THE EFFECT OF NATURAL WEATHERING EXPOSURE AND HYGROTHERMAL AGING ON THE PROPERTIES OF PULTRUDED HYBRID GLASS/KENAF FIBRE REINFORCED UNSATURATED POLYESTER COMPOSITES

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by

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DECLARATION

I hereby declare that I have conducted, completed the research work and written the dissertation entitled "The Effect of Natural Weathering Exposure and Hygrothermal Aging on the Properties of Pultruded Hybrid Glass/Kenaf Fibre Reinforced Unsaturated Polyester Composites". I also declare that it has not been previously submitted for the award for any degree or diploma or other similar title for any other examining body or university.

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LIST OF ABBREBIATIONS

ABS	Acrylonitrile Butadiene Styrene
AS	Acidic Solution
ASTM	American Society for Testing and Materials
BMC	Bulk Molding Compound
BPO	Benzoyl Peroxide
C-Glass	Chemical-resistance Glass
$CaCO_3$	Calcium Carbonate
CF	Carbon Fibre
CF/GF	Carbon Fibre / Glass Fibre hybrid composites
CFRC	Carbon Fibre Reinforced Composites
DW	Distilled Water
E-Glass	Calcium-Alumina-Borosilicate Glass (Electric-Glass)
E-modulus	Elastic Modulus
FAO	Food and Agriculture Organization of the United Nations
FRP	Fibre Reinforced Plastics / Polymer
GF	Glass Fibre
GF/PP	Glass Fibre / Polypropylene composites
GFRC	Glass Fibre Reinforced Composites
GMT	Glass Mat Thermoplastics
HDPE	High Density Polyethylene
LDPE	Low Density Polyethylene
LPMC	Low-Pressure Molding Compound

MDPE	Medium Density Polyethylene
$NaBF_4$	Sodium Tetrafluoroborate
NaOH	Sodium Hydroxide
PA	Polyamides
PC	Polycarbonate
PE	Polyethylene
PET	Polyethylene Terephthalate
PKRC	Pultruded Kenaf Fibre Reinforced Unsaturated Polyester Composites
PGKRC	Pultruded Hybrid Glass/Kenaf Fibre Reinforced Unsaturated Polyester Composites
PGRC	Pultruded Glass Fibre Reinforced Unsaturated Polyester Composites
PLA	Poly-Lactic Acid
PLLA	Poly-L-Lactic Acid
PMCs	Polymer-Matrix Composites
PP	Polypropylene
PP/EPDM	Polypropylene/Ethylene-Propylene-Diene-Monomer
PS	Polystyrene
PVC	Polyvinylchloride
RTM	Resin Transfer Molding
SMC	Sheet Molding Compound
USDA	United States Department of Agriculture
USP	Unsaturated Polyester
UV	Ultraviolet

LIST OF SYMBOLS

>>	much more than
≈	almost equal to
%	Percentage
$	US Dollar
ºC	Degree Celsius
Π	Pi (≈ 3.14)
√	square root
µm	Micrometer
α	Alpha
A	radius of the specimen
cm	Centimeter
D	diffusion coefficient
D	Diameter
g	Gram
g/cm^3	gram per centimeter cube (density)
g/m^2	gram per meter square (weight of 1 meter square of materials)
GPa	Giga Pascal
Ha	Hectare
J	Radius
kg	Kilogram
L	Length
m	Meter

Max.	Maximum
m_f	mass of fibres
mg	Milligram
MJ	Mega Joules
M_m	maximum moisture content
mm	Millimeter
mm/min	millimeter per minute (speed rate)
MPa	Mega Pascal
M_t	moisture content
N	Newton
nm	Nanometer
ρ	Density
pH	scale to measure acidity/neutrality/alkali of a solution
RM	Ringgit Malaysia (Malaysian Ringgit)
t	time (in seconds)
tex	mass per unit length (g/1000m)
W	Weight
W_o	initial weight of dry specimen
W_t	weight of wet specimen

KESAN PENDEDAHAN CUACA SEMULAJADI DAN PENUAAN HIGROTERMAL TERHADAP SIFAT-SIFAT KOMPOSIT PULTRUSI POLIESTER TAK TEPU DIPERKUKUH GENTIAN HIBRID KACA/KENAF

ABSTRAK

Dengan menggunakan teknik pultrusi, tiga jenis komposit pultrusi pada 70% isipadu gentian telah Berjaya dihasilkan iaitu komposit pultrusi poliester tak tepu diperkukuh gentian kenaf (PKRC), komposit pultrusi tak tepu diperkukuh gentian kaca (PGRC) dan komposit pultrusi tak tepu diperkukuh gentian hibrid kaca/kenaf (PGKRC). Tujuan kajian ini adalah untuk menentukan perilaku PGKRC dibandingkan dengan PGRC dan PKRC selepas 200 hari didedahkan kepada cuaca semulajadi dan enam minggu penuaan higrotermal dalam air suling pada suhu 65ºC. Dalam kajian pendedahan cuaca semulajadi, PGRC mencatatkan serapan kelembapan paling rendah dan PKRC mencatatkan serapan tertinggi. PGKRC berada pada kedudukan di antara PKRC dan PGRC tetapi lebih hampir kepada PGRC berbanding kepada PKRC. Corak yang sama dapat diperhatikan bagi kajian penuaan higrotermal. Ujian lenturan dan mampatan yang dijalankan terhadap ketiga-tiga jenis komposit menunjukkan penurunan sifat-sifat mekanikal selepas pendedahan berpanjangan. Serapan lembapan dipercayai menjadi faktor utama yang melemahkan ikatan antaramuka gentian dan matriks dan membawa kepada penurunan sifat-sifat mekanikal berbeza bagi setiap jenis komposit pultrusi oleh kerana sifat-sifat semulajadi gentian digunakan dan susunan gentian di dalam komposit hybrid pultrusi. Kesan-kesan corak lapisan di dalam PGKRC juga telah dikaji dan kesimpulan dibuat berdasarkan keputusan sifat-sifat mekanikalnya.

