



**DYNAMIC MECHANICAL ANALYSIS AND
EFFECTS OF MOISTURE ON MECHANICAL
PROPERTIES OF INTERWOVEN
HEMP/POLYETHYLENE TEREPHTHALATE
(PET) HYBRID COMPOSITES**

by

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LIST OF ABBREVIATIONS

ASTM	American Society for Testing and Materials
CO ₂	Carbon Dioxide
DMA	Dynamic Mechanical Analysis
DSC	Digital Scanning Calorimeter
EFB	Empty Fruit Bunch
FRP	Fibre Reinforced Polymer
HH	Woven Hemp Composite
HP	Interwoven Hemp/PET Hybrid Composite
NaOH	Sodium Hydroxide
PET	Polyethylene Terephthalate
PH	Interwoven PET/Hemp Hybrid Composite
POM	Polyoxymethylene
PP	Woven PET Composite
PVC	Polyvinyl Chloride
SEM	Scanning Electron Microscopy
TGA	Thermogravimetric Analysis
UTM	Universal Testing Machine

LIST OF SYMBOLS

m_{∞}	Maximum water uptake
$\Delta M(t)$	Moisture content percentage
M_0	Mass of dry sample
M_t	Mass of immersed sample at a specific time
D	Diffusion coefficient
k	Initial slope of moisture content versus square root of the time curve
h	Thickness
M_{∞}	Molar percentages of water uptake at infinite time
π	Pi
n	Intercept of k
T_g	Transition glass temperature
S	Sorption coefficient
P	Permeability coefficient
σ_f	Flexural strength
ϵ_f	Failure strain
E'	Storage modulus
E''	Loss modulus
$\tan \delta$	Damping factor

Analisis Mekanikal Dinamik dan Kesan Kelembapan Terhadap Sifat-sifat Mekanikal Komposit Anyaman Hibrid Hemp/Polyethylene Terephthalate (PET)

ABSTRAK

Bagi mengurangkan kebergantungan terhadap fiber yang berasaskan petroleum, fiber dari sumber semulajadi mula menjadi perhatian sebagai bahan penguat di dalam komposit kerana sifat-sifatnya yang bagus seperti tidak bertoksik, mudah diperoleh, dan kurang impak terhadap kesihatan manusia. Tetapi, satu kelemahan yang terdapat pada fiber semulajadi ialah sifat serapan air yang tinggi berbanding fiber sintetik. Oleh itu, bagi menambah baik sifat serapan air fiber semulajadi komposit adalah dengan menghasilkan hibrid komposit bersama bahan sintetik. Di dalam kajian ini, analisis mekanikal dinamik (DMA) diambil kira, dan kesan kelembapan terhadap sifat-sifat mekanikal komposit anyaman dan anyaman hibrid telah disiasat. Komposit diperbuat menggunakan proses infuksi vakum dengan pecahan isipadu 25 % gentian dan 75 % matrik epoksi. Lapisan anyaman hibrid dihasilkan dengan menggunakan anyaman gentian hemp dan PET secara ikatan matrik epoksi. Anyaman hemp, PET, dan hibrid hemp/PET komposit dihasilkan. Spesimen komposit diuji dengan ujian analisis termogravimetrik (TGA) dan analisis mekanikal dinamik (DMA). Ujian tegangan, lenturan, dan impak dijalankan pada spesimen anyaman dan anyaman hibrid kering dan juga basah megikut spesifikasi ASTM. Analisis imbasan mikroskop (SEM) telah dijalankan untuk menganalisa sifat patah dan kesan penembusan air terhadap ikatan fiber/matrik. Analisis termogravimetrik (TGA) menunjukkan kadar dikomposisi dan lebihan sisa yang tertinggal disebabkan oleh perubahan jisim komposit apabila suhu meningkat. Suhu perubahan kaca bagi anyaman hemp, PET, dan hibrid hemp/PET masing-masing ialah pada suhu 64, 66, dan 67 °C. Kajian ini menunjukkan serapan air anyaman hibrid hemp/PET dikurangkan kepada separuh. Hibridisasi gentian PET meningkatkan kekuatan tegangan, lenturan, dan impak sebanyak 4, 22, dan 5 % berbanding komposit anyaman hemp. Kekuatan berkurang akibat daripada kesan degradasi apabila masa rendaman komposit dipanjangkan. Pengurangan sifat-sifat mekanikal ini adalah disebabkan oleh keretakan pada matrik, ikatan fiber matrik, dan kesan plastik. Akhir sekali, hal ini dapat disimpulkan bahawa hibrid antara hemp dengan PET meningkatkan prestasi sifat-sifat terma dan mekanikal anyaman komposit dan mengurangkan kadar serapan air terhadap sifat-sifat mekanikal.

Dynamic Mechanical Analysis and Effects of Moisture on Mechanical Properties of Interwoven Hemp/Polyethylene Terephthalate (PET) Hybrid Composites

ABSTRACT

To reduce the dependence towards the petroleum-based fibre, the natural fibre started to receive attention as reinforcement materials in composite due to their advantages such as non-toxic, easy to get, and less harmful to human health. However, one limitation is that the natural fibre has high moisture absorption compared to synthetic fibre. Thus to improve the moisture absorption in natural fibre composite, the natural fibres are hybridised with the synthetic materials. In this research, a dynamic mechanical analysis (DMA) was undertaken, and the influence of moisture on the mechanical properties of the woven and interwoven hybrid composites was investigated. The composites were manufactured using a vacuum infusion process with a volume fractions of 25 % fibre and 75 % epoxy resin. Hybrid composite laminates were fabricated using the interwoven between hemp and PET fibre reinforced epoxy resin. The composite specimens were subjected to thermogravimetric analysis (TGA) and dynamic mechanical analysis (DMA). Tensile, flexural, and impact tests were conducted at dry and wet condition specimens of the woven and interwoven hybrid composites according to their ASTM standards. Scanning electron microscopy (SEM) analysis was performed to examine the fracture behaviour and the effect of the water penetration through the fibre/matrix interface. The glass transition temperature for the woven hemp, woven PET, and interwoven hemp/PET hybrid composites were 64, 66, and 67 °C, respectively. This study shows that the water absorption uptake reduces by half for the interwoven hemp/PET hybrid composite. The hybridisation of PET fibre enhanced the interwoven hemp/PET hybrid composite tensile, flexural, and impact strength by 4, 22, and 5 % compared to the woven hemp composite, respectively. Those reductions attributed by matrix cracking, debonding, and plasticization effect. Lastly, it can be concluded that hybridisation of hemp with PET fibre improved the thermal and mechanical properties performance of the woven composite and reduce the rate of water uptake on the mechanical properties.

