FABRICATION AND CHARACTERISATION OF SANDWICH COMPOSITES OF GLASS FIBER SKIN AND POLYURETHANE FOAM REINFORCED COCONUT COIR FIBER CORE

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ABSTRAK

Kajian ini tertumpu kepada fabrikasi dan perincian ke atas komposit sandwic berpermukaan komposit gentian kaca dan berteras busa poliuretana yang diperkuat gentian sabut kelapa. Objektif utama kajian ini adalah mengkaji sifat – sifat fizikal dan mekanikal komposit sandwic dan menjelaskan kesan penggunaan gentian sabut kelapa keatas busa poliuretana dan panel komposit sandwic. Panel komposit sandwic terdiri dari dua bahagian, iaitu permukaan komposit gentian kaca yang dihasilkan melalui proses pengacuanan tekanan dan teras busa poliuretana yang dihasilkan melalui kaedah pengacuanan berputar. Kedua – dua bahagian ini disatukan menggunakan perekat epoksi pada tekanan 100 KPa. Gentian sabut kelapa digunakan untuk memperkuat busa poliuretana yang akan digunakan sebagai teras komposit sandwich. Peratusan berat gentian sabut kelapa yang digunakan adalah daripada 5%berat sehingga 20 %berat. Dari kajian yang dijalankan, didapati bahawa penggunaan gentian sabut kelapa telah meningkatkan prestasi sifat teras poliuretana dan komposit sandwic. Sifat – sifat fizikal dan mekanikal teras busa poliuretana dan komposit sandwic mencapai peningkatan optimum pada 5 %berat gentian sabut kelapa. Walaubagaimanapun sumbangan gentian sabut kelapa terhadap peningkatan prestasi hanya terhad pada 5 %berat kerana prestasi sifat mekanikal bahan menurun apabila melepasi komposisi ini. Ketumpatan komposit sandwic menurun sebanyak 32.41% pada komposisi 5 %berat gentian sabut kelapa yang mana mempunyai ketumpatan yang rendah dan menyumbang kepada penghasilan panel bahan yang ringan. Daya maksimum, tegasan ricih, dan modulus bagi komposit sandwic menunjukkan peningkatan masing – masing sebanyak 12.69%, 29.46% dan 12.97% pada peratusan gentian sabut kelapa 5 %berat. Ini menunjukkan bahawa sifat – sifat komposit sandwic dapat dipertingkatkan dengan peranan penguat didalam busa poliuretana yang menahan tegasan ricih secara melintang.

ABSTRACT

This research focuses on the fabrication and characterisation of the sandwich composites panel using glass fiber composite skin and polyurethane foam reinforced coconut coir fiber core. The main objectives are to characterise the physical and mechanical properties and to elucidate the effect of coconut coir fibers in polyurethane foam cores and sandwich composites panel. Sandwich composites panel consist of glass fiber skins were fabricated via compression moulding technique while polyurethanes foam cores were fabricated by rotational moulding method. These two components were assembled using epoxy adhesive at 100 KPa pressure. Coconut coir fibers were used as reinforcement in polyurethane foams in which later were applied as the core in sandwich composites. The weight percentage of coconut coir used ranged from 5 wt% to 20 wt%. It was found that the coconut coir fibers increased the polyurethane foam cores and sandwich composites properties. The physical and mechanical properties were found to be significant at 5wt% coconut coir fiber in polyurethane foam cores as well as in sandwich composites. However, the significant contribution of coconut coir fibers addition only limits to 5 wt% since the mechanical properties of the composite start decreasing when this limit exceeded. Density of sandwich composites show decrement of 32.41% due to contribution of 5 wt% coconut coir fibers that offer low density which led to lighter panel's weight. Maximum flexural force, shear stress, and modulus of sandwich composites increased 12.69%, 29.46%, and 12.97% respectively with addition of 5 wt% coconut coir fibers. Thus it can be concluded that improvement of the sandwich composites properties are due to the role of reinforcement in polyurethane foam cores which facilitate and resist the transverse shear stress.

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LIST OF SYMBOLS AND ABBREVIATION

%	-	Percent
^{o}	-	Degree
^{o}C	-	Celcius degree
ASTM	-	American Society for Testings and Materials
CMC	-	Ceramic matrix composites
GFRP	-	Glass Fiber Reinforced plastic
KPa	-	Kilo Pascals
m	-	Meter
M_f	-	Final mass of the test samples after digestion or combustion, (g)
M_i	-	Initial mass of the test samples, (g)
MMC	-	Metal matrix composites
MPa	-	Mega Pascal
N	-	Newton
NaOH	-	Sodium Hydroxide
PMC	-	Polymer matrixcomposites
PU	-	Polyurethane
PUF	-	Polyurethane foam
SEM	-	Scanning Electron Microscopy
W_m	-	Matrix weight percent
W_r	-	Reinforcement weight percent
wt%	-	Weight percent

CHAPTER 1

INTRODUCTION

1.1 Introduction

Sandwich panels consist of two outer skins and core in the middle. The combination of these parts offer sandwich panels a relatively high strength and stiffness at low densities. Skins can be made of composite laminate panels, aluminium alloys, titanium steel or plywood. Core is the constituent that requires low density materials such as polymer foams, balsa wood, synthetic rubbers or inorganic cements (Mallick, 2008). Commonly sandwich composites were used in aerospace, automotive, sporting goods, marine, construction and civil structures.

Theoretically, the construction of sandwich materials requires thin and strong skin materials to be bonded to a lightweight core. The component skins or cores may be relatively heavy or weak by themselves, but when combined together, they provide stiff, strong and lightweight structures. A key motivation for the use of the sandwich configuration is the increment of flexural stiffness without any significant weight increase by separating the skins with a low density core (Stoll *et al.*, 2001).

The sandwich composite core becomes main component since it has thicker thickness and larger surface contact area compared to the other components. The role of a core is to resist any deformation and provides shear rigidity that bears the load applied perpendicular to the face plane to avoid buckling (Callister, 2007). One of the most used material as a core is polymer foam. Polymer foam offers low density compare to the other core material, and thus the weight reduction offered by polymer foam makes it significant to be selected (Klempner & Sendijarevic, 2004). Polymer foam offer wide range of mechanical properties and physical properties depending on density selected and material used (Rosato & Rosato, 2007).

Fiber composite skins are the most commonly used in sandwich construction as a skin panel, due to the similarity of strength and stiffness properties almost similar to metals or even higher than those of metals (Davies, 2001). The main function of the skin is to bear the in plane loading and transverse bending stresses (Carlsson & Kardomateas, 2011).

Various materials and structures were used to design the sandwich composites to meet the application requirement. Composite material that formed with natural fibers constitutes a current area of interest in composites research. A great development in this field has been noticed and currently applied in automotive industries (Pickering, 2008). Natural fibers are low priced and sustainable natural resources and have good mechanical properties (Chand & Fahim, 2008). Therefore, the used of this fiber reduce the materials cost of sandwich composites and in the same time improve its properties (Bledzki *et al.*, 2001). Furthermore the densities of natural fibers are close to the densities of thermoset polymer and glass fiber. On the other hand, polyurethane foam (PUF) resins are widely used in the engineering applications since exhibit its structural versatility as elastomer, thermoplastic, thermosetting, rigid and flexible foam. By combining the natural fiber with polyurethane foam (PUF) as a core, the sandwich construction development will enhance the properties of Polyurethane foam as well as sandwich composites panel (Silva, 2005).