THE EFFECT OF NATURAL WEATHERING EXPOSURE AND HYGROTHERMAL AGING ON THE PROPERTIES OF PULTRUDED HYBRID GLASS/KENAF FIBRE REINFORCED UNSATURATED POLYESTER COMPOSITES

ABSTRACT

By using pultrusion technique, three types of pultruded composites at 70 V/V% fibre loading have been produced which are pultruded kenaf fibre reinforced unsaturated polyester composites (PKRC), pultruded glass fibre reinforced unsaturated polyester composites (PGRC) and pultruded glass/kenaf fibre hybrid reinforced unsaturated polyester composites (PGKRC). The objective of this study is to determine the behavior of PGKRC as compared to PKRC and PGRC after being subjected to natural weathering exposure of 200 days and six weeks of hygrothermal aging in distilled water at 65ºC. In natural weathering exposure study, PGRC specimens recorded the least absorbed moisture while PKRC specimens showed the highest. PGKRC specimens took place in between these two specimens but closer to the PGRC instead of PKRC. Similar pattern were observed in the hygrothermal aging study. Flexural and compression tests carried out on all the three types of specimen had shown a decrement in mechanical properties after a prolonged exposure. Moisture invasion is the major factor that weakened the fibre-matrix interfaces which led to mechanical properties reduction and it acts differently for different types of pultruded composites due to the nature of the constituent fibres and the arrangement of the pultruded hybrid composites. The effects of different layering pattern in PGKRC were also studied and concluded based on the resulted mechanical properties.

CHAPTER 1

INTRODUCTION

1.1 Background

For the previous few years, the commercialization of fibre reinforced polymer (FRP) composites have been a successful breakthrough in engineering applications and instantly become an optional sources in some field such as automotive and construction. The reasons that researchers have selected FRP composites are due to its lightweight and corrosion resistance compared to traditional metal-based materials (Starr, 2000b). Besides that, ease of handling and cost effective fabrication of FRP composites have made it more beneficial compared to other competitor materials (Nosbi et al., 2011a). The development of FRP composites for the past years includes new combinations of fibre-matrix, new fabrication techniques and also chemical treatments to the fibre in order to improve FRP composites performance; mechanically and physically so that FRP composites become a more reliable materials.

Composite materials are materials that are made from two or more constituent materials; preferably with significant differences in their properties, that when combined will produce a materials with new properties that differ from its original constituents properties. The constituent materials can physically be distinguished on the final structure. The advantages of FRP composites that we all have known up to this day are mainly using synthetic materials as its constituents. The latest improvement that researchers are intensely studying is the use of natural fibre to replace synthetic unidirectional fibre in FRP composites.

Natural fibres, especially kenaf, have the potential to be an alternative material to replace synthetic material in FRP composites manufacturing. The reasons for this are mainly due to their properties such as good specific stiffness and high specific strength at low density (Dhakal et al., 2007b, Nosbi et al., 2011a). Furthermore, they are easily available in large quantity at relatively low cost compared to synthetic fibres. Besides, additional properties such as renewability and biodegradability which are a major concern nowadays, have made kenaf fibre fits well to become the material to be used in FRP composites fabrication (Edeerozey et al., 2007b, Akil et al., 2011). Besides that, the use of kenaf fibre has resulted in less abrasions to equipment and less irritation to skin and respiratory (Arbelaiz et al., 2005).

Significant advantages of natural fibre over synthetic fibre have caught the attentions of both academician and industrial sector. Till today, the use of natural fibre such as hemp, flax, wood, jute, bamboo and kenaf as reinforcement in plastic are intensely investigated (Nosbi et al., 2011a, Li et al., 2000, Mathur, 2006).

Pultrusion is one of the techniques in processing fibre reinforced composites and natural fibre reinforced composites are also using this technique due to its continuous process and able to produce large amount of product. The production of natural fibre reinforced composite using pultrusion technique have been studied and reported by several researchers (Angelov et al., 2007, Omar et al., 2010a, Nosbi et al., 2010b, Mazuki et al., 2011, Peng et al., 2011). Comparing the spray layup and the hand layup composites, the durability of pultruded composites are proven to perform better under corrosive environment (Ma et al., 2005, Starr, 2000b). Construction industries would be a suitable field to use pultruded composites due to their physical appearance which is long and continuous profile (Omar et al., 2010b, Bakis et al., 2002, Ma et al., 2005).