CHAPTER 1 : INTRODUCTION

1.1 Research Background

Nowadays, exploration of natural fibres as the reinforcing agent is in demand due to its relatively high strength, renewable, biodegradable, easier handling, excellent mechanical properties, and non-abrasive (Dittenber & Gangarao, 2012; Fartini et al., 2016; Revati et al., 2017; Ridzuan et al., 2015). Faruk et al., (2012) states that hemp, jute, sisal, ramie, and kenaf fibres are widely used as the reinforcement material studies for biocomposite. Despite the advantages, the natural fibre also has the limitation of their specification such as low strength, incompatible with the polymer, and high moisture absorption towards water. Furthermore, the investigation by the researcher throughout every year has found that the reinforcement material can be hybridised with the synthetic fibre while natural fibre can undergo treatments. Thus, the mechanical performance of the natural fibre composites that limit their capabilities as the outdoor applications can be improved.

Hybrid composite is the mixture of two or more reinforcing materials in a single matrix. To improve the natural properties of the natural fibre can either be hybridised with different natural fibre or synthetic to form a composite. Others reinforcement such as polyethylene terephthalate (PET), carbon, aramid, and glass fibres were used to hybridise with the natural fibre (Dhakal et al., 2012; Jawaid & Abdul Khalil, 2011). Besides, the different hybrid configuration can be applied as well to increase the toughness of the fibre reinforced composites through hybridisation. The three different types of hybrid configuration in combining the two fibre are interlayer or layer by layer,

intra-yarn or fibre by fibre, and intralayer or yarn by yarn (Swolfs et al., 2014). The hybrid composite is influenced by several factors such as fibre orientation, the volume fraction of the fibre, and fibre/matrix interfacial bonding.

One of the factors that influenced the strength properties of the polymer composites as the hybrid is the fibre orientation. Khan et al.,(2016) states that the mechanical properties of the woven jute reinforced poly(L-lactic acid) composite was stronger when tested along the warp yarn that parallel to the load direction compared the weft yarn. Textile processing methods for the polymer composite reinforcement such as weaving, knitting, and braiding can attain a higher degree of fibre alignment (Iqbal et al., 2014). As reported in the literature, the woven fabric composite attained greater strength in their mechanical properties than those unidirectional and randomly oriented composites (Alavudeen et al., 2015). The woven fabric structure gives an excellent interlocking arrangement between the reinforced fibres with a uniform stress distribution that enhanced the composite strength (Dan-Mallam et al., 2014).

The polar group (hydroxyl) of the cellulose and lignin in the natural fibre reinforced composite allows them to absorb high amounts of water molecules (Azwa & Yousif, 2013). Haameem et al., (2016) reported that when the composite is exposed to an environment with high level of humidity and moisture, water was more likely to penetrate through the gap and crack that caused by the fibre swelling. This factor results in poor fibre/matrix interfacial adhesion within the resultant polymer composite, and impair the mechanical properties of the composite. In addition, Akil et al., (2014) found that the water molecules penetrated the composite through three routes as follows; through the micro gaps between polymer chains, through the cracks in the polymer matrix caused by

fibre swelling, and through the flaws at the composite interphase because of the poor wettability between the fibre and the matrix. Water molecules act as a plasticiser that affects the fibre/matrix interface by creating a poor transfer efficiency, which leads to the decreasing of the composite mechanical performance.

The fibre/matrix interface of the composite can be studied using the thermal analysis (TGA) and dynamic mechanical analysis (DMA). The DMA separates the dynamic modulus (E) into storage modulus (E') and loss modulus (E''). The energy dissipation of material measured from the ratio of loss modulus and storage modulus (E''/E') that gives the damping characteristic, ($\tan \delta$). Thus, the glass transition temperature, (T_g) can be evaluated and obtained from the curve of $\tan \delta$ (Mazuki et al., 2011). The thermal stability of matrix polymer increases with the incorporation of bamboo and glass hybrid composite (Nayak et al., 2009). In addition, Ridzuan et al., (2016) reported that the amount of residue decrease as the alkali concentration used for treated *Pennisetum purpureum* increased. Moreover, the thermal stability of the composites was improved by hybridisation of natural fibre with glass fibre and chemical modification such as treated with NaOH and silane treated for the natural fibre (Lu & Oza, 2013).

In the present study, experimental investigations were conducted to evaluate the thermal, mechanical, and morphological properties of woven and interwoven hybrid composites. Hemp fibre was selected for the investigation because it is locally available and offers excellent water resistance (Azwa & Yousif, 2013). The mechanical characteristics of the cost-effective natural/synthetic hybrid composites were evaluated. In addition, the study of water absorption behaviour on the mechanical properties was also investigated to observe their response when subjected to moisture or aqueous environment. It is expected that the results of this study will provide evidence to support the development of hemp-reinforced PET composites with improved water resistance for outdoor structural applications.

