

SCHOOL OF MATERIALS OF MINERAL RESOURCES ENGINEERING

UNIVERSITI SAINS MALAYSIA

**HYGROTHERMAL AND WEAR BEHAVIOUR OF SHORT CARBON FIBER
REINFORCED POLYCARBONATE**

By

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DECLARATION

I hereby declare that I have conducted, completed the research work and written the dissertation entitled "Hygrothermal and Wear Behaviour of Short carbon Fiber Reinforced Polycarbonate Composite". I also declared that it has not been previously submitted for the award for any degree or diploma or other similar title of this for any other examining body or University.

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LIST OF SYMBOLS

$^{\circ}\text{C}$	Degree celcius
wt%	Weight percent
σ_f	Flexural strength
E	Flexural modulus
P	Maximum applied load
L	Length of support span
m	Slope of the tangent
b	Width
d	Thickness
%	Percentage
D	Diffusion coefficient
g	gram
rpm	Revolution per minute
μ	Micro

LIST OF ABBREVIATIONS

CFRP	Carbon Fibre Reinforced Plastics
PC	Polycarbonate
CFRTP	Carbon Fiber Reinforced Thermoplastic
CF	Carbon fibre
SEM	Scanning Electron Microscope
MMCs	Metal matrix composites
CMCs	Ceramic matrix composites
PMCs	Polymer matrix composites
PE	Polyethylene
PP	Polypropylene
PLA	Polylactic acid
FRP	Fiber reinforced polymer
ISO	International Organization for Standardization
LAOW	Low amplitude oscillating wear
BPA	Bis-phenol A
mm	milimetre
FDA	Food and Drug Administration
kW	Kilowatt
XHR – FESEM	Extreme High Resolution Field Emission Scanning Electron Microscope
ASTM	American Society for Testing and Materials
M _m	Maximum moisture absorption
CF/PC	carbon fiber/polycarbonate

**KELAKUAN HIGROTHERMAL DAN HAUS KOMPOSIT POLIKARBONAT
DIPERKUATKAN GENTIAN KARBON PENDEK**

ABSTRAK

Empat komposisi dengan 0, 5, 10 dan 15 % gentian karbon pendek diperkuatkan dengan polikarbonat telah disediakan menggunakan ekstrudat skru tunggal. Komposit yang telah disediakan kemudian menjalani ujian kehausan dan higrotermal. Pada ujian kehausan, didapati rintangan haus bergantung pada jumlah gentian karbon. Dalam ujian higrotermal, spesimen direndamkan di dalam air pada suhu bilik dan suhu 60 darjah Celcius sehingga ia mencapai tahap seimbang pada beratnya. Didapati pekali penyerapan bergantung pada jumlah gentian karbon dalam komposit. Apabila jumlah gentian karbon meningkat, pekali penyerapan akan berkurang, memberi makna spesimen kurang menyerap air. Selepas itu, spesimen yang direndam tadi menjalani ujian lenturan pada spesimen basah dan yang telah dikeringkan semula. Ujian itu menunjukkan bahawa kekuatan lenturan dan modulus menurun dalam keadaan spesimen basah dan meningkat semula apabila spesimen dikeringkan. Sifat lenturan pada suhu 60 darjah Celcius didapati lebih rendah berbanding suhu bilik kerana suhu tinggi boleh mendegradasi komposit lebih cepat berbanding suhu bilik.

HYGROTHERMAL AND WEAR BEHAVIOUR OF SHORT CARBON FIBER REINFORCED POLYCARBONATE

ABSTRACT

Four compositions with 0, 5, 10, and 15 % of short carbon fiber loading reinforced with polycarbonate was prepared using single screw extruder. The composite was then tested for the wear and hygrothermal behaviour. On the wear testing, it was found that the wear resistance depends on the carbon fiber loading. On the hygrothermal testing, specimens were immersed in water at room temperature and 60 °C until reached equilibrium in weight. It was found that diffusion coefficient also depend on fiber loading. As the fiber loading increased, the coefficient of diffusion reduced, means that it less absorb water. Then, the immersed sample was test with three points bending flexural testing on wet and redried samples. The observed flexural strength and modulus were these properties drop at wet condition and increased back upon recovery. The flexural properties at 60 °C were lower than room temperature. It can be proved that the high temperature tend to degrade composite faster than at room temperature.

CHAPTER 1

INTRODUCTION

1.1 Background

Short fibre reinforced composites are consistently expanding application in engineering fields and consumer goods (De and White, 1996). The demand of Carbon Fibre Reinforced Plastics (CFRP) is increasing in the aerospace, automotive and sports industries etc. CFRP has advantages in high-specific strength and high-specific modulus. When using CFRP, choosing an excellent matrix in strength, impact resistance, and heat resistance is crucial. Polycarbonate (PC) has a high impact strength compared to other plastics, thus it is expected to be used as the matrix in CFRTP(M. Shinohara, 2012).

The use of carbon fibre reinforced composite for primary and secondary structural components in aircraft construction promises not only benefits in weight savings, and with it, maneuverability and range of the aircraft, but also considerable savings in labour cost. This savings in labour cost more than components for the higher cost of the raw materials (Augl and Berger, 1976).

Since introduction in 1957, polycarbonate has evolved from a metal, glass, and plastics replacement material to a strong contender for initial specification. Polycarbonate has a strength and toughness to replace metals in some application, particularly when low weight is desirable. Polycarbonate parts do not corrode, rust, or pit and are available in glossy moulded-in colours. Polycarbonate can be used to combine many parts into one or only a few subassemblies, resulting in lower finished part costs (Margolis, 1985).

Polycarbonate is a versatile, tough plastic used for variety applications especially due to its unbeatable strength combined with lightweight (Park and Seo, 2011). It can be used for appliances such as small electrical and non-electrical appliances, automobiles applications due to resistance in brittle fracture on impact, lighting and medical applications.

Carbon fibres have been widely used as reinforcement materials in composite manufacturing due to their exceptional properties such as high specific modulus, strength, stiffness, electrical properties and low density. While chemical and thermal properties of composites mainly depend on matrix materials, mechanical properties of composites such as strength depend on properties of carbon fibre and fibre/matrix interfacial adhesion strength (Ozkan et al., 2014).

1.2 Problem Statement

The observation by earlier investigators that the flexural and shear strengths of short carbon fibre reinforced composites may deteriorate at ambient storage condition made it necessary to investigate the hygrothermal behaviour on short carbon fibre reinforced polycarbonate in order to get a better understanding and able to predict how these materials would behave in long term service and storage conditions. From this investigation, it describes the diffusion of water moisture which may serve as a basis for prediction of long term composite change in various environments.

Plastics do not always follow the classical laws of friction that apply because of the large plastic deformations that occur at the tips of the asperities. Larger range of elastic deformation means that the coefficient of friction is generally lower. Hence, this project investigates the wear behaviour on short carbon fibre reinforced polycarbonate to have lower coefficient of friction.

