# SCHOOL OF MATERIALS AND MINERAL RESOURCES ENGINEERING UNIVERSITI SAINS MALAYSIA

# MECHANICAL AND ELECTRICAL PROPERTIES OF SHORT CARBON FIBRE REINFORCED POLYCARBONATE COMPOSITES

By

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## DECLARATION

I hereby declare that I have conducted, completed the research work and written the dissertation entitled 'Mechanical and Electrical Properties of Short Carbon Fibre Reinforced Polycarbonate Composites'. 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 ABBREVIATIONS

ASTM	American Society of Testing Material
EC	Electrical conductivity
ER	Electrical resistivity
FRP	Fibre reinforced polymer
PAN	Polyacrylonitrile
PC	Polycarbonate
RoM	Rule of mixture
SCF	Short carbon fibre
SCFRP	Short carbon fibre reinforced polymer
SEM	Scanning electron microscope
SENB	Single edge notched bend

# LIST OF SYMBOLS

ρ	Fibre-fibre separation distance
$r_{f}$	Radius of fibre
Р	Property of the composite
<i>P</i> <sub>1</sub>	Property of component 1
<i>P</i> <sub>2</sub>	Property of component 2
$V_1$	Volume fractions of component 1
<i>V</i> <sub>2</sub>	Volume fractions of component 2
E <sub>c</sub>	Elastic modulus of composite
$E_f$	Elastic modulus of fibre
E <sub>m</sub>	Elastic modulus of matrix
$V_f$	Fibre volume fraction
V <sub>m</sub>	Matrix volume fraction
$\eta_o$	Fibre orientation factor
$\eta_L$	Fibre length distribution factor
$V_{v}$	Void volume fraction
$W_f$	Fibre weight fraction
$W_m$	Matrix weight fraction
$ ho_c$	Actual composite density
$ ho_f$	Matrix density
$ ho_m$	Fibre density
L	Span length
d	Thickness
R	Rate of crosshead motion
d	Depth of beam

Z	Straining rate of the outer fibre
K <sub>c</sub>	Critical stress intensity factor
У	Shape factor
а	Notch length
W	Specimen width
Р	Maximum load
В	Specimen thickness
$v_m$	Volume of matrix
$v_f$	Volume of fibre
W <sub>f</sub>	Weight of fibre
W <sub>c</sub>	Weight of composite
L	Fibre length
G <sub>m</sub>	Matrix shear modulus
$ ho_t$	Theoretical composite density
$ ho_{exp}$	Experimental composite density
$W_m$	Matrix weight percentage
$W_{f}$	Fibre weight percentage
D	Matrix density
d	Fibre density
$\sigma_c$	Composite strength
$\sigma_m$	Matrix strength
$\sigma_{f}$	Fibre strength
wt.%	Weight percentage

# SIFAT-SIFAT MEKANIKAL DAN ELEKTRIK BAGI KOMPOSIT POLIKARBONAT DIPERKUATKAN GENTIAN KARBON PENDEK

### ABSTRAK

Satu siri komposit telah disediakan dengan menggunakan PC sebagai bahan matriks, diperkuatkan dengan gentian karbon pendek (SCF) dalam pelbagai pecahan berat. Komposit tersebut telah disebatikan melalui mesin pengekstrudan skru tunggal dan sampel disediakan dengan mesin acuan suntikan. Pengaruh pecahan berat gentian terhadap sifat-sifat mekanik dan elektrik telah dikaji. Spesimen telah dihasilkan mengikut spesifikasi ASTM. 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 eletrik juga diselidik dengan menggunakan ujian rintangan permukaan. Modulus tegangan komposit juga diramalkan dengan menggunakan model Cox-Krenchel dan hukum percampuran (RoM). Keputusan ujian menunjukkan ketumpatan komposit bertambah dengan penambahan SCF. Panjang gentian didapati berkurang semasa penghasilan komposit. Peningkatan panjang gentian memberi kesan penguatan yang lebih baik, maka sifat mekanik juga lebih tinggi. Penambahan SCF telah meningkatkan kekuatan komposit, dan kesan adalah lebih ketara apabila nisbah gentian SCF meningkat. Dengan peningkatan kandungan SCF, rintangan permukaan berkurang secara mendadak dengan nilai ambang perkolasi antara 10% – 14%y pecahan berat SCF. Model Cox-Krenchel dibuktikan sebagai satu model teori yang sesuai dalam peramalan modulus tegangan komposit. PC diperkuatkan 14% gentian karbon pendek yang disediakan daripada kompaun komersial telah membukti penyebatian berkesan melalui pengestrudan dalam kompaun komposit yang disebatikan sendiri (PC diperkuatkan 5%, 10% and 15% SCF) dengan mempunyai sifat sederhana di antara PC diperkuatkan dengan 10% SCF dan PC diperkuatkan dengan 15% SCF seperti yang dijangkakan.

