SCHOOL OF MATERIALS AND MINERAL RESOURCES ENGINEERING

UNIVERSITI SAINS MALAYSIA

EFFECT OF KENAF TO GLASS FIBER RATIO ON THE PROPERTIES OF HYBRID PULTRUDED COMPOSITE

By

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Dissertation submitted in partially fulfilment
of the requirements for degree of Bachelor of Engineering with Honours
(Materials Engineering)

Universiti Sains Malaysia

JUNE 2017

DECLARATION

I hereby declare that I have conducted, completed the research work and written the dissertation entitled "**Effect of Kenaf to Glass Fiber Ratio on The Properties of Hybrid Pultruded Composite**". I also declare that it has not been previously submitted for the award of any degree or diploma or other similar title of this for any other examining body or university.

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ACKNOWLEDGEMENTS

I am feeling grateful for being able to complete this study and have written the dissertation entitled “Effect of Kenaf to Glass Fiber Ratio on The Properties of Hybrid Pultruded Composite ".

First of all, I would like to express my gratitude towards my supervisor, Prof. Hazizan Mohd Akil who has given me useful guidance, encouragement and assistance throughout this study. I would also like to thank Mr Hafiz Zamri and Mr Zaman for helping me patiently during the course of the project. Not forgetting all the lecturers, technicians and staffs who have directly or indirectly involved in this project.

To my parents, Mr. and Mrs. Loh, I can never repay their endless love and support. I am deeply indebted to them and I truly wish that I have made them proud. They kept me going whenever I feel difficult and strangled.

This project couldn't have come to a success without the support and help from all of you. For that I sincerely thank you for your contribution and apologise if I have caused any inconvenience during the process of this project. I have spent wonderful time with all of you.

Loh Wai Cheong

1/6/2017

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LIST OF ABBREVIATIONS

FRP	Fiber reinforced polymer
GFRP	Glass fiber reinforced polymer
PKGRC	Pultruded kenaf glass reinforced composite
PKRC	Pultruded kenaf reinforced composite
PGRC	Pultruded glass reinforced composite
NFRP	Natural Fiber Reinforced Polymer
PEEK	Polyether ether ketone
SiO_2	Silicon dioxide
Al_2O_3	Aluminium oxide
TiO_2	Titanium dioxide
B_2O_3	Boron trioxide
CaO	Calcium oxide
MgO	Magnesium oxide
Na_2O	Sodium oxide
K_2O	Potassium oxide
Fe_2O_3	Iron(III) oxide
C	Carbon
H	Hydrogen
O_2	Oxygen

C_6H_{100} Cellulose

CO_2 Carbon dioxide

PMC Polymer matrix composite

PLLA Polylactic acid

ASTM American Society for Testing and Materials

PJGRC Pultruded jute glass reinforced composite

CTE Thermal expansion coefficient

TGA Thermogravimetric analysis

OH Hydroxyl

D Diffusion coefficient

M_m Maximum moisture absorption

P Permeability coefficient

W_t Final weight

W_o Initial weight

∞ Radius

M_α Moisture at saturated level

LIST OF SYMBOLS

µm	Micrometer
≥	Equal or greater than
°C	Degree celcius
MPa	Megapascal
GPA	Gigapascal
g/cm^3	Gram per centimetre cube
%	Percent
º	Degree
<	Less than
cm	Centimeter
ton	Tonnes
MJ	Megajoule
kg	Kilogram
nm	Nanometer
h	Hour
J/m	Joule/meter
Vol %	Volume percent
mm	Millimeter
β	Beta

θ Delta

X Times

√ Square root

R^2 Coefficient of determination

KESAN NISBAH GENTIAN KENAF DAN KACA KEPADA SIFAT HIBRID KOMPOSIT

ABSTRAK

Matlamat projek penyelidikan ini adalah untuk menyiasat dan menentukan kesan nisbah gentian kenaf kepada gentian kaca terhadap sifat hibrid kenaf/kaca komposit. Sebelum menghasilkan sampel, ujian tegangan telah dijalankan dengan mesin tegangan mini, matlamat ujian ini adalah untuk mendapatkan bacaan diameter dan kekuatan tegangan gentian tunggal. Gentian berterusan kaca dan kenaf diperkuatkan poliester untuk menghasilkan sampel berbentuk rod dengan bacaan diameter sepanjang 12 mm. Sampel yang dihasilkan ialah hibrid komposit dengan jumlah peratus gentian sebanyak 33, 47, 51 dan 62% dan sampel ini dibandingkan dengan sampel PKRC komersial. Ujian mampatan dan ujian lenturan telah dijalankan untuk menentukan nisbah gentian kenaf/kaca yang terbaik dari segi kekuatan mekanikal. Selain itu, kajian sifat penyerapan air telah dijalankan pada semua sampel untuk mengkaji kesan penuaan kepada kekuatan mampatan sampel. Di samping itu, kajian TGA telah dijalankan untuk menyiasat kesan penambahan gentian kaca kepada kestabilan haba, keputusan TGA menunjukkan penambahan gentian kaca telah berjaya meningkatkan suhu degradasi sampel hibrid kaca/kenaf komposit. Dari hasil kajian mampatan dan lenturan, hibrid sampel dengan jumlah gentian 47% memiliki kekuatan yang paling tinggi sebelum dan selepas penuaan sampel. Tambahan pula, hasil kajian penyerapan air menunjukkan peratus berat tambahan sampel boleh dikait rapat dengan jumlah gentian penguat dan susunan gentian kaca di sekeliling gentian kenaf.