1.2 Problem Statement

Common mass production of polyurethane foam manufactures unreinforced foam due to processing complexibility (Landrock, 1995). The conventional method such as polyurethane moulding method produced non uniform polyurethane cell. In homogenous growth of foam cell, the nucleation growth proceed from bottom to the upper mould. This growth formation leads to differences in cell size. The importance of uniformity in polyurethane foam cell is to produce consistent properties in polyurethane foam panels (Mills, 2007).

In order to produce better uniformity in polyurethane foam cell and uniform cell nucleation growth, polyurethane moulding method can be modified by introducing new method known as polyurethane foams rotational moulding method. In this method, the polyurethane foams mould is rotated to 360º during foaming instead of using static mould. This method will lead to production of uniform polyurethane foams since cell nucleation occurs in every direction in mould.

In previous studies, there are some researches that combined the polyurethane foam with synthetic fiber such as glass, carbon and Kevlar in form of continuous fiber by using slabstock method and polyurethane foam moulding method. This is as to improve the mechanical properties of foams especially flexural strength and modulus (Ashida, 2006). However, polyurethane foam composites in those studies have non-uniform properties due to the affects of obstructed foaming reaction due to the continuous fiber arrangement (Landrock, 1995). During the growth of cell nucleation, the mixing between polyol and isocyanates generates the formation of foam to fulfill the mould cavity. If this formation obstructed, it will affect the mechanical properties of polyurethane foam (Yan *et al.*, 2012). By using short or discontinuous fibers, nucleation and formation of polyurethane foam still can occur since short fiber do not obstruct the formation as compared to continuous fibers.

Although the usage of synthetic fibers to reinforce polyurethane foam offers excellent properties, cost of the material fabrication could be increased due to fiber processing itself, especially carbon and Kevlar fiber (Mohanty *et al.*, 2005). In last decades researchers had started to find an alternative for synthetic fibers. Natural fibers become new interest as to increase the constituent material properties. Natural fibers offer a good properties and those fibers are sustainable natural resources (Pickering, 2008). In addition, due to the ease of obtaining natural fibers, the cost of the material will be decreased.

Furthermore, synthetic fibers have higher density for an example glass fiber is 2.58 g/cm^3, carbon is 1.8 g/cm^3 and Kevlar is 1.44 g/cm^3 as compared to natural fiber for example coconut coir fiber is 1.40 g/cm^3 (Mohanty *et al.*, 2005). This shows that combination of foams and coconut coir fibers produces lightweight panels. Besides, coconut coir fibers are resilient, strong, and highly durable due to high lignin but low cellulose content (Bismarck *et al.*, 2005).

1.3 Objectives

Objectives of this research are:

(i) To fabricate glass fiber skins and polyurethane foam cores (GFRP - PUC) sandwich composite panel *via* compression moulding for skins and sandwich bonding and rotational moulding method for cores.

(ii) To investigate the physical and mechanical properties of fabricated of GFRP – PUC sandwich composites.

(iii) To elucidate the effect of coconut coir fiber consolidation in GFRP-PUC sandwich composites.

(iv) To compare the physical and mechanical properties of GFRP-PUC sandwich composites with polyurethane foam cores (PUC).

1.4 Scope of Study

This research focuses on properties of sandwich composite which consists of glass fiber and polyurethane foam reinforced coconut fiber as a skin and core respectively. Scopes of this research are:

(i) Glass fiber reinforced epoxy matrices are used as skins. The skins were fabricated by using compression moulding method with pressure and temperature applied at 100 KPa and at room temperature respectively by using hot press machine. Glass composite skins via hand lay – up method were also fabricated as performance reference specimens.

(ii) Epoxy paste adhesive are used as the bonding medium between glass fiber skins and polyurethane foam cores. Hot press machine is used to apply pressure at 100 KPa in room temperature during skin – core.

(iii) Polyurethane foams were used as a core. Polyurethane was mixed by using polyol and isocyanate, with ratio 100:110 by weight. Polyurethane foams were fabricated by rotational polyurethane moulding method. Polyurethane foams were reinforced with 5, 10, 15, and 20 weight percent (wt %) coconut coir fibers with ranging from 0.5 cm to 1 cm length. Non-reinforced polyurethane foams were also fabricated as reference specimens. Alkaline treatment of 5 wt% sodium hydroxide (NaOH) was used as coconut coir fiber treatment for lignin and wax of coir fibers removal. The alkaline treatment solution of 5wt% sodium hydroxide (NaOH) has been proven able to improve the composites mechanical properties as compared to other different wt% of NaOH compositions (Ray & Rout, 2005).

(iv) To determine core and sandwich composites structure mechanical properties, flexural or three point bending tests according to ASTM C393 were conducted. Density test according to ASTM C271 was performed as to determine the physical properties of core and sandwich composites. Moreover as to determine properties of sandwich composites skin, the tests conducted were ASTM D3039 tensile test, ASTM D790 flexural test and

ASTM D3171 burn off test. Nonetheless, SEM analyses were performed for foam microstructure and coconut coir fiber surface microstructure observation. Table 1.1 shows the summary of tests conducted.

Table 1.1: Summary of testing and analysis.

NO.	COMPONENT	TESTING / ANALYSIS	STANDARD
1	Coir fibers	(i) SEM of fiber affect on treatment	
2	Glass fiber composite skins	(i) Tensile test (ii) Flexural test (iii) Burn off test	(i) ASTM D3039 (ii) ASTM D790 (iii) ASTM D3171
3	Polyurethanes foam cores	(i) Flexural test (ii) Density test	(i) ASTM C393 (ii) ASTM C271
4	Sandwich composites	(i) Flexural test (ii) Density test	(i) ASTM C393 (ii) ASTM C271

1.5 Potential Contribution

This study contributes as the following:-

(i) The consolidation of coconut coir increased both polyurethane foams and sandwich composites properties.

(ii) Rotational motion in polyurethanes foam fabrication is the new alternative to produce uniform polyurethane foam cell size.

(iii) Increase the value added of coir for sustainability and green technology development.

CHAPTER 2

LITERATURE REVIEW

2.1 Composites

Composites are a combination of two or more materials to enhance material properties compared to constituent material. Composites are separated into two main phases which are matrix and reinforcement, in which each phase plays an important role to offer better composites properties. In composite form, these two materials bear the load applied together in their original form. Composites can be categorised by the fiber orientation and structure arrangement as per Figure 2.1.