1.3 Research Objectives

In this study, attempts were made to produce composite of short carbon fibre (CF) reinforced with Polycarbonate (PC) on ratio of 100/0, 95/5, 90/10 and 85/15 wt%.

There are some research objectives in this study:

1. To study water absorption behaviour of short CF/PC at room temperature and 60 °C.
2. To investigate the flexural properties of short CF/PC at room temperature, 60 °C and the recovery properties.
3. To determine the wear behaviour of short CF/PC at different ratio of CF/PC using pin-on-disc machine.

1.4 Scope of the Research

This research focused on effectiveness of short carbon fiber reinforced polycarbonate matrix by using single screw extruder. The study of the effect of hygrothermal and wear behaviour of short carbon fiber reinforced polycarbonate will be conducted. Thus, this study will analyse the flexural strength of the short carbon fiber reinforced polycarbonate before and after immersion on water and also the recovery properties. In addition, for the wear behaviour, pin-on-disc machine will be used to determine the coefficient of friction towards different amount of fiber loading. The morphological changes of fiber surface will be acquired using Scanning Electron Microscope (SEM).

1.5 Thesis Outline

This thesis is divided into five chapters and each chapter gives information related to the research interest.

1.5.1 Chapter 1

Introduction of the research explained in this chapter. It covers brief introduction about short carbon fiber reinforced polycarbonate, problem statement, objectives of this research, scope of investigation and the thesis outline.

1.5.2 Chapter 2

Throughout this chapter, it contains literature review on the related topics relevant to the scope of work explained. This literature review is to convey to the reader what thoughts and information from previous researcher.

1.5.3 Chapter 3

A detailed method in producing short carbon fiber reinforced polycarbonate using single screw extruder. It also contains the information about materials specifications, experimental procedure and equipment or machine used in this study.

1.5.4 Chapter 4

Contains results and discuss the experimental results obtained from all the hygrothermal and wear behaviour of the short carbon fiber reinforced polycarbonate.

1.5.5 Chapter 5

The final chapter will conclude all the findings obtained in Chapter 4. Comments and suggestion on future works also includes here.

CHAPTER 2

LITERATURE REVIEW

2.1 Composite

2.1.1 Definition

Composites make up an extremely expansive and essential class of engineering materials with world yearly generation is more than 10 million tons and the market developed at 5 to 10 % each year. In addition, composites are utilized as a part of a wide assortment of application to suit the service conditions (Hull and Clyne, 1996).

According to Thomas et al. (2012), usually composites are used as materials in electronic packaging to medical equipment, making aircraft structures and space vehicle to home building. A composites fabricated by combining two or more components – selected filler or reinforcing agent and a compatible matrix binder (i.e., a resin) – in order to acquire particular properties and qualities.

It can be classified by their structural components: fibrous which is composed of fiber in a matrix, laminar which is composed of layers of materials and particulate which is composed of particle in a matrix (Lubin, 2013). Matrix phase is the primary phase having a continuous character usually more ductile and less hard phase. It holds the dispersed phase and shares a load with it. Dispersed (reinforcing) phase is embedded in the matrix is discontinuous form. The secondary phase is called the dispersed phase which is usually stronger than the matrix, thus sometimes called reinforcing phase. The basic difference between blends and composites is that two main constituents in the composites remain recognizable while in blends, these two main constituents may not be recognizable (Thomas et al., 2012).

2.1.2 Classification

Thomas et al. (2012) stated that composites can be classified on the basis of matrix phase and types of reinforcements used as shown in Figure 2.1. On the basis of matrix phase, there are metal matrix composites (MMCs), ceramic matrix composites (CMCs) and polymer matrix composites (PMCs). The classifications based on types of reinforcement are fibrous composites which composed of fiber, laminate composite which composed of laminates and particulate composites which composed of particles,. Fibrous composite can be further subdivided on the basis of natural (biofiber) or synthetic fiber. Biofiber can be classified based on the matrix which non-biodegradable matrix and biodegradable matrix.

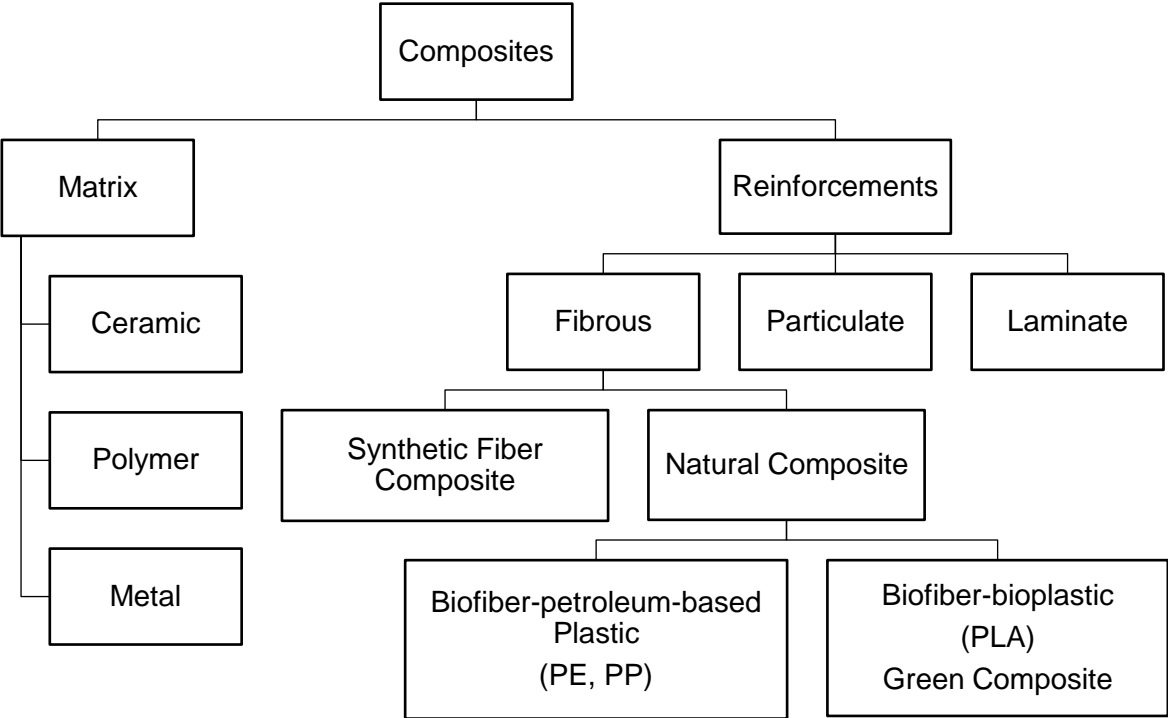


Figure 2.1: Classification of Composite (Thomas et al., 2012)

Metal matrix composites (MMCs) consist of at least two components. First component is metal matrix which in the most cases, an alloy. The second component is a reinforcement which in general is an intermetallic compound, an oxide, a carbide or a nitride (Taya and Arsenault, 2016). There are four kinds of MMCs which (i) laminated or layered MMCs (ii) short fiber or whisker – reinforced MMCs (iii) and (iv) particle – reinforced MMCs continuous fiber or sheet – reinforced MMCs according to Figure 2.2 (Chawla and Chawla, 2013).

