HYBRID EFFECT AND STACKING SEQUENCE ON MECHANICAL AND MORPHOLOGICAL PROPERTIES OF FLAX/GLASS FIBER REINFORCED EPOXY COMPOSITES

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by

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(Materials Engineering)

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DECLARATION

I hereby declare that I have conducted, completed the research work and written the dissertation entitled ‘Hybrid Effect and Stacking Sequence on Mechanical and Morphological Properties of Flax/Glass Fiber Reinforced Epoxy Composites’. I also declared that it has not been previously submitted for the award for any degree or diploma or other similar title of this for any other examining body or University.

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LIST OF ABBREVIATIONS

ASTM	American Society for Testing and Materials
BC	Before Christ
C	Carbon
CFC	Carbon-Flax-Carbon
F	Flax
FCF	Flax-Carbon-Flax
FFRE	Flax Fiber Reinforced Epoxy
FRP	Fiber Reinforced Polymer
FW	Fiber Weight
GF	Glass Fiber
GFRC	Glass Fiber Reinforced Composites
GFRE	Glass Fiber Reinforced Epoxy
GFRP	Glass Fiber Reinforced Polymer
HAP	Hazardous Air Pollutant
HW	Hazardous waste
NFRC	Natural Fiber Reinforced Composites
PE	Polyethylene
PP	Polypropylene Relative Humidity
PS	Polystyrene
PVC	Poly Vinyl Chloride
RH	Relative Humidity
RTM	Resin Transfer Molding
RW	Resin Weight
SEM	Scanning Electron Microscope
SW	Solid Waste
TW	Twill Weave
USM	Universiti Sains Malaysia
UTM	Universal Technical Machine
VARTM	Vacuum-Assisted Resin Transfer Molding

LIST OF SYMBOLS

A	Area
°C	Degree celsius
σ	Stress
ε	Elongation
%	Percentage
F	Force, sample length
g	Gram
g/cm^3	Gram per cubic centimeter
g/cm^2	Gram per squarecentimeter
Pa	Pascal
Gpa	Giga Pascal
Mpa	Mega Pascal
kV	Kilo Volt
kN	Kilo Newton
µm	Micro meter
ΔL	Displacement of the sample
L	Load span, original length
P_f	Load fracture
δ	Displacement of crosshead
b	Width
h	Thickness
R	Rate of cross speed motion
Z	Rate of straining of outer fiber
mm/min	Milimiter per minutes

m^2	Meter square
Nm^{-2}	Newton per meter square
D	Depth
wt%	Weight percent
$<$	Greater than
°	Angle
$\sim$	Approximately
r	Ratio
E	Young’s modulus
E_f	Flexural modulus
E_c	Absorbed energy
σ_c	Flexural stress
ε_c	Flexural strain
a_{cu}	Charpy impact strength

KESAN HIBRID DAN JUJUKAN TINDANAN KEATAS SIFAT MEKANIKAL DAN MORFOLOGI KOMPOSIT EPOKSI BERTETULANG GENTIAN FLAKS/KACA

ABSTRAK

Laminasi komposit hibrid baru-baru ini menjadi salah satu bahan yang paling aktif dikaji kerana ciri-cirinya yang menakjubkan. Penyelidikan ini melihat penggunaan flaks dan gentian kaca dimana kedua-duanya mempunyai potensi besar dalam bidang pembuatan komposit. Matlamat penyelidikan ini adalah untuk mengkaji kesan hibrid gentian asli dan sintetik serta kesan jujukan tindanan pada sifat mekanikal dan morfologi komposit epoksi bertetulang gentian flaks/kaca. Laminasi komposit dibuat daripada gentian flaks yang tidak dirawat dan tiada pengubahsuaian pada permukaan gentian kaca atau matriks. Laminasi komposit dihasilkan secara manual dengan menggunakan tangan dan kemudian dipadatkan dengan beg vakum. Sifat tegangan, lenturan dan hentaman enam lamina telah diukur. Keputusan menunjukkan bahawa sifat mekanikal komposit hibrid berada di antara komposit FFRE dan GFRE bukan hibrid, yang mengatasi prestasi sampel kawalan (FFRE). Antara komposit hibrid yang dibuat, sampel H2 [GF]s mempunyai jujukan tindanan terbaik dari segi modulus keanjalan, modulus lentur dan keliatan hentaman (masing-masing 2.07 GPa, 9.78 GPa, dan 10.14 kJ/m^2). Mikrograf SEM bagi komposit patah mendedahkan tanda-tanda kegagalan seperti pecah gentian, gentian tercabut, pecah matriks, penyahikatan, dan penepian, yang mencirikan tahap lekatan gentian dan matriks polimer. Retakan matriks yang tajam dan jelas menunjukkan kegagalan rapuh. Data yang dikumpul boleh digunakan untuk mencipta komposit berlamina hibrid baharu untuk aplikasi industri seperti aeroangkasa, automotif, struktur dan bukan struktur.

HYBRID EFFECT AND STACKING SEQUENCE ON MECHANICAL AND MORPHOLOGICAL PROPERTIES OF FLAX/GLASS FIBER REINFORCED EPOXY COMPOSITES

ABSTRACT

Hybrid composite laminates have recently become one of the most actively researched materials due to outstanding properties. This research looks at the use of flax and glass fibers which both have a great potential in the field of composite manufacturing. The aim of this research is to investigate the hybrid effects of natural and synthetic fibers as well as the effects of stacking sequence on the mechanical and morphological properties of flax/glass fiber reinforced epoxy composites. The composite laminates were fabricated from untreated flax fiber and no modification to the surface of glass fiber or the matrix. Composite laminates were produced by hand lay-up and then compacted by vacuum bagging. The tensile, flexural, and impact characteristics of six laminates were measured. Results indicate that the mechanical properties of hybrid composites fall between those of non-hybrid FFRE and GFRE composites, which outperformed the control sample (FFRE). Among the hybrid composites developed, sample H2 [GF]s has the best stacking sequence in terms of elastic modulus, bending modulus, and impact toughness (2.07 GPa, 9.78 GPa, and 10.14 kJ/m^2, correspondingly). The SEM micrograph of fractured composites reveals failure signs such as fiber breakage, fiber pull out, matrix breakage, debonding, and delamination, which characterize the level of fiber and polymer matrix adhesion. Crisp and clear matrix cracks demonstrate the brittle failure. The collected data could be utilized to create new hybrid laminated composites for industrial applications such as aerospace, automotive, structural and non-structural.