The main purpose of this investigation is to study the effects of natural weathering exposure and hygrothermal aging upon the pultruded composites produced. The hybridization of kenaf fibre with glass fibre pultruded composites samples with assigned fibre placement in the pultruded composites was produced with the aim to improve the resistance to water absorption and maintaining the mechanical properties of the composites. Comparative analysis between each type of the samples was investigated to figure out the effects of the exposure on the degradation behavior and properties changes of all the samples. From this research, it is expected that the hybridization of pultruded composites will be improve the degradation behavior of the samples and able to retain their mechanical properties so that the potential of pultruded hybrid glass/kenaf fibre composites to be used in demanding environments will increase. Theoretically, the layering pattern in this pultruded hybrid composites which glass fibre sits at the outer layer and kenaf fibre as the core have higher resistance towards moisture attack compared to hybrid pultruded composites with random fibre layering pattern. Better resistance to moisture absorption will ensure the hybrid composites perform better mechanically. Industries all around the world could plays a major role in helping to protect the environment sustainability by producing environmental-friendly and bio-degradable products and hybridization would be a great starters due to the usage of natural fibre and yet didn’t diminishes all the reliable properties of the produced composites which is a compulsory requirement in the fields of application.

1.2 Problem Statement

Conventionally, fibre reinforced composites available in the market are mostly made from synthetic fibre which does not comply with the sustainability issue of these days where products produced should be more ecological friendly, bio-degradable, renewable and recyclable. Thus natural fibre has become a perfect replacement in producing FRP composites. It is evident that some of the natural fibres possess a few advantages compared to synthetic fibre. However, in term of mechanical properties, natural fibre gives much lower strength compared to pultruded fibre made with synthetic fibre. The use of natural fibre can lower the cost of the composites, but at the same time the mechanical and other properties could not be compromised in order to make the samples function well in a demanding environment. And because of that, the idea of hybridization came up, where natural fibre will be used together with synthetic fibre to produce pultruded FRP composites. Theoretically, both advantages from each constituent can produce a very good and balanced properties of the samples produced.

In manufacturing composites profile, pultrusion technique is known as one of the highly cost-effective fabrication method (Gadam et al., 2000). Continuous process and easily automated process enable pultrusion to run at relatively high production rates thus make it a highly cost-effective technique of processing. Based on these factors, several researchers have developed the production of composites profile via pultrusion technique and using various types of fibre–matrix combinations (Angelov et al., 2007, Omar et al., 2010a, Nosbi et al., 2010b, Mazuki et al., 2011, Peng et al., 2011). Meanwhile, hybrid FRP composites are also being developed by many researchers utilizing bamboo-glass fibre (Thwe and Liao, 2002), palmyra-glass fibre (Velmurugan and Manikandan, 2007) and jute-glass fibre (Akil et al., 2010).

Nevertheless, stand-alone natural fibre FRP composites have it owns downside. They are facing some critical issues such as poor resistance to weathering, inconsistence properties and interface compatibility between fibre and matrix. In addition, natural fibres tend to absorb moistures and that may be the main cause to the previous issues when natural fibres were used as reinforcement in FRP composites. Studies had proven that natural fibre that was exposed to various environment at a prolonged period undergo certain degree of degradation and significant loss in their mechanical properties (Nosbi et al., 2010a, Mazuki et al., 2011). This vulnerability to environmental degradation after a long period of exposure has made natural fibre less desirable and not suitable to be used for outdoor applications. Based on these studies, hybridization of natural fibres with synthetic fibres could be the solution; but it needs to compromise the fact that it is not a whole natural fibre composite anymore. Although the synthetic fibres are still being used in this hybridization, but at least the portion of synthetic fibres used have been reduced and being replaced by natural fibres. The fibres arrangement also requires more attention since it may affect the properties of FRP composites based on where the fibres place themselves inside the composites.

1.3 Objectives

The primary objectives of this study are listed as follows:

1. To study and differentiate the effects of hygrothermal aging on the mechanical properties and water absorption behavior of PKRC, PGRC and PGKRC.

2. To evaluate and differentiate the effects of natural weathering exposure on the mechanical properties and water absorption behavior of PKRC, PGRC and PGKRC.
3. To study the effects of different fibres layering pattern to the flexural properties of PGKRC after both hygrothermal aging and natural weathering exposure.

CHAPTER 2

LITERATURE REVIEW

2.1 Composites materials

2.1.1 Definition of Composite Materials

Composite materials defined as engineered materials made of two or more constituent materials with significantly different physical or chemical properties which remain separate and distinct on a macroscopic level within the finished structure (Matthews and Rawlings, 1999, William and Callister, 2000). In other definition, it is also multiphase materials that are artificially made and chemically dissimilar and separated by a distinct interface. In the past decades, composite materials have been established as efficient workable engineering materials and widely used in sectors such as electronic, aerospace, automobiles and construction for various applications. The three key points that are perfectly used to define composite materials are:

1. The material must contains two or more materials with physical and mechanical differences. Both constituents have to be present in reasonable proportions.
2. The composite is only established when the constituents' phases have different properties; hence the materials properties are noticeably different from the single material properties.
3. The composite materials are produced by intimately mixing and combining the constituents by various processes.

These three key points have provided a guideline in order to determine whether a material is in composites group or not. For example, an alloy which has a two-phase microstructure produced during solidification will be classified as non-composite material (Matthews and Rawlings, 1999).

2.1.2 Classification of Composite Materials

There are three categories of composites in general which are structural, particle-reinforced and fibre-reinforced.