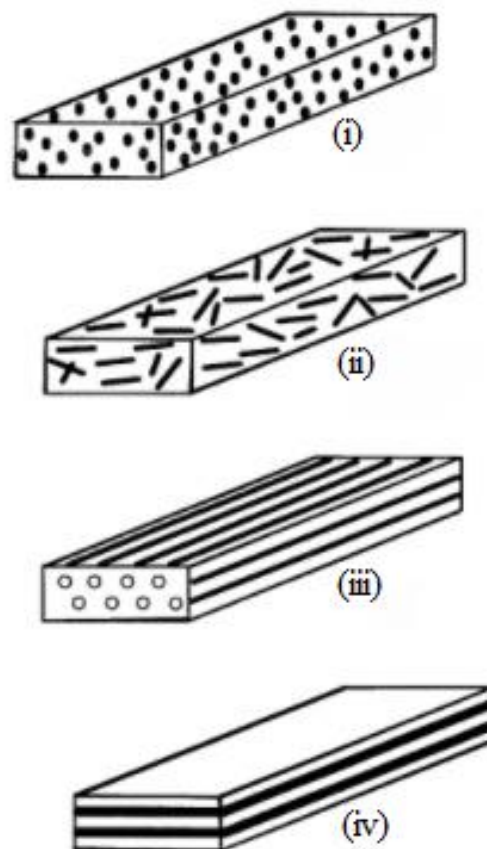


Figure 2.2: Different types of metal matrix composites (Chawla and Chawla, 2013).

Ceramic matrix composites (CMCs) are mix of different ceramic matrix materials with special suitable fibers, new properties can be made (Krenkel, 2008). CMCs have risen as potential applicants in perspective of their amazing physical and mechanical properties that are heterogeneous materials in which a second phase is embedded within a ceramic matrix. They combine ceramic characteristics such as

good hardness, high strength and temperature stability with specific tailored properties such as toughness and self – healing depends on the nature of the reinforcing phase. The unique ability of CMCs to repair through self – healing of cracks have proven to be useful for a wide range of applications such as military, aviation and building industry (Low, 2018).

Polymer matrix composites (PMCs) used in many applications such as automotive, aerospace and usually competes with other structural materials such as steel and alloys. Polymer served as the matrix material which can be thermoplastic polymer (polyether ether ketone and polypropylene) and thermosetting polymer (polyester and epoxy). The reinforcement used usually high – strength and high – modulus fibers. When the matrix and the reinforcement combined together, they have much higher modulus and strength than the polymer matrix itself which often called fiber – reinforced polymer (FRP). PMC has lower density, high strength – to – density ratio, high modulus – to – density ratio and easy to be processed compared to MMCs and CMCs. The variety of fibers used can be either continuous or discontinuous in length and arranged in unidirectional, bidirectional, multidirectional or random orientation as shown in Figure 2.3 (Mallick, 2017).

2.2 Reinforcements

Composites have developed as important materials because of their outstanding properties as compared to metallic alloy. The combination of outstanding physical, thermal and mechanical properties that makes composites attractive to use for some applications, especially when weight-saving is crucial. Fiber reinforced polymer (FRP) composite can be said as multi-constituent materials consisting of reinforcing fibers embedded in a rigid polymer matrix. The fibers used in FRP can be in the form of small particles, whiskers or continuous filaments. Most composites used in engineering applications contain fibers made of glass, carbon or aramid (Tong et al.,

2002). Fibers are classified as natural and synthetic as shown in Figure 2.4 (Carey, 2016).

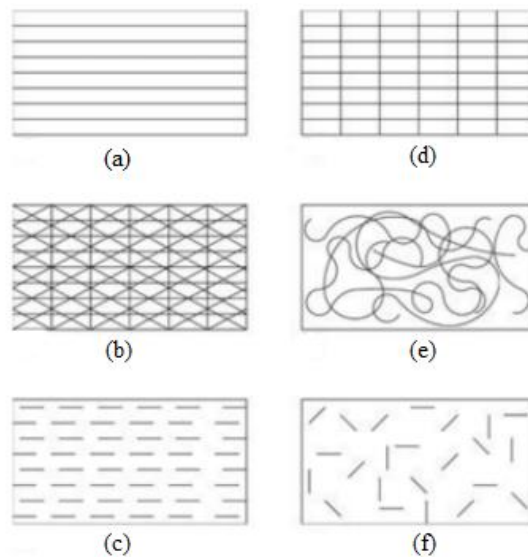


Figure 2.3: Schematic representation of fiber orientation in PMCs. (a) unidirectional, continuous; (b) multidirectional, continuous; (c) unidirectional, discontinuous; (d) bidirectional, continuous; (e) random, continuous; and (f) random, discontinuous (Mallick, 2017)

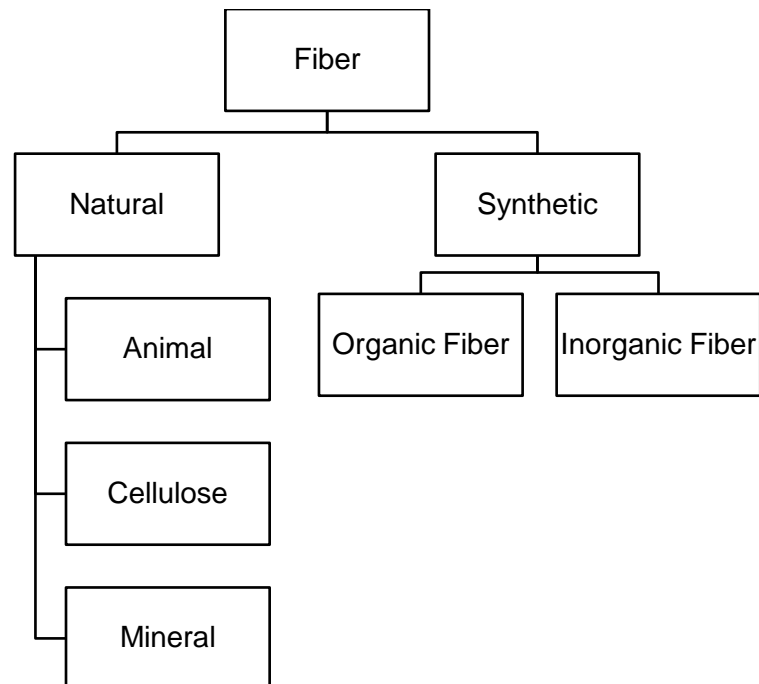


Figure 2.4: General fiber classifications (Al and Salit, 2017).

2.2.1 Natural Fiber

Natural fibers or species of natural plants can result in natural reinforcement fiber. Natural fibers can be used in three ways such as (i) for textiles, paper and fabrics, (ii) for biofuel and (iii) for reinforcement composite material. As for reinforcements, natural fibers can eventually be used to replace glass fibers in some applications. Natural fibers can be classified according to their origin (lignocellulosic fibers, animal fibers and mineral fibers) as shown in Figure 2.5 (Campilho, 2015).