CHAPTER 1

INTRODUCTION

1.1 Research Background

Composite materials, especially those with a polymeric matrix, are of particular interest to researchers and engineers due to their versatility, particularly for advanced applications such as aerospace, marine, and automobiles. For instance, aircraft engineers are searching for structural materials that have low densities, are strong, stiff, abrasion and impact resistant, and are not easily corroded, requirements that metal alloys cannot fulfil. Recent advances in materials science technology have encouraged researchers and engineers all over the world to come up with a wide range of new materials that can be used in sophisticated engineering structural elements as well as sustainable economic and environmental regulations (Singh et al., 2012). Innovative techniques are essential now more than ever to protect the environment or develop structures, which are less hazardous to the environment. This fundamental requirement has stimulated the growth of innovative multifunctional composite materials (Krishnan, 2012). Composites have received a lot of attention over the past few decades because they are stronger, lighter, and less expensive than other materials. There is a possibility that these composites will be developed into complex structures for use in high performance engineering applications by merging more varieties of reinforcements and matrices, (Ever, 2017)

Fiber-reinforced polymer (FRP) composites has become one of the most important materials in engineering application and is widely used in various applications such as aerospace, sports equipment, automobiles, civil and marine structures. The FRP composites are multicomponent materials consisting of reinforcing fibers embedded in a stiff polymer matrix. A wide range of polymers can be used as the matrix to FRP composites, and these are generally classified into two categories: thermoplastics and thermosetting. The most used thermoplastic matrices are polypropylene (PP), polyethylene (PE), and polyvinyl chloride (PVC) whereas the most used thermosetting matrices are phenolic, epoxy, and polyester resins. The characteristic of these polymers may improve when adequately reinforced with fibers. Their performance is well known for high strength-to-weight ratio, excellent corrosion and abrasion resistance. In general, FRP composites are developed mainly using high-strength synthetic fibers. Synthetic fiber composites are unavoidable in the manufacturing and production industries because of their excellence properties compared to the natural fiber such as high strength, rigidity, long fatigue life, and flexibility. Specific characteristics such as rigidity, great strength, and low weight, make the material used in a lot of advanced engineering components (Zhang and Matinlinna, 2012; Friedrich and Almajid, 2013).

Therefore, for this reason, the complete replacement of synthetic fibers with natural fibers is not a viable choice. Hybridization is the solution to incorporating natural fibers into applications requiring high performance from fiber reinforced polymer composites. A combination of synthetic and natural fibers is the most preferable concession to achieve the best balance between performance and environmental impact. The hybridization between these two fibers can constitute a promising solution to take advantage of natural fibers while keeping the interesting properties of synthetic fibers. The advantage of hybridization in composite reinforcement is that one type of fiber can fill in the gaps left by the other. By considering a hybrid composite, for example, the mechanical performance of some synthetic fibers can be combined with the numerous benefits that natural fibers provide, such as their ease of availability, biodegradability, non-abrasively, renewability, and friendliness to the environment. The combination of renewable and synthetic materials appears to reduce the weight, cost, and environmental impact compared to pure synthetic materials. Most natural fibers are generally treated with physical or chemical treatments, these treatments are for removing minerals, pectin, and waxes to create better bonding between fibers and matrices. This is done because strong bonds lead to better mechanical properties (Pickering, 2008). However, weak bonding is also useful to allow debonding and fibers pull out which are toughening mechanisms of composites laminates (Matthews and Rawlings, 1999). In contrast to some earlier research, Pantamanatsopa et al. (2014) found that treating natural fibers could also decrease the mechanical properties of composites and reduce the amount of damping (Mohanty et al., 2006). Thus, for this study, no additional treatment was made to the natural fiber and that fiber was used as its was fabricated.

In practical application, the mechanical properties of hybrid composites can be improved by adjusting the stacking sequence of fibers. It can make a composite material with diverse mechanical properties that can meet the performance requirements of different structures for practical applications. In this work, woven flax fiber and glass fiber were selected to make the non-hybrid and hybrid composites, so that the hybrid effects could be revealed more clearly. Deciding the stacking sequence of fiber placement is one of the most common problems during hybridization to improve the mechanical properties (tensile, flexural, and impact) of the composites. This study compares the different ways to the previous researchers in which the flax and glass fibers were placed through the composite preforms in an asymmetric configuration and no physical or chemical treatment was done to the natural fiber and no modification was done on glass and epoxy resin. The purpose of this study is to improve the mechanical properties of the composite by enhances the composite toughness and to know how much it will affect the mechanical properties if no modification was done on the natural fiber. The mechanical properties of the hybrid composite laminates, such as their tensile, flexural, and impact properties, were studied. The influence of hybrid effects and stacking sequence were investigated and the hybrid mechanisms were revealed with the aid of the scanning electron microscopy (SEM) observations.

1.2 Problem Statement

Refer to references from 2017, most polymer matrix composites are made up of synthetic fiber especially glass fiber, which causes challenges with disposal after end of life. Due to the continuous rise in consciousness regarding biodegradability and participation of the government in environmental safety, this diverts the attention of researchers to biodegradable materials. Unfortunately, natural fibers have several drawbacks, such as low and a wide range of mechanical properties, a high tendency to absorb water, poor resistance to aging in humid environments, and poor adhesion with several hydrophobic polymeric matrices. Also, the tensile strength of natural fiber is low compared with synthetic fiber (Srinivas et al., 2017). Especially nowadays almost all engineering applications require high performance from fiber-reinforced polymer composites which mostly consist of synthetic fibers. According to Sharifah and Martin (2004), synthetic fiber resulted in environmental effects, hazardous and disposable problems. The concern for the environment is an issue of increasing importance for our society. As production volume increases, so the need to deal with environmental effects increases. The major contributions to environmental degradation from composites are generation of hazardous air pollutants (HAPs) and hazardous and solid wastes (HW and SW). In order to comply with stringent environmental regulations and at the same time to produce high-performance composite materials, making the use of hybrid fiber composites (a hybridization of synthetic with natural fibers) is the most preferable concession that can be made between performance and the impact on the environment. The preferred characteristics might be achieved by appropriate material design.

The work presented in this study concerns the use of flax fibers as potential reinforcement when combining with glass fibers in polymer composites. The aim of this research is to study the hybrid effects between natural and synthetic fibers and to develop/design high-performance composites that are friendly to the environment by diversifying the stacking sequence to achieve the desired outcomes. In this context, we propose to analyze the mechanical properties of flax/glass hybrid reinforced epoxy composites. This choice is driven by the high mechanical performance of glass fiber as well as the interesting properties of flax fiber. Furthermore, the tensile properties of flax fibers are comparable to E-glass fibers. This research could be useful for those who wish to develop flax/glass hybrid composites for structural applications.