1.2 Research Problem

There has been a great deal of work focused on determining the natural fibre reinforced composites mainly driven by the environmental concern and limited petroleum resources. The natural fibre can be obtained with lower price. Hemp and PET fibres are produced in the form of fibre bundles (yarn) that have their own characteristics. From the previous literature states that the hemp reinforced polymer composites are lightweight, biodegradable and recyclable due to its natural criteria. Hence, they have potential in the industrial product or appliances. However, hemp fibre has low resistance towards water, thus affected the mechanical performance of the composite. This reduces the reliability of the material and the interfacial adhesion of the fibre reinforced polymer composites. Due to the hygroscopic nature, water absorption of the natural fibre (hemp) is higher than the synthetic fibre (PET). Thus, some researcher has conducted some experiment on how to overcome the limitation. One way through the fibre hybridisation with the synthetic

fibre for the improvement of moisture resistance and to increase their strength. The synthetic fibre shows a good potential in hybridisation with natural fibre because of high dimensional stability and high strength. In addition, hemp and PET yarn are knitted in the form of woven and interwoven hybrid fabric to provides balanced strength when induce into a composite. Woven are made of by interlacing fibre bundles (yarn) to form a fabric layer. It gives high packing density and good dimensional stability. Tight structure of the interwoven hybrid also gives the good interlocking between matrix and fibre of the composite material. Besides, PET fibre has good mechanical properties and hydrophobic characteristic. The hybridisation of hemp with PET fibre will improve the weakness of hemp characteristic toward water, thus strengthen the structure of composite.

1.3 Research Objectives

This study presents an investigation of woven hemp, woven PET, and interwoven hemp/PET hybrid reinforced epoxy composites that are fabricated using vacuum infusion technique. To analyse the effect of hybridisation between natural and synthetic fibres on their properties, the objectives are emphasised as follows:

- a) To investigate the thermal and mechanical properties of woven and interwoven hybrid composites.
- b) To study the effects of moisture exposure on the mechanical properties of woven and interwoven hybrid composites.
- c) To identify the fracture behaviour on the morphological surfaces of the hybrid composites.

1.4 Research Scopes

The reinforcement material that has been used in this research are non-treated hemp and PET fibre in yarn form. The yarn is manually weaved into a plain structure pattern fabric on a customised wooden frame. The construction of fabric is produced into two types which are woven and interwoven hybrid fabrics. The woven fabric has the same yarn for the warp and weft directions while the interwoven hybrid fabric is constructed with hemp yarn on the warp direction and PET yarn as the weft direction. The vacuum infusion manufacturing method is selected for the fabrication of the woven and interwoven hybrid composites using epoxy resin as the polymer matrix. Then, water absorption test is conducted at room temperature using distilled water for the immersion of composites according to the ASTM D570 standard. This is to determine the absorption properties and the water uptake percentage such as diffusion, sorption, and permeability coefficient. Next, the thermal properties are tested for TGA and DMA to study the fibre/matrix interface of the composites. For the mechanical test, the properties are determined as elucidated in ASTM D3039, ASTM D7264, ASTM D6110 standards for tensile, flexural, and impact tests, respectively. Each test is conducted for five specimens for each type of woven and interwoven composites, and average results are recorded. Finally, the fractured specimens of the mechanical test are examined on scanning electron microscopy machine (SEM) in order to analyse the interfacial adhesion on the fibre/matrix at dry and wet condition specimens.

1.5 Organisation of Thesis

The first chapter of this thesis presented the background theory, purpose, and limitation of the research conducted. Literature review in chapter two summarised the classification of fibre, matrix materials, hybridisation, a woven structure, fabrication method, water absorption behaviour, thermal properties, and mechanical properties of the fibre reinforced composite (FRP).

Then, followed by chapter three, where the materials selection and methods used in experiments been explained in details. Next, all the testing results that conducted are analysed and discussed for further understanding in chapter four. Lastly, the conclusions of this thesis are briefed in chapter five, and some future works suggestions are provided for further study or research in the future.

CHAPTER 2 : LITERATURE REVIEW

2.1 Introduction

This chapter provides a literature review and some methodologies from previous studies that can be utilised as an input in this research. The fibre reinforced polymer composites have been used in many applications and conducted in numbers of research. The increased demand for the natural based composites is mainly due to its cost and environmental issue. Thus, the improvement of natural fibre as the reinforcement material in the polymer composites from the previous research work was summarised in this chapter. The fibre classification is defined to explain the advantages and disadvantages that suit their mechanical properties as the reinforcing material in the polymer composites. Combination and configuration of fibre in hybrid composites are discussed to achieve the optimum performance for the fibre reinforced polymer composites. Then, the textile processing method in the fibre such as woven and interwoven hybrid was reviewed and explained accordingly. These aspects of fibre arrangement result in greater mechanical and thermal properties of the composites. The fabrication process of the composites was determined based on environmental criteria and easier way to handle the process. Research concerning the thermal and mechanical properties of the hybrid composites are subsequently reviewed. Finally, the behaviour of the fibre reinforced polymer composites was discussed as this criteria need to be considered for future work or application that can be pursued for the next research.

2.2 Fibre Classification

Due to the increasing cost of the concrete, steel, and timber, fibre reinforced polymer composites started to receive attention as an alternative to those conventional materials in the infrastructure industry (Dittenber & Gangarao, 2012). The reinforcement fibre and polymer matrix are the two main components in producing a composite fibre. The fibre can be classified into natural and synthetic fibres. Figure 2.1 shows that the natural fibre is divided based on their origin, which is animal, plants and minerals. On the other hand, the synthetic fibre is categorised in the organic and inorganic group (Jawaid & Abdul Khalil, 2011).

