

## **ABSTRACT**

**Vaidya, Neha. The Manufacturing of Wet-laid Hydroentangled Glass Fiber Composites For Industrial Applications. (Under the direction of Dr. Behnam Pourdeyhimi)**

The main focus of this research is to make a composite of sufficient strength from glass fibers using low melt polyester or bicomponent (polyester/polyethylene sheath/core) fibers as binder fibers for nonwoven preforms. A wet-laid hydroentangled sheet consisting of a blend of glass and low melt binder fibers is used to make compression molded composite. An appropriate white water recipe for dispersing glass and binder fibers was obtained after personal conversation with Owens Corning Company and after image analysis of the trial sheets. The amount of defects in the fabric was analyzed and optimum time of dispersion was established. Six layers of wet lay sheets were stacked and hydroentangled to get a high weight per unit length single hydroentangled sheet that is then heat pressed. When heat pressed, the binder fibers in the blend melt, adhere to the glass fibers and form a composite.

These composites were tested for stiffness, toughness and flexural strength. An instron machine was used for tensile and 4-point bending tests. Stress strain curves were obtained and the secant modulus at breaking strain was determined. The area under the curve was measured to determine the toughness of the material. The tensile strength and toughness increased significantly with increasing glass fiber content of up to 30-40%, after which the strength of the composite decreases. This may be caused by the reduction in binding points and lower adhesion between the glass fibers resulting in lower tensile and flexural strength.

The innovative aspect of this research is in the manufacturing of composites using glass fibers along with binder fibers. Some of the current composite manufacturing techniques use resin to bind the fibers/sheets. Resins are costly and also, not environment friendly. By using binder fibers, the need of using resin is eliminated. Elimination of resin and manufacture of high strength low cost composites with more process flexibility is an imperative objective of this research.

# The Manufacturing of Wet-Laid Hydroentangled Glass Fiber Composites for Industrial Applications

By

Neha Vaidya

A thesis submitted to the Graduate Faculty of  
North Carolina State University  
in partial fulfillment of the  
requirements for the Degree of  
Master of Science

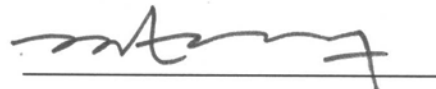
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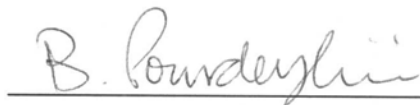
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## **Biography**

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# Table of Contents

<b>List of Figures</b> .....	<b>vi</b>
<b>List of Tables</b> .....	<b>viii</b>
<b>Chapter I, Introduction</b> .....	<b>1</b>
1.1 Relevance .....	1
1.2 Objective .....	2
<b>Chapter II, Literature Review</b> .....	<b>3</b>
2.1 Glass Fibers .....	3
2.2 Polyester and bicomponent fibers .....	6
2.3 Wet lay process .....	7
2.3.1 Why wet lay? .....	9
2.4 Hydroentanglement .....	10
2.5 Composite Basics .....	12
2.5.1 Resins and matrices .....	13
2.5.2 Reinforcement .....	14
2.5.3 Methods of making composites .....	15
2.5.4 Benefits of fibrous and polymer composites .....	17
2.5.5 Glass fiber composite properties and applications .....	18
2.5.6 Why are glass fibers used in automotives .....	20
2.5.7 Composites in PCB's .....	21
2.5.8 Copolymerization of Polypropylene on glass fiber .....	24
2.5.9 Other nonwoven composites .....	25
<b>Chapter III, Methodology/Experimental Approach</b> .....	<b>26</b>
3.1 Raw materials .....	26
3.2 Dispersion and composite perform formation .....	27
3.3 Chemicals for dispersion .....	29
3.4 ODF .....	30
3.5 DSC .....	32
3.6 Composite manufacture .....	33
3.7 Tests Performed .....	35
3.7.1 Tensile .....	35
3.7.2 4-point Bending .....	36