1.3 Research Objectives

This research is conducted to fulfill these objectives:

- To investigate the hybrid effect on mechanical properties of flax-glass fiber hybrid reinforced epoxy composites compared to the parent materials.

- To determine the effect of stacking sequence on mechanical properties of flax-glass fiber hybrid reinforced epoxy composites.

1.4 Scope of Research

FRP composites has been widely used in industries due to their low cost, lightweight, high strength, corrosion resistance, and ease of processing. Based on the problem statement, the issues of environmental and economic consistency have led to the use of natural fiber as reinforcement in polymer composites. Unfortunately, natural fibers possess several drawbacks that confine their application to structural or non-structural components. As a result, the natural fiber must be combined with synthetic fiber to create high-performance materials while lowering the environmental effect of synthetic fiber when compared to products composed completely of synthetic fiber. High-performance and environmentally friendly composites can be created by hybridization between synthetic and natural fibers. Hybrid polymer composites of which natural and synthetic fibers as reinforcement are utilized to improve material performance, minimize moisture absorption, balance fiber costs, reduce the negative impact on the environment, as well as energy consumption and carbon footprint (Safri et al., 2017).

The purpose of the research is to investigate the effect of stacking sequence on the mechanical and morphological properties of flax/glass fiber reinforced epoxy composite and at the same time to study the effect of a hybrid system by comparing the result between non-hybrid (parent materials) and hybrid composites. This project was aimed to determine the best stacking sequence of flax/glass fiber hybrid reinforced epoxy composite by comparing the result of flax/glass fiber hybrid composites. The materials used in this study are woven E-glass fiber and flax fabric. E-glass has excellent fiber forming capabilities and is widely used in various applications. Flax fibers are relatively abundant, inexpensive, lighter (lower density), biodegradable, and non-abrasive. In addition, flax fibers possess comparable tensile properties to E-glass fibers. The choice is driven by the high mechanical performance of glass fiber as well as the interesting properties of flax fiber. Untreated flax fiber is used in this study to promote composite toughness and reduce the use of the chemicals. After all, some literature also pointed out that the treatment of natural fibers may decrease mechanical properties of composites (Pantamanatsopa et al., 2014).

The first part represents the manufacturing process of the sample, the sample will be prepared using a hand lay-up method and vacuum bagging method due to several unavoidable factors. Furthermore, this method has been widely used because it is simple, less costly and can be completed at a short time. The second part represent the mechanical properties of the material will be determined by tensile, flexural, and impact tests according to the ASTM International standard and morphological properties of the material will be analyzed using scanning electron microscopy (SEM). The main findings and conclusion are presented at the end of the report. This study might clearly show the complementary potential between natural and synthetic fibers in terms of their mechanical performances and can be used to assess the best combination that can be applied to design the best structural or non-structural materials.

1.5 Thesis Outline

The following is an outline of each of the chapters presented in the thesis:

Chapter 1: Present the research background, problem statement, objectives of the research and general scope of the thesis outline.

Chapter 2: Review the literature relevant to the current study, with a focus on a fundamental overview of natural fiber, an overview of hybrid composites, the fundamentals of hybrid systems, the effect of stacking sequence on the mechanical properties of hybrid composites, materials overview, fundamental of fabrication method and defects, and the properties of the flax/glass fiber hybrid composite.

Chapter 3: Describe the experiment process that was conducted for the research. Provide the information of materials used, fabrication process with simple illustrations and the procedures for characterization and testing to analyze the mechanical and morphological properties of the sample.

Chapter 4: Provides results from characterization and testing and discusses the findings of the study. The discussions are divided according to research objectives.

Chapter 5: Summarizes the findings of this study and presents some ideas for future works

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter reviews the literature relevant to the current study, focusing on a basic overview of natural fibers, an overview of hybrid composites, the fundamentals of hybrid systems, the effect of stacking sequence on mechanical properties of hybrid composites, materials overview, fundamental of fabrication method and defects, and the properties of the flax/glass fiber hybrid composite.

2.2 Preliminary Studies on Common Natural Fibers Reinforced Composites

Natural fiber helps to move forward the development of composite structures, especially in the automotive industry. Natural fibers composites parts have a low density, are inexpensive, have good mechanical properties, renewability and are good for the environment (Faris and Mohd, 2017). Mechanical properties of some natural fibers have equivalent as compared to synthetic fibers. Natural fibers are a renewable resource that is cheaper, less dense, and can be reused or recycled. They serve as reinforcing fibers in thermoplastic and thermosets matrix composites, providing environmental benefits in terms of ultimate disposability and raw materials utilization (Senthilkannan, 2020). According to Yashas et al. (2019) natural fibers are about 50% lighter than glass, generally inexpensive, and renewable. According to Njoku et al. (2019) natural fibers reinforced composites (NFRC) exhibit several advantages over glass fiber reinforced composites (GFRC) such as low density, relatively less expensive, low equipment ware obtained from renewable resources and environmentally friendly. Recently, NFRC come forward for the fabrication of structural and nonstructural parts in various applications, like nonstructural parts for automobiles (Bajpai et al., 2012; Faris and Sauan, 2014; Guermazi et al., 2016; Gupta, 2016).

2.3 General View on Natural Fibers Reinforcement

Natural fibers can be sourced from plants, animals or mineral resources. Natural fibers can be classified according to their origin as shown in Figure 2.1