Generally, the plant fibre contains cellulose, hemicelluloses, lignin, some waxes in a structure for the main component of structural, whereas proteins are found in the animal fibres. As for the mineral, they existed in the asbestos group that once used widely. However, due to the health issues, it was discounted to be part of in the composite fibre for the most of the country (Wambua et al., 2003). In addition, the plant fibre is found to be the best choice as reinforcement material compared to those animal fibres and mineral based fibres due to the excellent criteria such as biodegradable, renewable, high strength, and good insulator (Jawaid & Abdul Khalil, 2011). This plant fibres with high specific strength can be used to improve the mechanical properties of the polymer matrix.

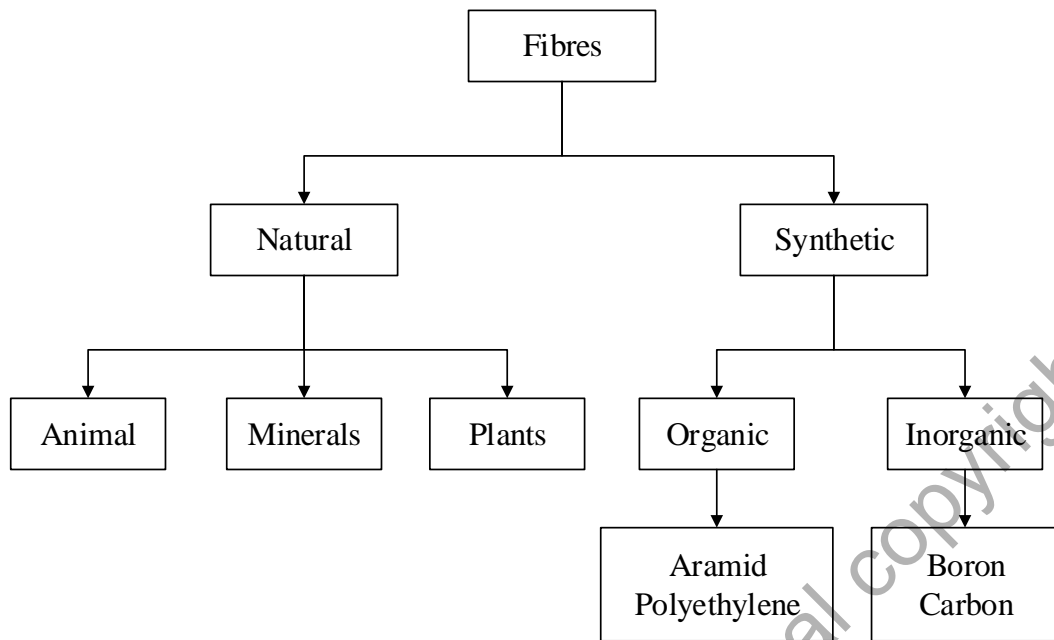


Figure 2.1: Classification of fibres (Jawaid & Abdul Khalil, 2011).

2.2.1 Natural Fibre

Figure 2.2 represents the structure of a natural plant cell wall. Dittenber & Gangarao, (2012) reported that the structure and content of the cell walls are different according to the species and each part of the plant. The structure of the cell wall is called microfibril that consists of lumen, which is the open channel in the centre, one primary wall, and three secondary walls of the microfibril. Each layer of the cell wall contains cellulose in a lignin-hemicellulose matrix. The properties of the natural fibres are determined from the three main chemical component such as lignin, cellulose, and hemicellulose. Other than that, this fibre also contains waxes, water-soluble substances, and a small amount of pectin (Faruk et al., 2012). The cellulose content measured the strength and stiffness while lignin and hemicellulose protect the fibre from the degradation response (Akil et al., 2011). Subsequently, lignocellulose fibres are hydrophilic in nature, which indicates its fibres are susceptible towards water.

The fibre structural constituents such as lignin, cellulose, and hemicellulose are sensitive towards the changes in temperatures. The natural fibre began to degrade at the temperature range of 240 °C. Previous study stated that the lignin began to degrade at 200 °C, whereas cellulose and hemicellulose constituents degrade at a higher temperature (Joseph et al. , 1996). The degradation of natural fibre is a significant issue for developing the natural fibre reinforced composites. Also, previous works reported the lignin and hemicellulose constituents could be removed by using chemical treatments on the natural fibre. This will improve the fibre/matrix adhesion of the natural fibre to the matrix. Most of the chemical treatments of natural fibre are alkalization, acetylation, benzylation, silanization, and etc. (Mishra et al., 2003; Sreekumar et al., 2009). They also can be used to increase the water-resistance of the natural fibre and their composite.