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# MECHANICAL AND ELECTRICAL PROPERTIES OF SHORT CARBON FIBRE REINFORCED POLYCARBONATE COMPOSITE

### ABSTRACT

A series of composites was prepared using polycarbonate (PC) as the matrix, reinforced with short carbon fibre (SCF) at different weight fractions. The composites were compounded by single screw extruder and specimens were prepared by injection moulding machine. The effect of fibre weight fractions on the mechanical and electrical properties of SCF reinforced polycarbonate composite was studied. The test specimens were fabricated in accordance to the ASTM specifications. 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). In addition, electrical properties were evaluated by surface resistivity test. Cox-Krenchel and rule of mixtures (RoM) were used to predict theoretical tensile moduli of the composites. Experiment results revealed that density of the composites increased with the addition of SCF. Fibre length was found to be greatly reduced during processing the of composites. Higher mean fibre length tends to provide better reinforcement effect, thus enhanced mechanical properties. Incorporation of SCF improved the strength of the composite, and the effect was more prominent at higher weight fraction of SCF. With increasing SCF content, the surface resistivity reduced drastically with the percolation threshold lie in between 10% - 14% of SCF weight fraction. Cox-Krenchel model showed to be a good approximation to predict the composites' tensile modulus. 14% SCF reinforced PC composite which was obtained from commercial compound proved the effective extrusion compounding of these self-compounded composites (5%, 10% and 15% SCF), by possessing intermediate properties in between 10% and 15% SCF reinforced PC composites as expected.

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#### **CHAPTER 1**

#### INTRODUCTION

#### 1.1 Background

In recent years, there has been growing interest for the use of fibre reinforced composites attributed to its unique characteristics of improved performance with a lightweight property. Fibre reinforced polymer (FRP) composites constitute the largest category among all developed advanced materials, amount up to 75% of the world composite market (Njuguna, 2016). FRP composites have found diverse range of applications, from non-structural applications to lightweight, high performance applications such as military, aerospace and automotive (Chanda, 2017).

FRP composites can be simply described as multi-constituent materials which consist of reinforcing fibres embedded inside a rigid polymer matrix. Various types of polymer can be used as the matrix to FRP composites which are able to be classified as thermoset (eg. epoxy, polyester) or thermoplastic (eg. polycarbonate, polyamide) resins. In engineering applications, most of the composites consist fibre made of glass, carbon or aramid.

FRP composites may be classified as continuous (long) fibre and short fibre composites. Anisotropic long fibre that extends over the entire length of the cut is appeared to be more efficient than short fibre reinforcement. Nevertheless, because of its less anisotropic properties, short fibre reinforced composites are advantageous in application where isotropy is desirable. Compared to most common metallic alloys such as steel and aluminum alloys, FRP composites have emerged as important materials attributed to their light-weight, high specific stiffness, high specific strength, excellent fatigue resistance and outstanding corrosion resistance (Tong *et al.*, 2002).

For FRP composites, thermosetting plastic is more widely used compared to thermoplastic. However, because of the lower damage tolerances and low service temperatures of thermosetting materials, interest has been shifted to thermoplastic

matrix composite recently. Thermoplastic polymers are less desirable to be used in continuous fibre composites as their high viscosities lead to low processability. Thermoplastic polymers are however ideal for short fibre reinforced composites because they can be easily moulded (Papathanasiou *et al.*, 1997).

Polycarbonate (PC) is one of the most widely used thermoplastic polymer in FRP composites. It is an amorphous and lightweight engineering thermoplastics resin that is characterized by a unique combination of characteristics such as optical clarity (amorphous and transparent), toughness, hardness, dimensional stability, ductility, high thermal resistance, and excellent electrical resistance. The major global application areas of polycarbonate areas are electrical and electronics (E&E), medical, appliances, recreation and safety (Ibeh, 2011).

Meanwhile, carbon fibres used as reinforcement in composites have maximum strength as compared to that of other fibre materials. Carbon fibers refer to fibrous carbon material fibers with carbon content more than 90%. With 1000-1500°C heat treatment, they are transformed from organic matter which are the substance with imperfect graphite crystalline structure arranged along the fiber axis (Donnet *et al.*, 1998). They can be short or continuous; their structure can be crystalline, amorphous, or partly crystalline. Commercially available carbon fibers can be divided into three categories, namely general-purpose (GP), high-performance (HP), and activated carbon fibers (ACF). For general-purpose type of carbon fibres, they have the characteristics of low tensile strength, low tensile modulus, low cost and consists of amorphous and isotropic structure. While high-performance carbon fibres are characterized by relatively high strength and modulus. Activated carbon fibers are characterized by the presence of a large number of open micropores, which acts as adsorption sites.