Natural fibers generally are those that already exist in nature and can be achieved via different mechanical and chemical processes. It consists of hollow cellulose fibrils held together by the lignin as a binder in the hemicellulose as a matrix, thus they are considered as composites. Other components of natural fibers are cell wall, primary wall and secondary walls. The middle layer consists of helical cellular microfibrils. The quality of the fibers is controlled by the microfibrillar angle. The amorphous matrix consists of hemicellulose, pectin and lignin. The hemicellulose molecule is hydrogen bonded to cellulose and performs as cementing matrix between the cellulose microfibrils to build the main structural element of fiber cell called cellulose-hemicellulose network. A schematic structure of a natural fiber illustrated in Figure 2.6 (Al and Salit, 2017).

2.2.2 Synthetic Fiber

Synthetic fibers is a fiber manufactured from polymers built up from chemical elements or compounds, in contrast to fibers made from naturally occurring fiber-forming polymer according to International Organization for Standardization (ISO). The fibers developed from solutions of high polymers by extrusion into non-solvents (wet-spinning) and into evaporative atmospheres (dry-spinning) and also about filament orientation by stretching and about subsequent downstream handling. An alternative method to classify the synthetic fibers depends on the nature of mechanism growth of

polymers either chain-growth or step growth mechanism (McIntyre, 2004). Figure 2.7 shows the classification of synthetic fibers.

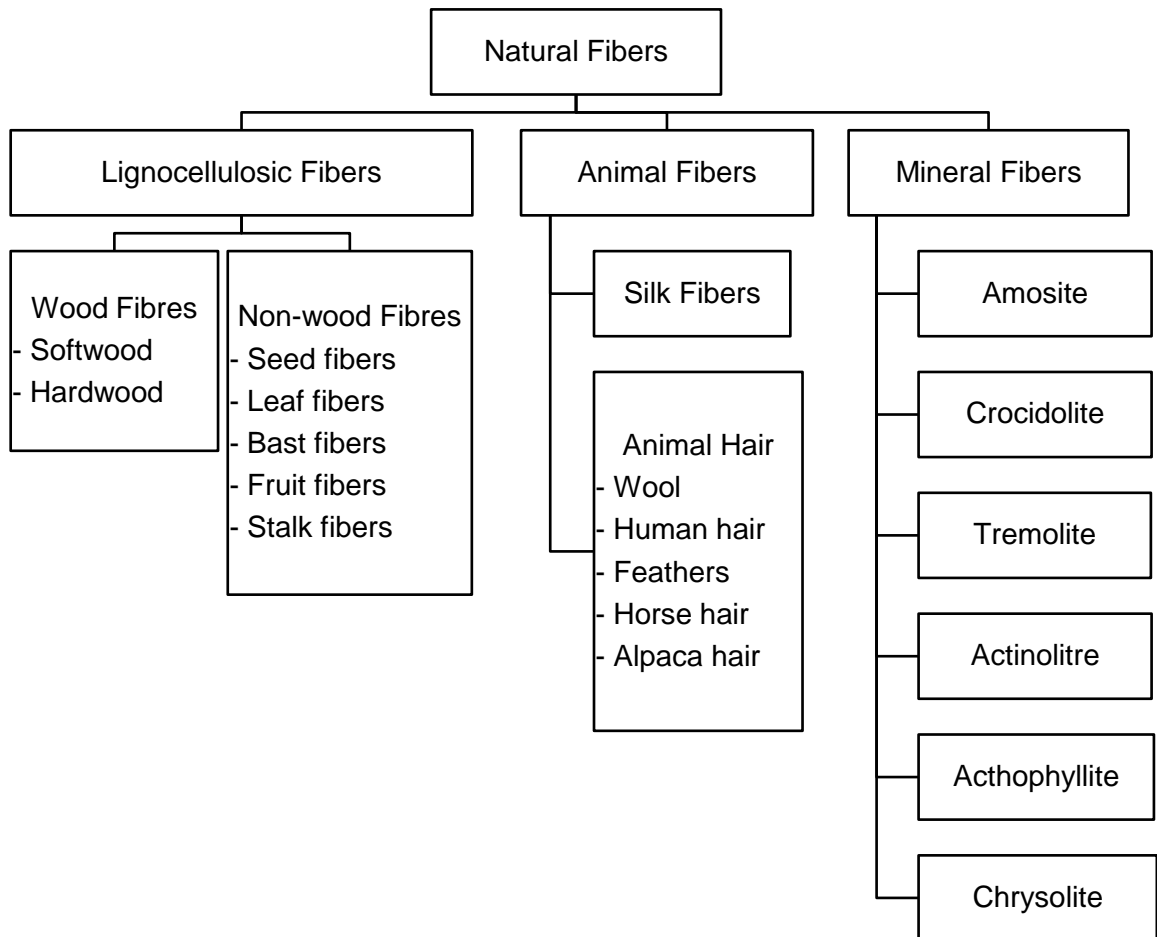


Figure 2.5: Classification of natural fibers (Campilho, 2015).

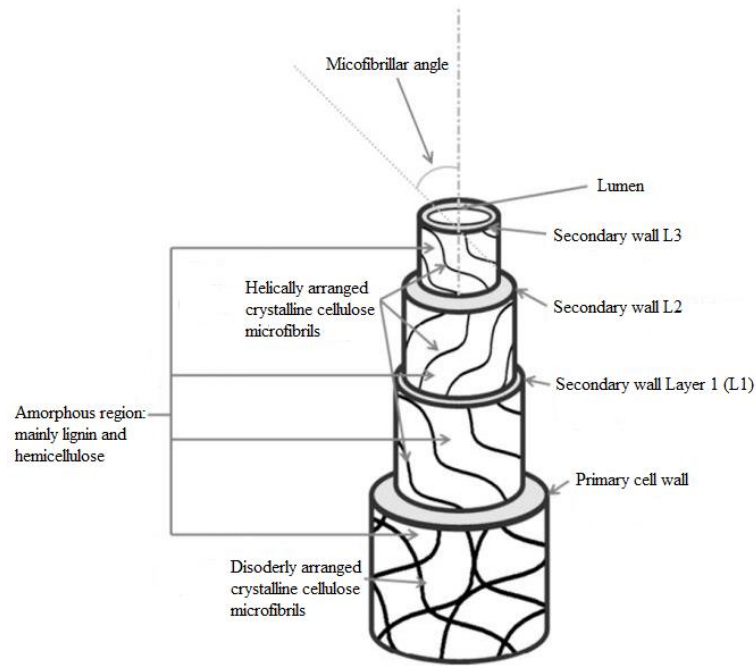


Figure 2.6: A schematic structure of a natural fiber (Al and Salit, 2017).