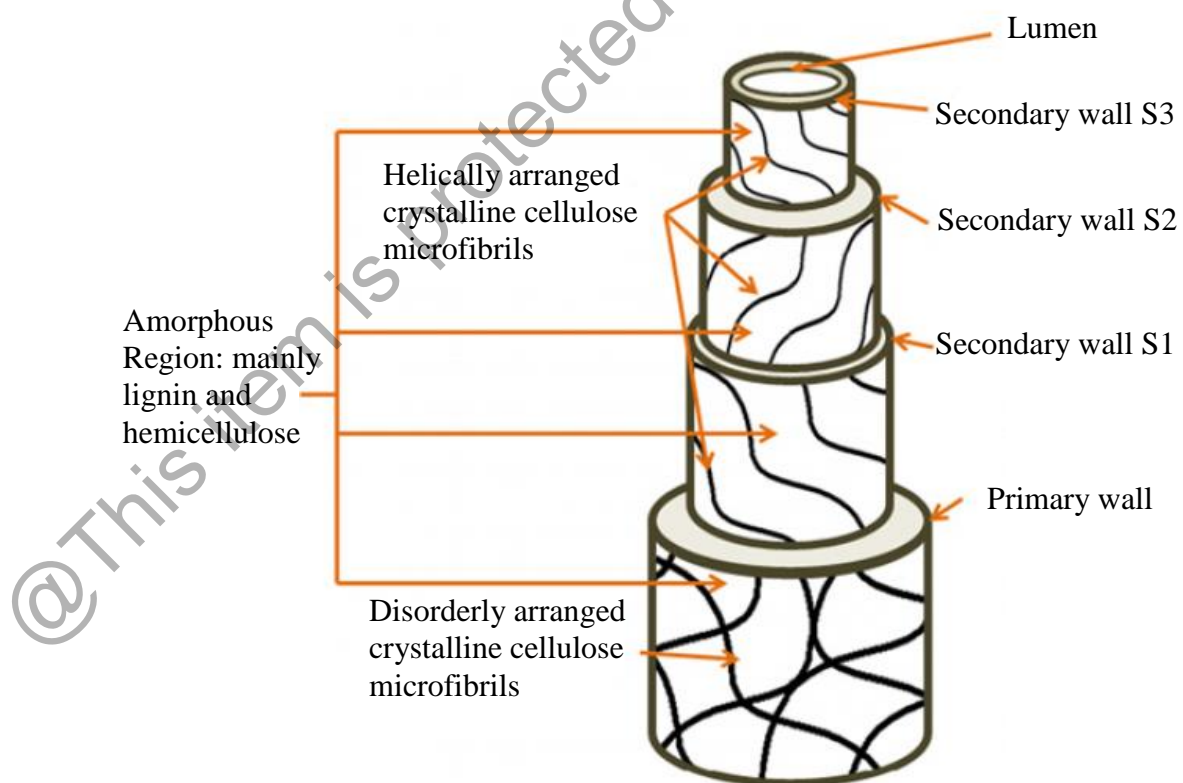


Figure 2.2: Structure of single fibre cell (John & Thomas, 2008).

The natural fibre can be categorised according to their sizes, shapes, the thickness of the wall, and orientations. However, the dimension of the individual cells is an essential aspect in determining the fibre strength. Species, fibre maturity, and fibre extraction process differ the diameter, width and length of the fibres obtained (Jawaid & Abdul Khalil, 2011). Faruk et al., (2012) states that the plant-based fibre can be separated into several groups. Bast based fibre contain higher cellulose content and microfibrils were oriented in the direction of the fibre are common fibre that can be seen in the literature. Besides, the natural fibre is renewable and recyclable, fewer residues when burned for disposal, and emits less carbon dioxide (CO₂) to the environment. Table 2.1 listed the advantages and disadvantages of the natural fibres.

Table 2.1: Advantages and disadvantages of the natural fibres (Jawaid & Abdul Khalil, 2011).

Advantages	Disadvantages
High strength and stiffness	Low strength
Low processing energy	Varies in quality, depend on fibres sources
Good insulator behaviour	Low durability
Excellent thermal and acoustic insulating properties	Poor fire resistant

Hemp fibre is produced mainly in China and United Kingdom which extracted from the bast of the Cannabis sativa plant. It has been widely used in the producing clothes, cord, and potentially in the fibre reinforced polymer area in constructing the composite. They have started manufacturing the hemp fibre for the non-structural component due to its high strength characteristic and lower price (Karus & Kaup, 2002). The flexural strength and modulus strength of the hemp fibre reinforced unsaturated polyester composites are reduced with the increase of fibre content (Sawpan et al., 2012). Hemp fibre reinforced modified polypropylene composite had higher energy absorbs, and energy dissipates at 30 wt% fibre loading. The hemp fibre can be an alternative material to conventional Polypropylene/glass fibre composite that can be used in the automotive parts (Panaitescu et al., 2015).

Yuanjian & Isaac, (2007) also studies on the hemp fibre reinforced unsaturated polyester composite that was subjected to the low-velocity impact test. The test was conducted to study the effect of the non-woven hemp fibre reinforcement on the impact properties. A significant improvement in the load bearing capability and impact energy absorption due to the hemp fibre reinforcement. Perrier et al., (2017) investigated the effect of water absorption on the non-treated hemp yarn. They observed that the crack area getting larger after 5 minutes the composite been removed from the water. Furthermore, the tensile and flexural properties of the composites were decreased due to the effect of moisture behaviour. The hemp fibre reinforced polyester composite exhibit non-Fickian behaviour at room temperature, whereas at elevated temperature its exhibit non-Fickian (Dhakal et al., 2007).

2.3 Matrix Materials

The composite is produced by mixing the reinforcement fibre with the matrix. The plastic matrix has a characteristic such as low in strength, stiffness, and density. Meanwhile, the reinforcement fibre has a high strength and stiffness characteristic, but they need a medium to hold the fibre together when transferring the loads among them. Thus, the matrix acts as a binder that holds the reinforcement material together and distributes the load applied to the reinforced fibres (Isaac & Ori, 2013). Also, the matrix protects the surface of the fibres from the adverse environmental effects that occur during the composite fabrication. The matrix is classified into polymer, metal, ceramic, carbon and graphite. Meanwhile, the polymer matrix is divided into two groups which is thermoset and thermoplastic matrix such as epoxy and polystyrene, respectively.

Thermoset resin is a plastic material that initially a liquid monomer. Thermosetting consist of cross-linked polymer joined together during the curing process in forming an irreversible chemical bond. Once the thermoset resin is hardened, it cannot be melted, reshaped, or reprocessed by applying the heat. The cross-linking prevent the product from remelting when heat is applied to make it suitable to be used for electronic appliances. Besides, the thermoset is brittle at room temperature and have low fracture toughness. When the composite is exposed to water, the cellulose present within the fibre caused the water molecules to penetrate the interfaces of the microcracks (Akil et al., 2011). This cause the changed in the composites dimensions and initiated microcracks within the matrix which eventually decreased the strength and stiffness of the composite. Moreover, the fibre/matrix adhesion can be improved by using a suitable chemical treatment on the fibre and select the matrix based on its properties.