<b>Chapter IV, Results and Discussion</b> .....	<b>38</b>
4.1 Dispersion .....	38
4.2 ODF .....	41
4.3 DSC .....	44
4.4 Tensile Tests .....	45
4.5 4-point bending test .....	48
<b>Chapter V, Conclusion and Future work</b> .....	<b>50</b>
<b>References</b> .....	<b>52</b>
<b>Appendices</b> .....	<b>57</b>
Appendix A .....	58
Appendix B .....	60

# List of Figures

Figure 2.1	Process of making fibreglass .....	4
Figure 2.2	Hydroentanglement machine manifolds .....	10
Figure 2.3	Schematic overview of the approaches employed in fabrication of polymer matrix composites .....	16
Figure 2.4	Multi-layer Circuit Board Schematic .....	23
Figure 3.1	Raw materials used .....	27
Figure 3.2	Orientation Distribution Function of 30/70 Glass/PET sample .....	32
Figure 3.3	Schematic for the compression-molding machine .....	35
Figure 4.1	Images of logs and ropes defects .....	38
Figure 4.2	Glass Fiber Dispersion .....	39
Figure 4.3	Polyester Fiber Dispersion .....	40
Figure 4.4	30/70 Glass/Polyester Blend Dispersion .....	40
Figure 4.5	Bicomponent Fiber Dispersion .....	41
Figure 4.6	Orientation Distribution Function for single layered sheets .....	42
Figure 4.7	Orientation Distribution Function for 4-layered sheets .....	43
Figure 4.8	Cosine squared anisotropy ratio for glass/polyester blend samples .....	44
Figure 4.9	DSC results for Polyester fiber .....	44
Figure 4.10	DSC results for Bicomponent fiber .....	45
Figure 4.11	Stress strain graph for 30/70 Glass/Bicomponent single layer sample .....	46

Figure 4.12 Average breaking Stress and Secant modulus for glass/pet and Glass/Bicomponent samples .....	47
Figure 4.13 Toughness for Glass/Bicomponent and Glass/Polyester samples .....	48
Figure 4.14 Average flexural stress for glass/bicomponent and glass/polyester samples ..	48
Figure 4.15 Average flexural stress for glass / resin samples .....	49
Figure A.1 Vacuum Bagging .....	58
Figure A.2 Vacuum Bagging .....	58
Figure A.3 Resin Transfer Molding .....	58
Figure A.4 Hand Lay-up .....	59
Figure A.5 Pultrusion .....	59
Figure A.6 Filament Winding .....	59
Figure B.1 Helicopter Rotor Blade .....	60

## List of Tables

Table 2.1	Composition of Glass Fibers .....	5
Table 2.2	Properties of glass fiber composites .....	18
Table 3.1	General Properties of glass fibers .....	26
Table 3.2	Glass/Binder percentages .....	29

# CHAPTER I

## INTRODUCTION

### 1.1 Relevance

The experimental work described here evaluates the issues associated with the process of making composites using wet laid hydroentangled glass fiber reinforcement. The glass fiber is blended with thermoplastic fiber as a route to a preform material for compression molded structural composite. Glass fiber reinforced composites are conspicuous materials to the automotive and aerospace industries, because of their high strength, low cost and good fatigue resistance. Chopped fiber reinforced thermoplastic composites bridge the performance gap between injection molded and continuous fiber composites <sup>[1]</sup>.

Composites are increasingly being considered as a potential replacement/alternative for metals. Glass/polyester composites are inherently resistant to corrosive environments. Currently, there are wet-laid composites made from glass fibers, but the process is very slow. The process includes making of a wet-laid sheet and drying it and then making a composite from this wet-laid sheet. All this happens as a continuous process and hence more time is consumed. By hydroentangling the wet-laid sheet, we can get a fabric of sufficient integrity for proper and easy handling of the fabric. Such fabric can be transported at any place and stacked as needed to make a composite. This eliminates the need of making the composites, the same time, when the wet-laid sheet is manufactured and hence provides flexibility in manufacturing.