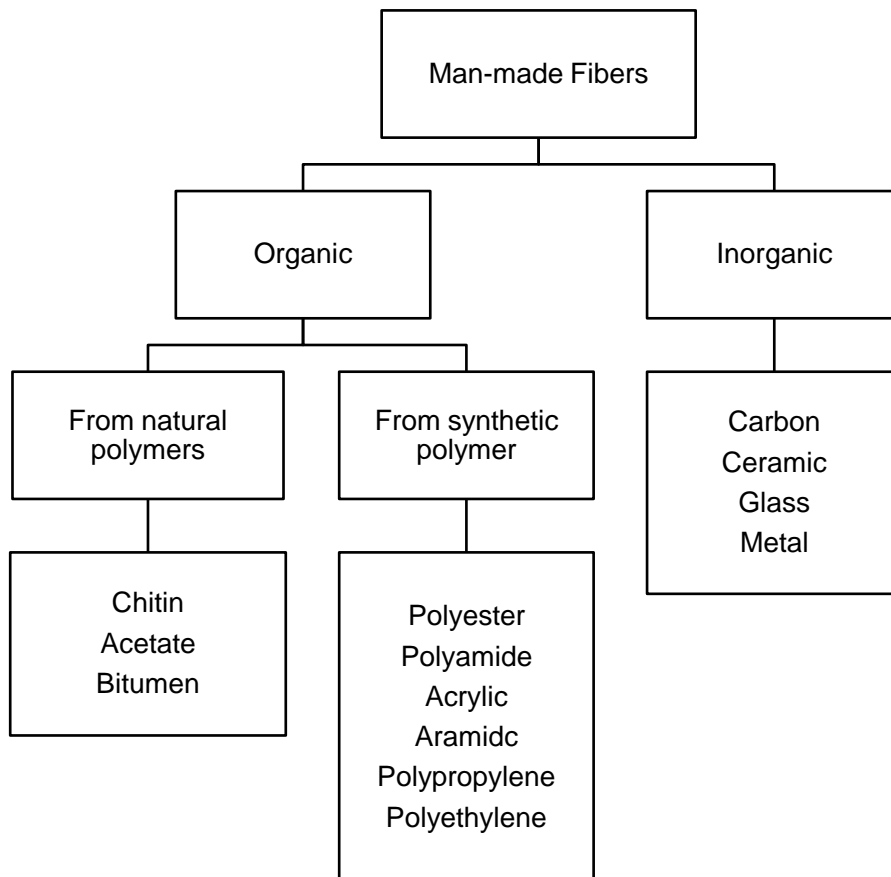


Figure 2.7: Synthetic fibers classification (Cherif, 2015).

According to Cherif (2005), synthetic fibers can be classified into three categories:

- i. Man-made fibers from natural polymers: these textile fiber materials can originate from plants such as viscose acetate, animals such as chitin, bitumen as precursor for carbon fiber production and alginate or from inorganic sources. Fiber materials produced from natural polymers or inorganic source have a significant influence in lightweight construction applications. A few examples are different types of silica glass, glass fiber, basalt and ceramics.
- ii. Man-made fibers from synthetic polymers: the macro molecules of synthetic fiber materials result from stringing together monomers based on single molecules or atoms. This types of fiber contains largest number of fiber types which also most common in practical applications. These synthetically produced fibers are used as thermoplastic matrixes for fiber-reinforced plastic composites reinforcement components or for crack minimization in concrete applications or as non-rigid textile structures stabilization.
- iii. Man-made fibers from non-polymer materials: including mono-crystalline and polycrystalline fiber and metal fibers such as those based on tungsten, steel and aluminium.

2.3 Fiber-matrix Interface

Fiber composite technology has high strength and stiffness of fibers that are combined with matrix materials of similar or dissimilar natures creating inevitable interfaces. Both fiber and its matrix retain their original physical and chemical properties and also together they produce a combination of mechanical properties that cannot be achieved with either of constituents acting alone due to presence of an interface between these two constituents (Kim and Mai, 1998). Besides affecting the mechanical, physical and chemical properties, excellent interaction between fibers and

matrix can reduce porous structures and hence, inhibit water penetration consequently reducing the moisture absorption of composites (Sreekala et al., 2002).

Kim and Mai (1998) stated that surface formed by a common boundary of reinforcing fiber and matrix that in contact with and maintains the bond in between for load transfer purpose as an interface in fiber composites. Kim and Mai (1998) reported that the earlier definition of interface by Metcalfe (1974) can be used for interphase as well: “An interface is the region of significantly changed chemical composition that constitutes the bond between fiber and matrix as illustrated in Figure 2.8.

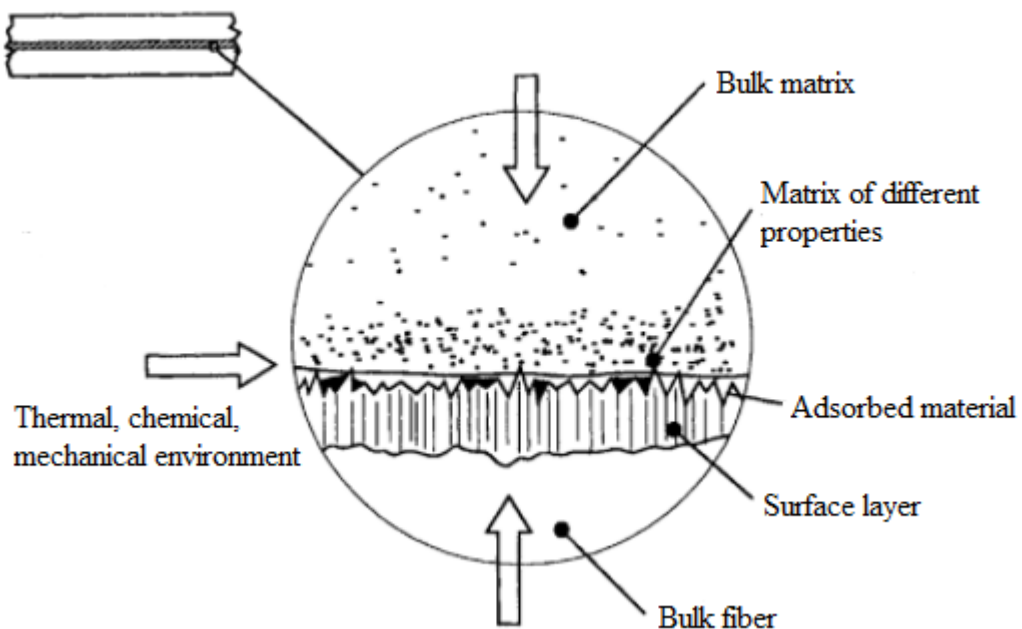


Figure 2.8: Schematic illustration of three-dimensional interphase between fiber and matrix (Kim and Mai, 1998).

Interfacial bond between fiber and matrix also may influence various aspects of composites behaviour such as composite strength, Young’s modulus, modes of failure, inter-laminar shear strength, compressive strength and bending stiffness. Hence, it is crucial to know what are properties of the interfacial bond should be establish and how the various properties are influenced to maximize composite performance (Greszczuk, 1969).