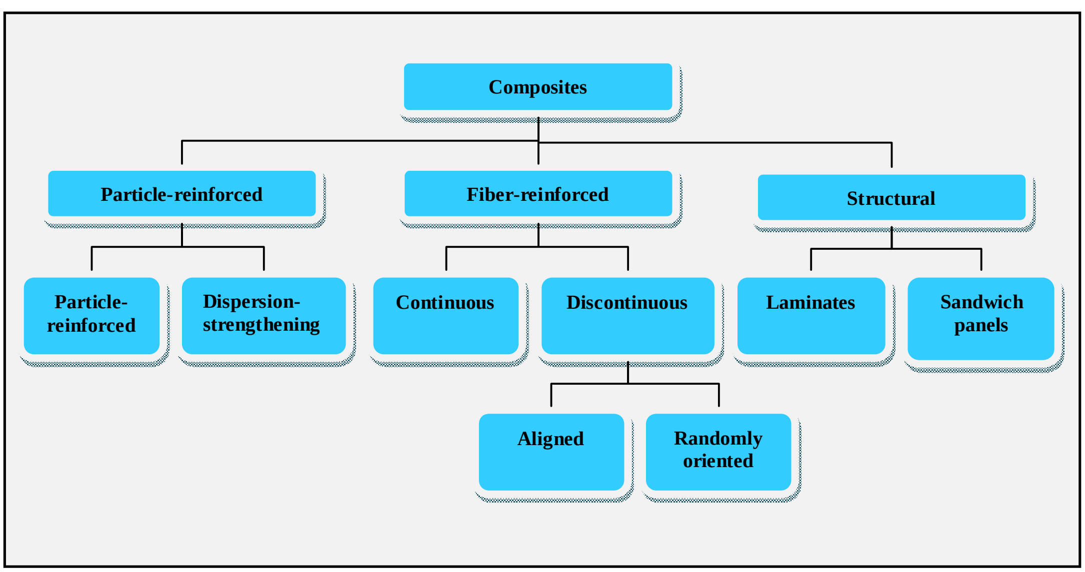

Figure 2.1: Types of composites (Callister, 2007).

Matrix is the medium that surrounds the fiber and forms specific shape of the composite products (Mazumdar, 2002). There are several types of a matrix commonly used in composites, namely polymer matrix, metal matrix and ceramic matrix as per Figure 2.2 (Matthews & Rawlings, 1999). The used of different matrix categorised composites into different groups which are polymer matrix composites (PMC), metal matrix composites (MMC), and ceramic matrix composites (CMC). The important functions of a matrix are to bind the fiber together and during the load applied, matrix will transfer the load to the fiber. Thus, the matrix offers rigidity to the composites properties. Besides, matrix acts as a fiber protector. Since it surrounds the fibers, the matrix protects the fiber against chemical attack and mechanical damage, especially to the natural fibers that are easily affected by environment exposure and mechanical load (Bismark *et al*., 2005).

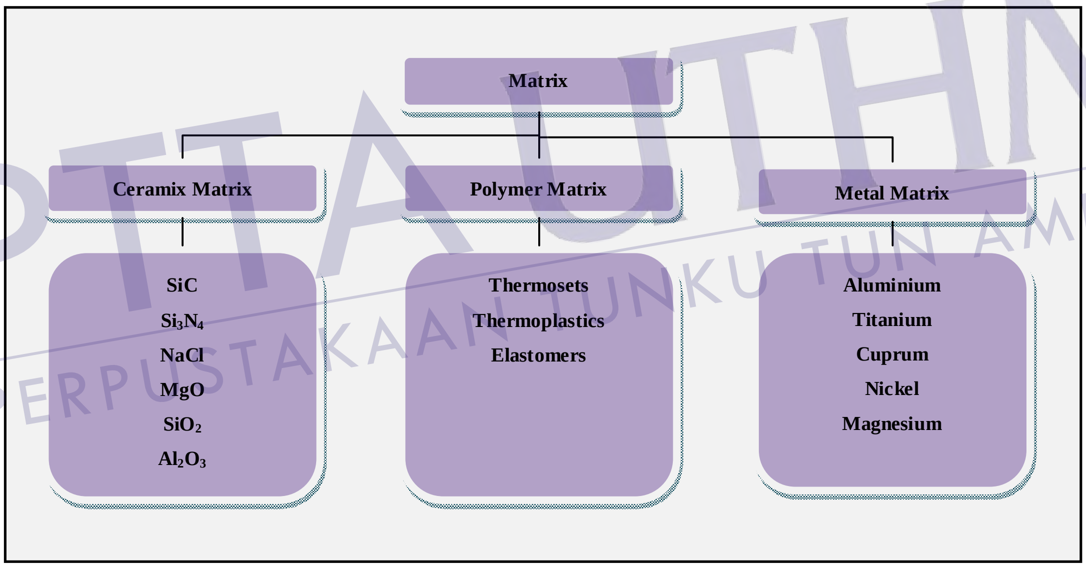

Figure 2.2: Types of matrix (Matthews & Rawlings, 1999).

Reinforcement is an important constituent in composite material. During load application, the matrix will transfer the load to the reinforcement (Callister, 2007). Reinforcement carries 70% to 90% of the load and if the matrix cracks, reinforcement will stop the crack propagations (Mazumdar, 2002). Reinforcement can be classified as whiskers, particles, fibers, and metallic wires which have different dimension range as per Figure 2.3 (Callister, 2007). Table 2.1 shows four common classifications of fiber reinforcements categorised by the length of the reinforcements (Tuttle, 2004).

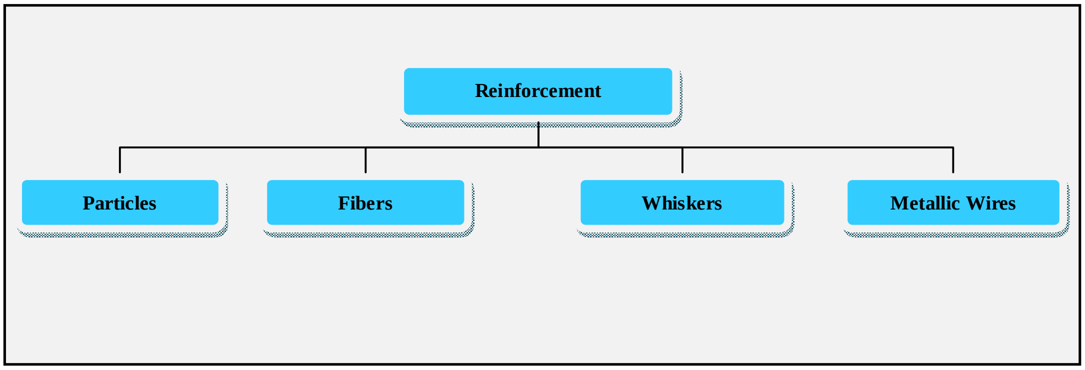

Figure 2.3: Types of reinforcement (Callister, 2007).

Table 2.1: Classification of Reinforcements (Tuttle, 2004).

Type of Reinforcements	Descriptions	Size
Particulates	Roughly spherical particles	Range from 1 to 100µm.
Whiskers	Very thin single crystals	Length less than 10mm.
Short	Discrete length	Length range from about 10 to 200mm
Continuous fiber	Whose lengths are in effect	Infinite

2.2 Polymer Matrix Composites (PMC)

This study focused on Polymer Matrix Composites (PMC) which are the most common composites used compared to other matrix composite. Although polymer material particularly have low strength and stiffness compared to the other matrix, it offer better properties by reinforcing the polymer using fibers (Matthews & Rawlings, 1999). PMCs are selected due to its lightweight properties, ease of fabrication and minimal cost (Callister, 2007).

