CHAPTER 1

INTRODUCTION

1.1 Composite Materials

Over 50 years ago, composites were used in a variety of products, applications and industries. A composite material can be defined as a heterogeneous mixture of two or more homogeneous phases (matrix and reinforcements) which have been bonded together to produce more complex structure [1].

Consideration of the modulus per unit weight (specific modulus) and strength per unit weight (specific strength) brings the advantages of composite materials. The weight of the components can be reduced when the specific modulus and specific strength are high. Reductions in weight results in greater efficiency and energy savings [2]. Thus, composites are being used in a growing number of industries, such as recreational boating, transportation industry, aerospace, high performance sporting goods, etc.

1.2 Fibre Reinforced Plastics

In fibre reinforced plastics, combination of fibres and plastics with some excellent physical and mechanical properties give a new material with superior properties. In very fine fibres with diameters in the range of 7-15μm, the fibres have very high strength and modulus but usually very brittle. Plastics may be ductile or brittle but they usually have considerable resistance to chemical environments [2]. The fibres are usually glass fibre, carbon, or aramid, while the polymer is usually an epoxy, vinyl ester or polyester. Fibre reinforcements can improve resistance to hot deformation, lowering or avoidance of low temperature embrittlement, higher strength, modulus, rigidity and stiffness, improved creep resistance and hence dimensional stability [3].

The mechanical characteristics of a fibre-reinforced composite rely on the degree to which an applied load is transmitted to the fibre by matrix phases. Under an applied stress, the fibre-matrix bond ceases at the fibre ends, yielding a matrix deformation pattern. Effective strengthening and stiffening of the composite material are influenced by critical fibre length, l_c which is dependent on the fibre diameter, d and its ultimate tensile strength, σ^*_f and on the fibre-matrix bond strength. Maximum fibre load is achieved at the axial centre of the fibre when a stress equal to σ^*_f is applied to a fibre having just the critical length.

The fibre reinforcement becomes more effective as fibre length increases, a stress-axial position profile for $l > l_c$ when the applied stress is equal to the fibre strength. Continuous fibre has $l >> l_c$ while discontinuous or short fibres have lengths shorter than this. For discontinuous fibres of lengths significantly less than l_c, the matrix deforms around the fibre such that there is virtually no stress transfer and little reinforcement by the fibre. To improve the strength of the composite, the fibre must be continuous [4].

Strength and other properties of fibre-reinforced composites are strongly influenced by the arrangement of the fibres, the fibre concentration and distribution. With respect to orientation, two extremes are possible, a parallel alignment of the longitudinal axis of the fibres in a single direction and a totally random alignment. Continuous fibres are normally aligned, whereas discontinuous fibres may be aligned, randomly oriented, or partially oriented. FRP composite is a two phased material which is composed of fibre and matrix. They are bonded at interface and each of these phases has different function based on mechanical properties. The reinforcing fibre provides FRP composite with strength and stiffness, while the matrix gives rigidity and environmental protection.

1.2.1 Matrix Phase

Matrix phase plays an important role for fibre-reinforced plastics which holds the reinforcing fibres together and acts as a medium when an external applied stress is transmitted and distributed to the fibres. Only small proportion of an applied load is sustained by the matrix phase. The matrix material should be ductile and generally, metals and polymers are used as matrix materials because the ductility is desirable. The matrix has the ability to protect the individual fibres from surface damage caused by mechanical abrasion or chemical reaction with the environment. These interactions may form a crack that lead to failure at low tensile stress levels. Finally, the matrix separates the fibres and prevents the propagation of brittle cracks from fibre to fibre which can result in catastrophic failure.

Bonding strength is an important consideration in the choice of the matrix-fibre combination. When some of the individual fibres fail, total composite fracture will not occur until large numbers of adjacent fibres have failed. Fibre pull-out can be reduced due to adhesive bonding forces between fibre and matrix. This shows that the matrix phase serves as a barrier to crack propagation.

Thermosets and thermoplastics are two groups of resin that used to reinforced plastics. The most common matrix materials used were thermosetting materials such as epoxy, bismaleimide, or polyimide. But nowadays, thermoplastics are widely used as matrix material to replace thermosets. One of their big advantages is that they are easy to produce. They are capable of being repeatedly softened by heating and hardened by cooling through a characteristic temperature range. They are also more durable and tougher than thermosets and they have higher elongation at break. Fibre reinforcement will achieve their maximum benefits if the elongation at break of matrix is higher than fibre. An increased in the elongation at break is also necessary to improve impact strength.