EFFECT OF KENAF TO GLASS FIBER RATIO ON THE PROPERTIES OF HYBRID PULTRUDED COMPOSITE

ABSTRACT

The objective of this project was to investigate and determine the effect of kenaf to glass fiber ratio on the properties of hybrid pultruded composite. Before the production of samples, glass fibers and kenaf fibers were tested with miniature tensile machine to verify its diameter and single fiber tensile strength. The continuous glass and kenaf fiber rovings were used to reinforced with unsaturated polyester resin to produce rod shape samples with 12 mm diameter. The samples produced were hybrid PKGRC samples with 33, 47, 51 and 62 vol% and compared with a commercial PKRC sample. Compression and flexural test was used to determine the best combination of kenaf fiber and glass fiber yarn that will give the highest mechanical strength. Besides, a water absorption test was done to study the effect of aging on the compressive strength of each samples. Moreover, TGA was carried out to study the thermal stability of hybrid composite after glass fibers were added, a positive result has been obtained as the degradation temperature had been increase for the PKGRC sample. From the compression and flexural test, PKGRC sample with 47 vol% acquired the highest compression and flexural strength before and after aging. In addition, the result of water absorption test shows that the weight gain is closely related to the fibers reinforcement volume percent and arrangement of glass fibers to the kenaf fibers.

CHAPTER 1

INTRODUCTION

1.1 Environmental Awareness

In order to preserve our environment, it is vital to develop materials that can degrade or are recyclable for some industries so that the materials will not remain for a long time. This consists a variety of materials including composite. Fiber reinforced composite based on natural materials, which are mainly made from plant sources, show promise in providing this, and may turn out to be one of the material revolutions of this century.

1.2 Composites

Composites are versatile materials containing of two or more chemically distinct constituents, on a macro-scale, having a different interface separating them. For a hybrid composite to form, it need more than two discontinuous phases embedded in a continuous phase. The discontinuous phase is usually harder and stronger than the continuous phase and it is called the hybrid reinforcement and the continuous phase is named the matrix. The matrix material can be divided into metallic, polymeric and ceramic. Recently, the polymer matrix composites have been widely used for many applications like vehicle parts, airplane interior parts, household appliances and construction materials(Sathishkumar et al., 2014a).

Generally, fiber are the major stress-carrying members, while the matrix around supports them in the desired location and orientation, acts as a stress transfer medium between them, and prevent them from being damage by environmental effect for example elevated temperatures and humidity (Surendra et al., 2015).

Fiber is made up of several hundred to thousands of filaments, each of them having a diameter in between 5 to 15μm (Harris, 1986), this allow them to be processed on textile machine, for example in the case of glass fiber, two semi finish fiber products are obtained as shown in Figure 1.1. These fibers can be purchased many forms, firstly is in the form of short fibers with lengths of the order of a fraction of a millimeter to a few centimeters, these are felts, mats, and short fibers used in injection molding. Another type is long fibers, usually cut during the time of fabrication of the composite material and used in the form of long fiber or woven.

The fibers have to be as thin as possible because their rupture strength decrease as their diameter increase. Besides, a very small fiber diameters make it possible to bend fibers until they reach radii of curvature on the order of half a millimeter. However, an exception is made for boron fibers (diameter in the order of 100 μm), which are formed around a tungsten filament (diameter = 12 μm). Their minimum radius of curvature is 4mm. Then, except for particular cases, weaving is not possible.

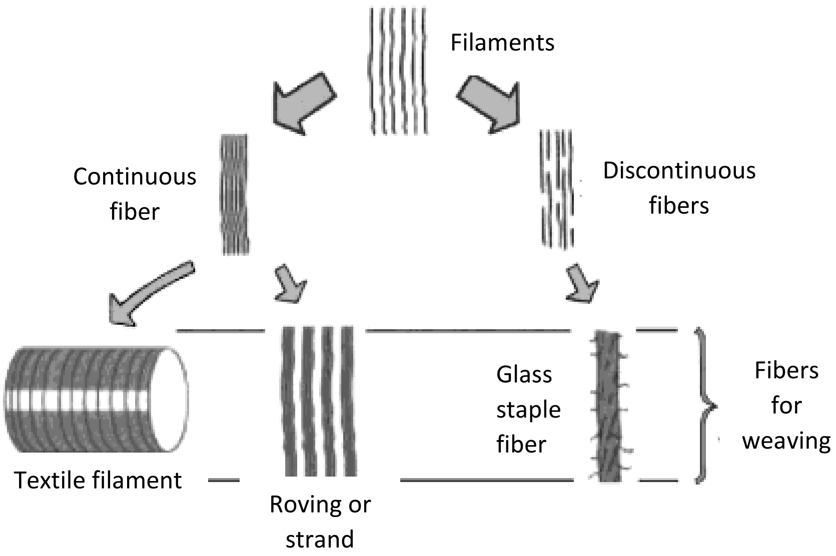

Figure 1.1: Two semi finish fiber product (Harris, 1986)

The principal fiber materials include glass, aramid or kevlar that have very light weight, carbon (high modulus or high strength), boron (high modulus or high strength), silicon carbide (high temperature resistance), high-density polyethylene, natural fiber (flax, hemp, sisal, kenaf, etc), the use of which is growing in forming fiber reinforcement, the integration of fibers to make fiber forms for the fabrication of composite material can take into three forms, first form is unidimensional for example unidirectional tows, yarns, or tapes. Another form is two dimensional, which is woven or nonwoven fabrics (felts or mats), while the last form is tridimensional, this include fabrics, sometimes called multidimensional fabrics with fibers oriented in several directions. (≥3)

Before the formation of the reinforcement, the fibers surface is treated or sizing to decreasing the friction of fibers when passing through the weaving machines and give better fiber-matrix adhesion.

The two common type of reinforcement is usually fiber or a particulate. Particulate composites have dimensions that are about equal in all directions. They may be spherical, platelets, or any other regular or irregular shape. Particulate composites tend to be much weaker and less stiff than continuous fiber composites, but their price is usually cheaper. Particulate reinforced composites usually contain less reinforcement (up to 40 to 50 vol%) due to processing limitation and brittleness (Soedel, 2004).

