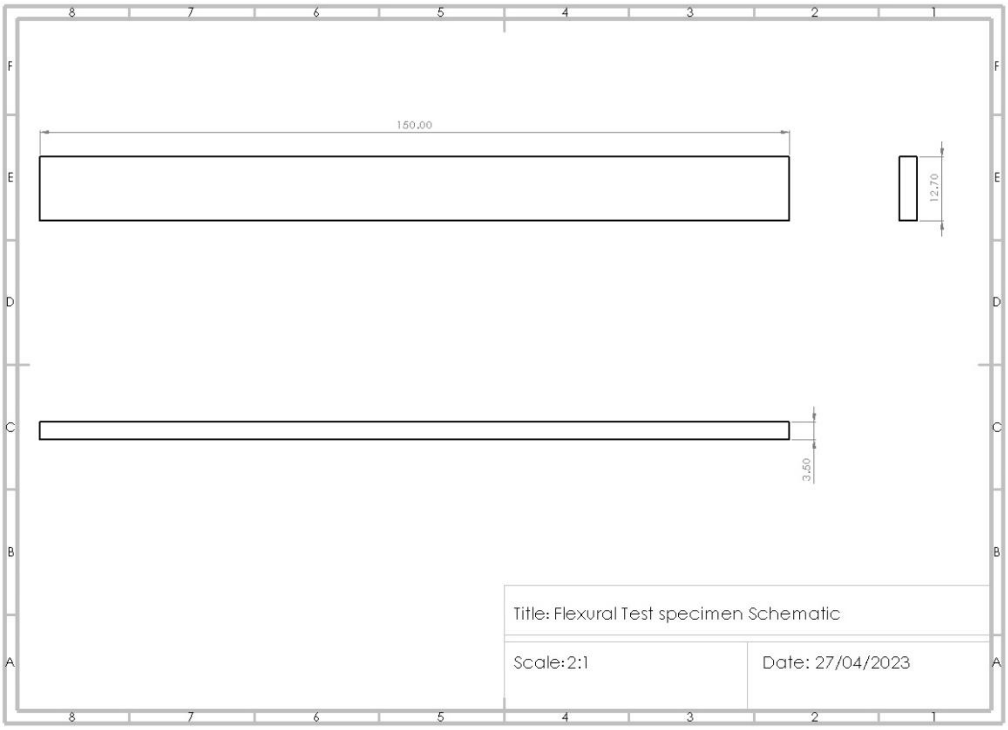
1. Compression test



2. Tensile Test



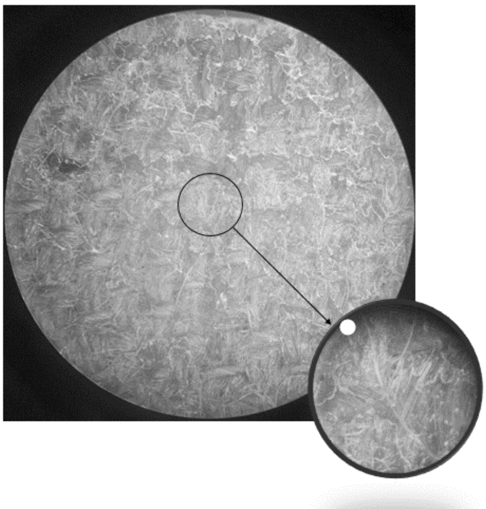
3. Flexural Test



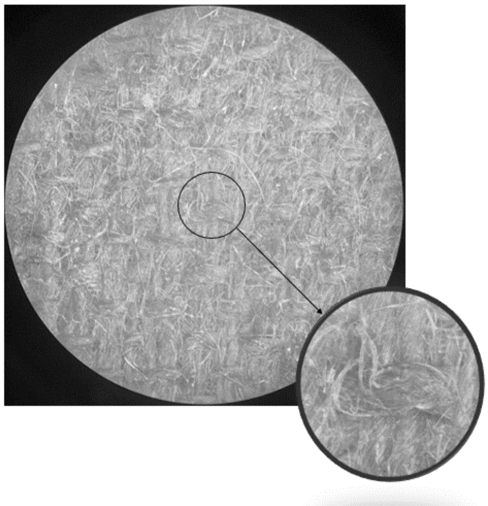
ANNEX 5:

Microscopic inspections

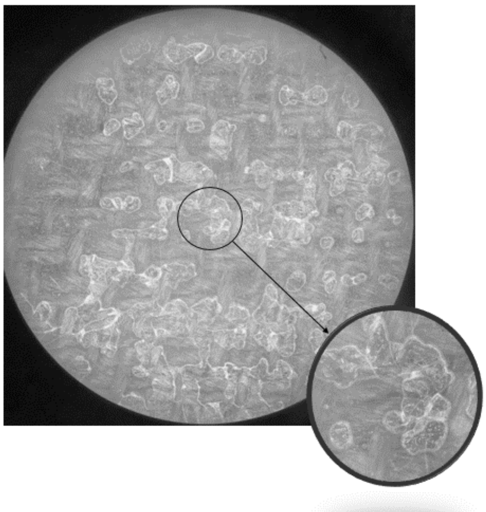
The pictures below are 7x and 40x magnified



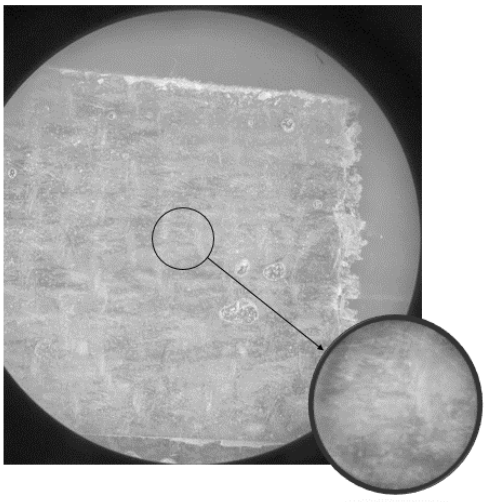
J46



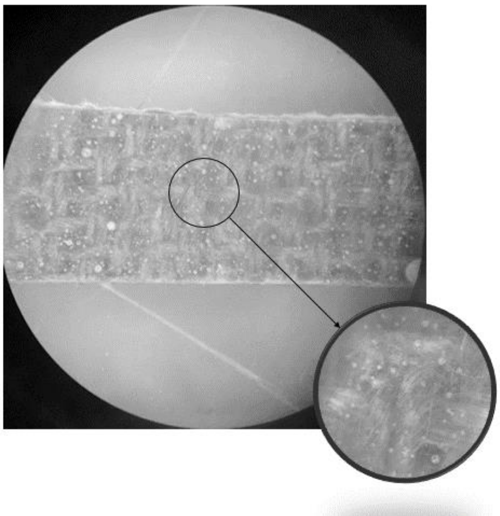
J55



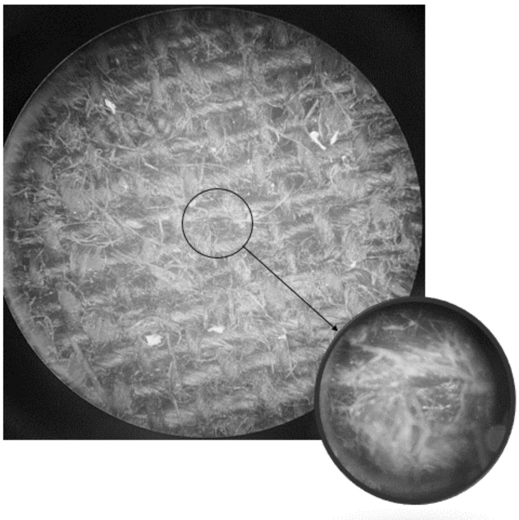
J64



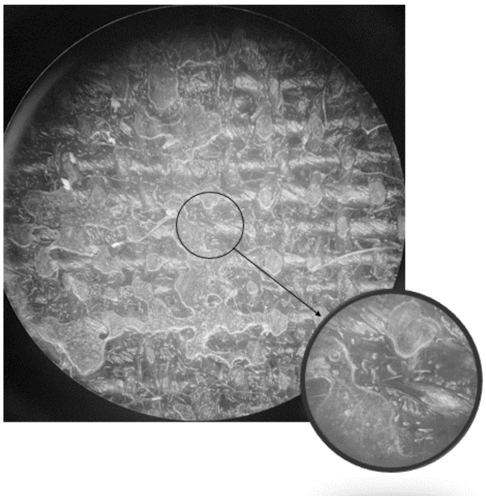
J73



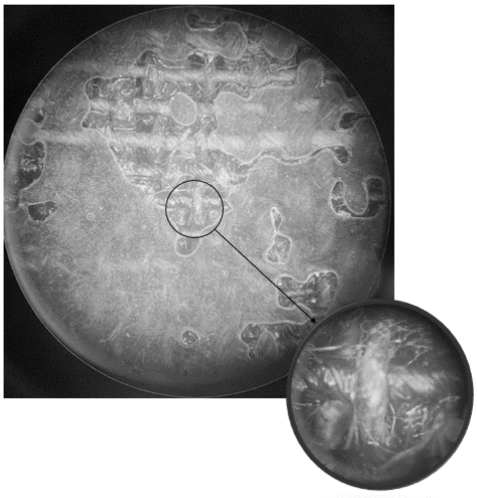