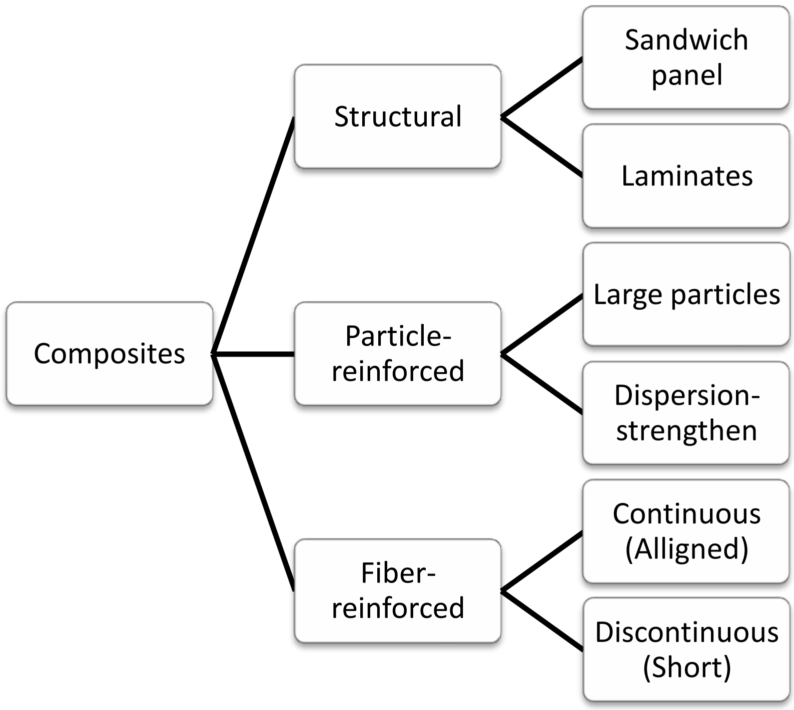

Figure 2.1: Classification of composite materials (William Jr, 2003)

One of the examples of structural composite is sandwich panels and laminates. The structure of typical sandwich structure consists of three principle layer, two thin face sheet layers separated by a thick core layer. Normally, the outer face layers are made from metals or composite laminates due to their high strength and stiffness. The face layers are bonded to the thick core layer which normally made from low density materials such as polymeric foam by adhesion (Hohe and Librescu, 2008). The other structural composite is called laminates. Laminates or also called laminar composite consist stacks of two-dimensional layers that have high-strength direction. All the layers were bound together so that each layer high strength direction varies within one another (William Jr, 2003). The main aims of laminates structure is to absorb low velocity impacts while in the field (Shyr and Pan, 2003). The field or industries that are extensively using laminates structure are such as marine, aerospace, and automotive industries (Rama Mohan Rao and Arvind, 2005).

As for particle reinforced composites, there are two types of composites that came out of it, which are dispersion-strengthened and large-particle composites. Particle reinforced composites contain hard particles dispersed homogeneously in a ductile matrix (Yin et al., 2002). In large-particle composite, the term "large" indicate that this particle-matrix interaction is not suitable to be analyzed nor characterized on atomic or molecular level. One of the large-particle composite examples that we daily see is concrete which have the matrix of cement and sand/gravel as the particulate reinforcements. Much smaller particles took place in dispersion-strengthened composites with the particulate size ranging between 10 and 100nm. Interactions between the particles and dislocation within the matrix are the strengthening mechanisms involved (William Jr, 2003).

Fibre-reinforced composite is the final category in classification of composite materials. Factors that influence the strength and properties of fibre-reinforced composites are such as fibre orientation, concentration and distribution of the fibres. The orientation of fibres in the continuous fibre-reinforced composites are normally parallel to longitudinal direction, while it can be aligned, partially oriented or randomly oriented in the discontinuous short fibre composites (William Jr, 2003). Generally, reinforcements in this type of composites are stiff and strong therefore serve as the primary load-carrying constituent (Saheb and Jog, 1999). Generally, reinforcements in this type of composites are stiff and strong therefore serve as the primary load-carrying constituent (Wambua et al., 2003).

2.1.3 Properties of Composite Materials

Composites materials possess a new properties contributed from their constituents, the microstructure and the reinforcement-matrix interface (Pothan et al., 2003). The interface between reinforcement-matrix has a huge impact upon composite materials as it transferred the load to the reinforcement and determines the final properties of the composites (Peijs, 2000). The properties such as creep resistance, fracture behaviour, fatigue and environmental degradation are depending on the characteristic of reinforcement-matrix interface.

Some general properties that most of composites materials have are such as high strength at low density includes good impact, compression, fatigue, and good electrical properties also excellent resistance to chemical, corrosion and environmental. Apart from that, low tool cost, high productivity rates and cost-effective manufacturing process are the additional advantages in the production of materials composites. Besides these beneficial advantages, most of composite materials possess unique abilities where the physical and mechanical properties also cost can be manipulated to meet the required performance. In contrary, properties such as poor ductility compared to metals, lower stiffness and limited range of working temperature may have restrict composite materials to be used in more wide applications (Starr, 2000a).