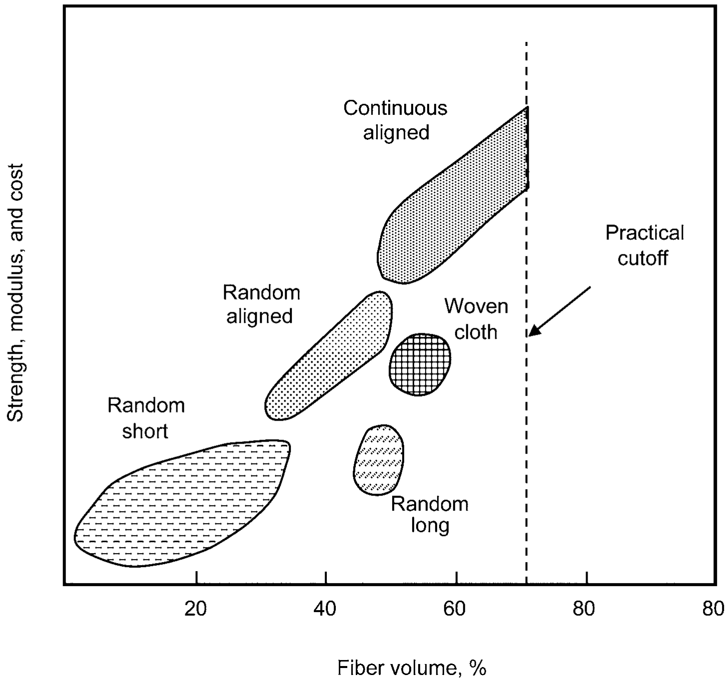

Figure 1.2: Influence of reinforcement type and quantity on composite performance (Hosseinzadeh et al., 2006)

Abundance of polymeric materials are used as matrix materials in fabrication of composites, this include thermoplastic resin, for instance polypropylene(PP), polyphenylene sulfone(PPS), polyamide(PA), polyether ether ketone (PEEK), etc. Another type of polymer resin used is thermoset resins, these include polyesters, phenolics, melamines, silicones, polyurethanes and epoxies.

The development of thermoplastic natural fiber composites is limited by two primary physical constraints: the maximum temperature at which the fiber can be processed and the huge difference between the surface energy of the wood and the polymer matrix. Processing temperature is a major limiting factor for the use of natural fiber in composites (Holbery and Houston, 2006). The perceived upper limit before fiber started to degrade occurs is on the order of 150°C for long processing durations, although fibers may withstand short-term exposures to 220°C. As a result of prolonged high-temperature exposure, the composite may experience discoloration, volatile release, poor interfacial adhesion, or embrittlement of the cellulose components (Holbery and Houston, 2006), therefore the use of thermoset resin is preferable in this study.

Unsaturated polyester resins are the most widely used thermoset resins in the world. More than 2 million tons of unsaturated polyester resins are utilized in the whole world for the manufacture of a wide range of products, including kitchenware, pipes, tanks, gratings and high performance components for the marine and automotive industry (Dholakiya, 2012).

Recently, there has been a growing interest on greener processes and technologies. This is where unsaturated polyesters have the most advantage compare to metal. Production of metals required natural resources and use the most of our fossil fuels as the process require high temperature. Unsaturated polyesters in the past is produced from fossil fuels but now can be manufactured from biological resources, for instance starches, plant oils and other naturally derived building blocks have been discovered that can be used to prepare unsaturated polyester resins. Collectively there is an ever increasing potential for unsaturated polyester resins. Their low cost, ease of use and weight advantages make them among the top candidates for a wide variety of structural and decorative applications.

1.2 Type of FRP

1.2.1 Glass Fiber Reinforced Composite

Glass Fiber Reinforced Polymer (GFRP) is a fiber reinforced polymer consist of a plastic matrix reinforced by thin fibers of glass. Fiber glass is a lightweight, strong, and versatile material used in different industries due to their excellent properties. Although physical strength properties are lower than carbon fiber and it is less stiff, the material is typically far less brittle, its bulk strength and weight properties are very attractive as compared to metals, and it can be easily formed using molding processes (Ashik and Sharma, 2015, Surendra et al., 2015).

By using glass fibers as reinforcement phase in epoxy resins, GFRP pultruded profiles have great market in the construction industry, presenting some advantages compare to traditional materials, one of the significant improvement is the durability under aggressive environments. The evidence of improved durability performance when submitted to aggressive environments, can be perceived by the history of their use in marine vessels, piping, storage tanks and in the above mentioned corrosive industries (Correia et al., 2005).

1.2.2 Natural Fiber Reinforced Composite

Natural Fiber Reinforced Polymer (NFRP) are derived from plants and animals in the form of woven, knitted, or braided to make textiles. In the past, they are also used for the reinforcement of matrix such as cob for building, cotton/phenolic, hemp/phenolic for technical parts.

In recent years, because of the growing concern on the environmental impacts, the development of composite reinforced with natural fibers is rapidly emerging. The vegetable fibers take the form of bundles of tens of elementary fibers (20-50) bonded with sticky substances. The degumming of these bundles is needed to release basic fibers. These fibers are largely cellulose fibrils. The fibrils follow helical curves around the axis of the fiber, with a helix angle of a few degrees called the microfrillar angle. The cellulose has an almost crystalline structure. Its longitudinal modulus of elasticity is 135,000 MPa, compared with that of the 'R' glass (86,000MPa) (Gay,D, 2014). Thus, it appears to be reasonable to obtain mechanical performance comparable to these of glass.

There are various of advantages offered by natural fibers, these include biodegradable, neutral with respect to emission of carbon dioxide, low energy cost, lightweight, and many of them have interesting values of specific modulus combined with excellent damping and shock-resistant properties. Some of the natural fibers, such as banana and kenaf are native plants. This ensures the supply and offers a significant and valuable perspective for agricultural industry.

Natural fibers will take a major lead in the growing "green" economy based on energy efficiency, the use of renewable materials in polymer products, industrial processes that reduce carbon emissions and recyclable materials that minimize waste. Natural fibers are a kind of renewable resources, which can be degraded by nature and human ingenuity for thousands of years (Ashik and Sharma, 2015). Recent studies have investigated the development of biodegradable composite materials using natural fibers such as flax, bamboo, sisal, and kenaf, as reinforcement for biodegradable polymer composites (Osman et al., 2013).