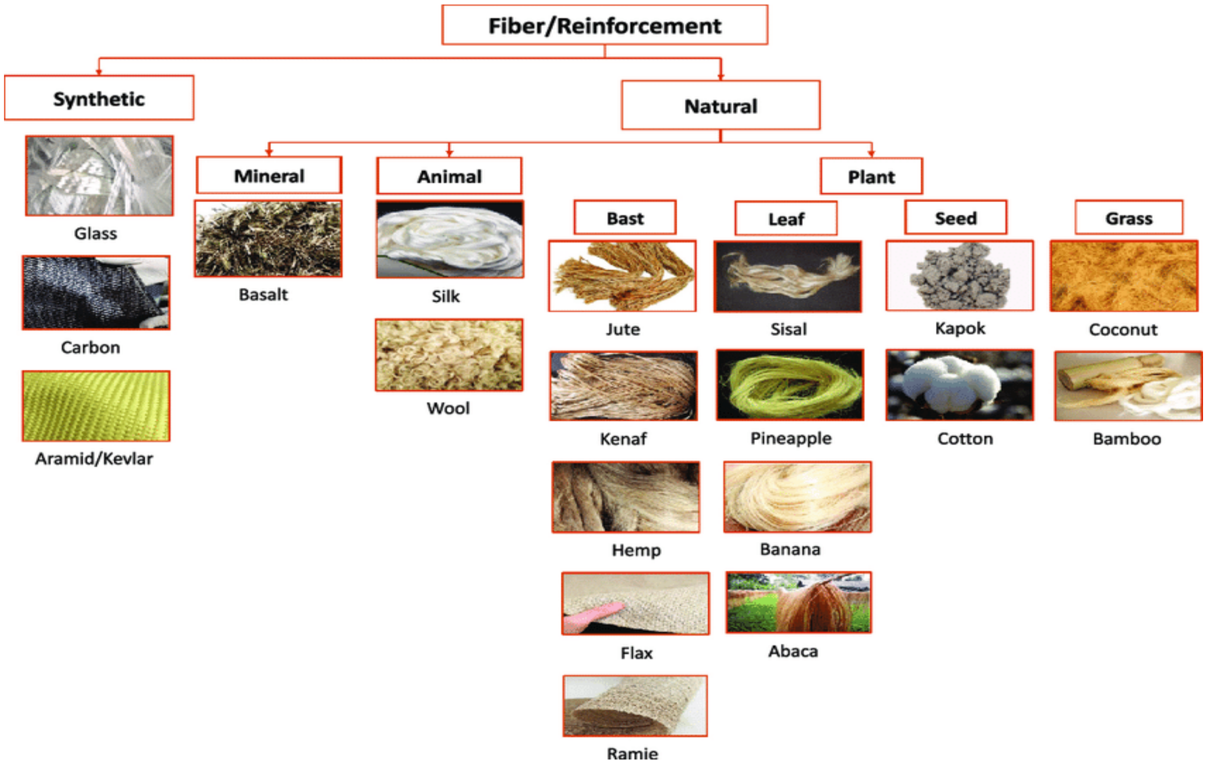

Figure 2.1 A common classification of fiber-reinforced polymer composite reinforcements (Khurshid et al., 2021)

According to Layth Mohammed et al. (2015), the disadvantage of natural fiber is that the properties of natural fiber raw products are strongly influenced by their growing environment, temperature, humidity, the composition of the soil and the air, which eventually affects the height of the plant, the strength of the fibers and the density of the fibers. The end properties of natural fibers will also be different because of how they are harvested and processed. In general, natural fibers have a hollow space called the lumen and nodes that are spread out at different times and divide the fiber into individual cells. However, one of the best things about natural fibers is that their surface is rough and uneven. This lets them stick well to the matrix in a typical composite structure. Besides that, thin natural fibers with a high surface-to-volume ratio resulted in good fiber-to-matrix adhesion Layth Mohammed et al. (2015). Table 2.1 is a summary of some of the advantages and disadvantages of natural fiber composites Layth Mohammed et al. (2015).

Table 2.1 Advantages and disadvantages of natural fiber (Layth Mohammed et al., 2015)

Advantages	**Disadvantages**
Renewable material. Give less problem concerning health and safety of workers. Friendly processing (no wear of tooling and no skin irritation). Low-energy production (reducing the greenhouse effect). Can be thermally recycled. Good thermal and acoustic properties. Light weight depended on product. Excellent price and performance (cheap and have a better stiffness per weight than glass).	Moisture absorption. Fluctuation in quality, price and availability (fluctuate by harvest results or agricultural). Dimension instability. Susceptibility to rotting. Swelling leads to micro-cracking. Restricted processing temperature. Smell of natural fibers when process at high temperature. Lower strength properties particularly its impact strength. Poor fire resistance whereby natural fibers must be worked at low temperatures at approximately 350°C and below.

2.4 Material Overview

2.4.1 Flax Fiber

Flax fibers or scientific name: Linum usitatissimum is one of the most extensively used bio/natural fibers. Flax was also one of the first fibers harvested, spun, and woven. Flax in textiles used was discovered in Egyptian tombs dating back to 5000 BCE (Benna Crawford, 2017). Flax grown for fiber and linseed grown for seed oil are cultivars (varieties of the same plant species bred with an emphasis on the required product) (Magdalena et al., 2015). Canada has historically been the world largest producer and exporter of flax since 1994. France, Belgium, and the Netherlands are also big flax producers, with 130,000 acres cultivated each year. The weather in these areas is perfect for growing flax, and the growing demand for linen makes it a profitable cash crop. The growing cycle of flax in the Western Europe is short, with only 100 days between seeding and harvesting (the Flax Council of Canada, 2018).

Long, fine and regular flax fibers are usually spun into yarns for linen textiles. Linen fabric has a strong traditional niche among high quality domestic textiles including bed linen, furnishing materials, and interior design accessories. Shorter flax fibers produce heavier yarns, which can be used to create kitchen towels, sails, tents, and canvas. Lower fiber grades are utilized as reinforcement and filler in automobile interior substrates and furniture composites (Mahir et al., 2019).

Based on the discussion, Ditterber and GangaRao (2012) concluded that among various natural fibers, flax fiber offers the best potential combination of low cost, light weight, and high strength and stiffness for structural application. The values of the characteristic variables, including fiber density, diameter, and mechanical properties, are presented in Table 2.2. The flax fiber has greater mechanical properties than other types of natural fibers due to its higher concentration of chemical constituents, such as cellulose (60–70 wt. percent), crystallinity (50–90 wt. percent), microfibrillar angle (10°), and high aspect ratio; these chemical constituents are responsible for its mechanical properties (Karimah et al., 2021).

Table 2.2 Characteristic values for the density, diameter and mechanical properties of fibers (Layth Mohammed et al., 2015)

Fiber	**Density (g/cm^3)**	**Diameter (μm)**	**Tensile Strength (Mpa)**	**Young's Modulus (Gpa)**
Flax	1.5	40-600	345-1500	27.6
Hemp	1.47	25-500	690	70
Kenaf	-	-	930	53
Jute	1.3-1.49	25-200	393-800	13-26.5
Sisal	1.45	50-200	468-700	9.4-22
Ramie	1.55	-	400-938	61.4-128
Abaca	-	-	430-760	-
Cotton	1.5-1.6	12-38	287-800	5.5-12.6
Coir	1.15-1.46	100-460	131-220	4-6
E-glass	2.55	<17	3400	73
Carbon	1.78	5-7	3400-4800	240-425
Kevlar	1.44	-	3000	60

2.4.1(a) Structure of Flax Fiber

Flax fiber is made from the stems of flax bast. Flax fiber is a natural cellulosic like cotton, but its structure is more crystalline, which makes it stronger, sharper, and harder to handle. It also wrinkles more easily. Figure 2.2 shows a schematic representation of multi-scale structures of flax from the stem to the cellulosic fibrils (Zeng et al., 2015). Flax plants can grow up to 100 cm long, with strong fibers along the length of the stem, and the average 12–16 μm in diameter. At the macroscopic level, a flax stem is made up of bark, phloem, xylem, and a central hole that goes from the outside to the interior while at the mesoscopic level, the cross section of a bundle contains between 10 – 40 fibers that are predominantly connected together mainly by pectin (Charlet et al., 2007).

