SCHOOL OF MATERIALS AND MINERAL RESOURCES ENGINEERING

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MECHANICAL AND ACOUSTIC PROPERTIES OF NONWOVEN NEEDLE PUNCHED FLAX FIBRE MAT/ ACRODUR RESIN COMPOSITE

By

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DECLARATION

I hereby declare that I have conducted, completed the research work and written the dissertation entitled '**Mechanical and Acoustic Properties of Nonwoven Needle Punched Flax Fibre Mat/ Acrodur Resin 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 of any other examining body of university.

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LIST OF ABBREVATIONS

ASTM	American Society of Testing Material
FRP	Fibre reinforced polymer
ROM	Rule of mixture
SEM	Scanning electron microscope
SENT	Single edge notched tension

LIST OF SYMBOLS

E_c	Modulus of composite
E_f	Modulus of fibre
E_m	Modulus of matrix
V_f	Volume fraction of fibre
V_m	Volume fraction of matrix
ρ	Theoretical density of composite
ρ_c	Experimental density of composite
ρ_f	Density of fibre
ρ_m	Density of matrix
W_f	Weight fraction of fibre
W_m	Weight fraction of matrix
w_f	Weight of fibre in composite
w_m	Weight of matrix in composite
σ	Strength of composite
K	Stress intensity factor
y	Geometry factor
a	Notch length of fracture toughness sample
W	Width of fracture toughness sample
B	Thickness of fracture toughness sample
P	Maximum load in fracture toughness testing
r	Radius of fibre
R	Fibre separation
wt%	Weight percent

α	Sound absorption coefficient
α_o	the coefficient of the dispersion medium (matrix)
α_η	the coefficient due to friction between particles (fillers) and the medium (matrix)
α_T	the coefficient related to the heat exchange between the particles and medium
α_S	the coefficient of attenuation of the acoustic wave in forward direction due to scattering by the particles
E_a	Energy absorbed by the sample
E_i	Total energy incident on the sample
η_L	Fibre length distribution factor
η_O	Fibre orientation distribution factor

SIFAT-SIFAT MEKANIKAL DAN AKUSTIK KOMPOSIT ACRODUR GENTIAN FLAX TIDAK TERANYAM

ABSTRAK

Kesan pemprosesan ke atas sifat mekanikal dan akustik gentian flax tidak teranyam/ Acrodur damar telah dikaji. Sampel telah dihasilkan dengan menggunakan kaedah pemprosesan impregnasi dan manual, kemudian dimampatkan menjadi komposit dengan ketebalan 1 mm. Sifat-sifat mekanikal bagi komposit dicirikan oleh ujian tegangan, lenturan dan keliatan patah, manakala sifat-sifat morfologi dicirikan oleh mikroskop imbasan elektron (SEM). Selain itu, sifat akustik ditentukan menggunakan tiub galangan. Tegangan dan sifat-sifat lenturan, serta keliatan patah didapati lebih baik dalam komposit yang diperbuat daripada kaedah pengisitepuan. Walau bagaimanapun, komposit disediakan secara manual telah mempunyai kandungan rowong yang lebih tinggi, yang menyebabkan penyerapan tenaga akustik yang lebih baik. Selain itu, kesan anisotropi ke atas sifat mekanik telah dikaji, tetapi perbezaan yang didapati adalah tidak signifikan. Kesan pecahan isipadu gentian ke atas sifat mekanik dan akustik komposit telah dikaji. Semua sampel disediakan menggunakan kaedah pengisitepuan dan dimampatkan ke ketebalan yang berbeza, untuk mengubah isipadu gentian. Kemudian, ujian mekanikal, morfologi dan akustik yang sama telah dijalankan untuk mendapatkan ciri-ciri komposit. Tegangan dan sifat-sifat lenturan, serta keliatan patah didapati lebih baik dalam komposit dengan pecahan isipadu gentian yang lebih tinggi. Walau bagaimanapun, komposit dengan pecahan isipadu gentian yang lebih rendah mempunyai penyerapan akustik yang lebih baik. Selain itu, kajian telah mendapati bahawa anisotropi gentian tidak menunjukkan kesan yang besar ke atas sifat-sifat mekanikal komposit.

MECHANICAL AND ACOUSTIC PROPERTIES OF NONWOVEN NEEDLE PUNCHED FLAX FIBRE MAT/ ACRODUR RESIN COMPOSITE

ABSTRACT

The effect of processing method on the mechanical and acoustic properties of nonwoven flax fibre mat/Acrodur resin was studied. The prepregs were produced using both impregnation line and hand lay-up methods, then compressed into composites with the same thickness of 1 mm. The mechanical properties of the composites were characterized by tensile, flexural and fracture toughness tests, while the morphological properties were characterized by scanning electron microscope (SEM). Also, acoustic properties were determined using impedance tube. The tensile and flexural properties, as well as fracture toughness were found to be better in composites manufactured from impregnation method. However, the composites prepared from hand lay-up method have higher void content, which results in better acoustic absorption. Besides that, the effect of anisotropy on mechanical properties were studies, but there was no significant different found between composite in longitudinal direction and transverse direction. Furthermore, the effect of volume fraction of fibre on mechanical and acoustic properties of composite was studied. All prepregs were fabricated using impregnation method, and compressed into different thicknesses, to vary the volume fraction of fibre. Then, the same mechanical, morphological and acoustic testings were carried out to characterize the composites. The tensile and flexural properties, as well as fracture toughness were found to be better in composites with higher volume fraction of fibre. However, the composites with lower volume fraction of fibre have better acoustic absorption. Apart from that, it was found that the anisotropy of fibres did not show significant effect on the mechanical properties of composites.