1.3 A Typical Example of Interest

In the airlines service sector, the concerns of manufacturers and the main characteristic properties of the composite material parts could be place parallel. The concerns of the manufacturers are performance and cost saving. The characteristics of composite components include the weight reduction which can reduce the fuel usage, increase in payload, or increase in range that improves performances. Besides, composites have good fatigue resistance leads to prolonged tool life, which involve saving in the long-term cost of the product. Another characteristic is the good corrosion resistance which means fewer requirements for inspection, result in saving on maintenance cost.

Furthermore, taking into consideration the cost of the composites solution as compared with the conventional solution, one can state that composites meet the requirement of airline manufacturers. Table 1.1 has stated some other example that using composite to replace the conventional materials.

Table 1.1: Example of significant cases (Zhu et al., 2004)

Application	Previous Construction	Composite Construction
65m^3 reservoir for chemicals	Stainless steel + installation: Price = 1	Price = 0.53
Nitric acid vapor washer	Stainless steel: Price = 1	Price = 0.51
Helicopter stabilizer	Light alloy + steel: Mass = 16kg Price = 1	Carbon/epoxy: Mass = 9kg; Price = 0.45
Drum for drawing plotter	Drawing speed = 15-30cm/s	Kevlar/epoxy, 40-80cm/s
Head of welding robot	Aluminum mass = 6kg	Carbon/epoxy: Mass=3kg
Projectile for loom	Aluminum: Rate = 250 shots/min	Carbon/epoxy: Rate=350 shots/min
Aircraft floor	Mass = 1; Price = 1	Carbon/Kevlar/ epoxy: Mass = 0.8; Price = 1.7

1.4 Fabrication of FRP: Pultrusion

FRP can be fabricated by almost all production techniques, including hand lay-up, press molding, resin transfer molding, and pultrusion. Pultrusion is a continuous, automated closed-molding process that is cost effective for mass production of uniform cross section parts (Hashemi et al., 2016). Due to uniformity of cross-section, fiber distribution and alignment, resin dispersion, excellent composite structural materials can be manufactured by pultrusion.

From the schematic diagram in Figure 1.3, this process involves pulling of continuous fibers through a resin impregnation tank, blended with a catalyst and then into pre-forming fixtures where the section is partially shaped & excess resin is removed. It is then passed through a heated die, which determines the sectional geometry and finish of the final product. The profiles produced with this process are comparable with traditional metal profiles made of steel & aluminum for strength & weight.

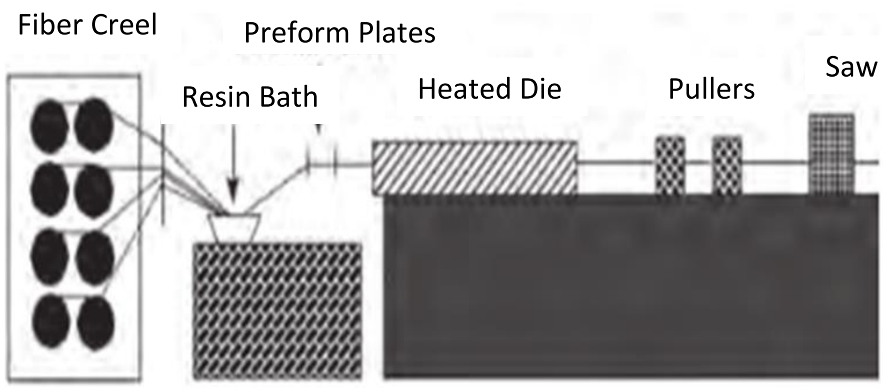

Figure 1.3: Schematic representation of pultrusion process *(*Osman et al., 2013)

1.5 Problem Statement

Based on this brief review, the application of kenaf fiber reinforced composite as an alternative composite material, especially in building and construction, is highly plausible with both lightweight and low cost as its main driving forces. However, the water absorption ability of the kenaf fiber composite is too strong and affected its properties for outdoor application.

Hence kenaf fibers were combined with the glass fibers to improve the stiffness and strength of the composites, hybridization of natural fiber, with stronger and more corrosion-resistance glass fiber can achieve a balance between environmental impact and performance.

More importantly, hybridization between kenaf fibers and glass fibers is expected to decrease their water uptake, and subsequently reduce the water absorption problem. By improving the water absorption resistance, the hybrid composites will maintain its properties, even though it is being used in humid environment. It is really important to consider the water absorption in composites, since the presence of moisture in the composite sample will reduce its mechanical properties.

This work is also trying to highlight the significance of replacing single phase reinforcement with hybrid reinforcement system that has different arrangement of fibers. The arrangement of fibers in the pultruded composite are very crucial for its properties, hence in this work, the arrangement changed whereby the fiber glass is use to surround the kenaf fiber, the objective of this approach is to shield and protect the kenaf fiber from expose to moisture, decrease the water absorption ability and improve the performance of the hybrid composites.

1.6 Research Objectives

- To fabricate pultruded hybrid kenaf/glass fiber reinforced composites (PKGRC) using pultrusion with a different volume fraction between glass and kenaf fiber.
- To characterize the properties of pultruded hybrid kenaf/glass fiber reinforced composites (PKGRC).
- To compare the properties of fabricated hybrid pultruded kenaf/glass fiber reinforced composites (PKGRC) produced with different volume fraction of reinforcement and matrix phase.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

A review presented in this chapter is aimed to provide a better understanding regarding the main materials studied in this project which is unsaturated polyester resin, kenaf fibers and glass fibers and the production method which is pultrusion Besides, this chapter will provide information about the related works done by researchers to provide a deeper understanding on our work.