Commercial carbon fibers are fabricated by using pitch or polyacrylonitrile (PAN) as the precursor. PAN, an atactic, linear polymer, is the predominant precursor of carbon fibers. These fibers able to reduce weight without sacrificing strength and modulus, thus they are widely used for structural material composites especially in aerospace and

industrial field and recreational goods. Carbon fibers made from pitch precursor have extensive properties, from low elastic modulus to ultra-high elastic modulus. Such fibers are available with isotropic or anisotropic structure, made from isotropic pitch and mesophase pitch respectively. When compared against each other, PAN-based carbon fibers tend to have higher tensile strength than pitch derived carbon fibers, which in turn tend to have higher Young's modulus and demonstrate better electrical or thermal properties than PAN-based fibers (Solutions, 2016).

## 1.2 **Problem Statement**

Short fibre reinforced thermoplastic composites provide better mechanical strength and stiffness, higher resistance to corrosion and higher dimensional stability. However, it increases the difficulties in the processing of composites, for example, the increase of polymer melt's viscosity after the addition of reinforcing fibres. This problem can be solved by raising the processing temperature. With the raised temperature, polymer melt's viscosity can be reduced but, degradation may occur as well.

The fabrication of fibre reinforced composite is a vital aspect because uniform dispersion of short fibres in the matrix are usually hard to achieve. The composite fabrication often associated with fibre breakage which consequently affects the fibre aspect ratio, leading to inefficient reinforcement and degraded load-carrying capability.

PC which has high melt viscosity tends to reduce its processability and thereby affect its usage in some applications. Additionally, PC which has lack of reactivity can result in the poor matrix-fibre adhesion. PC does not bond well particularly to carbon fibres. The poor interfacial adhesion may bring about poor mechanical properties as stress cannot transfer efficiently from matrix to the reinforcing fibres.

Nowadays, conductive polymers are becoming more attractive for electrical applications especially with the increasing miniaturization of electronic consumer products. Most polymer resins including PC are electrically insulating. By decreasing the electrical resistivity (EC) (ER = 1/electrical conductivity, EC) of the resins, they can be

used in other applications. One important application area is the packaging of sensitive electronics, where conductive containers are required to dissipate static charge. Besides electrostatic dissipative application, conductive polymer composites can also be used in shielding application (computer and cellular phone housings) with ER lower than 10 ohmcm. An approach to improve the electrical conductivity of a polymer is through the addition of conductive filler such as carbon fibres (Via *et al.*, 2012).

However, electrically conductive composites must also meet the application specific required values of mechanical properties such as tensile modulus. This can be easily achieve with the incorporation of fibres, which can enhance the mechanical properties of a composite as well as its electrical conductivity (Via *et al.*, 2012). Hence, composites made from short carbon fibre with polycarbonate resin was proposed for the use in mechanically-enhanced electrical applications and automotive applications. Basically, the composites with higher fibre loading illustrates higher electrical conductivity accompanied with improved mechanical performances (McMahon, 1984).

## 1.3 Objectives

- i. To study the effect of weight fraction of filler (0%, 5%, 10% and 15%) on the mechanical properties of short carbon fibre reinforced polycarbonate resin composites.
- ii. To investigate the loading effect of fibre (0%, 5%, 10% and 15%) on the electrical properties of short carbon fibre reinforced polycarbonate resin composites.
- iii. To validate composite models in predicting the moduli of composites.

### 1.4 Organization of Thesis

**Chapter 1** introduces the development of short carbon fibre reinforced polymer (SCFRP) in 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 carbon fibre and polycarbonate resin are discussed together with different manufacturing 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 theoretical density of composite and volume fraction of fibre and void contents are included. In addition, the description of the sample characterization methods such as tensile, flexural, fracture toughness, morphological and electrical are given in this chapter.

**Chapter 4** focuses on the experimental result and discussion. Further elaboration on the effect of fibre loading on mechanical, morphological and electrical properties of short carbon fibre reinforced polycarbonate resin composites are provided in this chapter. 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 given.

### 1.5 Scopes of Research Study

In this study, short carbon fibre reinforced polycarbonate composites loaded with different fibre weight fractions were prepared through injection moulding. Pellets with specific weight fraction of carbon fibres were first prepared by using single screw extruder with pelletizer. They were then moulded with injection moulding machine for testing and characterization purpose. The effect of fibre loading on the mechanical and electrical properties of carbon fibre reinforced polycarbonate resin composites were investigated. The mechanical properties of the short carbon fibres reinforced polycarbonate resin composites were characterized by tensile, flexural and fracture toughness tests. Also, morphological properties of the composites were characterized by using scanning electron microscope (SEM). Range of resistivity value of the short carbon fibre reinforced polycarbonate resin composite was obtained by using a surface resistivity meter. Composite models were used to speculate the moduli of the short carbon fibre reinforced polycarbonate resin composites. The predicted values were compared with the experimental values.