The incorporation of materials in composites structure produces a lot of advantages such as listed below:

1. High strength

The main advantage of composite material is the ability to adjust the composites system strength according to specific strength needed by detailing the constituent selection which to be used in the composite structure. By combining and adding the reinforced materials, the composites structure will improve the mechanical properties. Mechanical properties of composites normally come from the properties of its constituents used to reinforce the matrix.

2. Flexibility

Composite materials are very high potential to be used in civil engineering applications due to their high strength-to-weight and stiffness-to-weight ratios, corrosion resistance, light weight and relatively high durability. It suits best to be used in the renewal of constructed facilities infrastructure such as buildings, bridges, pipelines, and many more (Van Den Einde et al., 2003). Recently, their usage of composite materials has increased in structural applications due to their flexibility characteristics, ease of application and low life cycle costs.

3. Low density

The most important advantage of composite over metals and other materials is, it promises the low density, ρ. The benefit of low density becomes apparent when Young's modulus per unit mass and tensile strength per unit mass (specific properties) are considered. It means that the weight of certain components can be reduced without compromising the properties of the materials.

2.2Fibre Reinforced Polymer (FRP) Composites

Fibre-reinforced composites is composite structure consist of fibrous reinforcing materials which can be synthetic or natural and the matrix constituents which can be metal, polymer or ceramic. The most common used in composites matrix is polymer and thus it is known as polymer-matrix composites (PMCs). Typical PMCs have polymer resin as the matrix and fibres as the reinforcement thus also called fibre reinforced polymer composites (FRP) (William Jr, 2003). Since the FRP has caught the attention to be studied, researchers intensively trying to find the best combinations of fibres, matrix and processing to put up with the production of FRP.

FRP composites have been successfully developed and commercialized in various applications since the last few decades. Due to its lightweight and non-corrosive properties, FRP is more desirable to be used in certain applications compared to steel and other similar materials (Starr, 2000a). Apart from that, high adaptability, high damage tolerance, ease of handling and low fabrication cost have made it become more desirable and capable to make a breakthrough into new markets (Nosbi et al., 2011b). Despite the advantages, researchers still needed optimization in term of its cost effectiveness regarding their mechanical properties (Bakis et al., 2002, Oksman et al., 2003). Thus, it is crucial to figure out the best choice of fibres, matrix and manufacturing process.

Overall performance of the composite mainly relying on the fibre reinforcement. Interaction between fibres and the matrix in the composites have enable it to redistribute the stresses applied thus make it stronger as compared to the individual constituents (Abu-Sharkh and Hamid, 2004). In addition, the composites strength and properties are improved by using the fibres reinforcement (Starr, 2000a). Two major category of the fibre reinforcement of FRP composites are synthetic fibres and natural fibres. Glass, aramid and carbon which are hydrocarbon origin materials are the most common synthetic fibres available. Meanwhile, plant, mineral and animal were the sources of natural fibres. Figure 2.2 simplifies the FRP composites classification.

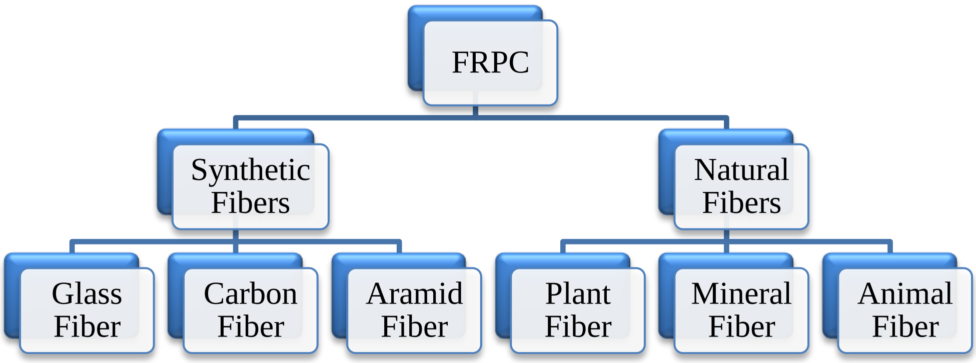

Figure 2.2: Fibre type classifications of FRP composites

2.2.1 Synthetic Fibre Reinforced Polymer Composites

Synthetic product is defined as products that are artificially produced by human through research using available natural resources. In order to fulfil the requirement for engineering applications, numbers of synthetic fibres develop and produced. Some synthetic fibres material characteristics are as shown in Table 2.1.

Table 2.1: Characteristics of some synthetic fibre materials (Rösler et al., 2007)

Fibre Material	Density (g/cm^3)	Young's Modulus (GPa)	Tensile Strength (MPa)
Glass	2.50-2.60	69-85	1500-4800
Carbon	1.75-2.20	140-280	1400-7000
Aramid	1.40-1.50	65-147	2400-3600

The most common used fibres as reinforcement in FRP composites are glass, aramid and carbon. Since the last few decades up to this day, applications in aerospace, military, construction, transportation, leisure, recreational and sporting industries had been familiarize with the use of these composites as raw materials.

Nowadays, Glass Fibre Reinforced Composites (GFRC) or also known as fibre glass is a very popular materials used in varieties of application. Due to low cost aspect, glass fibres are widely used as reinforcement in FRP compared to aramid and carbon fibres (Wambua et al., 2003). Another thing is, glass fibres have better resistance upon impact and higher strain to failure as compared to carbon fibres (Helbling and Karbhari, 2008). Several reasons that made glass fibres are widely used as reinforcement in FRP composites are such follows (Akil et al., 2010):

1. Readily available and may be economically fabricated using various composite-manufacturing technique.
2. Easily drawn into high-strength fibres from the molten state.
3. Relatively strong and able to produce very high specific strength composites.
4. Inert to chemical attacks when coupled with various plastics.