2.4 Composite Material

2.4.1 Hybrid Composites

Nowadays, the hybrid composites are widely used in the automobile and industrial application. They are composites having into two or more reinforcement materials incorporated in a mixture and filling materials in a single matrix (Fu et al., 2002). The hybrid composite improved the single fibre by utilising one of the positive attributes to reduce the low properties of other fibre in the composite (Jawaid & Abdul Khalil, 2011). The hybrid composite properties are influenced by the fibre content, fibre length, and orientation of fibres. The selection of the constituent fibre for the hybrid composite affected the hybridisation purpose and the requirement of the material being constructed.

The selection of compatible fibres and fibres properties is the critical aspect of designing the hybrid composite (John & Thomas, 2008). This is important in order to achieve the best performance of the hybrid composite. A previous study found that the sisal and oil palm fibres are compatible combinations for the hybrid composite due to high tensile strength and toughness of the sisal and oil palm fibres, respectively (Jacob et al., 2004). Hybrid composite has a broader range in the potential application due to its advanced criteria than that other fibre reinforced composites. Furthermore, the natural-synthetic composite gives potential advantages in the fibre hybridisation area (Dan-Mallam et al., 2014; Ridzuan et al., 2016). They studied the potential hybridisation of kenaf/PET and Napier/glass reinforced composites. The advantages of the hybrid composites could complement the other fibre constituent.

As the result of the hybridisation between the fibres, a balance in cost and performance whether in thermal and mechanical can be achieved. Khanam et al., (2010) found that the mechanical properties of sisal fibre reinforced polyester composites were improved with the addition of carbon. Also, the mechanical properties of woven jute/glass fabric were investigated by Ahmed & Vijayarangan, (2008). Dan-Mallam et al., (2015) stated that hybridisation of kenaf with PET reinforced POM composite improves the mechanical performance of the composites due to the high strength of PET fibre. The polymer composite can be possibly hybridised with a different combination such as the synthetic/synthetic fibre, cellulosic/cellulosic fibre, and cellulosic/synthetic fibre (Jawaid & Abdul Khalil, 2011). Figure 2.3 shows the three main hybrid configuration of the composites for the two fibre in a single polymer matrix case. This configuration consists of (a) interlayer or layer-by-layer, (b) intra-yarn or fibre-by-fibre, and (c) intra-layer or yarn-by-yarn.

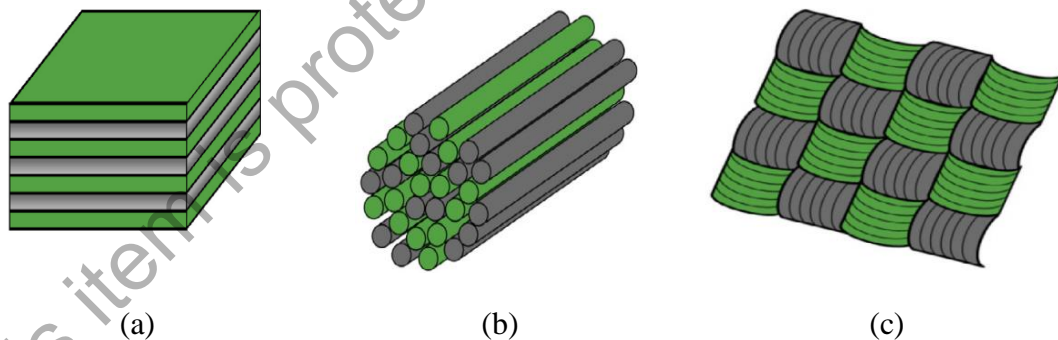


Figure 2.3: Hybrid configurations; a) interlayer, b) intrayarn, and c) intralayer (Swolfs et al., 2014).

2.4.1.1 Synthetic/Synthetic Fibre Reinforced Composites

The polymer composites with the hybrid that solely of synthetic fibre were explored by some researcher even though they are non-environmental friendly. The glass/carbon reinforced polymer composite not only reduce the cost, but also exhibit similar flexural properties as the carbon fibre polymer composite (Wu et al., 2006). Some hybrid composite such as carbon/glass reinforced epoxy hybrid composite that works as a load bearing in the voltage electric transmission was capable of operating at higher temperatures when being compared to the other conventional conduction. This is due to the characteristic of thermal expansion of the carbon fibre. Besides, the hybrid composite also enhanced the electric energy transmission with more efficient (Burks et al., 2011). Furthermore, the hybrid composite of glass/carbon reinforced epoxy composites have the capability to resist breaking that is suited for use as the warning sign structural applications (Czél & Wisnom, 2013).

2.4.1.2 Cellulosic/Cellulosic Fibre Reinforced Composites

Due to the environmental awareness, the potential of solely constituted cellulosic fibre hybrid composite was investigated even though there are less reported by the researcher in the literature. FlexForm Technologies used the reinforcement material of the mixed hemp and kenaf fibres in the composite fabrication such in Chrysler's Sebring convertible door panel and currently looking to produce the vehicle part with the help of other natural fibre composites (Jawaid & Abdul Khalil, 2011). Previous study reported that the physical properties were improved for the hybrid EFB/jute reinforced epoxy composite. Besides, hybrid EFB/jute composite has higher in tensile and young modulus

than those EFB composite (Jawaid & Abdul Khalil, 2011; Jawaid et al., 2013). This can be concluded that the superior properties are contributed by the strong interphase bonding of the hybrid composite. Another study shows that mechanical properties of the banana reinforced epoxy composite were improved with the hybridisation of sisal fibre in the composite (Venkateshwaran et al., 2011).