CHAPTER 1

INTRODUCTION

1.1 Background

FRP usually referred to as fibre reinforced polymer composite is a quite new material in the various applications such as construction and building industry compared to concrete and steel (Saba, 2015). Carbon, aramid, glass, high modulus polyethylene, boron fibres are very common for composite reinforcement and they already gained a reputation due to their excellent properties such as lightweight, high strength to weight ratio and high thermal stability. They are also known as high-performance reinforcement besides they dominate the aerospace, automotive, leisure, construction and sporting industries. Although these fibres/fabrics are excellent in terms of mechanical properties, they also possess some drawbacks such as high cost, non-biodegradable, non-recyclable, high health risk when inhaled, high-energy consumption and high density (Misnon, 2014).

In recent years, there has been a growing interest for the use of renewable materials such as plant fibres, also known as lignocellulosic fibres, due to the unique criteria of these fibres. These include abundant availability, renewability, biodegradability, as well as reduced weight, increased flexibility, greater moldability, reduced cost and sound insulation (Merkel, 2014). The shortage of petroleum and environmental concern has resulted in a considerable increase in the usage of renewable natural resources in recent years. Lignocellulosic natural fibres can be obtained from pulping processes, such as thermal mechanical pulping or chemical pulping. These fibres, processed from wood, kenaf, hemp, flax or more, may be used as reinforcements in the polymer composites for both non-structural and structural applications, including but not limited to doors, decking, window frames, fencing, flooring, walls, automobiles furniture, and electronic products (Liang, 2014).

Due to world population awareness on the environmental issues, there is an interest of research which focusing on the developing, creating and innovating eco-friendly materials. Natural textile fibres offer a good opportunity to be used as reinforcements in composite materials (Misnon, 2013).

The use of flax fibres as reinforcement is not a recent innovation due to their high-performance mechanical properties, low density and natural origin (Goudenhooft, 2017). According to Haag (2017), different processing techniques of flax fibres give significant effect on the composite properties. The highest strength and modulus values can be achieved by pultrusion, where composites with high fibre content, high orientation and low damage of the fibre can be produced. However, pultruded products will have limited shape complexity as compared to compression moulding. Thus, in this study, compression moulding method was used to fabricate the composites.

Due to the strong polar character of natural fibres, the problems of incompatibility are found with most thermoplastics especially polyolefins (Khalfallah et. al., 2014). Thus, in this study, Acrodur resin was used. Acrodur resin is a thermoset acrylic polyester resin that exhibits a good adhesion with natural fibres. Apart from that, it can be cured under short hot compression time (Khalfallah et. al., 2014).

1.2 Problem statement

Flax fibres have become the focus of intense interest because of their tremendous advantages such as low density, biodegradability and excellent mechanical properties. Hence, this research aims to study the effect of different processing methods and fibre loading on the mechanical, morphological and acoustic properties of the flax fibre/ Acrodur resin composite.

Nowadays, the manufacturing processed using modern equipment, usually generate higher sound pressure. This implies the need of new sound absorbing materials in order to improve the human comfort. The undesired noise mainly presence in the automotive industry and building, which increase the demand of sound absorbing materials. The commonly used materials are usually unporous, such as ceramic tile, concrete, cement, fibreboard and plywood. These materials are characterized by poor sound absorption properties, where they are having sound absorption coefficient below 5%, under frequency of 125 Hz to 8000 Hz (Markiewicz, 2012). Hence, the use of composites made from nonwoven needle punched flax mat with Acrodur resin as sound absorbers was proposed. Basically, the composites with higher void content shows better acoustic absorption performance (Markiewicz, 2012). However, a balance between the mechanical performance and their damping properties should be considered.

1.3 Objectives

i. To determine the effect of different processing methods (hand lay-up & impregnation) on the mechanical and acoustic properties of flax fibre mat/ Acrodur composites.
ii. To study the effect of volume fraction of filler on the mechanical and acoustic properties of flax fibre mat/ Acrodur composites.
iii. To validate composite models in predicting the modulus of composites.

1.4 Organization of thesis

Chapter 1 introduces the development of natural fibre composites in the recent years and their applications. The problem statement, objectives, organization of thesis and scope of study are included in this chapter.

Chapter 2 includes the literature review of this study. The properties of flax fibre and Acrodur resin are discussed together with different manufacturing, testing and characterization methods for FRP. Besides that, the development of composite models is presented in this chapter.

Chapter 3 provides the information about the material and method used in this study. The equations used to calculate the density of composite, volume fraction of fibre, volume fraction of voids are included. Also, the general description of the sample characterization methods such as tensile, flexural, fracture toughness, morphological and acoustic are given in this chapter.

Chapter 4 focuses on the experimental result and discussion. Further elaboration on the effect of different processing methods and fibre loading on mechanical, morphological and acoustic properties of flax fibre/ Acrodur resin composites are provided in this chapter. Also, the experimental modulus values are compared with the predicted values from composite models.

Chapter 5 summarizes the significant findings in this study. Suggestions for future studies are also recommended.

1.5 Scope of study

In this study, nonwoven flax fibre mat/ Acrodur resin composites were prepared via compression moulding. The prepregs were first prepared by using impregnation line or hand lay-up, followed by compression moulding. The effects of different prepregs fabrication methods on mechanical, morphological and acoustic properties of the flax fibre/ Acrodur resin composites were studied. The flax fibre/ Acrodur resin composites with different volume fractions of fibres were also prepared by using impregnation line and compression moulding. The effects of fibre loading on the mechanical, morphological and acoustic properties flax fibre/ Acrodur resin composites were investigated. The mechanical properties of the flax fibre/ Acrodur resin composites were characterized by tensile, flexural and fracture toughness testings. Also, morphological properties of the composites were characterized by using scanning electron microscope (SEM). Sound absorption coefficient of flax fibre/ Acrodur resin composites were obtained by using a four-microphone impedance tube. Composite models were used to predict the modulus of the flax fibre/ Acrodur composites, and the predicted values were compared with the experimental values.