PMCs processing does not require high temperatures and pressures and thus the reason why the PMCs processing equipments much simpler and have been developed rapidly (Matthews & Rawlings, 1999). Conventionally PMCs are reinforced by glass, carbon and aramid, however nowadays these synthetic fibers are replaced with natural fibers such as animal, mineral and plant due to the low priced and sustainable resource (Bismarck *et al*., 2005).

There are two types of most common structural composites applied in PMCs fabrication namely laminate panels and sandwich panels in which the main focus of this study. Both structures are important elements in composites, as to produce outstanding properties, as it does not solely depends on the properties of constituent material. Geometrical arrangement also plays a vital role to create excellent composites materials (Callister, 2007).

Laminate panels are composite panels that layered or shaped to be a plate or shell (Shenoi & Wellicome 1998). The reinforcement layers are stacked layer by layer and between layers, the matrix is used to ensure the laminate bonded subsequently. Laminate panels have high strength which depends on the orientation and direction of the layers (Callister, 2007).

Sandwich panels have two outer face sheets and a core in between. The combination of these parts offer sandwich panels a relatively high strength and stiffness at low densities. Face sheets can be made of composite laminate panels, aluminium alloys, titanium steel or plywood. The core is the element that requires low density materials such as polymer foams, balsa wood, synthetic rubbers or inorganic cements (Davies, 2001).

Figure 2.4 shows the summary of the PMCs main elements which are the common matrix and reinforcement. In addition, the figure also shows the structural types in PMCs.

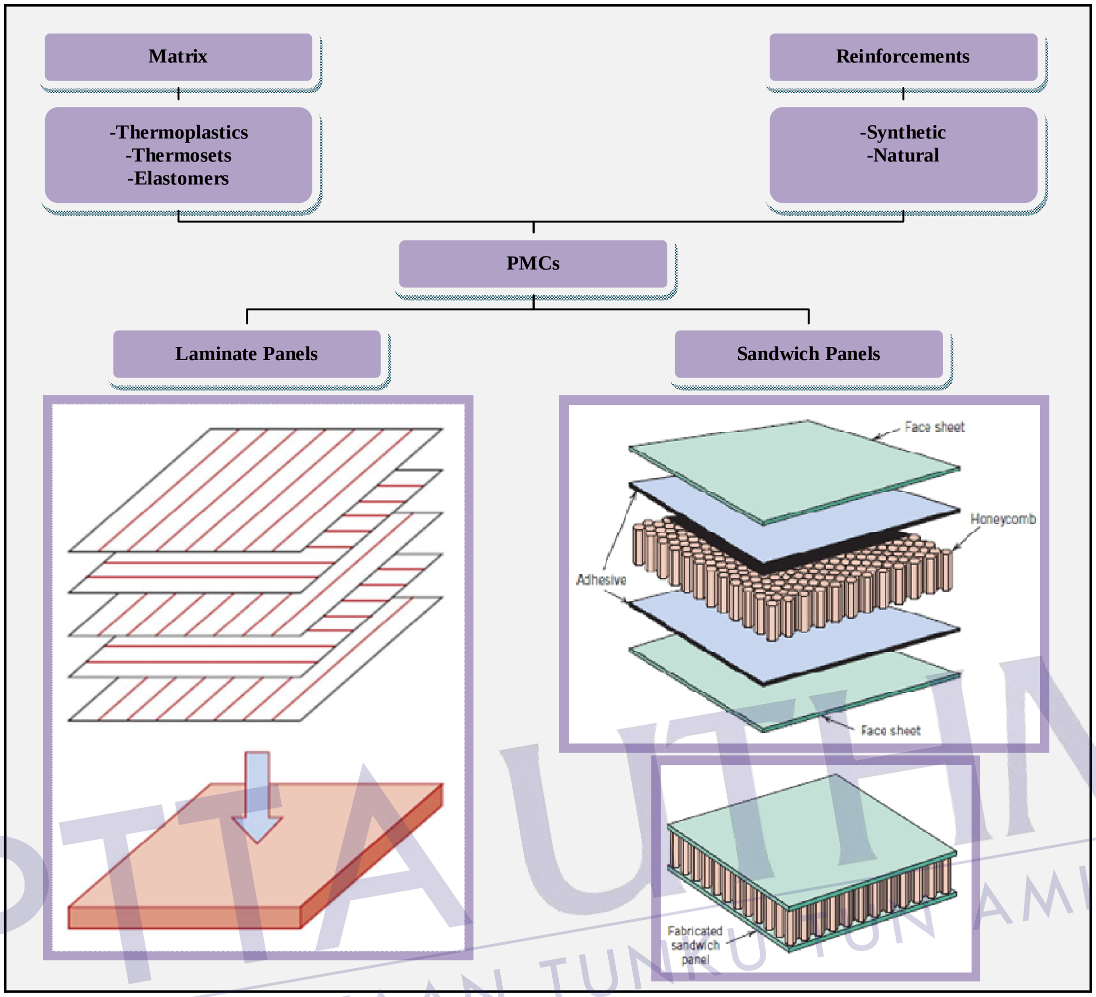

Figure 2.4: Summary of PMCs (Callister, 2007).

Structural composites commonly used in aerospace, automotive, sporting goods, marine, construction and civil structures. In fact, transportation industry is the largest user of composites materials. These products were fabricated using composites because these materials are lighter and stronger; in which have increased the performance of products (Mazumdar, 2002). Table 2.2 shows the composites application category, example of products, processing methods for composites and selection factor of composites as industrial materials.

Table 2.2: Composites application and description (Mazumdar, 2002).

Application Category	Material	Products	Processing Method	Factor of Selection
Aerospace	Glass, carbon, Kevlar fiber composites, honeycomb core,	Doors, vertical/ horizontal tails, ailerons, spoilers, wings, elevators, flaps, fairings, stabilizer, stabilizer skins, fins, fin box, rudders, speed brakes, flats, slats, inlets,	Prepreg lay up, wet up, filament winding, resin transfer moulding (RTM)	High performance characteristics, increase competency, weight reduction 20-35%,
Automotive	Glass fiber composites, carbon fiber composites (rarely used)	Bumper beam, seat / load, floor, hood, radiator support, roof panel.	Injection moulding, compression moulding, filament wound, blow mould, structural reaction injection moulding (SRIM),	High quality surface finish, various processing option,
Marine	Glass fiber composites itself or with foam or honeycomb core	Passenger ferries, buoys, power boat,	Wet lay - up, resin transfer moulding (RTM), spray up,	Lightweight, corrosion resistance, the used of adhesive bonding minimize welding cost,
Sporting Goods	Glass fiber, carbon fiber composites	Golf shafts, tennis rackets, snow skis, fishing rods, bicycle frames, snowboards	Roll wrapping, prepreg lay - up, wet lay - up, resin transfer moulding (RTM),	Lighter, provide higher performance, easy handling
Consumer Goods	Short fiber	Sewing machines, bathtubs, tables, chairs, computers, printers	Compression moulding, injection moulding, resin transfer moulding (RTM), structural reaction injection moulding (SRIM),	Lightweight
Construction and Civil Structures	Glass fiber, carbon fiber, aramid fiber composites	Bridges, columns coating, beams, handrails,	Pultrusion, filament winding,	Corrosion resistance, reduced installation, handling, repair and life cycle costs,