Factors like high corrosion and fatigue resistance, high strength to weight ratio and ease of handling (Mukherjee and Arwikar, 2007) GFRC becomes an alternative substitution to replace steel in concrete and constructions industries. Meanwhile, transportation industries use GFRC to lighten the vehicle weight thus able improves fuel efficiency. Besides, other applications that are using GFRC includes storage containers, industrial floorings, plastics pipes, automotive and marine bodies, insulators and consumer products (William Jr, 2003, Starr, 2000a).

On the other hand, Carbon Fibre Reinforced Composites (CFRC) has dominated aerospace and automotive technologies which demands high-performance materials; where fibreglass did not meet the requirements mechanically. In addition, common CFRC appearance which is the unique black-woven provides an aesthetic value and becomes an exclusive trend in automotive parts such as body panels, spoiler and hood. Unique appearance of CFRC is just a bonus because the main reason of CFRC are used is due to its high specific modulus, high specific strength and high stiffness for advanced lightweight structure (Aoki et al., 2008, Miyano et al., 2008). Similar with fibre glass, CFRC are also being used for a certain parts in aerospace industries which require higher strength. Besides the advanced applications, due to its lightweight, CFRC are also being used extensively to produce sports and recreational equipments such as golf clubs, fishing rods and racquet (William Jr, 2003).

Aramid or commonly called as Kevlar, is a high modulus and strength fibre of highly oriented polyamide (nylon) incorporating an aromatic ring structure. Additionally, it can insulate electricity and heat, fire resistance and also has amazing resistance to organic solvents, lubricants and fuels. In fact, due to its high tensile properties and high tenacity, it has what it takes to be used as armour or ballistic protection materials (Starr, 2000a). Although aramid belongs to thermoplastic family, it has a good combustion resistance and able to remain stable at relatively high temperature. Other than ballistic protection products, it is also used as raw materials to produce tires, sporting goods, pressure vessels, tires, ropes and missile cases (William Jr, 2003).

Nevertheless, some issues arise from the application of synthetic fibres in FRP composites. One example is the most common used glass fibres in GFRC, E-

Glass. Its composition contains a little alkali in it. Effects of the alkali content are high susceptible to environment attack and stress corrosion (Hazizan et al., 2010). High performance CFRC even face problem when in used for aircraft structure as it being exposed to so-called “hot-wet” environments. Diffusion of moisture into the CFRC interface act as plasticizers and affecting the performance of the composites such as strength, stiffness and damage growth (Aoki et al., 2008). On top of that, CFRC is known to have high processing cost and this is the major drawbacks for it to be use in a lot more applications (Starr, 2000a). As for aramid fibres, despite its high longitudal tensile strength and tensile modulus, it is relatively weak in compression compared to other polymeric fibre materials. Aramid fibre is also chemically susceptible to degradation by strong acids and bases (William Jr, 2003).

Above all, these non-biodegradable, non-renewable and unrecyclable synthetic fibres may harm the environment when being disposed by incineration (Wambua et al., 2003, Nishino et al., 2003). The recyclability awareness rises from the consumer and environmental legislation give the kick-start to researchers in order to find substitute resources with similar properties to the synthetic fibres. The emerging demand of green technology makes natural fibres being considered as competitive replacement to these synthetic fibres. The major concern is the performance of these natural fibres and the ability and potential to replace the synthetic fibres as reinforcements in composite materials.

2.2.2 Natural Fibre Reinforced Polymer Composites

One of the efforts to create a more sustainable future is to work on products that are biodegradable, renewable and recyclable by using new eco-friendly resources. One of the factors that motivated a line of researchers to develop the use of natural resources on producing products with equal quality compared to conventional resources is the environmental awareness. Up till today, numbers of new composites have properly used natural fibres as reinforcement and the uniqueness of natural fibres properties has become add up factor to attract more usage of them in composites structures. The sources of natural fibres may have come from plants, animals and minerals. Generally, stem, leafs and fruits from plants can be extracted to obtain natural fibre and they composed of cellulose while animal fibres which composed with protein can be extracted from hair, silk and wool (John and Thomas, 2008, Peng et al., 2011) and mineral fibres can be extracted from geological rocks such as basalt, ceramics and wollastonite (Szabó and Czigány, 2003, Carbonari et al., 2011). Table 2.2 shows the list of some plant fibre sources taken from certain parts of its species.

Table 2.2: List of some important natural fibres (John and Thomas, 2008)

Fibre source	Species	Origin
Coir	*Cocos Nucifera*	Fruit
Cotton	*Gossypium Sp.*	Seed
Flax	*Linum Usitatisssimum*	Stem
Hemp	*Cannabis Sativa*	Stem
Jute	*Corchorus Capsularis*	Stem
Kenaf	*Hibiscus Cannabinus*	Stem
Ramie	*Boehmeria Nivea*	Stem
Sisal	*Agave Sisilana*	Leaf

Plant fibres are the one that caught greater attention since they are the commonly used natural fibres in composite manufacturing. Researchers have intensely searching around the globe with an objective to search for natural fibres that have the capabilities and high potentials to be introduced into the world of polymer composites especially as the reinforcement elements and they have discovered a number of it.