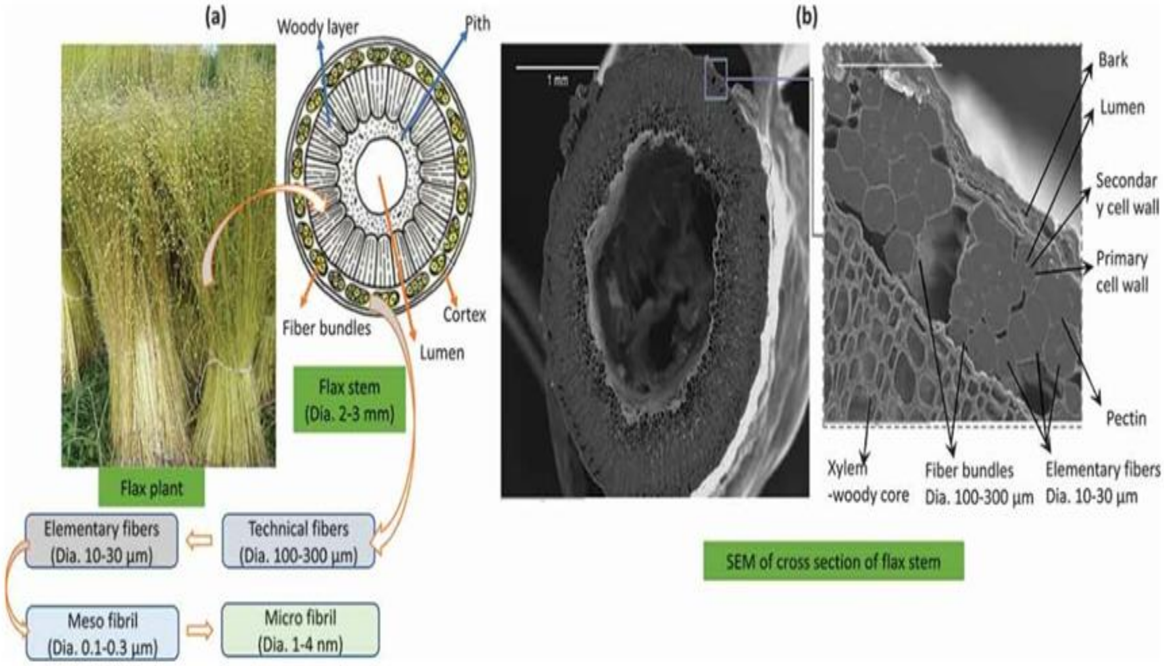

Figure 2.2 (a) Schematic of flax stems and fibers, and (b) SEM images for cross-sectional of flax stem (Zeng et al., 2015)

The microstructure of a flax fiber is extremely complex due to the hierarchically organization at different length scales and the numerous components present in varied proportions (Baley, 2002). At the microscopic level, each elementary fiber is composed of concentric cell walls that vary in thickness and arrangement of its constituents components. As shown in Figure 2.2, at the center of the elementary fiber, the concentric cylinders with a small open channel in the middle known as the lumen, which contributes to water uptake. The outside of the primary cell wall is only about 0.2 m thick (Bos and Donald, 1999). On the outer side, the thinner primary cell wall wraps around the thicker secondary cell wall. The thicker secondary cell wall gives the fiber strength and encloses the lumen. Each layer is composed of cellulose microfibrils that run parallel to each other and make an angle with the direction of the fiber. This angle is minimum in the secondary cell wall (Charlet et al., 2007). As shown in Figure 2.2, the majority of the fiber is essentially constituted by the layer S2 of the secondary cell wall (dominating the cross-section). As shown in Figure 2.3, this thickest cell wall (S2) is made up of numerous crystalline cellulose microfibrils and amorphous hemicellulose which are oriented at 10° with the fiber axis and gives fiber its high tensile strength (Baley, 2002; Wang et al., 2001).

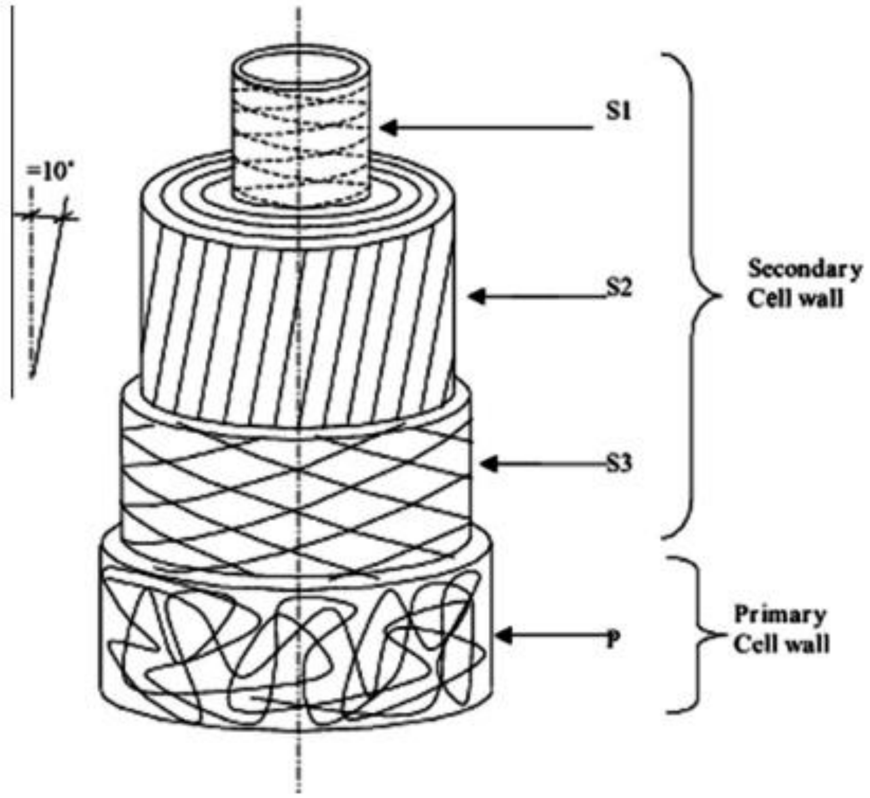

Figure 2.3 The micro-structure of a flax fiber cell (reproduced with permission from (Baley, 2002)

At the nanoscale, a microfibril is made up of cellulose chains (crystalline zones) that are embedded in an amorphous matrix primarily composed of pectins and hemicelluloses (Charlet et al., 2007). The cellulose crystallites in the secondary cell wall are deposited in oriented, highly crystalline microfibrils that are held together by an amorphous hemicellulose/pectin matrix (Baley, 2002). These microfibrils made up around 70% of the weight of flax fiber and are likely to serve as reinforcing material within the fiber (Baley, 2002). The angle produce by the axis and the fiber fibrils could affect the strength of the fibers.