2.3 Sandwich Composites Structures

Sandwich composites consist of two main components in their structure which are the skin or also known as face sheet and core as the main part that represent the main sandwich composites overall thickness, weight and density. During sandwich composites service, the skin of sandwich composites bears most of the in plane loading and any transverse bending stresses. Usually skins are materials made of polymer matrix composite laminate (PMC) or aluminium plate. On the other hand, the sandwich composite cores serve two functions, (i) separates the faces and (ii) resists deformation perpendicular to the skin plane. There are several categories of core which are balsa wood, foam, corrugated and honeycomb. Sandwich composites also need an adhesive as a joining between skin and core as a permanent lock to transfer the load applied. Figure 2.5 shows the structure of sandwich composites.

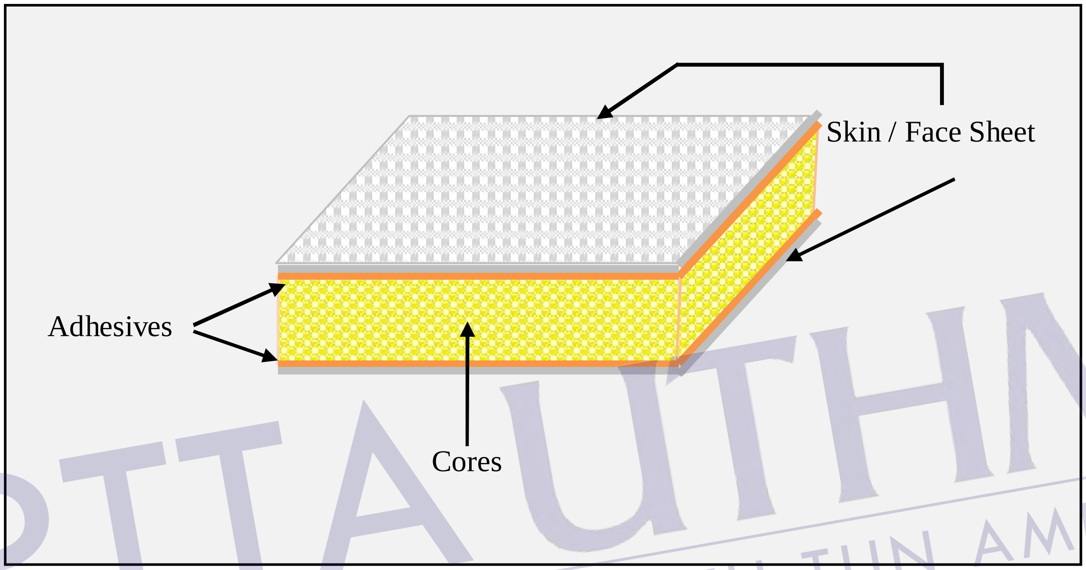

Figure 2.5: Sandwich composite structure.

2.4 Sandwich Composite Skin

One of the most common used types of sandwich composite skin is polymer matrix composites that were fabricated into laminate structure. This substance used polymer as a matrix and various type of reinforcement such as fibers, particles, whiskers and powders. Sandwich composite skins are placed as outer surface of sandwich composites. Figure 2.6 shows the arrangement in laminated polymer matrix composite.

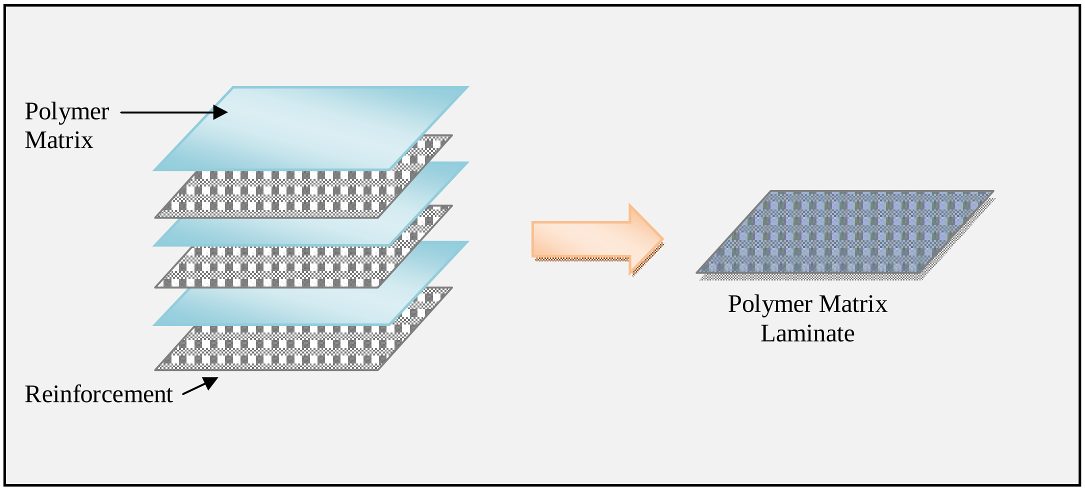

Figure 2.6: Arrangement in polymer matrix composites.

2.4.1 Polymer Matrix

Polymers are the most widely used type of material in the composites matrix. Polymers are described as being either thermosets (epoxy, polyester, phenolic) or thermoplastics (polyamide, polysulfone, polyetheretherketone). Among the polymers, epoxies and polyesters are the mostly used polymer matrix in PMCs fabrication (Gibson, 1994). In polymer composites, matrix plays its role to bind the fiber, transfer the load to the fiber, protect the fibers and prevent crack propagations. Figure 2.7 shows the importance of matrix in polymer matrix composites.