CHAPTER 2

LITERATURE REVIEW

2.1 Composites

Composites are referring to materials which consist of two or more different constituents or phases, where the combination of the distinct materials results in a material with totally different properties from the individual components. Typically, composites would consist of a stiff and strong reinforcement phase, which is embedded in a continuous matrix phase. The matrix is often weaker and less stiff than the reinforcement materials. Composites show an interesting feature, where the different phases often act synergistically, leading to resultant material with improved properties (Hughes, 2000).

There is an increased in the demand for natural fibre reinforced composites because natural fibres offer both reduction in density and cost savings as compared to synthetic fibres. Even the strength and modulus of natural fibres is not as high as synthetic fibres such as glass fibres, specific properties of these two fibres are comparable. This raised the interest of car manufactures on integrating natural fibre composites, either for interior or exterior parts (Messiry, 2013).

There are several factors affecting the performance of fibre-reinforced composites, which include the processing methods and volume fraction of fibres. These parameters can alter the properties in different aspects, namely by affecting the properties of the fibre-matrix interface. Good interfacial bonding is a primary requirement to maximize the reinforcement properties, where it ensures efficient load transfer from matrix to reinforcement (Gu, 2000).

2.1.1 Matrix

Matrix is an important component in composite because the matrix properties will affect the resistance of the composites to degradative processes, which can eventually cause failure of the structure. For instance, impact damage, water absorption, chemical attack, delamination and high-temperature creep (Nichols, 1988).

Apart from that, loads applied to the composite will be transferred to the fibres, which acts as the principal load-bearing component in the composite, through the matrix. This stress transfer mechanism then enables the composite to withstand compression, shear and flexural forces, as well as tensile loads. The quality of the fibre-matrix interfacial bonding is the main factor which affects the efficiency of this load transfer (Messiry, 2013).

For polymer composites, the matrix phase can be classified into two, which are thermoset and thermoplastic (Nichols, 1988). Thermoset resins are predominating, meanwhile thermoplastic plays only minor role in advanced composites manufacturing. This is because thermoset resin is initially low viscosity liquid under room temperature, which make it very versatile and easy to work with. It can be used for producing composites with complex shape and large size.

Under uncured state, thermoset resin is having high flowability, thus providing better wetting to the reinforcement material. During curing, gelation starts to happen, where the thermoset resin loses its ability to flow, then resulting in poor processability. Eventually, it will form strong covalently bonded crosslinks network. This high crosslink densities between the polymer chains in thermoset will improve their strength and modulus (Jr, 2006).

2.1.2 Reinforcement

The function of reinforcement material in composite is to bear the load in the composite system. This load carrying ability makes the composite to have higher mechanical properties as compared to the neat resin system. In advanced composites, the reinforcing fibres play important roles for their high strength and stiffness. The choice of reinforcement in the composite system is important for the properties of the composites, which include mechanical properties such as modulus, strength and stiffness (Clyne, 1996).

Basically, the types of reinforcement can be classified into two, which are particle and fibre reinforcement materials. Particles usually have aspect ratio of about one, whereas fibres have higher aspect ratio. Hence, fibres can provide better reinforcement to the composite system, thus, being widely used in high-end application (Nichols, 1988).

Fibres can be divided into two types, which are synthetic and natural fibres. Partial biodegradability is a very important feature of natural fibres reinforced composite (Ewa Markiewicz, 2012). Recently, the strict environmental regulations are leading to increasing interest in renewable resources, such as bio-based materials (Bodros, 2007).

Natural fibres can be subdivided based on their origins. As shown in Figure 2.1, they can be derived from animals, plants, or minerals (Akil et.al., 2011).

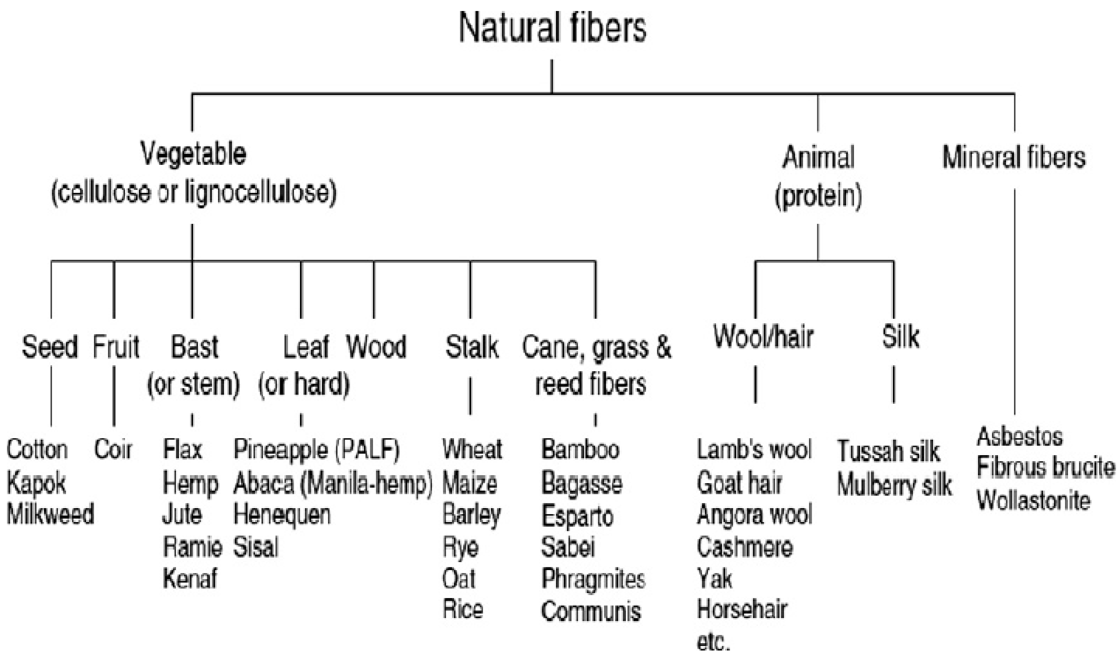

Figure 2.1: Classification of natural fibres (Akil et.al., 2011).