2.2 Unsaturated Polyester Resin

Unsaturated polyester resins are the condensation products of unsaturated acids or anhydrides and diols with/without diacids. The unsaturation present in this type of polyesters provides a site for subsequent cross-linking (Boenig, 1964, Parkyn et al., 1967).

2.2.1 Synthesis of Unsaturated Polyester Resin

These resins are mixed with varies fillers, reinforcements and cured by using free radical initiators to yield thermoset articles having a wide range of chemical and mechanical properties based on the selection of diacids, diols, cross-linking agents, initiators and other additives (Boenig, 1966).

2.2.2 Versatility of Unsaturated Polyester Resin

Their versatility in function allows unsaturated polyester resins to be used in a wide range of composite applications. Composite parts can be fabricated at temperatures as low as 15°C to as high as 150°C depending on the processing requirement of the application.

The matrix (continuous phase) plays several important functions, including maintaining the fibers in the proper orientation and spacing and protecting them from abrasion and the environmental damages. In polymer and metal matrix composites that form a strong bond between the fiber and the matrix, the matrix transmits loads from the matrix to the fibers through shear loading at the interface (Soedel, 2004).

Unsaturated polyester resins also have excellent service temperatures. They have good freeze-thaw resistance and can be used in many low to moderate temperature machines ranging from refrigerated enclosures to hot water geysers.

In comparing the weight and cost, unsaturated polyester resins are preferable over their metallic counterparts. With the current fuel and processing costs, the increasing prices of steel and aluminum are pushing more manufactures to use unsaturated polyester resin composites instead.

2.2.3 Reduce Productivity Cost

Another prime advantage is the increased in volume of production. While metals involve the use of specific smelters, expensive tooling and processing requirements, unsaturated polyester resins are far cheaper and afford the use of low cost tooling. An unsaturated polyester resin can be mold at ambient temperature or around 150℃ whereas metals need to be heated to well over 2000°C before they are melted and poured into mold cavities. Although the perception is that metals are generally structurally superior, there has been much advancement in the development of technologies for producing higher strength composites made from unsaturated polyesters resins.

2.3 Fibers Reinforcement

2.3.1 Synthetic Glass Fiber

Glass fibers are the most popular fibers, the two common forms are continuous and discontinuous. Chemically, glass is silicon dioxide (SiO_2), there are two type of glass fibers used in structural applications: E-Glass and S-Glass. E-Glass is produces in much larger volumes vis-à-vis S-glass (Sathishkumar et al., 2014b).

The various form of GF reinforcements like long longitudinal, woven mat, chopped fiber (distinct) and chopped mat in the composites have been produced to enhance the mechanical properties of the composites. The properties of composites depend on the fibers laid or laminated in the matrix during the composites preparation. The major classification of glass fibers and the physical properties are shown on Figure 2.1. Also, the chemical compositions of glass fibers in wt% are shown in Table 2.1. The physical and mechanical properties of GF are shown in Table 2.2.

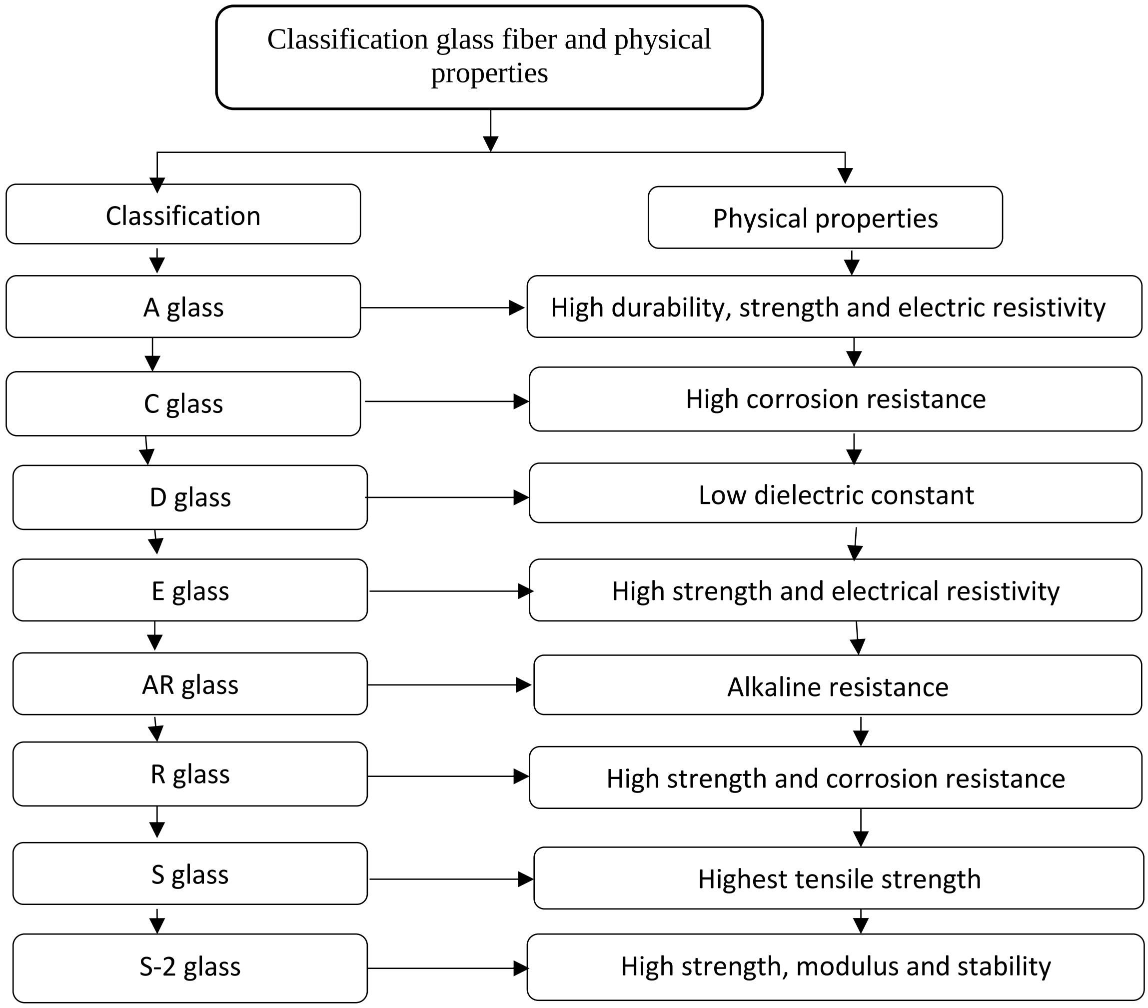

Figure 2.1: Classification and physical properties of various glass (Sathishkumar et al., 2014b)