2.4 Hygrothermal Ageing of Composite

Nowadays, the needs for more environmentally-friendly products in industry are growing rapidly resulting from ecological concern, environmental attentiveness and new rules and regulations (Scida et al., 2013). The level of environmental degradation that occurs in a fiber reinforced composites is measured by the amount of moisture absorbed by the materials. The absorbed moisture known to give some effects to performance of composite especially in long-term services and may be sufficiently enough to influence failure (Ray, 2006).

The term ageing can range from more benign physical ageing effects – such as swelling from moisture absorption – that are largely reversible, to be more serious chemical ageing that is irreversible. Ageing of composites was done to know their long-term properties when exposed to environment. Environmental ageing of composite materials occurs from surface of edge inwards and requires time to penetrate into material's centre. This is an analogous to fluid diffusion and can be anisotropic, and the rate can be dependent on temperature because representing the true service history for long-term structural life prediction is a vital step to validate any short-term (Martin, 2008).

Hygrothermal ageing of composites was investigated under two different approaches which are quantifying chemical degradation of the matrix and mechanical approach aims at modelling the evolution of the mechanical properties during ageing (Foulc et al., 2005). Water absorption and its effects on mechanical properties of fiber composites are important due to water absorption can cause weight gain of composite materials and also dimension changes and loss in mechanical properties (Poursartip and Street, 1995).

2.5 Wear Behaviour of Composite

Tribology is the study of surfaces in moving contact, having its origin in the Greek word *tribos* which means rubbing. Polymers are being used increasingly in tribological applications due to their elasticity, accommodation to shock loading, low wear and friction resistance (Abdelbary, 2015).

Friction related to energy dissipation at the surface and the measure of energy dissipation cause by mechanical and chemical damage. According to an early theory of friction based on adhesion alone, it was assumed that asperities of the surfaces in contact from welded junctions that shear during sliding causing friction. Hence, friction taught to be dependent on the actual contact area which in turn, depends on applied and tangential load. According to modified theory, coefficient of friction between sliding surfaces is combination of asperity deformation, ploughing by wear particles and hard surface asperities and the adhesion between flat surfaces (Chand and Fahim, 2008).

Figure 2.9 illustrated typical curve between coefficient of friction and sliding distance. From the figure, adhesion does not play significant role initially due to contaminated nature of surface. As sliding progress, frictional force increases due to enhanced adhesion. As further increase the sliding duration, frictional force increased linearly due to ploughing by entrapped wear particles. With further increase in sliding time, frictional force become steady as the number of entrapped particles between interface becomes constant. Initial increase in the value of frictional force known as static friction coefficient while the steady state known as dynamic friction coefficient (Chand and Fahim, 2008).

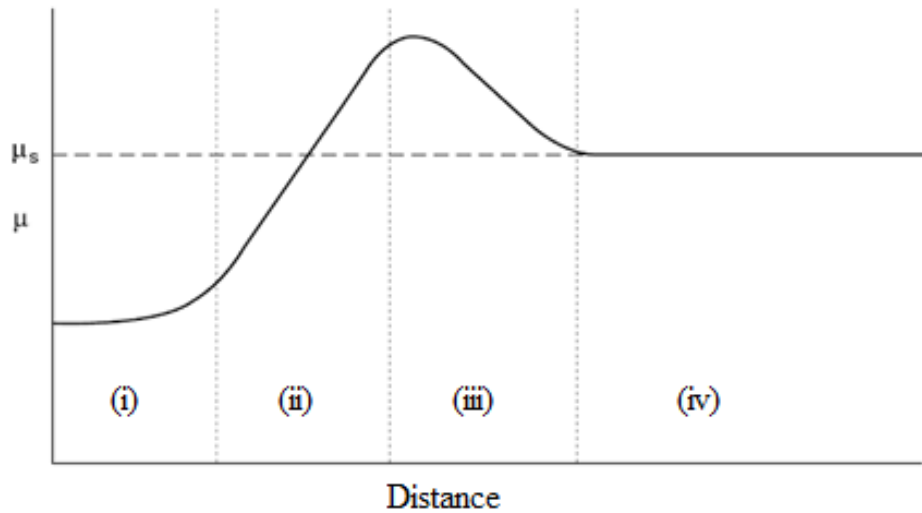


Figure 2.9: Typical friction curve (Chand and Fahim, 2008).

According to Pascal (1970), The Committee of the Institution of Mechanical Engineers has defined wear as the progressive loss of substance from the surface of a body brought about by mechanical action. Studying the wear of polymers is important from both scientific and technological because the use of polymers in tribological applications, gears, bearings and biomaterials (Abdelbary, 2015).

Chand and Fahim (2008) define the common forms of wear as follows:

- i. Adhesive or sliding wear illustrated in Figure 2.10 occurs when two bodies slide over each other and fragments are pulled off from one surface, which then adhere to the other surface. This form of wear generally termed as adhesive wear.

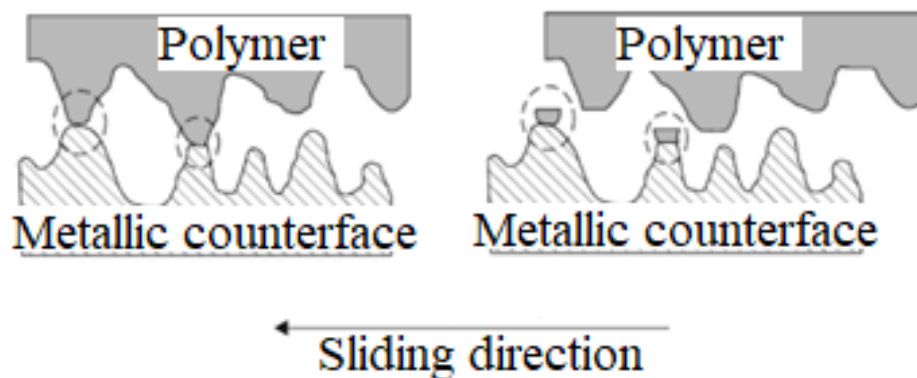


Figure 2.10: Schematic illustration of adhesive wear (Abdelbary, 2015).

- ii. Abrasive wear occurs when rough and hard surface or soft surface containing hard particles slides on a softer surface and plough a series of grooves in it. This type of wear also arises when hard abrasive particles are introduced between sliding surfaces. Two forms of wear involving hard rough surface and abrasive grains referred to two-body (does not occur when hard, sliding surface is smooth) and three-body abrasive wear (does not occur when the particles in system are small or when they are softer than sliding materials) process as shown in Figure 2.11.