J82



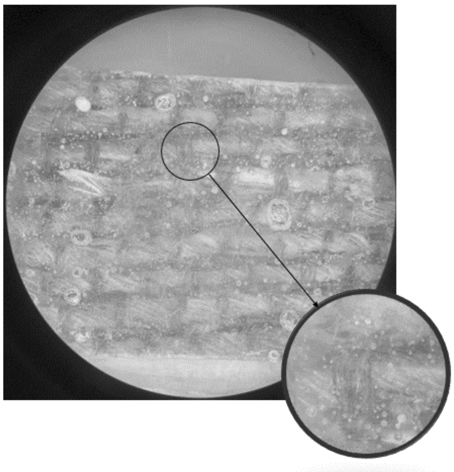
H46



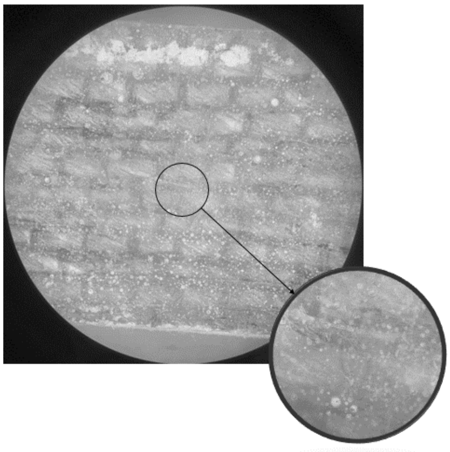
H55



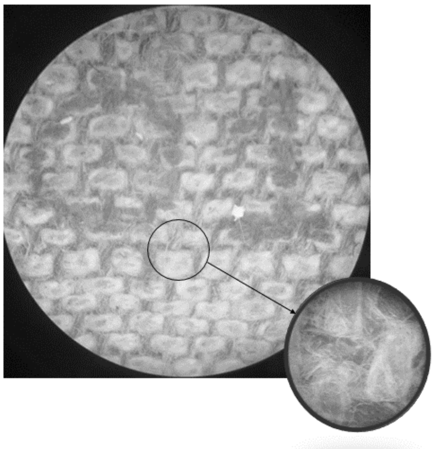
H64



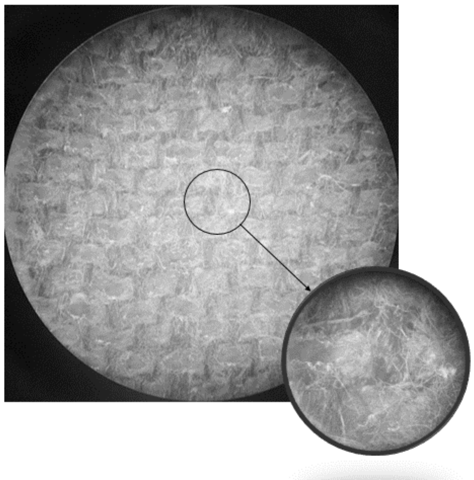
H73



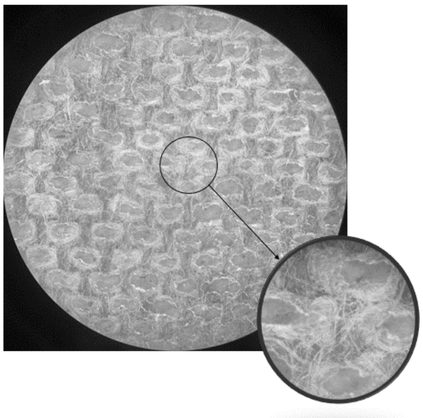
H82



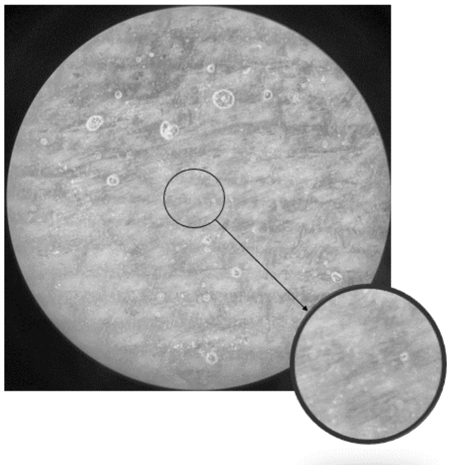
FC46



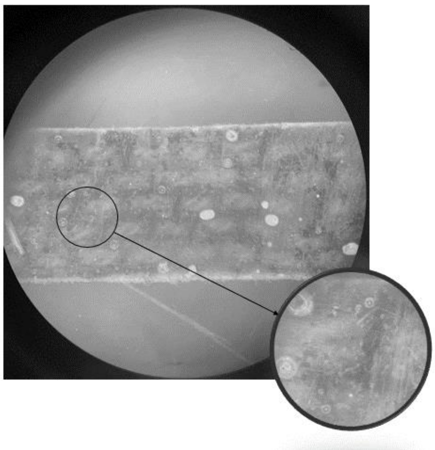