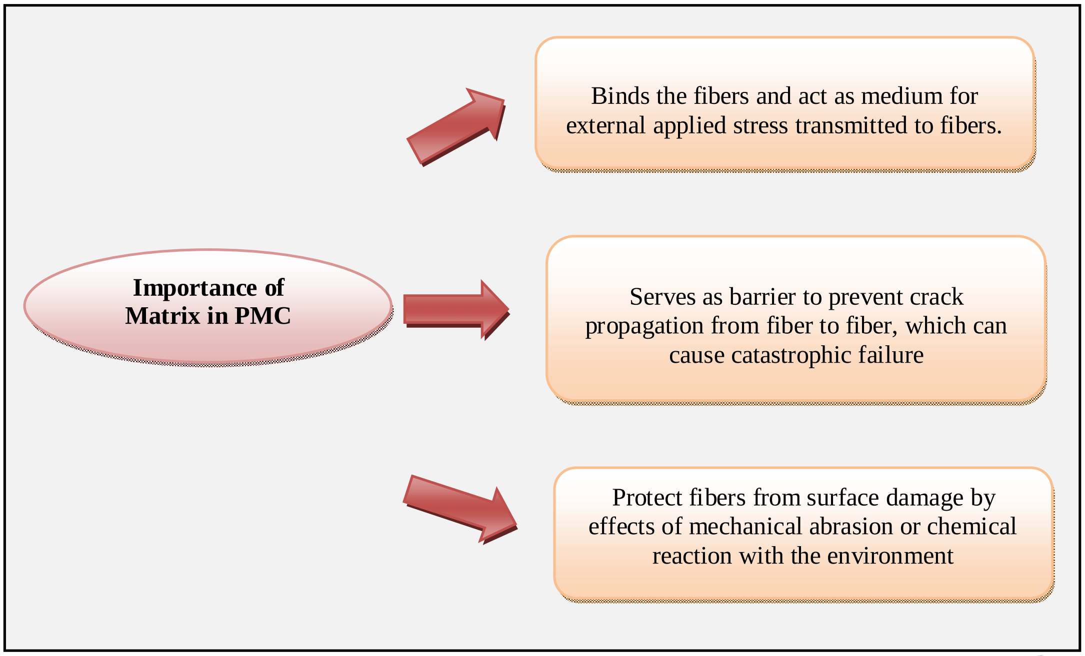

Figure 2.7: Importance of matrix in PMC.

2.4.1.1 Epoxy

Epoxy is a very flexible resin system due to wide range of properties and various processing parameters. Epoxy offers excellent adhesion to various substrates for bonding purpose. Epoxies are the most widely used resin materials in many applications, from aerospace to sporting goods (Strong, 2008). Table 2.3 shows the properties of epoxies compared to other resins. In which the wide range of property values is shown.

Table 2.3: Thermosetting resin/matrix properties (Mazumdar, 2002).

Matrix Material	Density, g/cm^3	Tensile Modulus GPa	Tensile Strength, MPa
Epoxy	1.2 - 1.4	2.5 – 5.0	50 – 110
Phenolic	1.2 - 1.4	2.7 – 4.1	35 – 60
Polyester	1.1 - 1.4	1.6 – 4.1	35 - 95

Epoxies can be used either in liquid, solid, and semi-solid forms. Liquid epoxies are used in resin transfer moulding (RTM), filament winding, pultrusion, hand lay - up, and other processes with various reinforcing fibers such as glass, carbon, aramid, and boron. Semi-solid epoxies are used in prepreg for vacuum bagging and autoclave processes. Solid epoxy capsules are used for bonding purposes. Epoxies are more costly than polyester and vinylesters and are therefore not used in cost sensitive markets such as automotive and marine unless specific performance is required (Mazumdar, 2002).

There are many grades of epoxies to suit various requirements of various applications. Epoxies formulation could be designed by mixing with other materials or other epoxies grade to meet the performance required. By altering the epoxies formulation, epoxies properties, such as cure rate, processing temperature, cycle time, toughness and temperature resistance can be justified. Cure rates can be controlled through proper selection of hardeners or catalysts. Each hardener provides different cure characteristics and different properties to the final product. The higher the cure rate, the lower the process cycle time and thus higher production volume rates (Baker *et al.*, 2004).

Epoxy matrix composites offer excellent properties at both room temperature and elevated temperatures. During service, epoxies can resist high temperature condition ranging from 90 ºC - 120 ºC. Some higher grades of epoxies usage can reach up to 200ºC. Although the higher performance epoxies will lead to cost increment, they provide good chemical resistance and corrosion resistance. Epoxies are generally brittle, however, it could be improved by combination with high toughness thermoplastic to meet various application needs (Baker *et al.*, 2004).

2.4.2 Synthetic Fibers

Reinforcements are important constituents of a composite material and offer necessary stiffness and strength to the composite. Reinforcement fibers have thin rodlike structures. The most common reinforcement fibers are glass, carbon, aramid and boron fibers. Typical fiber diameters range from 5 μm to20 μm. The diameter of a glass fiber is in the range of 5 to 25 μm, a carbon fiber is 5 to 8 μm, an aramid fiber is 12.5 μm, and a boron fiber is 100 μm. Due to this thin diameter characteristic, fiber is flexible and easily conforms to various shapes (Mazumdar, 2002).

In general, fibers are made into strands for weaving or winding operations. For delivery purposes, fibers are wound around a bobbin and collectively called a "roving." An untwisted bundle of carbon fibers is called "tow". In composites, the strength and stiffness are provided by the fibers. The matrix gives rigidity to the structure and transfers the load to fibers. Fibers for composite materials can be in many forms, from continuous fibers to discontinuous fibers, long fibers to short fibers, organic fibers to inorganic fibers (Mallick, 2008).

The most widely used fiber materials in fiber-reinforced plastics (FRP) are glass, carbon, aramid, and boron. Glass can be found in abundance and glass fibers are the cheapest compared to other types of fibers. There are three major types of glass fibers; E-glass, S-glass, and S2-glass. The properties of these fibers are given in Table 2.4. The cost of E-glass is around USD1.00/lb, S-glass is around USD8.00/lb, and S-2 glass is USD5.00/lb. Carbon fibers range from low to high modulus and low to high strength. Cost of carbon fibers fall in a wide range from USD8.00 to USD60.00/lb. Aramid fibers cost approximately USD15.00 to USD20.00/lb (Mazumdar, 2002). Some of the common types of reinforcements include:

i) Continuous carbon tow, glass roving, aramid yarn
ii) Discontinuous chopped fibers
iii) Woven fabric
iv) Multidirectional fabric (stitch bonded for three-dimensional properties)
v) Stapled
vi) Woven or knitted three-dimensional performs

Continuous fibers are applied for filament winding, pultrusion, braiding, weaving, and prepregging applications. Continuous fibers are used mostly with thermoset and thermoplastic resin systems. Chopped fibers are consolidated using injection moulding and compression moulding compounds and are made by cutting the continuous fibers. In spray-up and other processes, continuous fibers are used but are chopped by machine into small pieces before the application. Woven fabrics are used for making prepregs as well as for making variety of laminates. Preforms are processed by braiding and other processes and used as reinforcements for Resin Transfer Moulding (RTM) and other moulding operations (Baker, *et al.*, 2004).

Table 2.4: Properties of the selected commercial's reinforcing fibers (Mallick, 2008).

Fiber	**Typical Diameter (μm)**	**Density (g/cm^3)**	**Tensile Modulus GPa (Msi)**	**Tensile Strength GPa (ksi)**	**Strain-to-Failure (%)**	**Coefficient of Thermal Expension ($10^{-6}/^{o}C$)**	**Poisson's Ratio**
Glass							
E-glass	10 (round)	2.54	72.4 (10.5)	3.45 (500)	4.8	5	0.2
S-glass	10 (round)	2.49	86.9 (12.6)	4.30 (625)	5.0	2.9	0.22
S-2 glass	10 (round)	2.38	80.5 (11.8)	3.90 (565)	4.9	3	0.19
PAN carbon							
T-300	7 (round)	1.76	231 (33.5)	3.65 (530)	1.4	-0.6 (longitudinal) 7.12 (radial)	0.2
AS-1	8 (round)	1.80	228 (33)	3.10 (450)	1.32		
Pitch carbon							
P-55	10	2.0	380 (55)	1.90 (275)	0.5	-1.3 (longitudinal)	
P-100	10	2.15	758 (110)	2.41 (350)	0.32	-1.45 (longitudinal)	
Aramid							
Kevlar 49	11.9 (round)	1.45	131 (19)	3.62 (525)	2.8	-2 (longitudinal) 59 (radial)	0.35
Kevlar 149		1.47	179 (26)	3.45 (500)	1.9		

2.4.2.1 Glass fibers

Glass fiber reinforced plastics (GFRP) is the type of material that is commonly used as a sandwich composites skin (Mills, 2007). This fiber is produced as the largest quantities in the world (Aird, 2006). The diameter of the fiber between 3 to 100 μm.