Apart from the advantages of being recyclable, biodegradable, renewable and environmentally friendly (Sgriccia et al., 2008, Nosbi et al., 2010b, Edeerozey et al., 2007a), a good specific properties have also made natural fibres are more competitive as compared to synthetic fibres especially glass fibres. Additionally, natural fibres have less respiratory irritation during handling as well as less tool wear during processing (Arbelaiz et al., 2005). Furthermore, they have good specific strength and modulus and high specific stiffness at low density (Dhakal et al., 2007a, Nosbi et al., 2011b). Ultimately, they are abundantly available worldwide at relatively lower cost (Akil et al., 2011, Beckermann and Pickering, 2008). Some mechanical properties of plant-based natural fibres are as shown in Table 2.3.

Table 2.3: Characteristics of some natural fibre materials (Bismarck et al., 2001, Akil et al., 2011)

Fibres	Density (g/cm^3)	Young's Modulus (GPa)	Tensile Strength (MPa)
Coir	1.15-1.46	4.0-6.0	131-220
Cotton	1.50-1.60	5.5-12.6	287-800
Flax	1.50	27.6	345-1500

Hemp	1.47	70.0	690
Jute	1.30-1.49	13.0-26.5	393-800
Kenaf	1.20-1.60	53.0	930
Ramie	1.55	61.4-128.0	400-938
Sisal	1.45	9.4-22.0	468-700

Attractive properties of natural fibres are not the only the attraction of using it compared to synthetic fibres, but it also gives positive impact in various aspects to the community. From economy aspect, the high demand of natural fibres will give the opportunity for developing countries to generate a new source of income for the country and creates job opportunities by planting these natural fibres. The whole process of being a supplier of natural fibres will involve activity such as collecting, transporting and development of natural fibres which will provide jobs for the local community (Satyanarayana et al., 2009). In term of energy consumption, manufacturing process of natural fibres consumes less energy and may due to its non-abrasiveness to the processing equipment (Peng et al., 2011). Natural fibres also give positive impact on health since they cause less skin and respiratory irritation (Sgriccia et al., 2008), which means that they are low or free from health hazard during handling (Peng et al., 2011, Akil et al., 2009). When being incinerated, natural fibres are carbon neutral and helps reducing greenhouse effect to the environment (Wambua et al., 2003).

Based on the properties and benefits that can come out from using natural fibres, researches have been conducted to make it to be used as much as possible in commercial industries. The fibres extracted from wide sources of natural fibres have the potential to be used as reinforcement in polymer matrix composite (Dhakal et al., 2007a, Satyanarayana et al., 2009, Edeerozey et al., 2007a). Some automotive industries nowadays are using hemp and flax fibres in producing non-structural car components (Dhakal et al., 2007a). Construction field used paddy's straw and sugarcane's bagasse as reinforcements in polymer or cement composites. Additionally, sugarcane bagasse is being used to produce polyhydroxyalkanoates in Brazil and used for medical applications (Satyanarayana et al., 2009).

Nonetheless, some obstacles need to be overcome for most of the natural fibres in order to be able to commercialize globally. One of the reasons is the inconsistencies of natural fibres properties even though they came from the same origin area. The origin environment, age, retting and separating techniques are factors that makes controlling the properties of composites that used natural fibres as reinforcements difficult physically and mechanically (Akil et al., 2009). Besides, the composite made from natural fibres have a restriction on which polymeric matrices that can be used such as polypropylene, polyesters and epoxy (Peng et al., 2011). Moreover, incompatibility issue rises due to the hydrophilic nature of natural fibres and the hydrophobic nature of thermoplastic and thermoset matrices which later on produce composites with weak interface bonding. Hairy surface of some natural fibre are also contributing to poor matrices wetting which also lead to poor mechanical properties. Adhesion between fibre and matrix can be improve with an appropriate use of chemical treatments (Dhakal et al., 2007a). Other limitations of natural fibres that restricts them to be use in composites are such as lower modulus and strength as compared to synthetic fibres composites and poor moisture resistance (Akil et al., 2009).

2.3 Kenaf Fibre

Kenaf (*Hibiscus Cannabinus L.*) is mainly grown in Asia (India, China and Thailand) and some production in Italy, United States and Mexico as fibre crops is a member of *Malvaceae* family (Lips et al., 2009b). Similar with jute and cotton, kenaf is a warm season annual fibre crop. In the early days of kenaf, it was commonly used as rope, sackcloth and twine. Nowadays, kenaf applications can be found in building materials, paper products, animal foods and absorbents materials (Edeerozey et al., 2007a).

Normally, kenaf plants are grown from seeds or in some tropics and subtropics area grown as perennials. Table 2.4 shows the optimum climate environment which kenaf can be grown and shows that it can be grown under a wide range of weather conditions. Kenaf plant can reach the height more than 3m with a base diameter of 3 to 5cm in just three months after sowing the seeds (Figure 2.3). In year of 2000, kenaf was priced from USD 278 to USD302 (RM 888 to RM 965) per tonne. The rapid growth of kenaf plant together with the relatively low cost has made kenaf become attractive renewable natural fibres to be used in various fields.