Nowadays, many automotive parts are being made from flax fibre reinforced polymers. Eco-friendly marketing of flax fibre composites is the principal reason for their adoption in automotive industry, rather than technical demand. However, due to the short fibre length, the mechanical properties of natural fibres are relatively low. Therefore, flax fibre composites are mainly being used for non-structural automotive parts. For example, car roof, door panel and parcel shelves (Summerscales, 2010).

2.1.3 Fibre microstructure

There are several factors which will affect the composite properties. For instance, fibre orientation is a contributing factor to the performance of composite. This is because the higher the proportion of fibres in the loading direction will dominate the fibre behaviour in the composite (Haag, 2017).

However, the relative proportions of the phases, or in the other word, volume fraction of the components (V_f), is the most important parameter that determine the properties of the composite. Since reinforcement is generally having higher strength and stiffness as compared to the matrix, the composites will have better strength and stiffness when they are having a high volume fraction of reinforcement. However, there is an upper limit of V_f, where above the limit, the mechanical properties of the composites will be reduced. This is because when the amount of resin is relatively lesser than fibre, the resin may not be enough to wet all the fibres, thus, stress transfer mechanism cannot be performed effectively during application of load (Clyne, 1996).

Ideally, fibres should be assembled in hexagonal close packing, in order to obtain high fibre volume fraction composite. By assuming that the fibres are of circular cross section of radius r, mathematical models have been developed in order to predict the fibre volume fraction in composite. The mathematical model used to calculate volume fraction of fibres in hexagonal close pack are as shown in Equation 2.1 (Messiry, 2013).

$$V_f = \frac{\pi}{2\sqrt{3}}(\frac{r}{R})^2 \qquad \text{Equation 2.1}$$

Where V_f is the volume fraction of fibre, r symbolized radius of fibre and R is referring to the fibre separation.

Figure 2.2 illustrates the hexagonal close packing of fibre in composite system. A maximum volume fraction of fibre will be obtained if the fibre separation, R is equal to the radius of fibre, r. By substituting R=r in Equation 2.1, the maximum value of volume fraction of fibre will reach 0.907. This maximum volume fraction of fibre will only be acquired by assuming fibres are perfectly oriented in hexagonal close packing (Messiry, 2013).

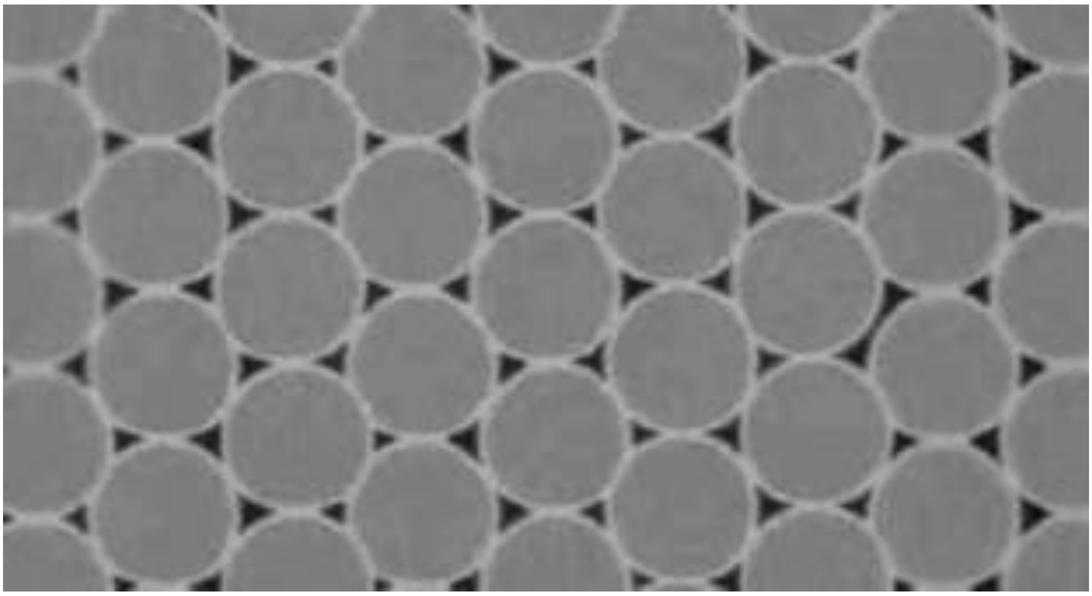

Figure 2.2: Hexagonal close packing fibre arrangement in composite cross section (Messiry, 2013).

2.2 Acrodur resin

Acrodur® resin is manufactured by BASF. It is an aqueous acrylic resin, which based on polycarboxylic acid and polyalcohol, so, it is free of phenol and formaldehyde (Rasyid, 2016).

In order to optimize the adhesion of other hydrophobic polymer matrices on natural fibres, treatment of either fibre or matrix is needed, due to the hydrophilic nature of natural fibres. However, Acrodur resin is able to form hydrogen bonding with the hydroxyl groups present in cellulose of natural fibres, through ester groups. Since it does not show adhesion problems with natural fibres, the processing costs of Acrodur resin composite will be lower, by avoiding treatments on either the resin or the fibres (Khalfallah et. al., 2014).