FC55



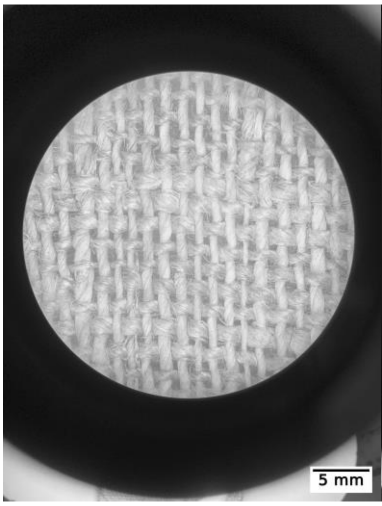
FC64

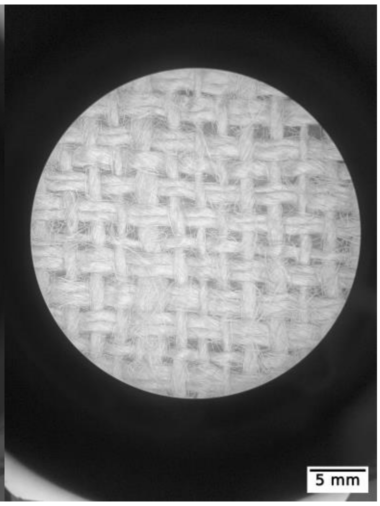


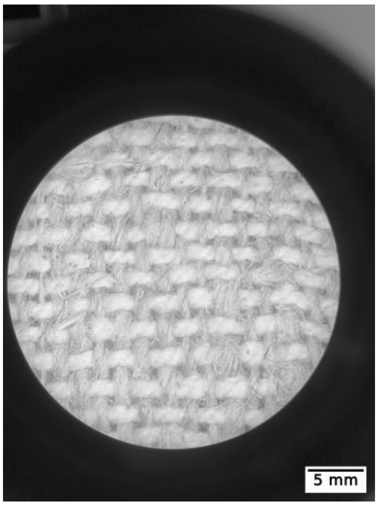
FC73



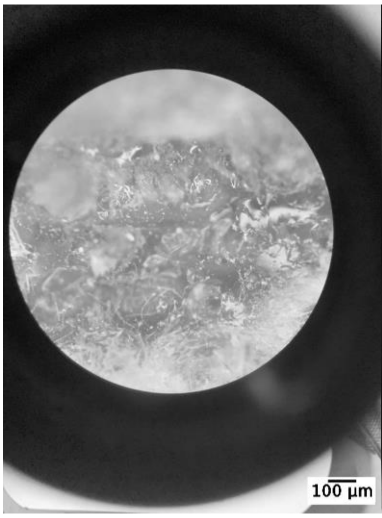
FC82

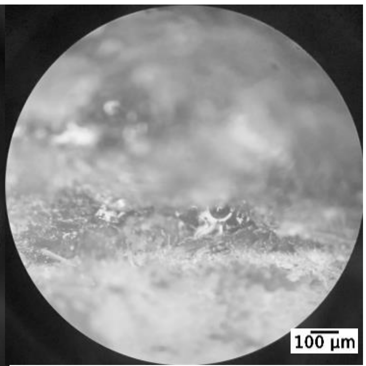






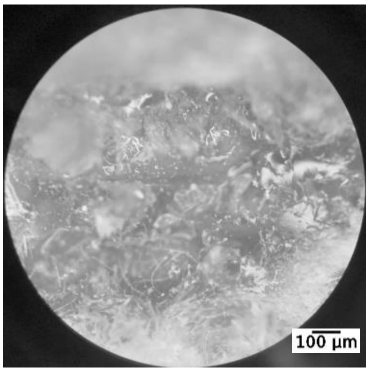
H J FC

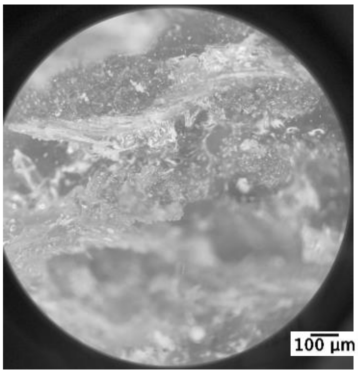