Generally, the fibers are more flexible if the micro-fibrils are spiralled around the fiber axis. Microfibril as shown in Figure 2.2 (a), comes from the stem through various process (Bos et al., 2006). It has excellent specific properties such as easy and safe to handle, and widely available, which makes it a very popular material for fiber-reinforced polymer composites.

2.4.1(b) Chemical Composition of Flax Fiber

The chemical composition and placement of elements in the flax stem define the properties of flax fiber. The flax fiber composites reported by various authors are summarized in Table 2.3. The major constituents of flax fiber include cellulose, hemicellulose, wax, lignin, and pectin in varying proportions. The main components that determine the physical properties of the fibers are cellulose, hemicellulose, and lignin. Cellulose is the stiffest and strongest organic constituent in the fiber. But cellulose is a semicrystalline polysaccharide with a high amount of hydroxyl group, which giving natural fiber a hydrophilic character when they are used to strengthen hydrophobic matrices, as a result, the contact is poor and the resistance to moisture absorption is low (Bledzki et al., 2008).

Table 2.3 Chemical composition of flax fiber by different authors

References	Cellulose (%)	Hemi-cellulose (%)	Pectin (%)	Lignin (%)	Wax (%)	Moisture Content (wt.%)
Troger et al. (1998)	65	-	-	2.5	-	-
Lilholt et al. (1999)	67	11	-	2.0	-	-
Khalil et al. (2000)	73.8	13.7	-	2.9	-	7.9
Ditterber and Hota (2012)	62 - 72	18.6 – 20.6	2.3	2 – 5	1.5 – 1.7	8 - 12
Cristaldi et al. (2010)	71 - 75	18.6 – 20.6	2.2	2.2	1.7	10.0
Bastra (1998)	64.1	16.7	1.8	2.0	1.5	10.0

In composite materials, natural fibers adhere poorly to hydrophobic matrices, often to the point that the composite is mechanically inferior to either the natural fibers or the matrix alone. In order to improve the mechanical properties of the composite, the fiber or matrix must be altered. Hemicellulose is more likely tightly bound to cellulose fibrils by hydrogen bonds. Hemicellulosic polymers have a molecular weight that is much lower than that cellulose and they are also branched and completely amorphous. Because hemicellulose has an open structure and a lot of hydroxyl and acetyl groups, it is slightly soluble in water and attracts moisture (hygroscopic behaviour). Lignin and pectin are typically used as bonding agents (Salnikov et al., 1993). Lignins are amorphous, very complex polymers of phenylpropane units that absorb the least amount of water of any natural fiber component (Bledzki et al., 2008).

The waxy substances in flax fiber influence the wettability and adhesive properties of the fiber. Table 2.3 shows that flax fiber is rich in cellulose, which accounting for over 70% of the total chemical composition. Because of this, flax fibers can be widely used as a reinforcement in composites. The proportion is highly influenced by the species and variety of the plant, agricultural factors like soil quality, weathering conditions, plant maturity, and the quality of the retting process, as well as measurement conditions that include or exclude moisture (Baley, 2002; Charlet et al., 2009). Consequently, these factors may influence the physical and mechanical properties of the flax fibers.

2.4.1(c) Physical and Mechanical Properties of Flax fiber

The tensile deformation of flax fiber is influenced by the specimens, even when these fibers are grown in the same location and tested with the same parameters (Charlet et al., 2009). Due to its fibrous nature, the primary cell wall (P zone in Figure 2) breaks in a brittle manner, whereas the secondary cell wall (S zone) develops a coarse, fibril-bridging crack. The secondary cell wall splits relatively easily along the length direction, indicating that the lateral strength of the fiber is lower than its tensile strength, which explains the lower compressive strength of the fiber relative to its tensile strength, i.e., the measured tensile strength of elementary flax fibers was found ranged from 1500 to 1800 MPa and the measured compressive strength was around 1200 MPa (Bos et al., 2002). Since flax fibers are highly hydrophilic, their tensile moduli are strongly dependent on the relative humidity (RH) of their surroundings (Davies and Bruce, 1998). There are various factors that affecting physical and mechanical properties during production of natural fiber such as plant growth, harvesting stage, fiber extraction stage, supply stage, etc. Table 2.4 shows the factors that affecting the natural fiber during production.

Table 2.4 Various factors affecting natural fiber during the production (Dittenber and Ganga Rao, 2012)

Fiber Category	Characteristic
Plant growth	Species of plant
	Crop cultivation
	Crop location
	Fiber location in plant
	Local climate
Harvesting stage	Fiber ripeness, which affects:
	Cell wall thickness
	Coarseness of fibers
	Adherence between fibers and surrounding structure
Fiber extraction stage	Decortications process
	Type of retting method
Supply stage	Transportation conditions
	Storage conditions
	Age of fiber

2.4.2 Glass Fiber

Glass fiber (GF) is one of the most commonly used advanced fibers in the composites industry. GF are the most widely used to reinforced plastics due to their low cost compared to aramid and carbon and have good mechanical properties like high tensile strength, high chemical resistance, and good insulating properties. Various forms of glass fiber, such as long longitudinal, woven mat, chopped strand fiber, and chopped strand mat, were added into the polymer matrix to improve the mechanical and tribological properties of polymer composites.

In this study, E-glass fiber is used due to its chemical composition that provides excellent electrical insulator. It is also used in high-end applications, such as parts for aircraft and automobiles. E-glass is used in almost every industry because it can withstand high levels of mechanical impact. The general comparison between natural fibers and glass fibers are shown in Table 2.5.