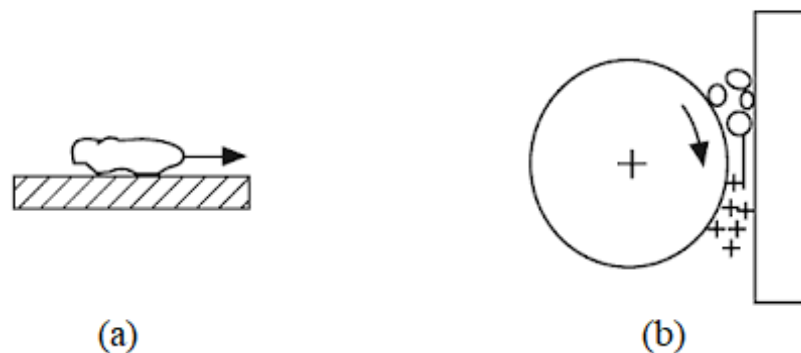


Figure 2.11: Schematic of (a) two-body and (b) three-body abrasive wear (Chand and Fahim, 2008)

- iii. Corrosive wear occurs when sliding takes place in a corrosive environment. In absence of sliding, products of corrosion would form a film on surfaces, which would tend to slow down or even arrest corrosion. Sliding action wears the film away corrosive attack to continue.
- iv. Erosive wear defines as the damage produced by sharp particle impingement on the body. The surface roughness produced becomes relatively greater because an impinging particle readily removes material from a low point on surface.
- v. Fatigue wear as shown in Figure 2.12 occurs due to repeated slides or rolling over a track results in breakup of surface with formation of loose fragments, leaving large pits in the surface.

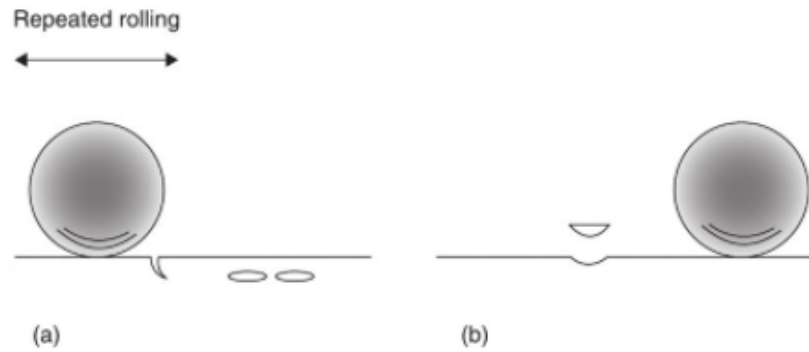


Figure 2.12: Schematic illustration of typical surface fatigue wear due to cyclic stress (Abdelbary, 2015).

- vi. Fretting wear of low amplitude oscillating wear (LAOW) occurs when in contact surfaces undergo oscillatory tangential displacement of small amplitude. The motion is too small (per cycle) that it is difficult to anticipate the overall large volume of wear debris produced in the process. When amplitude is large it is known as reciprocating wear.
- vii. Cavitation is when a portion of liquid is under tensile stresses, it boils and bubbles suddenly collapsed to produce mechanical shock.

2.5.1 Factors Affecting Friction and Wear of Polymer Composite

Friction mainly results in loss of energy while wear results in material loss (Kar, 2016). Various factors can influence the friction and wear rate that can be divided into application parameter and environmental factors. Application parameter includes sliding speed, bearing pressure and temperature. Environmental factors like the presence of fluid, inert gases or vacuum (Friedrich, 2012).

The effects of sliding speed on the wear rate of polymer can be happened by influenced of the sliding surface and temperature. Frictional heat generated on the surface of friction occurs can increase proportion to sliding speed. Steady state means that the surface friction temperature attained, θ depends on the heat transfer properties of the samples. Hence,

$$\theta = R\mu PV$$

where R is thermal resistance of the samples, μ is the coefficient of friction, P is the pressure apply and V is the sliding velocity. So, the effects on sliding speed on wear rate can be said as same effect to the temperature (Friedrich, 2012).

Wear rate of can also be affected if the samples were run in the vacuum condition. The wear rates of certain materials in vacuum and air are compared in Table 2.1. For example graphite – filled polyimide, the wear rates is different if conducted in air and vacuum conditions. Wear rates increased when conducted to vacuum environment compared to air environment due to composite graphite – filled polyimide contains type I carbon fibers. Its shows different result for molybdenum disulphide where the wear rates decreased when conducted in vacuum conditions. This happened because molybdenum disulphide does not depend on adsorbed vapours to lubricate.

Table 2.1: Comparison of wear rate on certain materials in air and vacuum condition.

Materials	Wear Rate ($\text{m}^3 \text{N}^{-1} \text{m}^{-1} \times 10^{-15}$)	
	In air	In vacuum
Unfilled polyimide	0.45	0.15
Polyimide + PTFE	0.75	0.075
Polyimide + graphite + PTFE	0.15	45
Polyimide + molybdenum disulphide	0.45	0.15
Polyimide + type II CF	1.5	15
Polyimide + type I CF	0.15	22
PTFE/glassfiber/molybdenum disulphide	0.19	0.015
PTFE + Pb/ Bronze sinter	0.15	0.3

2.5.2 Material Selection

Procedure of selecting the materials is very crucial as it also can affect the wear rates of the composites. Step by step procedure to select suitable materials for composites for sliding application is shown in Figure 2.13.