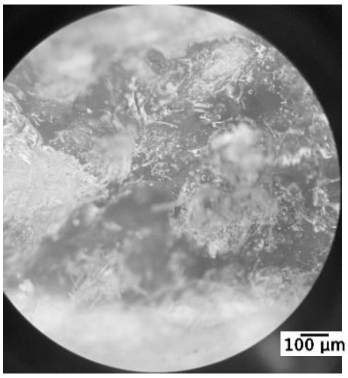


J73C40

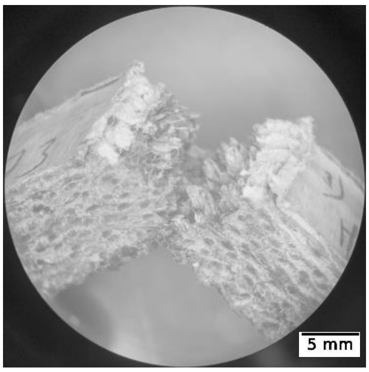
H73C40 H82C40

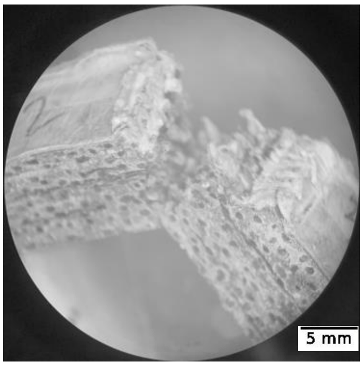


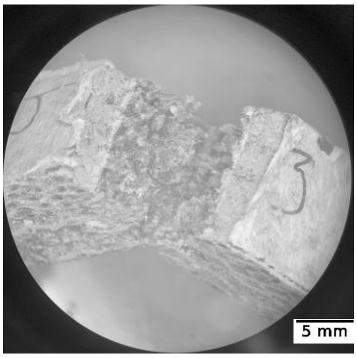




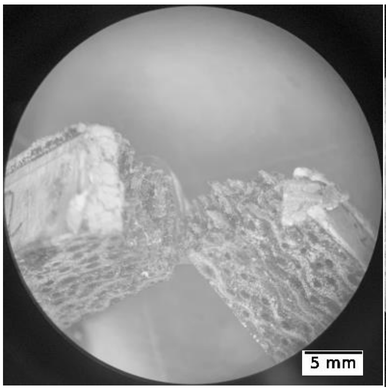
FC73C40 J82C40 F82C40

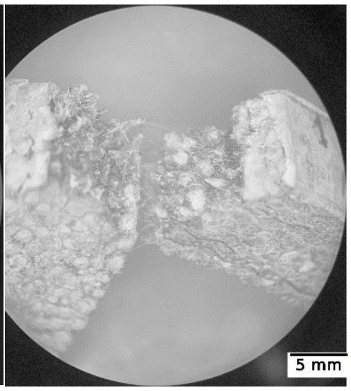


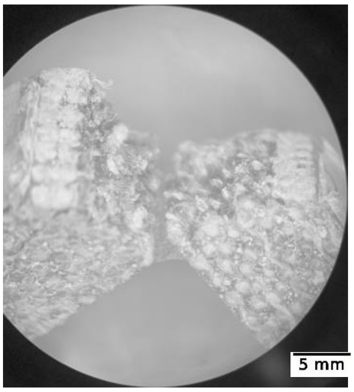