1.2.2 Reinforcing Phase

The matrix structural characteristics can be improved by adding a dispersed phase such as fibre, tape, particulate, flake and whisker in various ways. In polymer matrix composites, reinforcing fibres are mainly used to improve stiffness and strength. The diameter of most of these fibres varies from a few hundred microns, whereas their length ranges between a few millimetres. Properties of the composites structures, including impact resistance and damage tolerance, are strongly dependent on the quality of the fibre-matrix interfaces. The properties of carbon, glass and aramid fibres used in composites are generally discussed below.

1.2.2.1 Carbon Fibre-Reinforced Polymer Composites (CFRP)

Carbon is a high performance fibre material that is usually used to reinforced polymer-matrix composites [4]. There are some reasons why carbon fibres are used in the manufacture of advanced composite materials:

i) Carbon fibres have high specific modulus and strength in reinforcing fibre materials.

ii) They can retain high tensile modulus and high strength at elevated temperatures.

iii) Carbon fibres are not affected by moisture or a wide variety of solvents, acids, and bases at room temperature.

iv) They allow the composites to have specific engineered properties because these fibres exhibit a diversity of physical and mechanical characteristics.

v) Manufacturing process for fibre and composite have been developed that are relatively cheap and cost effective.

Manufacturing techniques for producing carbon fibres are relatively complex. Large scales of production of carbon fibres are currently limited to polyacrilonitrile (PAN), cellulose and pitch. Lower-quality fibre can be manufactured using pitch or rayon as the precursor instead of PAN. Generally, the oxidation and thermal pyrolysis of polyacrylonitrile (PAN), which usually comprise 93-95% of carbon fibres was used. Polyacrylonitrile molecules have long chains like other polymers, which are aligned in the process of drawing fibres. These chains bond side-to-side when they are heated in the correct fashion. The modulus or strength of carbon fibre can be improved by heat treatment processes. The theoretical modulus of graphite is in the vicinity of 1,035 GPa, and the theoretical value of strength range from 100 GPa to 200 GPa [5].

Carbon fibres itself are not totally crystalline, they are composed from both graphitic and non-crystalline regions. They can be further classified into five classes in terms of their tensile modulus, E and strength, σ_u : ultrahigh modulus (E >400 GPa), high modulus (300 GPa < E< 400 GPa), intermediate modulus (250 GPa < E < 300 GPa), high strength (σ_u > 3.8 GPa) and high strain carbon fibres (ε_f >1.8%) [5]. Fibre diameters are normally range between 4 μm and 10 μm. In recent years, the fibre manufactures have been reduces the diameter to improve the strain to failure of carbon fibres. They also improved the strain energy absorbing ability of composites and hence improved their impact resistance.

Most of the sports and recreational equipment (fishing rods, golf clubs) and aerospace applications used carbon-reinforced polymer composites to produce high performance product due to high modulus and high strength properties of carbon fibre.

1.2.2.2 Glass Fibre-Reinforced Polymer Composites (GFRP)

Glass is the most widely used reinforcing materials. The fibre composite is a materials consisting of glass fibres contained a polymer matrix such as polyamide, polyester, etc. Fibre diameters usually range from 3 μm to 20 μm. Glass is an amorphous material which no long range order of the positions of the atoms, the crystalline structure, solids or the characteristics of liquids. The advantages of glass fibres include low cost, high tensile and impact strengths, and high chemical resistance. Their drawbacks include a relatively low modulus, self-abrasiveness, low fatigue resistance, and poor adhesion to matrix resins [5].

Nevertheless, they are not very stiff and sometimes do not display the rigidity for some applications such as airplanes structure and bridges. Most of them are limited to service temperatures below 200^{o}C and at high temperature the polymers start to flow [4]. Glass reinforced polymer composites widely used to produce automotive and marine bodies, plastic pipes, storage containers and industrial floorings. These industries used glass fibres to reduce vehicle weight and boost fuel efficiencies.