Epoxy resin is a common thermoset resin used in fabricating polymer composite. It needs more than 1 h at 150 ^{o}C - 200 ^{o}C to form cross-linking between the polymer chains. However, Acrodur resin is a water-based resin, where the cross-linking needs less than 3 minutes curing time at 160-180 ^oC. This reduction in processing time can then decrease the production cost, which make it a more favourable choice (Khalfallah et. al., 2014). The curing mechanism of Acrodur resin is as shown in Figure 2.3.

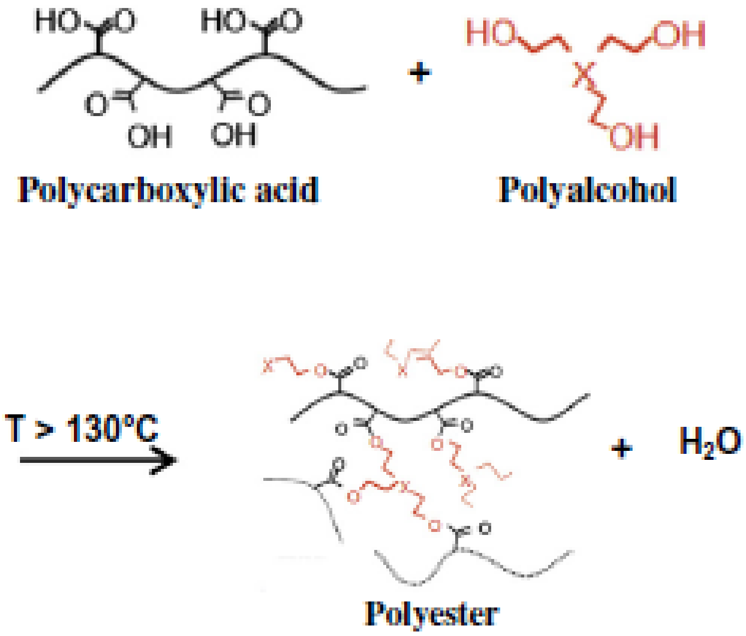

Figure 2.3: Crosslinking reaction of Acrodur resin (Khalfallah et. al., 2014).

2.3 Flax fibre

Cellulose is the main constituent of any plant fibre. It is the natural homopolymer (polysaccharides), where its structure is shown in Figure 2.4. It is composed of three elements, which are C, H, and O, where the general formula is $C_6H_{10}O_5$ (Akil et. al., 2011).

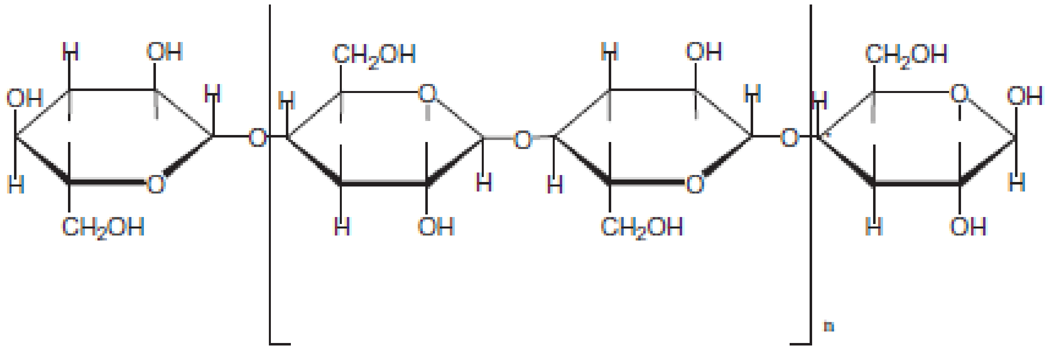

Figure 2.4: Chemical structure of cellulose (Akil et. al., 2011).

Most of plant fibres consists of 65–70% cellulose, which are in crystalline structure. Besides cellulose, the fibre contains lignin and other non-cellulosic substances, which are associates with the cell walls. Their presence can modify the final properties of the fibre (Akil et. al., 2011).

Flax fibres are natural plant fibres which are made up of cellulose. They exhibit some unique mechanical properties. For example, they are having specific tensile strength greater than those of glass fibres. This is contributed by its high strength and low density genuine. Thus, flax fibre is one of the natural fibre which being widely used in automotive industry (Alimuzzaman, 2014).

2.3.1 Needle-punched flax fibre

There are generally three reinforcement forms for fibres, which are fabric, fibre and yarn. When comparing all these reinforcement forms, fabric is easier to handle and is able to maintain its dimensional stability during the composite manufacturing in comparison with other two forms (Misnon, 2014).

Three common fabric types are knitted, woven and nonwoven fabrics, which are produced by knitting, weaving and various nonwoven processes respectively (Misnon, 2014). Nonwoven fabric can be defined as a fabric that produced by a variety of processes except weaving and knitting. Nonwoven webs are commonly used in making composites because they possess lightweight, good blend of strength and flexibility compared to conventional materials such as ceramic, cement and so on (Alimuzzaman, 2014).

Nonwoven is a textile structure fabricated by the interlocking or bonding of fibres, accomplished by mechanical, thermal, chemical or solvent means or combinations of the above ways. One of the main advantages of nonwoven fibres manufacturing is that it is generally a continuous process, where the raw material can be directly transformed to the finished fabric. However, there are some exceptions to this (Misnon, 2014).

Needle punching is the oldest fabricating technique of producing nonwoven products. Figure 2.5 shows the barbed needle that will be used in this needle punching process.