Table 2.5 Typical differences between glass and natural fibers (George, 2008)

Material Characteristics	**Natural fibers**	**Glass fibers**
Density	Low	Twice that of natural fibers
Cost	Low	Higher
Renewable	Yes	No
Recyclable	Yes	No
Energy consumption	Low	High
Distribution	Wide	Wide
CO2 neutral	Yes	No
Abrasion to machine	No	Yes
Health risk when inhaled	No	Yes
Disposal	Biodegradable	Not biodegradable

2.4.2(a) Types of Glass Fiber

There are numerous types of glass fiber such as A-glass, E-glass, S-glass and etc. Glass fiber is classified according to the constituent raw materials used and their composition.

Different applications required different types of glass fiber, for example, E-glass is known as electrical glass, A-glass fiber is known as alkali glass which often used in the food and beverage industries, while C-glass is known as chemical which often used in the outermost lamination layer of pipes and tanks that hold chemicals, water, and other liquids. The letters above the name of a glass fiber refer to their characteristic. Table 2.6 lists the most common types of GF with their characteristic.

Table 2.6 Common glass fiber categories and characteristic (ASM Handbook, 10th Ed. 2001)

Fiber Category	**Characteristic**
A: alkali	Soda lime glass/ high alkali
AR: alkali resistance	Alkali resistance
C: chemical	High chemical resistance
D: dielectric	Low dielectric constant
E: electric	Low electrical conductivity
M: modulus	High tensile modulus
S: strength	High tensile strength
	Special Purpose
ECR	Long term acid resistance and short-term alkali resistance
R and Te	High tensile strength and properties at high temperatures

2.4.2(b) Chemical Composition of Glass Fiber

The GF contains different chemical compositions for different purposes. Table 2.7 displayed the chemical composition of different types of glass fibers.

Table 2.7 Chemical compositions of different types of glass fibers (Sathishkumar et al., 2014)

Type	$\mathbf{SiO_2}$	$\mathbf{Al_2O_3}$	$\mathbf{TiO_2}$	$\mathbf{B_2O_3}$	**CaO**	**MgO**	$\mathbf{Na_2O}$	$\mathbf{K_2O}$
A-glass	67.5	3.5	-	1.5	6.5	4.5	13.5	3.0
C-glass	64.6	4.1	-	5.0	13.4	3.3	9.6	0.5
D-glass	74.0	-	-	22.5	-	-	1.5	2.0
E-glass	**55.0**	**14.0**	**0.2**	**7.0**	**22.0**	**1.0**	**0.5**	**0.3**
S-glass	65.0	25.0	-	-	-	10.0	-	-
R-glass	60.0	24.0	-	-	9.0	6.0	0.5	0.1

2.4.2(c) Properties of Glass Fiber

GF possesses exceptional material properties, which are dependent on its composition, structure, and type. Each type of GF has different properties. GF is utilized in polymer composites due to its high strength and an outstanding chemical resistance. In addition, GF is lightweight, resistant to corrosion, and has stable performance. Due to its low price, chemical resistance, non-flammable and high production rate, commercial E-glass is widely used in applications. The properties of glass fiber are summarized in Table 2.8.

Table 2.8 Properties of glass fibers (Mazharul, 2012)

Fiber Type	**Density (g/cm^3)**	**Tensile Strength (Mpa)**	**Modulus (Gpa)**	**Elongation (%)**
A-glass	2.44	3300	72	4.8
C-glass	2.56	3300	69	4.8
D-glass	2.11	2500	55	4.5
E-glass	**2.54**	**3400**	**72**	**4.7**
ECR-glass	2.72	3400	80	4.3
R-glass	2.53	4400	86	5.1
S-glass	2.53	4600	89	5.2
S-2 glass	2.53	4600	89	5.2

2.4.3 Epoxy Resin

Epoxy resins have been used since 1927 and the first synthesis of resins occurred in 1936 to the point where it would become commercially applicable. Nowadays researchers are focusing more on thermosets than on thermoplastics. This is because thermoset polymers have superior mechanical properties, chemical resistance, thermal stability, and overall durability compared to thermoplastics. In addition, thermosets offer greater structural fiber shape flexibility and can be processed at room temperature or within the safe temperature range for natural fibers. The most common thermoset is epoxy, e.g., studies in (Yan et al., 2012; Charlet et al., 2007; Oksman et al., 2003; Van de Weyenberg et al., 2006; Liu and Hughes, 2008; Assarar et al., 2011; Liang et al., 2012). In another study, Malik et al. (2021) discovered that epoxy had superior mechanical and compatibility properties when compared to other thermoset matrices. Epoxy resins offer excellent mechanical performance (in terms of tensile strength and modulus, and compressive strength) and are resistant to solvent degradation in the environment. Also, various studies that has been conducted evaluation on natural fiber as a reinforcement in the thermoset resin, shows that the mechanical properties of NFRCs are improved.

Alpha-epoxy or 1,2-epoxy is the most basic type of epoxy that has a three-member ring structure. Epoxy resins are made up of long chains of molecules that have reactive sites on both ends. These reactive sites are formed by epoxy groups in the epoxy resin system. The epoxy molecule also has two ring groups in the centre that can absorb mechanical and thermal stresses, giving the epoxy resin excellent stiffness, toughness, and resistant to heat. The typical chemical structure of an epoxy is depicted in Figure 2.4, whereas Table 2.9, lists the advantages and disadvantages of epoxy.

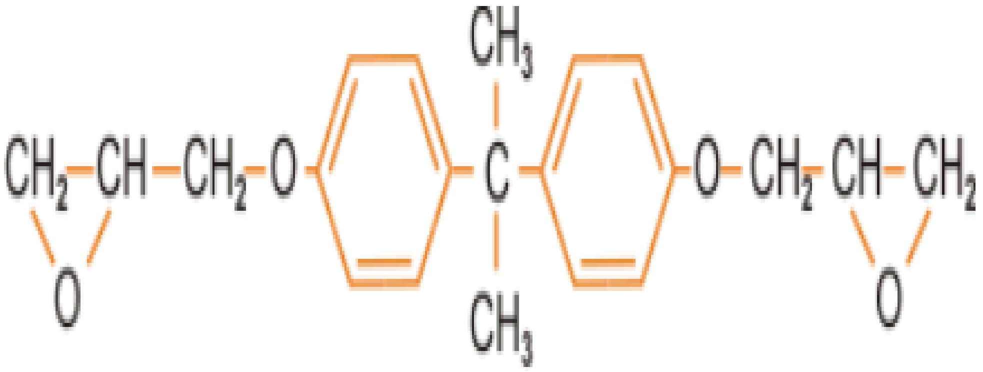

Figure 2.4 Idealized chemical structure of a typical epoxy (Liu et al., 2006)

According to Mohanty et al. (2005), the following characteristics are required for a resin system used in the fabrication of natural fiber composites:

a) Resin should provide good impregnation to allow all fibers work as a single composite structure, thus producing higher load capabilities. The matrix should have adequately low viscosity to ensure good impregnation of the reinforcing fibers.

b) The moisture content of resin should be controlled where post processing of natural fibers already contains a significant amount of water.

c) The fabrication stage should be based on the allowable processing temperature for typical natural fibers.

d) The resin system should not damage the natural fibers and provides good adhesion to their surfaces.