Table 2.1: Chemical compositions of glass fibers in wt% (Sathishkumar et al., 2014b)

Type	SiO_2	Al_2O_3	TiO_2	B_2O_3	CaO	MgO	Na_2O	K_2O	Fe_2O_3
E-glass	55.0	14.0	0.2	7.0	22.0	1.0	0.5	0.3	-
C-glass	64.6	4.1	-	5.0	13.4	3.3	9.6	0.5	-
S-glass	65.0	25.0	-	-	-	10.0	-	-	-
A-glass	67.5	3.5	-	1.5	6.5	4.5	13.5	3.0	-
D-glass	74.0	-	-	22.5	-	-	1.5	2.0	-
R-glass	60.0	24.0	-	-	9.0	6.0	0.5	0.1	-
EGR-glass	61.0	13.0	-	-	22.0	3.0	-	0.5	-
Basalt	52.0	17.2	1.0	-	8.6	5.2	5.0	1.0	5.0

Table 2.2 Physical and mechanical properties of glass fiber(Sathishkumar et al., 2014b)

Fiber	Density (g/cm^3)	Tensile strength (GPa)	Young's modulus (GPa)	Elongation (%)	Coefficient of thermal expansion (10^{-7}/m)	Poison's ratio	Refractive index
E-glass	2.58	3.445	72.3	4.8	54	0.2	1.558
C-glass	2.52	3.310	68.9	4.8	63	-	1.533
S2-glass	2.46	4.890	86.9	5.7	16	0.22	1.521
A-glass	2.44	3.310	68.9	4.8	73	-	1.538
D-glass	2.11-2.14	2.415	51.7	4.6	25	-	1.465
EGR-glass	2.72	3.445	80.3	4.8	59	-	1.579
AR glass	2.70	3.241	73.1	4.4	65	-	1.562

2.3.2 Natural Fiber

Fiber crops have been appeared in this mother nature since the beginning of time. A variety of fiber crops have been developed in large scale through breeding and selection according to societies' needs and values (Aziz and Ansell, 2004). Natural fibers can be found all around the globe and other abundantly accessible agro-waste is responsible for this new polymer science and engineering research, and the search for a sustainable technology.

Natural fibers were used with the purpose of yielding lighter composites, coupled with lower costs compared to existing fiber glass reinforced polymer composites. Natural fibers have a lower density (1.2–1.6 g/cm^3) than that of glass fiber (2.4 g/cm^3), which ensures the production of lighter composites (Huda et al., 2006).

All these natural fibers are found in all life cycles of all walks of life, are shown in Figure 2.2. Many natural fibers can be used as composites, but mostly in applications that sustain a low level of stress. Some of the fibers are obtained by processing agricultural, industrial, or consumer waste (Bullions et al., 2006). These materials have already been embraced by European car manufacturer and this trend has reached North America and the Natural Fibers Composites Sector has registered a 40–50% growth during the year 2000 (Pothan et al., 2008). Natural fibers can be classify into three main categories which include vegetable, animal and mineral fibers as shown in Figure 2.3.

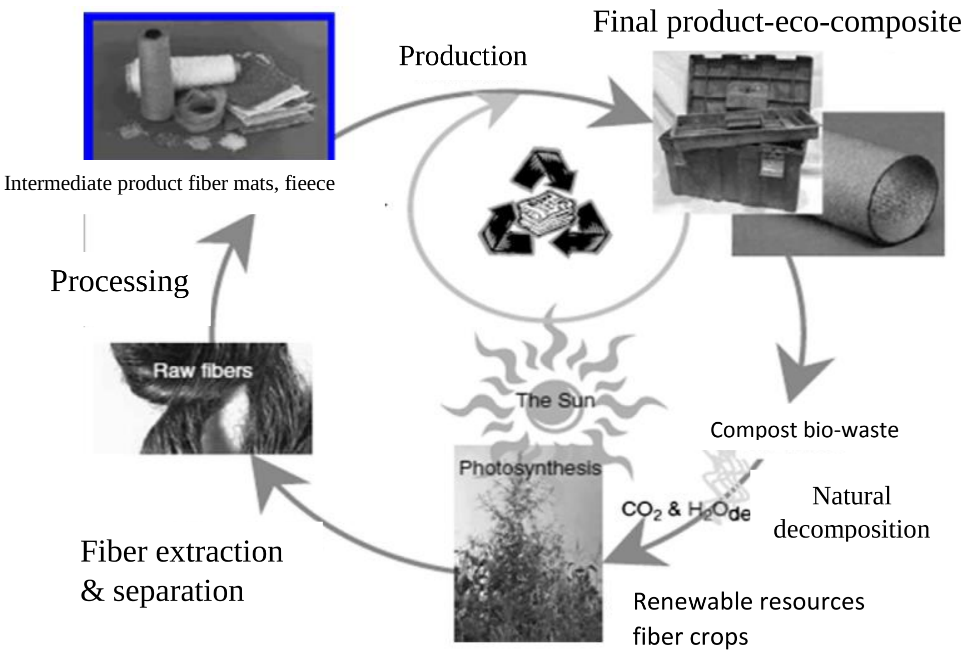

Figure 2.2: Life cycle of bio-composites (Akil et al., 2011)