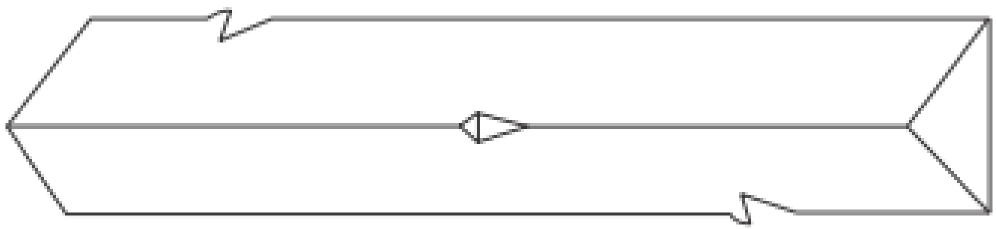

Figure 2.5: Diagram of three needle barbs on a section of a needle (Anand, 2000).

Generally, needle punching method involves the descend of barbed needles into the batt, where the barbs will catch some fibres, then pull them through the other fibres. The loops of fibre which formed at the downstroke tend to remain in position when the needles return upwards, because they are released by the barbs. This needling action interlocks fibres mechanically and holds the structure together. The concept of needle punching is as shown in Figure 2.6 (Anand, 2000).

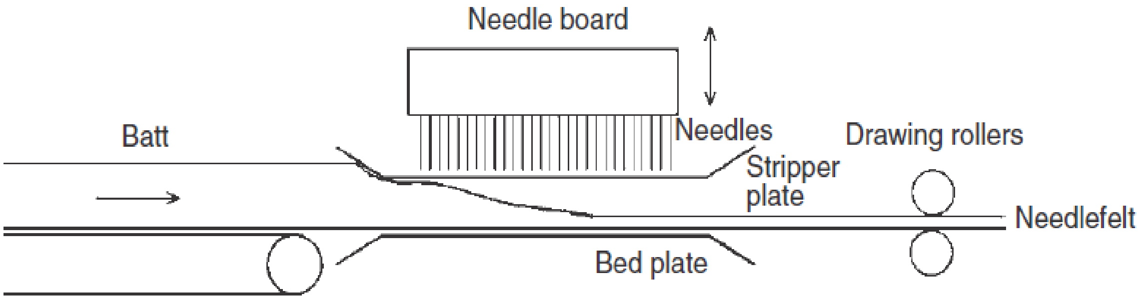

Figure 2.6: Diagram of a needleloom (Anand, 2000).

Needle punching is a method used to give provide sufficient cohesion to a web of fibres by mechanical bonding. During the needle punching process, the fibres are mechanically entangled and hold together by penetrating barbed needles through the web (Martin, 2016).

Number of punches per unit area is known as needle density. The increase in needle density and penetration enhances the fibre consolidation. In the other words, the resistance of the needle-punched nonwoven mat is given by the mechanical entanglement of the fibre (Martin, 2016). However, beyond a certain limit, this punching action will cause greater fibre damage, which leading to deterioration in fibre characteristics (Mukhopadyay, 2005).

2.4 Composites processing of fibres

There are various approaches to fabricate polymer matrix composites. The techniques include vacuum bag, pultrusion, compression moulding resin transfer moulding and others. Among these manufacturing methods, direct component production without intermediate stages will lead to higher non-uniformity in the final component. In this type of fabricating process, two distinct steps can be established, which are the fibres impregnation and stacking, and curing procedure.

Due to the poor drapability of fabrics and prepregs, the fabrication of composites into parts or components with a complex shape induces high cost. These materials can hardly be moulded into complex shapes. As a result, assembly is needed for some composite components. A large number of separate parts need to be joined by adhesive bonding, co-curing or mechanical fastening (Alimuzzaman, 2014).

2.4.1 Hand lay-up

According to Avila (2005), the most important process of composites manufacturing for composites in aerospace application is hand lay-up of prepregs and autoclave cure. Although the fabricating processes have constant technical changes, the hand lay-up process still persists as the technique in use for most of all advanced aerospace composite structures. This is due to the extreme flexibility of hand lay-up, which allows the fabricating of a large variety of shapes. Apart from that, hand lay-up does not require high tooling cost and capital investments.

2.4.2 Impregnation line

In prepreg manufacturing technique, the fibre mats will be pre-impregnated with resin to form prepregs, which can be stored for later use. This method will give a more uniform resin wetting on the fibres, due to consistent apply of pressure on the fibre mats (Medina, 2009).

Basically, the fibre mat will be first pass through a polymer resin bath in this process. Then, nip rollers are used to control the degree of resin take up by the fibre mat. After that, heating chamber will be used to remove the volatiles components. This is to minimize the void formation during curing of composite material (Medina, 2009).

2.4.3 Compression moulding

Compression moulding is one of the conventional methods in manufacturing polymer matrix composites. It is widely accepted as the fabricating process, due to its simplicity (Akil et. al., 2011). Intermediate stages can be used to produce prepregs before moulding operation, in order to obtain composite with minimum defect. The intermediate stages used in this experiment are hand lay-up and impregnation. The effectiveness of these stages to maximize final properties of composites are compared (Akil et. al., 2011).

2.5 Testing and characterization

The composite processing methods', or specifically impregnation methods' quality can be assessed in terms of void content in the final parts. This can be evaluated by mechanical, morphological and acoustic testing. These testing can also be used to evaluated the effect of fibre content in the final properties of composite. The details of each testing will be discussed in this section.

2.5.1 Mechanical testing

The mechanical behaviour of the composite is dependence on a number of parameters. For example, fibre-matrix interface properties, fibres content and orientation, matrix properties and composite porosity are affecting the mechanical properties of the composites (Khalfallah M., 2014).

Porosity is a component which has long been known to show a significant influence on mechanical properties of natural fibre composites in general. Porosity arises due to the limited wettability of fibres, inclusion of air during processing, lumens and other hollow features within the fibres or fibre bundles, and low ability of fibres to compact. Porosity in natural fibre composites is dependent on fibre type and orientation of fibre. It has been shown to increase with increasing in fibre content, especially when geometrical compaction limit are exceeded (Pickering, 2016).