#### **CHAPTER 2**

#### LITERATURE REVIEW

#### 2.1 Composites

Composite material is a kind of complex multi-component multi-phase system. It is defined as a multi-phase combination material of two or more component materials with distinct properties as well as distinct forms and is developed through compounding processes It not only maintains the main characteristics of the original components, but also shows new character which are not possessed by any of the original components (Wang *et al.*, 2011). In other words, composites comprised of two or more chemically distinct constituents having a distinct interface, which separates them as reinforcing particle and matrix.

It has a unique combination of properties that are noticeably different from the constituent properties. Generally, a discontinuous phase (called reinforcement) is embedded into a continuous phase (called matrix). These materials are generally classified on the basis of geometry of the reinforcement used. The reinforcement may be found in the form of short fibres, long fibres or particles (Kar, 2016).

Fiber Reinforced Polymer (FRP) composite materials are currently considered as universal engineering materials and they are utilized in a spacious range of applications, because of their elevated specific strength and high specific stiffness. Its usage has been revealed in a diverse range of applications such as lightweight structures, furniture, automobile parts and consumer goods (Law *et al.*, 2016).

The performance of fibre-reinforced composites is influenced and controlled by several factors including 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. *et al.*, 2000).

#### 2.1.1 Matrix

Matrix plays a vital role in determining the properties of the composite particularly degradative properties that can eventually cause failure of the structure. Examples of degradative processes include impact damage, delamination and chemical attack. Thus, matrix sometimes can be regarded as the weak link in the FRP (Nichols, 1988).

According to Gupta (2007), matrix is required to perform several functions which are vital to the satisfactory performance of composites. The matrix binds the fibers together and aligns them in the important stress direction. When loads are applied to the composite, they will be transferred through the matrix into the fibres, which constituent the principal load bearing component. This enables the composite to withstand various types of loads such as tensile, flexural and shear forces as well as compression loads. To ensure the fibres can act as separate entities, they must be isolated by the matrix.

Another function of the matrix is to protect the reinforcing fibres from mechanical damage and from environmental attack. For example, the matrix of a composite which operates at elevated temperature, it should protect the fibres from oxidative attack (Gupta, 2007).

A ductile matrix can slow down or stop cracks that might have originated at broken fibres. Contrarily, a brittle matrix may depend upon the fibres to act as matrix crack stoppers. Matrix can be an important means of increasing the toughness of the composite by controlling the quality of its grip on the fibres which is in turn determined by the interfacial bond strength. While toughness of the composite can be manipulated by the interfacial bond strength, which is correlation to the quality of its grip on the fibres (Gupta, 2007).

The matrix phase used in a polymer composites can be classified into two, namely thermosetting and thermoplastic polymer. Both thermosetting and thermoplastic polymers are often called resins in the composite industry. Today, most of the continuous FRPs in aerospace, automotive and many industrial applications contain a thermoset resin such as epoxy or polyester resin. However, majority of discontinuous or short FRPs

use thermoplastic polymer, such as polycarbonate or polypropylene. This is attributed to the reason that continuous fibres are difficult to be incorporated into and wetted by thermoplastic polymers due to their high viscosity. Short fibres can be relatively easily incorporated in thermoplastic polymers using common melt processing methods including extrusion compounding and injection mouding (Mallick, 2017).

Thermoplastics are supplied by polymer manufacturers in the polymerized form. They are available as pellets or granules, which are the starting materials for injection moulding and extrusion processes. Short fibres, typically 1-3mm in length, are first mechanically blended with the thermoplastic pellets and then compounded in a single screw extruder or twin screw extruder. During the compounding process, the pellets melt into a viscous liquid which mixes with the fibres and coats their surfaces. The meltcompounded mix is then extruded through a strand die to form continuous strands or through a sheet die to form a continuous thin sheet. The cooling arrangement outside the extruder transforms the liquid polymer in the extruded material into its solid state.

Then, the short fibre-reinforced composite part is produced by either injection moulding or thermoforming. For injection moulding, the extruded strands are first pelletized to make small pellets, which are then fed into an injection moulding machine to produce injection-moulded parts. During the injection moulding process, the thermoplastic in the pellets goes through a cycle of meting and solidification (Mallick, 2017).

Thermoplastics are not cross-linked as in thermosetting resin. Their strength and stiffness are derived from the inherent properties of the monomer units and the very high molecular weight. This ensures that there is a high concentration of molecular entanglements in amorphous thermoplastics which act like cross-links. Heating of amorphous materials leads to disentanglement and a change from rigid solid to a viscous liquid (Hull *et al.*, 1996).

#### 2.1.2 Reinforcement

Reinforcement material in composite is served to bear the load in the composite system. This load carrying ability enables the composite to have higher mechanical properties than the neat resin system. The choice of reinforcement in the composite system is important for the properties of the composites, which include mechanical properties such as modulus and strength (Hull *et al.*, 1996).

Reinforcing fillers are normally compounded with thermoplastics to enhance the mechanical properties including yield stress and modulus of elasticity. However, a dramatic loss of elongation at break and impact strength can be induced by increasing the filler load (Rouabah *et al.*, 2007).