Table 2.9 Advantages and disadvantages of epoxy (Johannes, 2018)

Advantages	**Disadvantages**
Higher durability, low porosity and strong bond strength. Epoxy resins are easily and quickly cured at any temperature from 5°C to 150°C, depending on the choice of curing agent. Special epoxy formulations increased chemical resistance, increased temperature resistance, the ability to be applied underwater, and enhance resistance to yellowing and UV damage. Underwater epoxies generally have excellent adhesion to most submerged surfaces. Low viscosity and easily processed systems. High electrical insulation.	Expensive and more costly than polyester and vinyl ester. Hazardous can cause eyes, nose, skin and throat irritations. Critical in mixing ratio where wrong mixing will affect the final properties after cure and effect the matrix pot life.

2.5 Fundamental of Hybrid System

Hybrid composites is generally a mixture of two or more different reinforcing fiber to improve strength, flexibility, and durability. Hence, hybrid composites may utilize in different designed based on the number of layers, different forms, and orientation of fiber reinforcement, as shown in Figure 2.5.

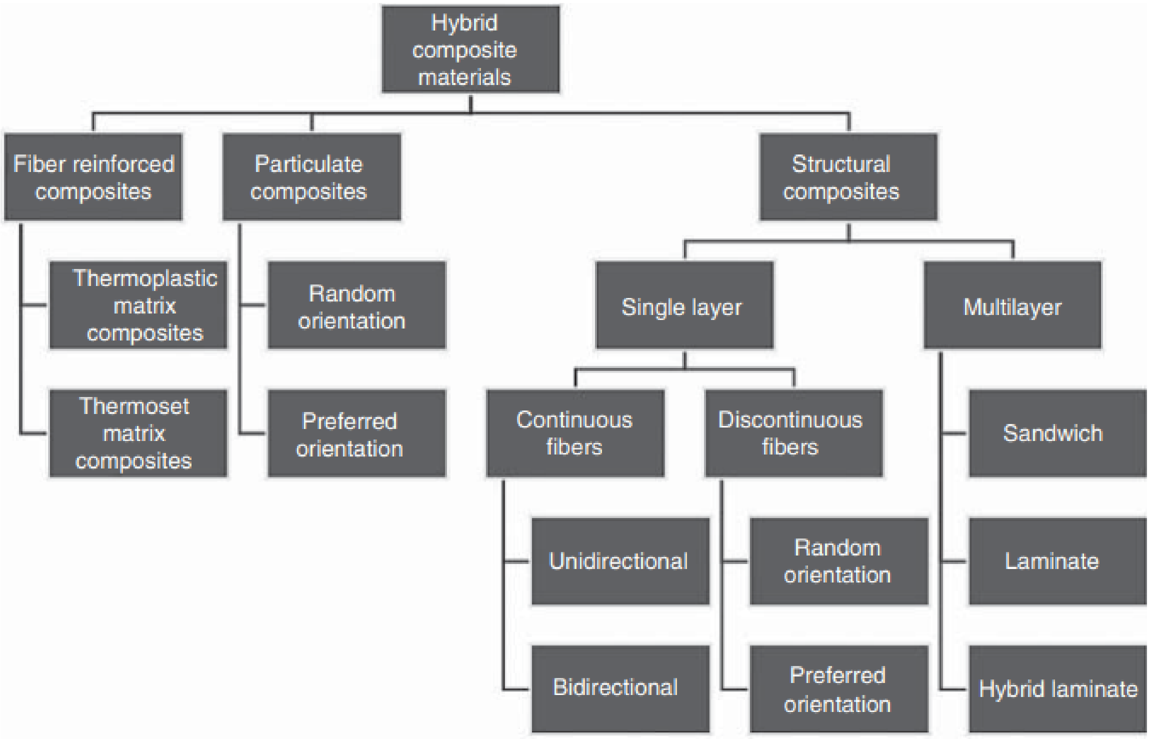

Figure 2.5 Types of hybrid composites (Loganathan et al., 2019)

The hybrid concept aims to reduce the cost of the structure while maintaining its high strength and acceptable characteristics, as would be achieved by using a less costly material. The primary factors influencing the mechanical properties of hybrid composites are fiber properties of the materials, fiber volume fraction, stacking sequence, fiber treatment, fiber orientations and thickness (Soung, 2017)

2.6 The Effect of Stacking Sequence on Mechanical Properties of Composites

The influence of the stacking sequence on the mechanical properties of composites is investigated in the literature. Sabeel et al. (2008) found that stacking sequences significantly affected the flexural properties of the studied composites. Similar results were obtained with other hybrid composites made of glass fibers and natural fibers such as flax, sisal, kenaf, and bamboo (Zhang et al., 2013; Atiqah et al., 2014; Nayak et al., 2009) or with carbon fibers and flax fibers (Fehri et al., 2017). Amico et al. (2010) investigated the mechanical properties of pure sisal, pure glass, and a hybrid sisal/glass composite using various stacking sequences of fiber mat layers. The significance of controlling the stacking sequence in order to improve properties was made clear.

Stacking sequence and fiber volume fraction are the important parameters that affect the mechanical properties of hybrid composites. The tensile properties of hybrid composites are less affected by the fiber stacking sequence. However, other properties, such as flexural, have a sound effect (Selver et al., 2018). The best flexural properties could be achieved by the amalgamation of the synthetic fiber layer as a skin in the hybrid composites (Fiore et al., 2012). Abd El-baky et al. (2020) studied the mechanical properties of ternary hybrid composites. They discovered that the stacking sequence had a significant effect on the tensile and flexural properties of the composites. The stacking sequence in hybrid composites also has an impact on performance. Sarasini et al. (2016) investigated the relationship between stacking sequence and impact performance of flax/carbon reinforced epoxy hybrid composite using two unique configurations. The first arrangement employed flax fiber as a skin layer and carbon as an inner layer (FCF), whereas the second employed the inverse (CFC). It was concluded that the FCF hybrid composite showed better impact damage tolerance compared to the CFC hybrid composite because the skin or outer layer of the flax fibers deter crack formation in the hybrid