Figure 2.3: Kenaf Plant (Akil et al., 2011)

Table 2.4: Optimum climatic requirements for growing kenaf (Rowell and Stout, 2007)

Plant	Temperature (ºC)	Min. Moisture (mm)	Soil pH	Growing Cycle (days)
Kenaf	22-30	120	6.0-6.8	150-180

Kenaf is categorized as jute-like fibres by Food and Agriculture Organization (FAO) of the United Nations which 386,000 ton of these types of fibres were harvested in 2004 only (Lips et al., 2009b). Kenaf has been selected as the most promising crop in term of growing, harvesting, quality in the 1960s by United States Department of Agriculture (USDA) research for paper industry. Malaysia would not miss the opportunity thus National Kenaf Research and Development Program was formed by the Malaysian government in effort to develop kenaf as a new industrial crop for Malaysia after realizing the diverse possibilities of commercially exploitable derived products from kenaf. Under the 9th Malaysia Plan (2006-2010) RM 12 million has been allocated by the Malaysian government for the research and development research of kenaf-based industry for its commercial potential (Edeerozey et al., 2007a).

2.3.1 Structure of Kenaf Fibre

Structure of kenaf plant is a single, straight and branchless stalk. 30-40% of the stalk is the outer fibrous bark surrounding the 60-70% inner woody core. Kenaf fibre is extracted from the outer fibrous bark which is also known as bast fibre. Bast fibre is known to have excellent flexural strength and good tensile strength. Kenaf fibres becomes the material of choice with the combination of these properties and can be used for a wide range of extruded, moulded or non-woven products (Edeerozey et al., 2007a, Akil et al., 2011).

Most natural fibres have the structure consist a number of non-homogeneous membrane layers. Figure 2.4 shows the cell wall of the first outer layer or primary wall where it is made up from disorderly arranged crystalline cellulose microfibrils networks. Three layers secondary wall are encircled by the primary wall and the middle section is called lumen. Each cell wall consists of microfibrils networks and the angle is different from one layer to another. Due to the complex structure of natural fibre, the characteristic values differs from one fibre to another (John and Thomas, 2008).

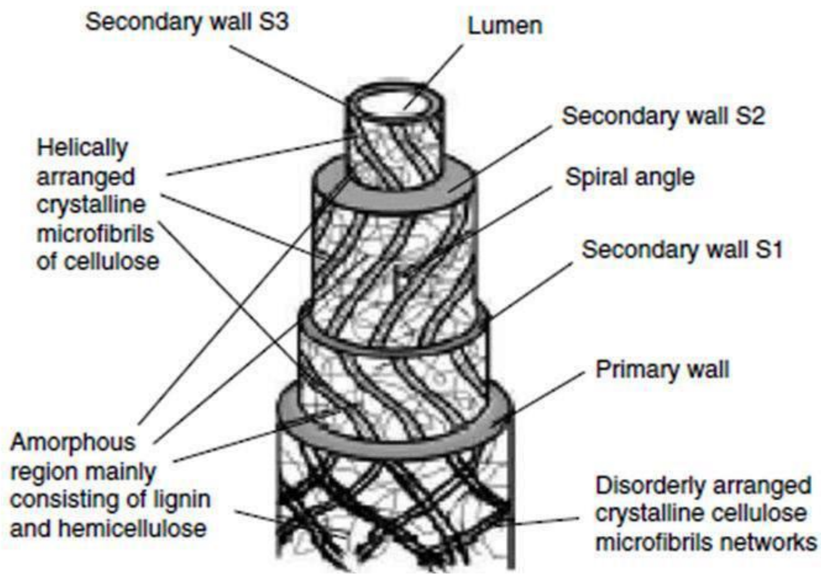

Figure 2.4: Standard schematic structure of most natural fibre (John and Thomas, 2008)

Both kenaf bast and core fibres can be used in wide range of applications. It is common for kenaf fibres mat to be used as insulation mats in automotive industry and in fibre-reinforced composites in these recent years. Some other applications that used the bast fibres are papers, textiles and ropes. Applications for the core fibres are such as bedding materials for animals, summer forage and potting media. Research were carried out to study the potential of kenaf core particles to be used as absorbent element in paper products like tissues and hygienic products (Akil et al., 2011, Lips et al., 2009a).

2.3.2 Chemical Composition of Kenaf Fibre

A lot of batches and a series of testing are required to determine the chemical composition of natural fibres. Since the fibre growth cannot be controlled and differs from each other according to their region, it is very difficult to get specific standard values for chemical properties. As a last resort, researchers agreed to come out with a certain range of values as a standard to represent the chemical composition of natural fibres. Kenaf fibres have the main components of cellulose (α-cellulose), hemicelluloses, lignin, pectin, and waxes (John and Thomas, 2008). The compositions consist of 60-80% cellulose, 5-20% lignin (pectin), and up to 20% moisture (Akil et al., 2011). Minor constituents in the composition of kenaf fibres are 0.4-0.8% fats and waxes, 0.3-5% inorganic matter and 0.8-1.5% nitrogenous matter and pigments (Rowell and Stout, 2007). Table 2.5 shows the microfibrils size and chemical content of kenaf stem.

Table 2.5: Microfibrils size and chemical content of kenaf stem (Nishino 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