There are two types of reinforcement available for composite materials, namely particle and fibre reinforcement materials. Particles usually have aspect ratio of about one while fibres have higher aspect ratio. Thus, compared to particulate composites, the performance level of fibre reinforced composites is very high. This enables fibres reinforced composites to be widely used in high-end application (Rana *et al.*, 2016).

FRP composites can be further classified into continuous fibre reinforced composites and short fibre reinforced composites (Law *et al.*, 2016). In continuous-fibre composites, the long continuous fibres are reinforced. While in discontinuous or short-fibre composites, the fibres are in the form of short fibres, nano-tubes (1nm in diameter and 1000nm in length approximately), or whiskers. Although the fibers are short, the lengths of the fibers are long compared to their diameters. In other words, they have high aspect ratio. Short fibres can all be oriented unidirectional or in a random orientation pattern. In general, composite materials tend to be markedly anisotropic, discontinuous fibres can be regarded as a quasi-isotropic composite (Saha, 2016).

Owing to their low cost, high processability and superior mechanical performance over parent polymers, short fibre reinforced polymer composites have found extensive applications in automobiles, durable consumer items and electrical industries. Hence,

they are the only one class among a variety of composite materials with a high growth rate at present (Fu *et al.*, 2009).

In short fibre reinforced polymer composite, the deformation of the matrix transfers stresses by means of the fibre-matrix interface traction to the reinforcing fibres. Therefore, the mechanical properties of a short fibre reinforced composite are critically determined by the efficiency of stress transfer from the matrix to the embedded fibres (Fu *et al.*, 2009). Short fibre reinforced polymer composites are developed mainly to fill the property gap between continuous fibre laminated composites which are widely used in the space industry and unreinforced polymers that mainly used for non-load bearing applications (Eftekhari *et al.*, 2015).

## 2.1.3 Fibre Microstructure

Fibres are the principal constituents in a FRP composite material and they share the major portion of the external load acting on a composite structure. There are several factors which will affect the composite properties, including fibre orientation, fibre type and fibre length. For example, the presence of more fibres in the loading direction will enhance the mechanical behaviour in the composite. Hence, fibre orientation is an influential characteristic to a composite material's performance (Mallick, 2007).

The fibre volume fraction is important for designing composites. Fiber volume or weight fraction can affect most of the mechanical and thermal properties of composites (Kim *et al.*, 2017). When composites contain high volume fraction ( $V_f$ ) of reinforcement, they tend to possess better strength and stiffness since reinforcement generally has higher strength and stiffness as compared to the matrix. Nevertheless, there is an upper limit of  $V_f$ , where above the limit, the mechanical properties of the composites will be reduced. This is because the resin may not be enough to wet all the fibres when the amount of resin is relatively lesser than fibre and causes the stress transfer mechanism cannot be performed effectively during application of load (Hull *et al.*, 1996).

Mechanical properties of a composite, such as stiffness, are related to  $V_f$ . However, there could be a third variable, namely the fibre-fibre separation distance,  $\rho$ , that is related to both the mechanical properties and  $V_f$ . The  $\rho$  is expected to vary depending on the fibre packaging configuration. According to Goh (2016),  $V_f$  tends to increase with decreasing  $\rho$  and vice versa. In order to obtain high fibre volume fraction  $(V_f)$  composite, fibres should be assembled in hexagonal close packing whereby the small value of  $\rho$  can be achieved. Figure 2.1 shows different fibre arrangement in the matrix. By assuming that the fibres are of circular cross section of radius  $r_f$ , mathematical models have been developed in order to predict the fibre volume fraction in composite. Equation 2.1 represents the mathematical model that is used to calculate volume fraction of fibres which are hexagonally close-packed (Goh, 2016).

$$V_f = \left(\frac{\pi}{2\sqrt{3}}\right) \left(\frac{r_f^2}{\rho^2}\right)$$
 Equation 2.1

where  $V_f$  is the volume fraction of fibre,  $r_f$  refers to radius of fibre and  $\rho$  symbolizes the fibre separation.



Figure 2.1: Fibre arrangement in the matrix. (a) Hexagonal (triangular-edge) packing configuration. (b) Square-edge packing configuration. (c) Square-diagonal packing configuration. Shaded circles indicate the (primary) fibres of interest. Symbol r<sub>f</sub> denotes radius, ρ denotes fibre-fibre separation distance (Goh, 2016).

Figure 2.2 illustrates the hexagonal close packing of fibre in a composite system. A maximum volume fraction of fibre will be obtained if the fibre separation,  $\rho$  is equal to the radius of fibre,  $r_f$ . By substituting  $\rho = r_f$  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: SEM pictures of hexagonal close packing of fibre in a composite system (Wu *et al.*, 2008).