2.4.1.3 Cellulosic/Synthetic Fibre Reinforced Composites

The cellulosic fibre combined with the synthetic fibre (glass) in such producing the polymer composite is commonly found in the literature due to the rapid growth of natural based fibre. Researchers indicate that, the introduction of the glass fibre with cellulosic fibre reinforced composites such as jute, hemp, kenaf, Napier, and banana yielded superior mechanical properties than those of the single fibre reinforced composites (Bhoopathi et al. , 2014; Braga & Jr, 2015; Ridzuan et al., 2016). In addition, an exciting research work done by Davoodi et al., (2010), developed a passenger car bumper beam from the hybrid of kenaf and glass composites. The composite possesses similar mechanical properties except in impact properties as the typical bumper beam. This work represents that the hybridisation of kenaf/glass can be utilised in the future work for the use of making a structural component of the car.

2.4.2 Woven and Interwoven Hybrid Reinforced Composites

The fibre orientation is the crucial feature for the excellent properties of the hybrid composites. This criterion can be obtained from the composite when the fibre is placed in the aligned direction of the applied load when testing (Pickering et al., 2016). The textile processing method such as weaving, knitting, and braiding is used to give the fabric a greater fibre alignment (Misnon et al., 2015). Figure 2.4 shows that the fabrics form of the composite before fabrication process. This indicates that the fabric is much easier to handle during the composite process and the good fibre orientation increased the fibre/matrix wettability. Moreover, to improve the mechanical properties, the positioning of fibre in the matrix and fibre distribution should be considered (Dan-Mallam et al., 2014).

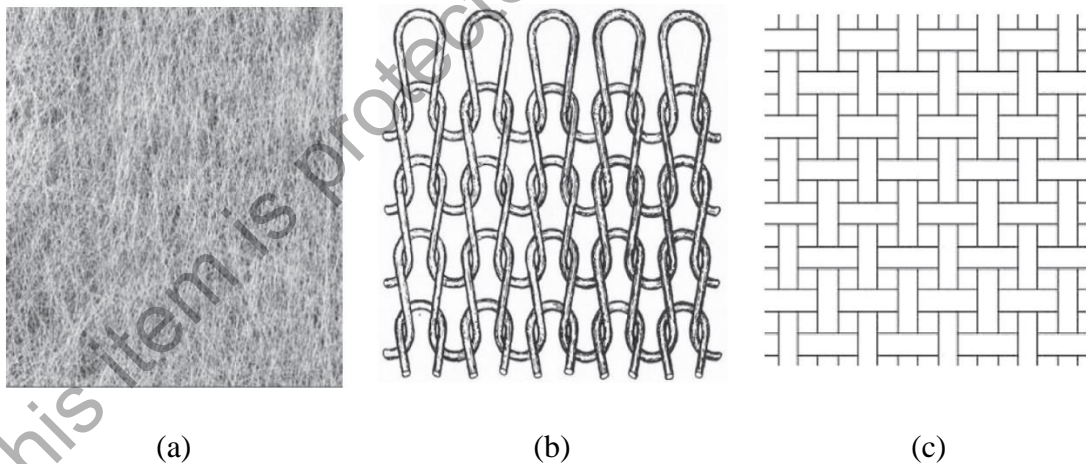


Figure 2.4: Weaving type; (a) random, (b) knitted, and (c) woven (Misnon et al., 2015).

In addition, weaving is done by interlacing two sets of the fibre bundles (yarn) to form the woven fabric layers. The weaving fibre will give the high strength of the fibre due to the better intertwining with the matrix. Meanwhile, the interwoven fabric use different sets of fibre bundles when weaving. Thus, gives them a better high packing density and excellent dimension stability. These woven and interwoven hybrid fabrics of the weaving process are shown as in Figure 2.5. For example, the plain weave states that the yarn that runs along the length of fabric is the warp yarn while the weft yarn is the yarn that weaved passing over and underneath the warp yarn (Salman et al., 2015). As reported by the previous researcher, the mechanical properties (tensile, flexural, and impact) of the woven and interwoven fabric are superior to those of randomly oriented and unidirectional composites (Alavudeen et al., 2015; Khan et al., 2016; Venkateshwaran et al., 2011).

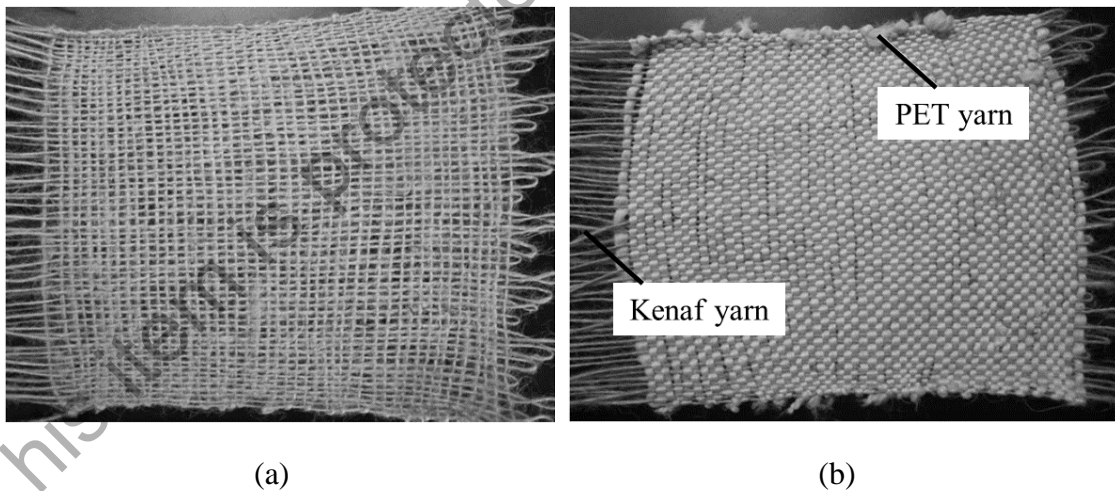


Figure 2.5: Fabric types; a) woven fabric and b) interwoven hybrid fabric (Dan-Mallam et al., 2014).