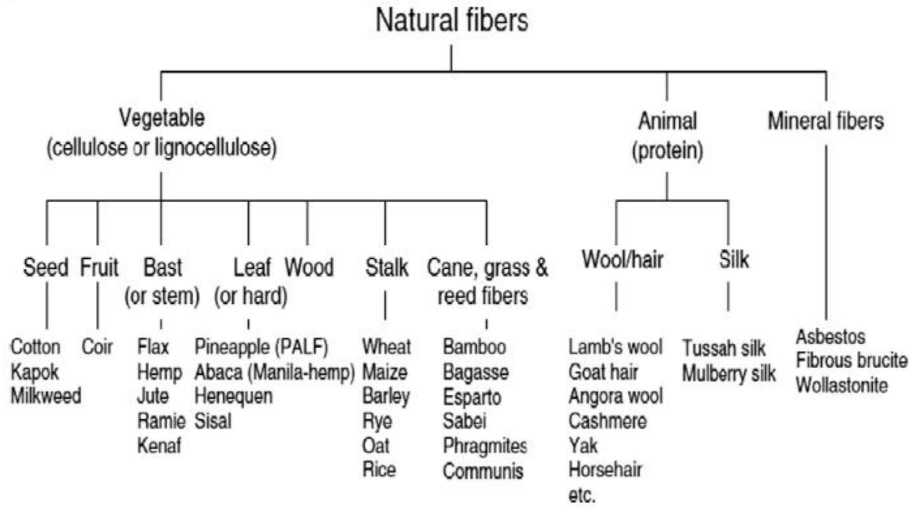

Figure 2.3: Classification of natural fibers (Akil et al., 2011)

The structure and chemical composition of plant fibers is very complicated (as illustrated in Table 2.3). Plant fibers are composite materials designed by nature. The fibers are basically consists of a rigid, crystalline cellulose microfibril reinforced amorphous lignin, and/or hemicelluloses matrix. Most plant fibers, except for cotton, are composed of cellulose, hemicelluloses, lignin, waxes, and several water-soluble compounds; where cellulose, hemicelluloses, and lignin are the primary constituents.

The main component of any plant fiber is cellulose (Chawla, 1998). Cellulose is the natural homopolymer (polysaccharides), where D-glucopyranose rings are linked to each other with b-glycosidic linkages, as shown in Figure 2.4. Cellulose is relatively high modulus, fibril component, of many naturally occurring composites, such as wood; where it is found in association with lignin. In a past study by Chawla (1998), most of plant fibers contained 65–70% cellulose, which is composed of three elements, C, H, and O_2, with a general formula of C_6H_{100}, which are crystalline.

Table 2.3: Chemical composition, moisture content and microfibrillar angle of plant fibers (Akil et al., 2011)

Fibers	Cellulose(%)	Hemicellulose(%)	Lignin(%)	Pectin(%)	Moisture content(wt%)	Waxes(%)	Micro-fibrillar angle(°)
Flax	71	18.6-20.6	2.2	2.3	8-12	1.7	5-10
Hemp	70-74	17.9-22.4	3.7-5.7	0.9	6.2-12	0.8	2-6.2
Kenaf	45-57	21.5	8-13	3-5			
Jute	61-71.5	13.6-20.4	12-13	0.2	12.5-13.7	0.5	8
Ramie	68.6-76.2	13.1-16.7	0.6-0.7	1.9	7.5-17	0.3	7.5
Nettle	86				11-17		
Sisal	66-78	10-14	10-14	10	10-22	2	10-22
Henequen	77.6	4-8	13.1				
PALF	70-82		5-12.7		11.8		14
Banana	63-64	10	5		10-12		
Abaca	56-63		12-13.1	1	5-10		
Oil palm EFB	65		19				42
Oil palm mesocarp	60		11				46
Cotton	85-90	5.7		0-1	7.85-8.5	0.6	-
Coir	32-43	0.15-0.25	40-45	3-4	8		30-49
Cereal straw	38-45	15-31	12-20	8			

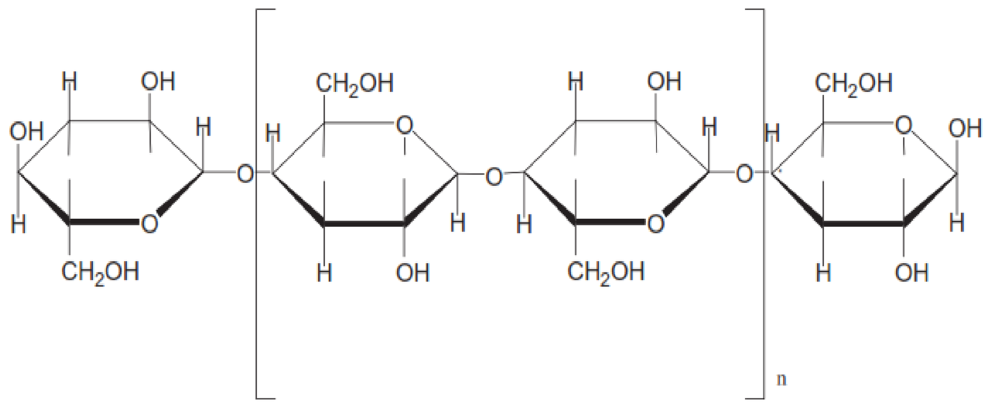

Figure 2.4: Chemical structure of cellulose (Akil et al., 2011)

Table 2.4 summarizes characteristic values for the density, diameter, and mechanical properties, of natural (plant) and synthetic fibers. Natural (plant) fibers will not provide any damage towards mixing and molding equipment(Bismarck et al., 2005), which can contribute to significant equipment maintenance cost reductions.