1.2.2.3 Aramid Fibre-Reinforced Polymer Composites

In the early 1970s, aramid fibres were introduced as high strength and high modulus materials. It was defined by U.S. Federal Trade Commission as *a manufactured fibre in which the fibre forming substance is a long chain synthetic polyamide in which at least 85% of the amide (-CO-NH-) linkages are attached to the two aromatic rings.* This group of materials chemically known as poly (p-phenylene terephthalamide) (PPTA) and the most common names are Kevlar® and Nomex®.

These materials are very tough, resistance to impact, resistance to creep and fatigue failure. The theoretical modulus of the PPTA molecule has been calculated to be about 250 GPa. However, the modulus of commercially available p-aramid fibres ranges from 60 GPa to 186 GPa [5]. These aramids are thermoplastics but they are resistant to combustion and stable at high temperatures between -200°C and 200°C which retain their mechanical properties. Chemically, they are inert in other solvents and chemicals; however they will degrade in strong acids and bases.

1.2.3 Interfaces

Mechanical performance of fibre reinforced plastic composite is dependent on these three constituents. i.e., strength and modulus of the fibre, strength and chemical stability of the resin matrix and the effectiveness of the bond between matrix and fibre in transferring stress across the interface [6]. The interface in composites is the part of the matrix surrounding the fibre surface, which exhibits local properties different from those of the bulk matrix. The size and type of interface varies strongly and depend on the nature of the fibre and its surface as well as on the type of polymer matrix [7,8].

Generally, the interface plays an important role to transfer stress in the composites. The efficiency of stress transfer from the resin matrix to the fibre has an influence on good mechanical properties in a composite material. This was reviewed by Lopattananon *et al.* [9]. The properties of a thin interface significantly altered the nature of load transfer, with some systems exhibiting full debonding, while others did not. This was attributed to varying levels of adhesion through control of the functionality of the fibre surface. Too strong an interface may cause successive adjacent fibre breakage and subsequently reduce composite toughness. A strong interface creates a material that displays high strength and stiffness but is brittle in nature with easy crack propagation through the matrix and fibre.

In contrast, a weaker interface may reduce the efficiency of stress transfer from the matrix to the fibre and hence lower the strength and stiffness. Zafeiropoulos *et al.* [10] explained that the weaker interfaces are important when the fracture properties of the composite are an important criterion. A crack propagating transversely through a composite is more likely to deviate from its path and grow along the fibre–matrix interface if the interface is weak, resulting in debonding and fibre pull-out. Both mechanisms contribute to an increase in the composites fracture toughness. The degree of adhesion between fibre and matrix must be controlled if a composite is to be used as a structural material. Thus, it has been recognized that the mechanical properties of semi-crystalline polymers and the composites made from them are dependent on the crystallinity and crystalline morphology, which are strongly affected by the processing conditions [11,12].

Mechanical and physical behaviour of composite materials are mostly dependent on the structure and properties of the fibre–matrix interface. Matrix morphology, fibre surface condition, presence of residual stresses, and moduli of the fibre and matrix influenced the interactions at the interface regions in composites. These characteristics are determined by processing conditions, including moulding temperature, cooling rate, holding time/temperature, and annealing conditions.

1.3 Hybrid fibre composites

Hybrid fibre composites are dynamic materials which have been applied in a wide area such as transportation, construction and recreation. It offers great characteristics such as excellent specific stiffness and strength, resistance to corrosion, lower in material cost and easy to fabricate. It is also use to increase the modulus, strength and fatigue performance of glass reinforced plastics (GRP) which include carbon fibres, and improve impact properties of carbon fibre reinforced plastics (CFRP) with combination of some glass or aramid fibres [13].