### 2.2 Short Fibres Reinforced Composite

Due to its high strength to weight ratio as well as high processability, short fibre reinforced composites have gained increasing attention. There are numbers of works and researches focusing on the improvement of its properties including mechanical and electrical properties. Ease of fabrication is one of the advantages provided by short fibre reinforced composites. This type of composite allows the manufacturers to fabricate in a more cost-effective way by using common processing techniques similar to those used for unreinforced materials. The commonly used processing technique such as injection moulding and extrusion, permits rapid and large volume production of components with complex shapes.

Short fibre reinforced composites are influenced by a number of characteristics, namely, fibre dispersion, fibre-matrix adhesion, fibre aspect ratio, fibre volume fraction and composite posrosity. Normally, short fibres are randomly distributed inside the composite system. Unidirectional composites are normally tend to be stiff and strong in the fibre direction but they are weak in the transverse direction. Thus, they are only useful in the applications where the direction of stress is well known. However, if the external applied loads are omni-directional or their direction varies with time, short fibre reinforced composites are said to be isotropic where it has the same material properties in all directions (Tenek, 1999).

#### 2.2.1 Polycarbonate Resin

Among all the polymer materials, special attention has been directed to polycarbonate (PC) for the past decades. PC is a polyester of carbonic acid or its derivative with dihydroxy compounds (aliphatic, aromatic, or mixed type compounds) with carbonate (—OCOO—) linkages (Zaikina *et al.*, 1977). There are many commercial processes used for the synthesis of polycarbonates. These includes interfacial technology, transesterification (melt or solventless) process, and general redistribution method (Bendler, 1999). Figure 2.3 represents the general structure of polycarbonates while Figure 2.4 shows the general transesterification melt bisphenol A polycarbonate (BPAPC) synthesis scheme.



Figure 2.3: General structure of polycarbonates (Sandler, 2012).

$$xHO - \bigcirc - \bigcirc CH_3 \\ CH$$

Figure 2.4: General "melt" BPAPC synthesis scheme (Bendler, 1999).

Polycarbonate resin is an amorphous, ductile and transparent engineering thermoplastic material. It is distinguished by high strength and rigidity, impact toughness, high light transparency and stability of dielectric properties over a broad range of frequencies and temperatures. PC also characterized with its properties which is physically and dimensional stable in the temperature range of -100 to +135°C. Due to its wide range of properties and product options such as flame retardancy, scratch resistance, toughness, heat resistance, weatherability and optical quality, PC portfolio provides broad design versatility (Brouwer *et al.*, 2015).

PC can be melt-processed with all the commonly used thermoplastic processes such as injection moulding, extrusion and thermoforming. Because of its macromolecular structure, PC possess high viscosity and low melt flow properties, and therefore, high processing temperatures (280°C-350°C) is needed. At PC's typical processing temperature, small amounts of moisture can result in the degradation of the carbonate linkage and subsequent chain scission with resultant molecular weight and other physical properties reduction. Pre-drying is always recommended for efficient processing of PC resins (Andrew, 2016).

#### 2.2.1.1 PC Composites Reinforced with Short Fibres

Polycarbonates (PC) are amorphous and highly transparent polymer. Short fibre reinforcement such as short carbon fibres are usually used to enhance the properties of this amorphous polymers. As with most of the fibre reinforced composites, the stiffness and strength are much better than in the unfilled polymer. Fibre inclusion can also give rise to a useful increase in the maximum service temperature of the short fibre reinforced PC composites (De *et al.*, 1996).

Short fibre reinforced PC composites can be moulded in conventional injection moulding machines which are designed for unfilled thermoplastics. Without sacrificing the mouldability of the composites, the composites give the benefits of enhanced properties. Nevertheless, wear of the processing equipment due to the abrasive filler particles can be considerable and it should be taken into consideration particularly during material selection. There are few potential applications of PC reinforced with short fibre, namely electromagnetic shielding gasket, electronic device covers and automotive parts (De *et al.*, 1996).

### 2.3 Carbon Fibre Reinforcement

Carbon fibre was commercially introduced and manufactured since 1970. It is recognized as a significant engineering material used in the manufacture of advanced composite materials owning to its lightweight, high flexibility, strength and fatigue-resistance. Many of the properties of fibrous composite materials are highly dependent on parameters such as fibre length, volume fraction of fibres and packaging arrangement of fibres. For example, in the case of randomly oriented short fibre composite, volume fraction and length of carbon fibres play critical role in determining the final fibre properties. Void content is found to be higher for short carbon fibre composite which has relatively higher processability as compared to long or continuous carbon fibre composite (Kumar *et al.*, 2008).

Short carbon fibre (SCF) provides strong, stiff and low density reinforcement but it is comparatively expensive and brittle than other synthetic fibres such as glass fibre (Law *et al.*, 2016). SCF are used in various forms such as polyacrylonitrile carbon fibres (PAN) and pre-carbonized carbon fibres (Precarb-CF) (Srivastava *et al.*, 2016).