Table 2.4: Characteristic values for the density, diameter, and mechanical properties of natural and synthetic fibers (Fuqua et al., 2012)

Fibers	Density (g/cm^3)	Diameter (μm)	Tensile strength (MPa)	Young modulus (GPa)	Elongation at break(%)
Flax	1.5	40-600	345-1500	27.6	2.7-3.2
Hemp	1.47	25-500	690	70	1.6
Jute	1.3-1.49	25-500	393-800	13-26.5	1.16-1.5
Kenaf			930	53	1.6
Ramie	1.55		400-938	61.4-128	1.2-3.8
Nettle			650	38	1.7
Sisal	1.45	50-200	468-700	9.4-22	3-7
PALF		20-80	413-1627	34.5-82.5	1.6
Abaca			430-760		
Oil palm EFB					
Oil palm mesocarp			80	0.5	17
Cotton	1.5-1.6	12-38	287-800	5.5-12.6	7-8
Coir	1.35-1.46	100-460	131-220	4-6	15-40
E-glass	2.55	<17	3400	73	2.5
Kevlar	1.44		3000	60	2.5-3.7
Carbon	1.78	5-7	3400-4800	240-425	1.4-1.8

The use of natural fibers also safer in term of handling and working conditions compared to synthetic reinforcements, such as glass fibers. Their processing is environmental friendly, offering better working conditions and therefore, a reduction in risk of health issues for example dermal or respiratory problems. The most interesting feature of natural (plant) fibers is their positive environmental impact. Natural (plant) fibers are renewable resources, where they are biodegradable and their production requires only a low energy (Mohanty et al., 2002).

A major disadvantage of natural (plant) fibers compared to synthetic fibers is their non-uniformity, variety of dimensions, and their mechanical properties, even between individual natural fibers in the same cultivation (Bismarck et al., 2005).

An important attribute of plant fibers is their water absorption ability from the atmosphere in comparatively large quantities (Chawla, 1998), because cellulose is hygroscopic. Most polymeric fibers swell due to moisture absorption. This absorption leads to change in weights and dimensions, as well as in strengths and stiffness. Moreover, plant fiber is exposed to biological aging. Most plant fibers darken and weaken with age and exposure to light. Plant fibers are not as durable as synthetic polymeric fibers. They are all susceptible by a variety of organisms, at high humidity and temperature, leading to rot and mildew. Therefore, plant fibers are considered as renewable resources and they do not exacerbate the CO_2 emissions problem (Akil et al., 2011).

However, most plastics are hydrophobic in nature, addition of hydrophilic natural fibers to hydrophobic plastic will result in a composite with poor mechanical properties due to uneven fiber dispersion in the matrix, and an inferior fiber matrix interphase (Mehta et al., 2004). This polar nature also results in high moisture absorption in natural fiber based composites, leading to fiber swelling and voids in the fiber matrix interphase. The moisture which is not remove from natural fibers prior to compounding by drying, will result in a porous product. High moisture absorption could also cause a deterioration in mechanical properties and loss of dimensional stability (Alvarez et al., 2004, Baiardo et al., 2004). These problems are generally solved by fiber surface treatment or matrix modifications (Masirek et al., 2007).

2.4 Kenaf Fiber

2.4.1 Low Energy Source of Fiber

Kenaf is one of the natural fibers used as reinforcement in Polymer Matrix Composites (PMCs). Kenaf (Hibiscus cannabinus, L. family Malvacea) has been found to be an important source of fiber for composites, and other industrial applications (Karnani et al., 1997).

Kenaf is famous as a cellulosic source with both economic and ecological advantages; in 3 months after sowing the seeds, it can grow well under a wide range of weather conditions, to a height of more than 3 m and a base diameter of 3–5 cm (Aziz et al., 2005). The growing speed of kenaf may reach 10 cm in a day under optimum surrounding conditions. The price of kenaf was $400 per ton in 1995 and from $278 to $302 per ton in 2000 (Baillie, 2005).

From the aspect of energy consumption, it requires 15 MJ of energy to produce 1 kg of kenaf; whereas it requires 54 MJ to produce 1 kg of glass fiber (Baillie, 2005). The kenaf plant have many useful components (e.g., stalks, leaves, and seeds) and within each of these there are various usable portions (e.g., fibers and fiber strands, proteins, oils, and allelopathic chemicals) (Webber III and Bledsoe, 2002). The yield and composition of these plant components can be influenced by many factors, including cultivar, planting date, photosensitivity, length of growing season, plant populations, and plant maturity (Coates, 1996).

2.4.2 Structure of Kenaf Fiber

The schematic representation of the natural plant cell wall is shown in Figure 2.5. This structure is often named as the microfibril, microfiber, or primary/elementary fiber (Fuqua et al., 2012). The chemical content and microfibril size of the kenaf stem, is shown in Table 2.5. On average, natural fibers, including kenaf fibers, contain 60–80% cellulose, 5–20% lignin (pectin), and up to 20% moisture (Coates, 1996, Mohamed et al., 1995).

Table 2.5:Macrofibril size and chemical content of kenaf stem (Wambua et al., 2003)

	Bark	Core
Fibril length, L (mm)	2.22	0.75
Fibril width, W (µm)	17.34	19.23
L/W	128	39
Lumen diameter (µm)	7.5	32
Cell wall thickness (µm)	3.6	1.5
Cellulose (%)	69.2	32.1
Lignin (%)	2.8	25.21
Hemicellulose (%)	27.2	41
Ash content	0.8	1.8

As stated by some researchers, the overall properties of kenaf fiber depends on the individual properties of each of its components (Fuqua et al., 2012). Cellulose component provide the strength and stiffness to the fibers via hydrogen bonds and other linkages. Hemicellulose is responsible for biodegradation, moisture absorption, and thermal degradation of the fibers. While lignin (pectin) is thermally stable, but responsible for the UV degradation of the fibers (Akil et al., 2011).

The primary (outer) cell wall is mostly very thin (<1µm), but the secondary cell wall is composed of three layers. Of these, the secondary layer is the thickest and is the major contributor (at 80%) to the overall properties. The secondary layer is formed by microfibrils, which contain larger quantities of cellulose molecules. Furthermore, the microfibril is composed of alternating crystalline and amorphous regions; the crystallite size is approximately 5–30 nm in a lateral direction and between 20 and 60 nm along the