Tensile, flexural and fracture toughness testing can be used to characterize the mechanical properties of composites. Fracture toughness is an important material property, which is used to describe the capacity of a material containing a crack to resist fracture during applied loading. The stress intensity factor, K is able to characterize both a crack driving force and the material toughness in fracture mechanics analysis of a structure containing a crack (Zhu, 2016).

2.5.2 Acoustic testing

Acoustic insulation power of natural fibre composites is promoting their applications in the automotive sector (Martin, 2016). The acoustic performance can be defined by experimentally determined constants, namely absorption coefficient (Tiwari & Shukla, 2004).

According to Vinogradov (2004), the sound absorptive ability of a given material sample can be determined by the sound absorption coefficient, α, which is defined as the ratio of the acoustic wave energy, E_a absorbed by the sample to the total energy E_i incident on the sample, as shown in Equation 2.2:

$$\alpha = \frac{E_a}{E_i} \qquad \text{Equation 2.2}$$

Composites are generally known to exhibit better sound absorption as compared to the homogenous materials. This is resulted from the additivity of all different kinds of acoustic energy losses. When the sound wave propagated through inhomogeneous medium, it interacts with a great number of suspended particles, that are differ by the compressibility, density and thermophysical parameters from the matrix. This results in the additional acoustic energy losses as compared to that in the matrix (Markiewicz, 2012).

The property of the additivity expresses the sound absorption coefficient of composite, α' as Equation 2.3, which is a sum of four components (Vinogradov, 2004):

$$\alpha' = \alpha_O + \alpha_\eta + \alpha_T + \alpha_S \qquad \text{Equation 2.3}$$

Where,

α_O = the coefficient of the dispersion medium (matrix)

α_η = the coefficient due to friction between particles (fillers) and the medium (matrix)

α_T = the coefficient related to the heat exchange between the particles and medium

α_S = the coefficient of attenuation of the acoustic wave in forward direction due to scattering by the particles.

The scattering plays an important role in sound absorption when the particle sizes in the composite are comparable or larger than the wave length of sound (Vinogradov, 2004). On the other hand, in the case of interaction between low frequency acoustic wave and micrometer or millimetre dimensions particles, the losses in acoustic energy occur due to friction. In this scenario, interfacial heat exchange plays the main role (Markiewicz, 2012),

In addition, the different densities of the matrix and the particles is another contributing factor to sound absorption. This is because there is friction existing between them, which makes the sound wave induced motions of both components can be considered as the separate ones. In the composite, viscous forces arise balancing the motions of the matrix and the particles, thus giving rise to the sound absorption (Markiewicz, 2012).

2.5.3 Morphological testing

Scanning electron microscopy spectroscopy (SEM) is a widely-used surface analytical technique. A focused electron beam is utilized in SEM, to systematically scan across the surface of specimen, thus producing large numbers of signals (Zhou, 2007).

The electron gun in SEM, which is on the top of the column, will produce the electrons and accelerate them to an energy level of 0.1–30 keV. The morphological images taken under 1 kV can give more surface details as comparing to that of 20 kV. This is because the surface resolution is lost at high accelerating voltages (Zhou, 2007).

Generally, SEM machine will be attached to a vacuum pump. This is because a high-vacuum environment is needed to perform morphological analysis by SEM, since the vacuum environment allows electron to travel without scattering by the air (Zhou, 2007).

2.6 Analytical model

Since the 1950s, a great deal of theoretical work with the aim of modelling the mechanical performance of fibre reinforced composites has been carried out. A composite can be modelled as an isotropic in the simplest possible case. The elastic matrix filled with directionally aligned elastic fibres that span the full length of the specimen. By assuming that the fibres and matrix are very well-bonded, upon application of a stress in the fibre alignment direction, the fibres and matrix will be equally strained (Coleman, 2006).

2.6.1 Rule of mixtures (ROM)

The rule of mixtures is the simplest model that can be used to predict the elastic modulus of composites. This model allows elastic modulus for composites to be calculated, by assuming equal amount of strain experienced on both matrix and fibres. The strain is originated from the application of uniform stress on a uniform cross-sectional area. The equation of the model is expressed as Equation 2.4 below.

$$E_c = E_f V_f + E_m V_m \qquad \text{Equation 2.4}$$

Where E_m, E_f, V_m and V_f represent the moduli and volume fractions of the matrix and fibre respectively and E_c represents the modulus of composite.

2.6.2 Cox-Krenchel modification

However, the ROM could not give a good prediction on the actual case, because there are some factors which are not being taken into consideration. Thus, there was another model proposed by Cox in 1952, which is known as Cox-shear lag model (Clyne, 1996). This theory is utilized to model the modulus of random-in-plane short fibre composites was developed by Cox. For a unidirectional composite, a correction factor, η_L must be considered in the rule of mixture to justify the length of fibre is not entirely contributing to the improvement of the stiffness of the composite. This is due to the shear stress transfer between each fibre and the matrix as shown in Figure 2.7 (Clyne, 1996).

Figure 2.7 (a) shows the fibre and matrix configuration during un-stretched state. When the composite is strained, the continuous phase deforms around the fibre. This resulting in shear strains in the matrix, which then lead to shear stresses (τ) at the interface. As may be noted from Figure 2.7 (b), the distortion is greatest at the fibre ends. Thus, a correction factor is introduced in the composite modelling equation, in order to predict the mechanical properties of the composite precisely (Clyne, 1996).