Carbon fibres are produced either by pyrolyzing fibres spun from polyacrylonitrile (PAN), by chemical vapor deposition (CVD), or from pitch. Microscale carbon fibres (diameter  $>5\mu$ m) can be manufactured by spinning method whereas CVD process can synthesize carbon fibres with diameters ranging from micro to nano diameter. At an

industrial level, carbon fibres are generally produced from various materials such as polyacrylonitrile (PAN), mesophase pitch and rayon (Srivastava *et al.*, 2016).

#### 2.3.1 PAN-based Carbon Fibre

At present, carbon fibres are predominantly made of polyacrylonitrile (PAN) precursors. Attributed to its higher carbon yield (>50% of the original precursor mass), PAN-based carbon fibre is stronger than other types. In composite technology, most PAN-based carbon fibres are extensively used, and due to their enhanced physical and mechanical characteristics, they are highly ideal for high performance composites of automotive and aerospace industries (Wangxi *et al.*, 2003). Figure 2.5 represents the chemical structure of PAN.



Figure 2.5: Chemical structure of PAN (Park et al., 2015).

There are three general steps for the conversion of PAN-fibres precursor to carbon fibres, namely stabilization or oxidation, carbonization (>1600°C) and graphitization which involves heating up to 3000°C (Srivastava *et al.*, 2016). Figure 2.6 shows the detailed schematic for manufacturing process of carbon fibres from PAN-based precursors.



Figure 2.6: Schematic for manufacturing process of carbon fibres from PAN-based precursors (Park *et al.*, 2015).

The first step takes around 120 minutes to be completed. This step is essential lthough it is time consuming. There are several chemical reactions occur during this step including cyclization, dehydrogenation, aromatization, oxidation and crosslinking, then ending with the formation of the conjugated ladder structure. Also, heat treatment involved in stabilization of PAN fibres at the temperature range of 200-300°C will be carried out for 30-120 minutes. Optimum stabilized PAN fibres can offer higher modulus carbon fibres. However, the stabilizing temperature should be well monitored. With an excessively high stabilizing temperature, the fibres can overheat and fuse or even burn. While a too low stabilizing temperature will lead to carbon fibres of incomplete yield and poor quality (Hanna *et al.*, 2012).

Carbonization process only occurs in inert ambient. During the first stage, the carbonization process is carried out via thermal pyrolysis with temperature up to 600°C at a lower heating rate (5°C/min) and higher heating rate is employed at second stage. Carbonization removes most of the non-carbon elements from the fibre by heating them, violently shaking them off and reducing the fibre mass. An optimum carbonization

temperature is required in order to produce final carbon fibre with desired properties (Hameed *et al.*, 2016).

For further performance improvement, graphitization process at the temperature up to 3000°C is needed to be done on the carbonized fibres. At this stage, about 99% of PAN-based fibres are converted into carbon structure and carbon fibres of high modulus are formed (Hanna *et al.*, 2012).

#### 2.4 Fabrication of Composites

Thermoset polymers undergo irreversible chemical reactions by creating cross-links between the molecular chains during curing. However, thermoplastic polymer such as polycarbonate do not undergo any chemical reaction and thus, there is no crosslinks formed between molecules. When heat is applied, the weak bonds between molecules break. Subsequently, the movement of the molecules takes place relative to each other and the molecules flow to a new configuration of a predefined shape on application of pressure. By restoring the intermolecular forces on cooling, the solidification of the molecules takes place.

Every material possesses unique physical, mechanical and processing characteristics. Therefore, a suitable fabrication method must be employed to transform the material to the final shape without deterioting their properties. There are numerous processing techniques have been developed to fabricate fibre reinforced polymer (FRP) composites to meet functional design requirements at a reasonable cost. A cost-effective and reliable fabrication method is important for the successful production application of a material.

Hand layup technique is one of the early manufacturing method for fibrereinforced composite structural parts. It is by nature very slow and labour-intensive although it is a reliable process. Recently, manufacturing methods such as compression moulding, injection moulding and pultrusion as well as filament winding have been developed in order to cope and support the mass production (Mallick, 2007).

Filament winding has been commonly used to build highly efficient structures. Wet winding is one type of the filament winding process in which dry fibre rovings are pulled through a resin bath prior to winding on the mandrel. Sometimes, prepreg, roving or tows can be the filament wound as well. In compression moulding, a pre-weight charge is placed between two dies and then followed by the application of heat and pressure to allow the moulding compound to flow and fill the die.

While in injection moulding, pellets with embedded fibres or chopped fibres are fed into a hopper together with resin. They are heated up to their melting temperature and injected into the mould under high pressure. When the thermoplastic part cools down, they are ejected and another cycle is started. Pultrusion is a composite manufacturing technique that is capable of producing long parts with constant thickness. After rovings are pulled through a wet resin bath, they are preformed to the desired shape before entering a heated die (Campbell, 2003).