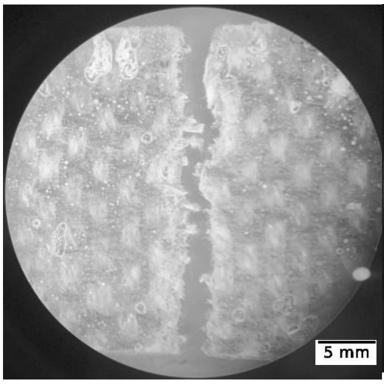
H73C7 H82C7 J73C7

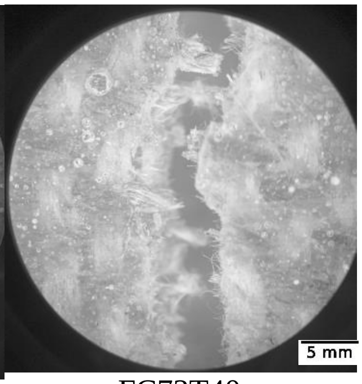


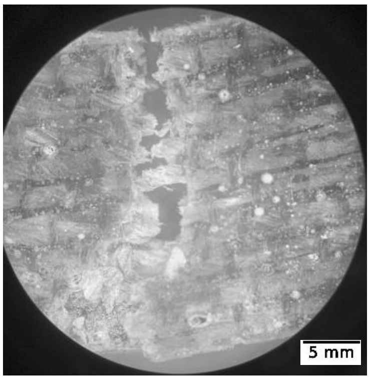




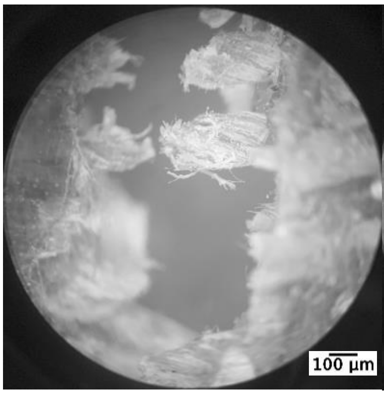
J82C7 FC73C7 FC82C7

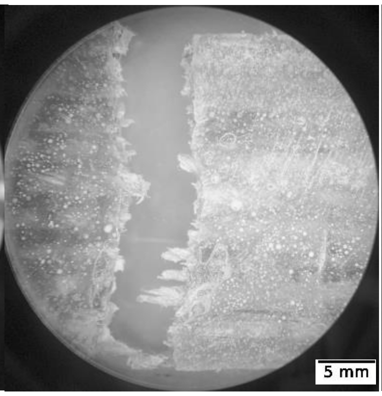


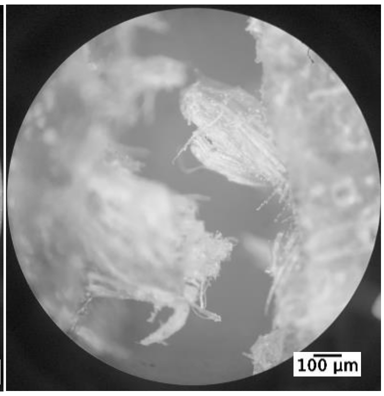




FC73T7 FC73T40 H73T7







H73T40 H82T7 H82T40