Glass fibers are widely used because glass fibers offer high strength and produces high specific strength when embedded in a plastic matrix to form a composite. Figure 2.8 shows the characteristics of glass fiber. Glass fiber can be produced using wide variety of composites manufacturing technique such as lay - up, spray - up, compression moulding, resin transfer moulding, filament winding, pultrusion, injection moulding and roll wrapping process. Glass fiber could be produced either in continuous or discontinuous fiber and glass fibers could be arranged in woven, chopped strand or unidirectional depending on the application (Mazumdar, 2002). Figure 2.9 shows the chopped strand glass fiber.

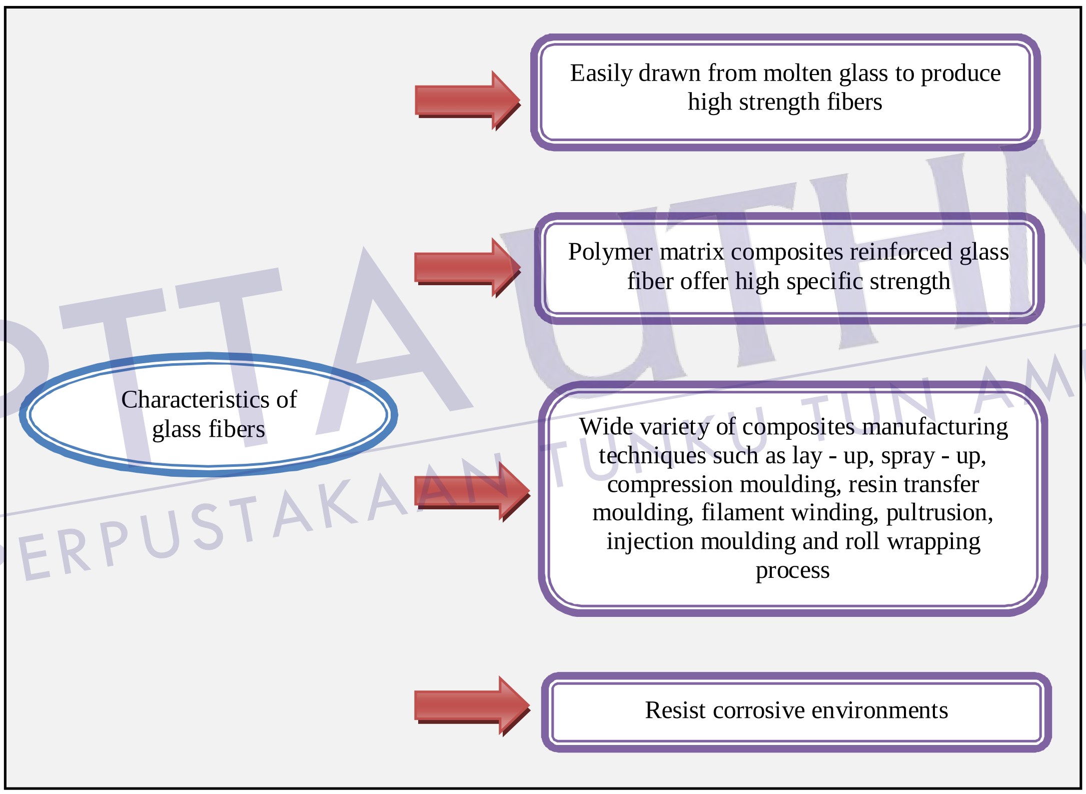

Figure 2.8: Characteristic of glass fiber (Callister, 2007).

Figure 2.9: Chopped strand glass fibers.

The two types of glass fibers commonly used in the industry are E-glass and S-glass. Another type, known as C-glass, is used in chemical applications requiring greater corrosion resistance to acids. E-glass has the lowest cost of all and is commercially available as reinforcing fibers, which is the reason for its widespread use in the GFRP industry (Chawla, 1998).

S-glass, originally developed for aircraft components and missile casings, has the highest tensile strength among all fibers in use. However, the compositional difference and higher manufacturing cost makes it more expensive than E-glass. A lower cost version of S-glass, called S-2-glass, is also available. Although S-2-glass is manufactured with less-stringent non-military specifications, tensile strength and modulus are similar to those of S-glass (Mallick, 2008). Table 2.5 shows the differences of glass fiber composition.

Glass fiber composites are widely used in automotive and marine bodies, plastic pipes, storage containers, and industrial floorings. The transportation industries are also utilizing increasing amounts of glass fiber-reinforced plastics in an effort to decrease vehicle weight and boost fuel efficiencies. A host of new applications are being used or currently investigates by the automotive industry (Callister, 2007).

Table 2.5: Typical Compositions of Glass Fibers (in wt %) (Mallick, 2008).

Type	SiO_2	Al_2O_3	CaO	MgO	B_2O_3	Na_2O
E-glass	54.5	14.5	17	4.5	8.5	0.5
S-glass	64	26	-	10	-	-

The properties of glass fibers depend on the fibers manufacturing methods. The raw materials used for making E-glass fibers are silica sand, limestone, fluorspar, boric acid, and clay. Silica compositions exceed 50% of the total ingredients. By formulating the amounts of raw materials and the processing parameters, other types of glass fiber can be produced. During process, the raw materials are mixed thoroughly and melted in a furnace at 1300°C to 1700°C. The melt flows into one or more bushings containing hundreds of small orifices. The glass filaments are formed as the molten glass passes through these orifices and successively goes through a quench area where water and/or air quickly cool the filaments below the glass transition temperature. The filaments are then pulled over a roller at a speed around 81 km/h. The amount of sizing used ranges from 0.25 to 6% of the original fiber weight. All the filaments are then pulled into a single strand and wound onto a tube. Figure 2.10 shows the schematic of glass fibers manufacturing. Sizing is applied to the filaments to serve several purposes; (i) it promotes easy fiber wetting and processing, (ii) provides better resin and (iii) fiber bonding, and protects fibers from breakage during handling and processing (Mallick, 2008).