Hybrid composites can be defined as composites which contain more than one type of fibres in a common matrix [14]. In contrast, composites containing one type of fibre are known as single fibre. Generally, the term 'hybrid' is used to indicate the mixture of two different types of material into one single material. Moreover, hybridization is used to tailor a new material that will retain the advantages of its constituents. The designer used hybridization to reduce cost and weight while getting improved post-failure behaviour and fatigue performance [15]. There are several types of hybrid composites which classified according to the way constituent materials are mixed [13,15]:

a) Type A – Dispersed Fibre

   Consists of an intimate mixture of two or more types of fibres but are randomly dispersed throughout a common resin matrix. Hence, the concentrations of either type are not present in the material.

b) Type B – Dispersed Fibre Ply

   This type consists of a random or alternating mixture of two or more types of fibre ply and the laminates are not symmetrical to a centre plane. Hence, random lay-ups are not frequently used because laminates are prone to distortion on cooling temperature or when stressed.

c) Type C – Fibre Skin and Core

   This type of hybrid which consists of outer skins of one or more sorts of fibre laminate applied to a core made of another fibre laminate. Usually, they have the stiffer fibre in the skins and symmetrical to a centre plane structure.

d) Type D – Fibre Skin, Non Fibre Core

Also known as sandwich hybrids, in which one material is sandwiched between two layers of another. An adhesive layer, other than the resin matrix, is used to bond the skins and the core in many cases.

1.4 Short Fibre Reinforced Composites

Short-fibre composites (SFC) have grows for some years because of the combination of low price with nearly same strength and stiffness as long-fibre composites. They have been manufactured by extrusion process incorporated chopped strands/ fibres into plastic melt on a compounding extruder with an initial length of 3 mm to 6 mm to produce homogeneous and well wetted granules for injection moulding. Most of the injection moulded products are highly anisotropic and the average of fibre length is in the range 0.2 mm to 0.4 mm [16, 17].

Short fibre composites have become attractive engineering materials since they can produce moduli of elasticity and tensile strengths of 90% and 50% respectively. Moreover, they can be used to reinforce a polymer matrix, the mechanical load is shared between the matrix and the filler, and most mechanical properties of the composite are improved to greater or lesser extents in comparison of the matrix.

Normally, when the fibre orientation is random, short and discontinuous fibres are used to produce composite materials. Under these circumstances, a rule of mixtures expression as shown in below equation has been used to predict the modulus.

$$E_{cd} = KE_f(E_m V_m) \qquad (1.1)$$

In this expression, K is refers to a fibre efficiency parameter, which depends on V_f and the E_f/E_m ratio. The modulus increases in some proportion of the volume fraction of fibre for random fibre reinforcement since the magnitude only in the range 0.1 to 0.6 which is less than unity [4].

Short fibre reinforced thermoplastics can be processed by injection moulding, compression moulding or extrusion. Production rates for short fibre composites are rapid and they find use in large scale applications such as automotive parts, electrical appliances, electronic equipment, furniture, etc.

1.5 Processing of fibre reinforced composite

Moulding is the most common method to form plastics polymers. Moulding techniques such as compression, transfer, blow, extrusion and injection moulding are among the famous process to produce high quality product. For each, a finely palletised or granulised plastic is forced at an elevated temperature by pressure, to flow into, fill, and assume the shape of a mould cavity. In this study, only injection moulding machine will be used to produce single and hybrid fibre composites.

The injection moulding industry is relatively young compared to other manufacturing processes. The first commercial plunger machines were developed in the late 1920s and 1930s. Injection moulding is the thermoplastic processing method which chosen to produce a large quantities of identical parts. Quantities in the millions are possible with one or more moulds that can form several parts at one time.

One of the strengths of this technique over other plastic forming processes is that parts can have three-dimensional (3-D) details in their shape and surface finish. Typical nominal-wall thickness ranges from 0.5 mm to 6.4 mm; however, thickness of 0.08 mm to 50 mm is also possible. In addition, the properties of injection-moulded parts are unique and they can be flexible or stiff, soft or hard, tough or brittle, clear or opaque, specific chemically resistant and flame retardant [18].

1.6 Objectives

The aims of this research are to study on thermal, physical and mechanical behaviour of glass and carbon fibre reinforced PA 6,6 composites and short carbon/short glass hybrid fibre reinforced PA 6,6 composites through tensile, flexural and impact tests. The entire tests have been done using the American Standard for Testing and Materials (ASTM). All the specimens are subjected into dry as moulded, 50% RH, and wet conditions.

Microstructural studies have been done to determine brittle and ductile failure transition in relation to moisture absorption. Fibre population due to fibre loading have been observed physically.

According to the excellent properties of hybrid fibre composites, the property comparison between the hybrid and single fibre composites will also be made. Wherever possible, the experimental results will be compared with the theoretically calculated values using certain models or formula.