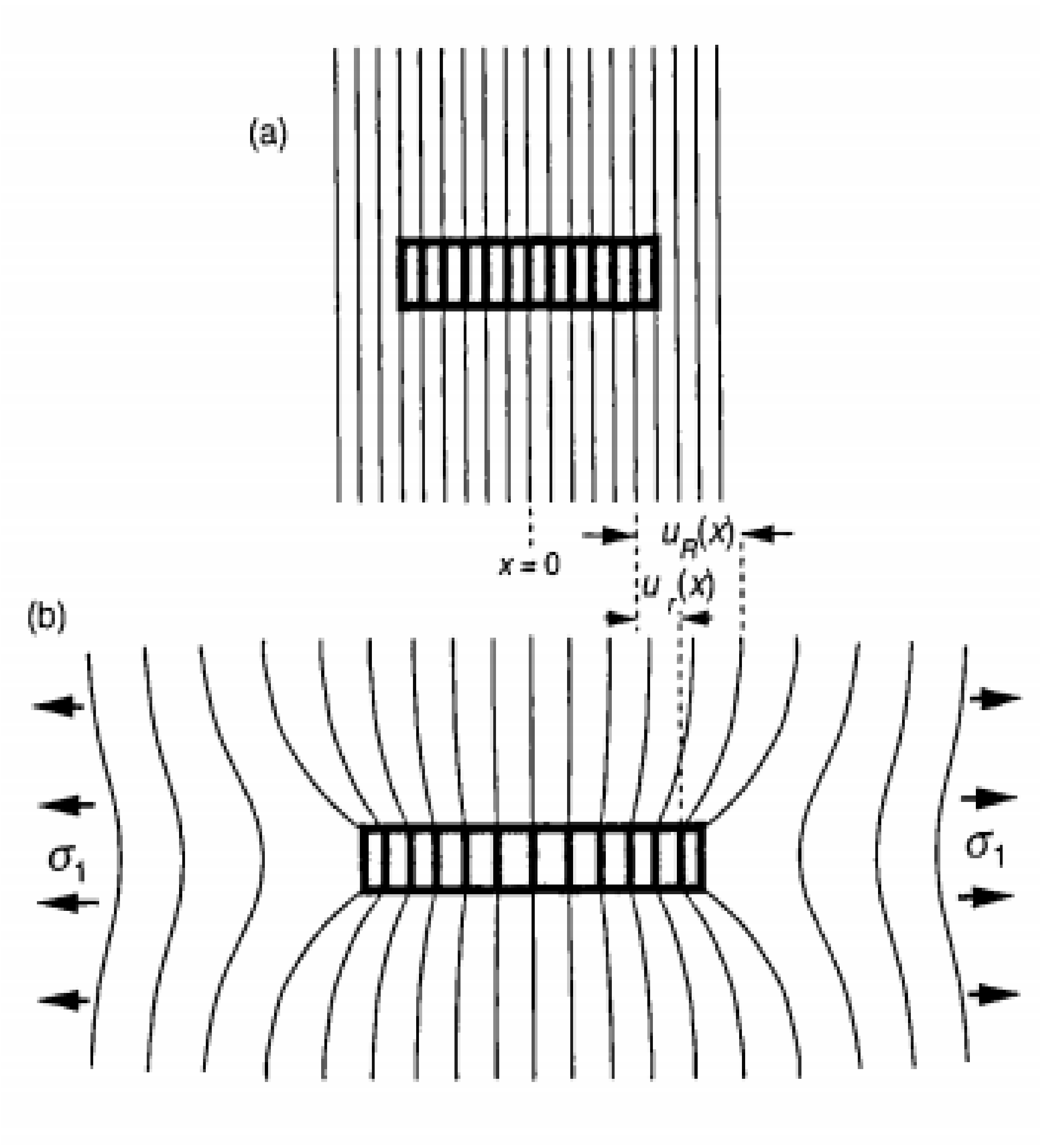

Figure 2.7: Schematic representation of a Cox-type shear-lag distortion in the matrix surrounding a reinforcing fibre (Clyne, 1996).

This Cox shear-lag model was then modified by Krenchel. Nonetheless, Krenchel expanded this study to consider fibre orientation by the addition of a fibre orientation factor, η_o, into the rule of mixture as shown in Equation 2.5 (Masoomi, 2015).

$$E_c = \eta_O \eta_L E_f V_f + E_m V_m \qquad \text{Equation 2.5}$$

The above scenario assumes that there is a perfect bonding between fibre and matrix. It is assumed that there is no slippage between fibre and matrix during straining of the composite, in other words the system remains elastic. However, this is only true for composite system with good interfacial bonding (Clyne, 1996).

The assumptions and calculations of modulus using Cox-Krenchel equation will be further discussed in Chapter 3.

2.7 Summary

Taking into consideration all the points discussed regards composite processing methods, it is possible to conclude that there is a need for a study on effects of prepregs manufacturing processes on mechanical properties. Hence, one of the purposes of this paper is to study the effect of hand lay-up and impregnation line manufacturing processes on composite's mechanical, morphological and acoustic properties.

In addition, it is found that there are some different composite models that have been derived and modified. Thus, the precision of different composite models in predicting the modulus of polymer composite can be determined through this research.

CHAPTER 3

METHODOLOGY

3.1 Materials

3.1.1 Acrodur resin

Acrylic resin used in this research was Acrodur® resin 950L and it was obtained from BASF, USA. It is a water-based and formaldehyde-free cross-linking acrylate resin, which will produce water as by product during curing. The properties of the Acrodur resin is shown in Table 3.1.

Table 3.1: Properties of Acrodur resin.

Solids content	50 wt%
pH-value	3.5
Viscosity	900-2500 mPa•s

3.1.2 Flax fibre

Needle-punched nonwoven flax fibre mat was purchased from EcoTechnilin SAS, France. The average density value of this flax fibre mat is 1.37 g/cm^3 and areal density is 1000 g/m^2.