## 2.4.1 Composite Compounding by Extrusion

Extrusion compounding can be done to mix compound with several components by using an extruder. In extrusion compounding, a screw acts as a transport mechanism with the ability of the screw geometry to perform all the elementary steps of polymer processing including feeding, pumping, melting and mixing. In compounding step, composites are fabricated by incorporating fillers into the molten polymer. The compounded materials can then be formed into pellets for further processing. There are few advantages of screw plasticizing such as:

- i. the comparatively large quantity of compound material,
- ii. the higher melt homogeneity and
- iii. the relative ease of temperature control of the melt compared to other techniques,for example, plunger equipment of similar size

There are three different types of compounder, namely single screw extruders, twin screw extruders, and co-kneaders. Single screw extruders are also often to be used in raw material blending and mixing other than twin screw extruder. By depending on the product requirements, sometimes pre-blending or mixing may be required prior to extrusion process.

During extrusion, the melted material is driven through the extruder die with sufficient forward pressure. The shaped material is then cooled and cut to specific length after leaving the die. As the compound travels along the barrel, heat is generated by friction between the contacting surfaces of the screw and the barrel and by friction between the compound materials themselves. The polymer materials in the compound melts gradually as it travels from the feeding end to the other end of the barrel. When the charge reached the barrel's end, the polymer material in the compound should be melted and inorganic fillers such as short carbon fibres should be well-mixed with the polymer matrix (Fu *et al.*, 2009).

#### 2.4.1.1 Single Screw Extruder

Single screw extruder allows simplified production process for compounding applications. It consists of only one screw. The screw serves to melt, mix and meter the polymer while rotating continuously inside of a cylindrical barrel and conveying the material to the die. The feed can either in the form of a pre-blend or pellets.

There are five main components in a single screw extruder, which are drive system, feed system, screw (barrel) system, die system and last but not least, instrumentation and control system. Figure 2.7 represents the schematic diagram of a single screw extruder. Other than conveying and melting, the extruder also possesses the function of pumping, mixing, devocalization and die forming (Jr *et al.*, 2004). Figure 2.8 illustrates the functionality of the six zones for a typical single screw extruder.



Figure 2.7: Schematic diagram of a typical single screw extruder (Painter et al., 2008).



Figure 2.8: Zones of single screw extruder and their functionality (Painter et al., 2008).

Melting and pressurization of materials are the primary concerns for the single screw extruder. Plasticating extruders are always the choice for single screw compounding. For compounding process, the homogeneous compounded material will be discharged by temperature kept inside the extruder. There are several steps that involved in the mixing or compounding process. Thus, before feeding into the extruder, pre-mixing or blending is essential. Transport of material, melting and pumping will be carried out in the extruder during compounding (Muralisrinivasan, 2015). Figure 2.9 shows the melting of polymer and additives in single screw extruder.



Figure 2.9: Melting stages during the processing of polymer pellets and additives in a single screw extruder (Muralisrinivasan, 2015).

As compared to twin-screw extruder, single screw extruder has several advantages such as a more economical melting and lower compounding cost by using "mixing screws". "Mixing screws" are popular due to its ability to reduce the raw materials costs as well as scrap disposal, and, therefore lesser environmental impacts. Thus, single screw extruders are extensively used as mixing devices in industry, however, with limited mixing intensity.

#### 2.4.2 Injection Moulding

Injection moulding is the most suitable and widely employed manufacturing process for the manufacture of fibre-reinforced thermoplastic composites. It is a cyclical and continuous process of rapid mould filling that is followed by cooling and ejection. After adding the materials into the hopper, the injection unit serves to plasticize and inject the materials into a clamped mould under high pressure. There are some raw materials that are usually used in this technique and they are shown in Table 2.1. A reciprocating screw injection moulding machine is normally employed.

Polymers	Polypropylene	(PP),	polyethylene	terephthalate	(PET),
	polycarbonate (PC), nylon and so on				
Reinforcements	Kevlar fibre, glas	ss fibre,	carbon fibre an	d so on	

Table 2.1: Raw materials suitable for processing in injection moulding (Debnath *et al.*, 2017).

The fibre filled polymeric materials which are in pellets form will be fed into the injection moulding machine at which the machine is used to transport, melt and pressurize those pellets. Temperature control is important in the injection moulding. The polymer melts with the heat generated from conduction through the barrel wall and shearing action.

During plastication, the materials accumulates in front of the screw, which is drawn back against an adjustable pressure in the hydraulic system until specific melt volume or shot size is achieved. It is then followed with the pushing action of screw that force the melts into the cold cavity of the clamped mould. The mould opens and ejects the moulded product after it is cooled and achieved sufficient rigidity (Goodship, 2017). Figure 2.10 shows the schematic diagram of a typical reciprocating screw injection moulding machine while Figure 2.11 illustrates the process of injection moulding in a reciprocating screw injection mouding machine.



Figure 2.10: A typical reciprocating screw injection moulding machine (Kemal Karasu *et al.*, 2014).