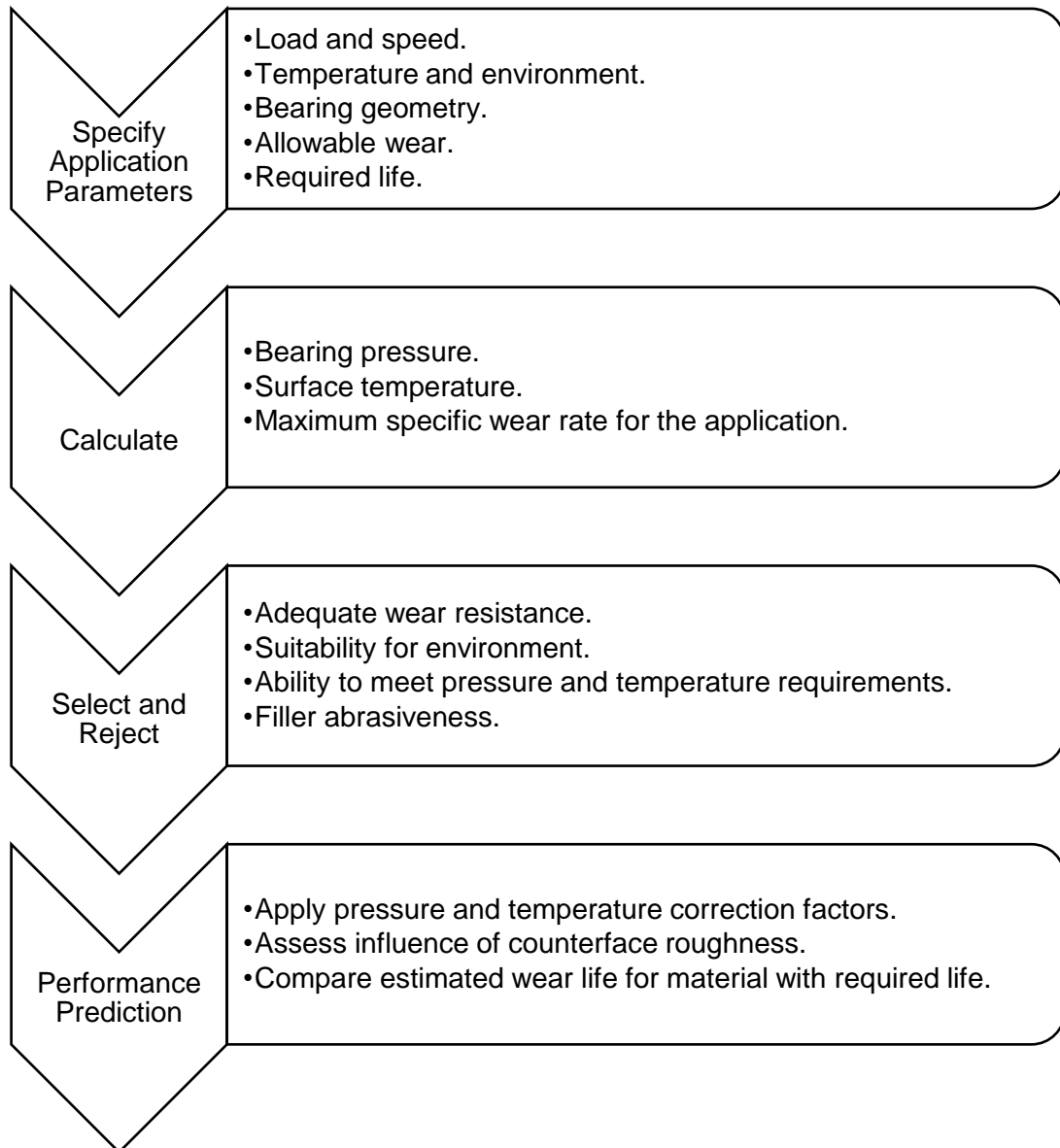


Figure 2.13: Step by step of material selection.

2.5.3 Role of Fillers and Reinforcements

Fillers in composites plays an important part in wear and friction during sliding of polymer based materials against metallic counter-faces by modified its topography as a result of corrosion, transfer and corrosion. When fillers were added to polymers, it improves one or more of these following properties:

- I. Friction and wear characteristics
- II. Mechanical properties such as impact strength or resistance to deformation under load which will decide load carrying capacity of bearing
- III. Thermal properties such as thermal conductivity. This will affect expansion coefficient and operating temperature will results the dimensional stability of bearing.

Transfer may be either gives harm or benefit to wear characteristic for unfilled polymers. Wear rate depends on transfer film developed in the former test, while in latter, no appreciable transfer occurred. Wear increased for brittle polymers and low wear for ductile polymers in polymeric transfer film.

When the filler present in polymeric materials, transfer film may developed from polymer, filler or both. This is the reason why certain additives (graphite or polytetraflouroethylene) can reduce friction coefficient and wear rate. The combination of filler and polymer lowers elongation to fracture and fracture strength (Abdelbary, 2015).

2.6 Flexural Testing

Flexural behaviour of mechanical system can be used to identify the system characteristics including parts and system failure (Yilbas et al., 2014). From this flexural testing, flexural strength and flexural modulus will be evaluated. Flexural strength is a force applied per square inch at the sample failure, normalized with support span and specimen cross-sectional configuration while flexural modulus is a force applied per square inch and causing a certain deflection of sample, normalized with support span and specimen cross-sectional configuration (Klyosov, 2007).

According to Salit et al., (2015), flexural strength and flexural modulus can be calculated using the equations 2.1 and 2.2 respectively.

$$\text{Flexural strength, } \sigma_f = \frac{3PL}{2bd^2} \quad (2.1)$$

$$\text{Flexural modulus, } E = \frac{L^3 m}{4bd^3} \quad (2.2)$$

Where P is maximum applied load, L is length of support span, m is slope of the tangent, b is width and d is thickness of the specimen.

Flexural tests usually conducted on simply supported beams of cross-sectional area with no involvements with end-tabs. Two methods usually used to determine the flexural properties which are three-point and four-point bending tests illustrated in Figure 2.14 and 2.15 respectively (Hodgkinson, 2000).

In this research, the flexural testing used three-point bending testing method. Beam loaded in three-point flexure can be either rectangular or circular beam (Freiman and Mecholsky, 2012).

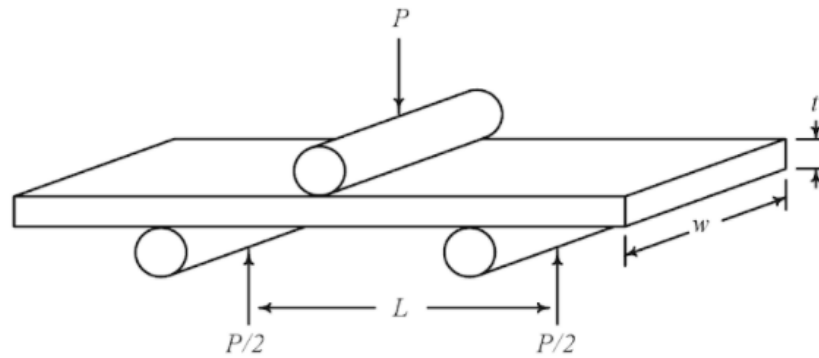


Figure 2.14: Schematic of three-point flexure test. P is the load, L is span length, t is thickness and w is width (Freiman and Mecholsky, 2012).

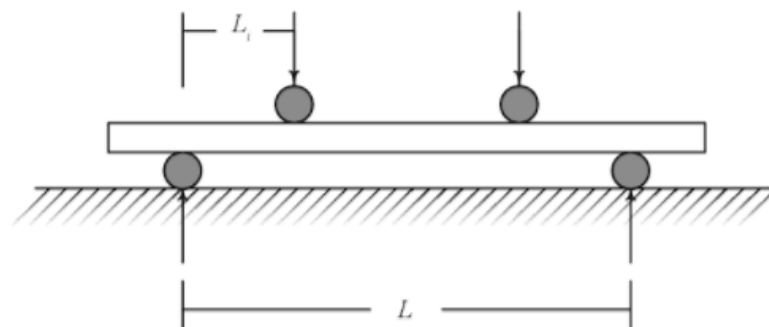


Figure 2.15: Four-point flexure test. Each arrow represents half of load which is $P/2$ (Freiman and Mecholsky, 2012).

2.7 Polycarbonate

Polycarbonate (PC) is classified as engineering thermoplastics due to its high-performance characteristics which are tough, rigid and dimensionally stable (Ashter, 2016). The chemical structure of Polycarbonate have carbonate linkages as illustrated in Figure 2.16 in their polymer chains (Shi, 2006). The first synthesis of PC was done by thermal polymerization of tri-methylene carbonate but recently, the synthesis have two routes which are (i) ring-opening polymerization of a cyclic carbonate di-ester and