The interlocking structure of the reinforced fibres of the woven fabric also increases the strength of the composite due to the uniform distribution of stress in the matrix (Dan-Mallam et al., 2013, 2014). Khan et al., (2016) states that, the mechanical properties of the woven jute reinforced poly (L-lactic acid) composite exhibit greater strength when the fibre is tested along the warp direction than those of the weft direction. This indicates that the fibre orientation of the composite influenced the strength of the composite. Besides, a study by Yahaya et al, (2016) about the layering sequence of the woven kenaf aramid hybrid composite in the mechanical properties show promising potential for the high-velocity impact application. Another successful finding by Sapuan, (2005) on the fabrication of household telephone stands using the woven banana/epoxy composites was able to replace the conventional material in the furniture industry.

2.5 Fabrication Method

The natural fibre reinforced composite commonly used extrusion, injection and compression moulding fabrication technique to produce in the composites manufacturing. These fabrication methods have been developed to meet the specific designs of the product. The material, application, and product design influenced the fabrication methods selection for developing the composite product. The extrusion process transport softened thermoplastic beads or pellet mix with the fibre by means of single or double rotating screws. Then it is compressed and forced out from the chamber at a constant rate through a die. Meanwhile, the injection moulding makes a variation of fibre occur across the mould with shear flow along the wall because of friction results in fibre aligned. This fabrication technique can be carried out with the thermoplastic and thermoset matrices. However, the injection moulding is limited to the composites of less

than 40 wt% fibre content due to the viscosity requirement. The compression moulding is the most well know method due to its low cycle time and high reproducibility. It is used for the mat, randomly oriented or aligned fibre with stacked alternately before heat and pressure are applied. Good quality of composite can be produced by controlling the pressure, the temperature for the type of fibre and matrix, holding time and the viscosity (Pickering et al., 2016).

2.5.1 Vacuum Infusion Technique

From the fabrication technique mentioned, vacuum infusion is one of the methods that provide better fibre to ratio, biodegradable, cleaner, less excess resin, and consistency in the resin usage (Salman et al., 2015). This process is suitable for low producing product and at the same time the component strength can be achieved for the specimens. Besides, this technique differs from the hand lay-up method because of the in-mould laminate air pressure during composite production (Wanberg, 2009). Epoxy and phenolic are the types of resin suitable for this method. The vacuum infusion system consists of the main component which is a vacuum pump, resin distribution channel, glass plane, and vacuum bag to construct the vacuum mould (Boccarusso et al., 2016).

For the vacuum environment, the air inside the mould needs to be evacuated before starting with the infuse resin mixture. The vacuum infusion laminate is illustrated as in Figure 2.6. This step could be done by controlling the in-mould pressure to be approximately below 300 Pascal (Petrucci et al., 2013). This action was done to reduce bubble formation in the composite during the suction process by the vacuum pump. The resin would flow through the moulded laminate and with the excess resin flow into the residual resin container. The vacuum bags help to reduce the high amount of volatiles emitted during the curing process. However, this method has extra labour work and disposable bagging material waste.

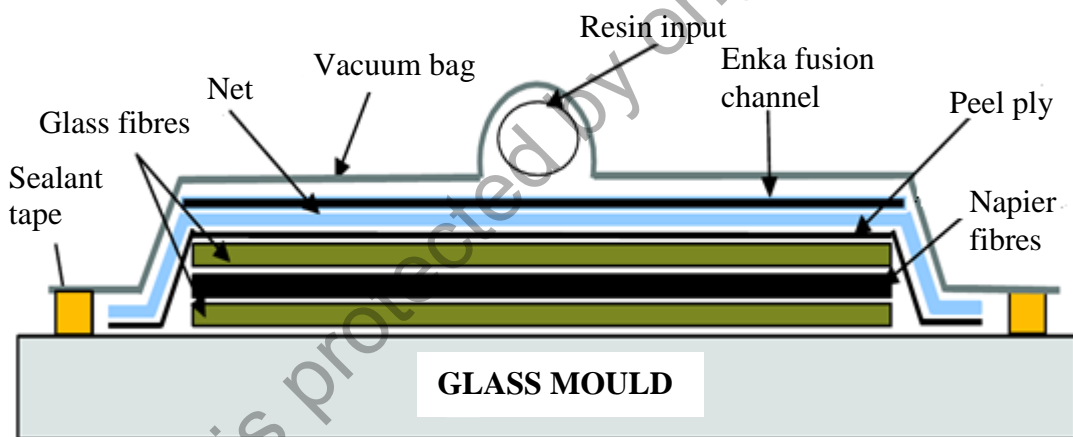


Figure 2.6: Vacuum infusion laminates (Ridzuan et al., 2016).

2.6 Composite Properties

2.6.1 Water Absorption Behaviour

The presence of polar groups (-OH) in the natural fibre based composite allow them to absorb moisture from the environment and also make them incompatible with the polymer matrix. Haameem et al., (2016); Salleh et al., (2012) shows that, the presence of water to the natural based composite weaken the mechanical properties and dimensional stability of the composites. This factor also leads to poor fibre/matrix bonding of the composite. Besides, a similar conclusion that had been arising found that the water absorption affects the mechanical properties of the interwoven kenaf/jute and kenaf/hemp hybrid composites following their immersion in tap water at room temperature (Maslinda et al., 2017).

The water absorption behaviour is affected by several factors such as diffusivity, interfacial bonding, fibre type, fibre volume fraction, temperature, and the reaction between water and matrix (Akil et al., 2014). According to the diffusion of water, three ways allow the water molecules to penetrate the composite. Firstly, the water goes through the composite interphase due to the poor wettability of the fibre and matrix. Second, the water went through the crack of the polymer matrix that produces from the fibre swelling. The third one is that the water went through the micro gaps between the polymer chains (Espert et al., 2004).