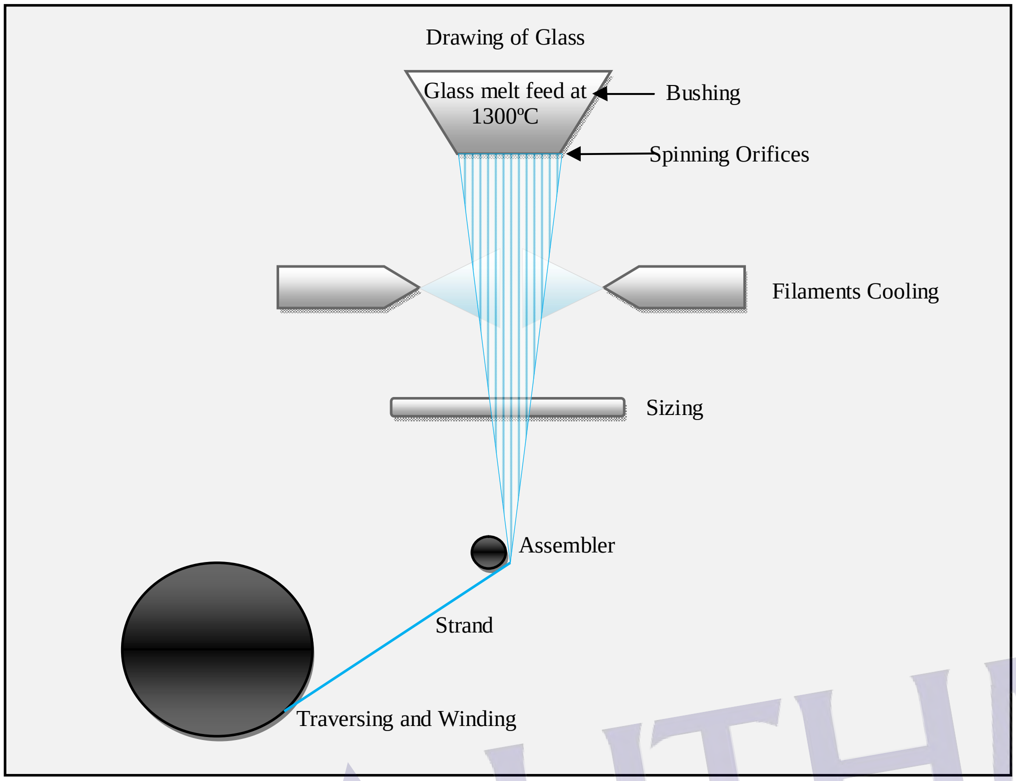

Figure 2.10: Schematic of glass fibers manufacturing.

2.5 Sandwich Composite Cores

The core is the main part of sandwich composite material. It is made of low density material and represent total panel weight and over all thickness. There are many types of core being used as a part of sandwich composites; (i) polymer foam, (ii) balsa woods, (iii) metal foam, (iv) corrugated structures and (v) honeycomb structures (Mills, 2007). Table 2.6 shows various types of sandwich composite cores properties, advantages and application of sandwich composite cores.

Cores that are suitable for sandwich panels must have appropriate properties especially mechanical strength and stiffness, low density and manufacture ability. Low density cores to produce lightweight composite is the key objective of these materials selection. Core must have the ability to resist shear modulus and shear strength since the core carries the bulk of the shear loads. High strength and stiffness values are very important to structural performance (Beckwith, 2008). Besides, core materials must carry the loads perpendicular to the laminate face sheets to cater with compression stiffness and strength (Often *et. al.*, 2004). Furthermore cores also act as insulator to minimize the heat transfer (Mouritz & Gardiner, 2002).

Table 2.6: Core properties: advantages and application (Beckwith, 2008).

Types of core		**Advantages**	**Application**
Wood	Balsa	• High compressive • Good thermal insulator • Good acoustic absorption	Marine construction
	Cedar		
Honey comb	Nomex	• High mechanical properties • Expensive	Aircraft
	Aluminium	• More cheaper than Nomex • Offers similar strength and stiffness	Marine
	Thermoplastic	• Low densities • Low stiffness	Marine
Foam	Polyvinyl Chloride (PVC) -Crosslinked -Uncrosslinked	• Good static and dynamic properties • Resistant against many chemicals • High performance	Marine
	Polystyrene (PS)	• Low mechanical properties	Board manufacture
	Polyurethane (PU)	• Moderate properties	Automotive, furniture, footwear, aerospace
	Polymethyl Methacrylamide (acrylic)	• High thermal stability • Specific strength and stiffness	Aerospace constructions
	Polyetherimide (PEI)	• Outstanding fire performance • Can be used in a huge temperature range	Aircraft Trains
	Styreneacrylonitrile (SAN)	• Higher elongations and toughness • Higher temperature performance • Better static properties	Wind energy

2.5.1 Polyurethane Foam

Polyurethane foams are also known as urethane foams. The abbreviation PU is commonly used for polyurethane. Polyurethane foam component consists of polyol and isocyanate. Polyols can be considered as the building blocks, and isocyanates can be considered the joining agent. Therefore, polyurethane foam chemistry is considered building block chemistry. All kinds of polyurethane foam are prepared by the choice of polyol and polyisocyanate in respect to chemical structure, equivalent weight, and functionality (Rapra, 2012)

.

Polyurethane foam is a type of material that is commonly used as a sandwich composite core (Mills, 2007). Polyurethane foam is a thermoset polymer with high volume percentage of small pores (Callister, 2007). It is usually used in automotive cushion, furniture and thermal insulations. The different compositions of polyols and isocyanates would yield polyurethanes into three categories which are flexible polyurethane foams, semi rigid/flexible polyurethane foams and rigid polyurethane foams with different properties, characteristic and applications as explain in Table 2.7 and Figure 2.11 (Ashida, 2006). Figure 2.12 shows the polyurethane foam.

Table 2.7: Elastic modulus of polyurethane foams (Ashida, 2006).

Properties	**Rigid Foam**	**Semi Rigid Foam**	**Flexible Foam**
Elastic Modulus at 23°C (MPa)	>700	70-700	<70

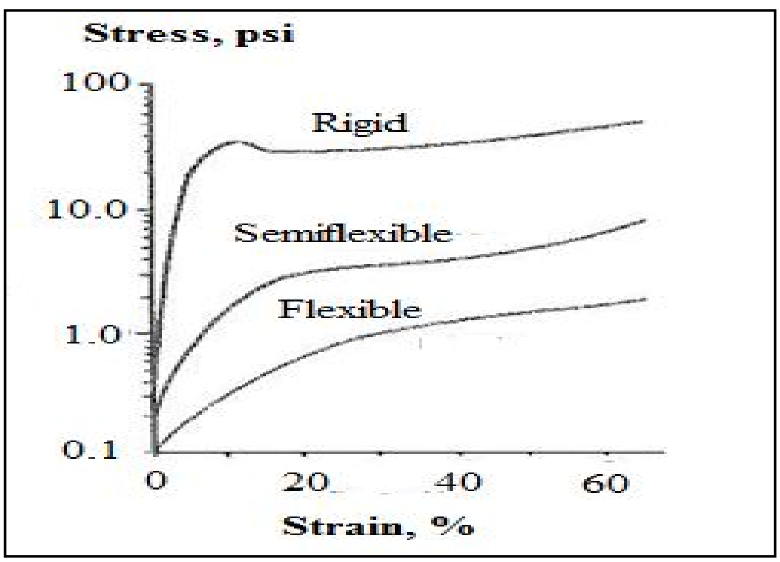

Figure 2.11: Stress-Strain curves for foam (Landrock, 1995).

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