Research has been done on dispersing wet chop glass fiber of 13-micron diameter and 1 inch length with wet dispersible polypropylene or polyethylene terephthalate fiber of 0.25-inch length <sup>[3]</sup> and on analysis of wet laid sheet of 100% glass fibers of 0.5 " length and 16 micron diameter and its comparison with blends of glass/pet (0.5" length, 1.5 denier). Air permeability and tensile strength was found to decrease with increase in the amount of polyester. The reduction in tensile strength may be because polyester elongates compared to glass prior to breakage and bond sites may become deformed during elongation. The tear and burst strength increased with increase in amount of polyester <sup>[2]</sup>. This research focuses on 1/4<sup>th</sup> inch length, 6.5-micron diameter glass fibers providing an aspect ratio of 977 (Approx.) sufficient to obtain a good well-dispersed glass fiber composite according to composites theory.

Fiber dispersion was found to play an important role in hydrosheet properties of hybrid glass fibers with aramid fibers <sup>[3,4,5]</sup>. Fiber hybridization is advantageous since stiff fibers give excellent off-axis properties without a reduction in impact resistance.

## **1.2 Objective**

To investigate the feasibility and suitability of the hydroentanglement process to produce fabrics from glass-binder fiber nonwovens to be used in manufacturing short fiber reinforced composites.

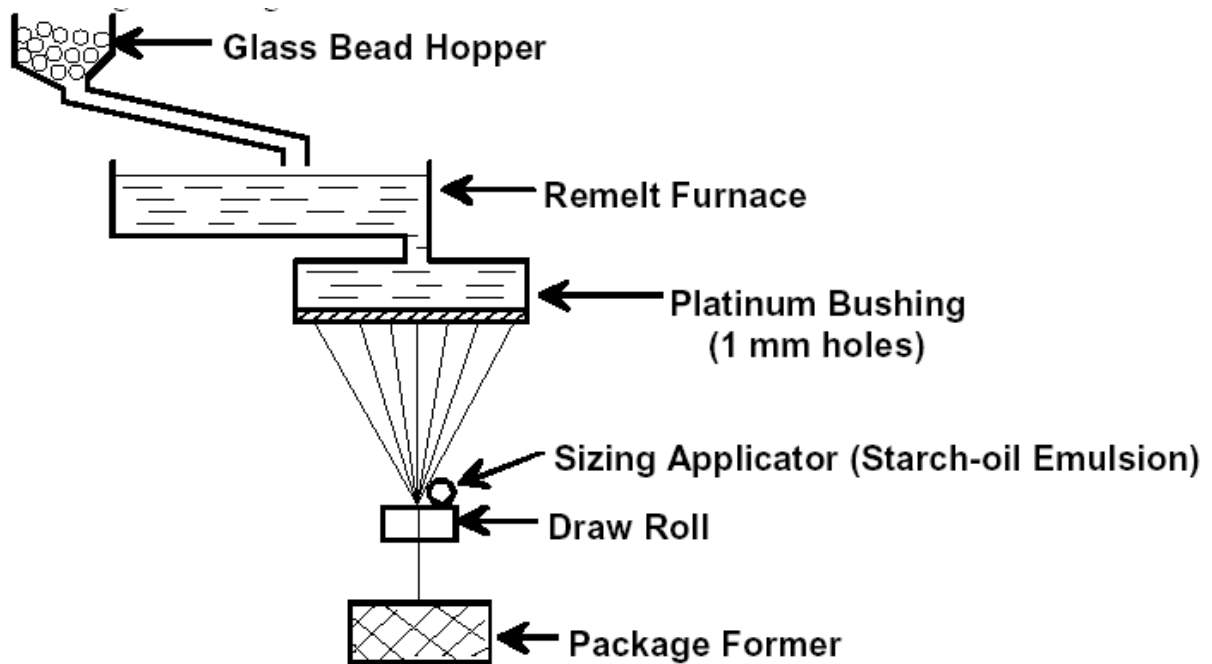
# **CHAPTER II**

## **LITERATURE REVIEW**

### **2.1 Glass Fibers**

Glass fibers demonstrate excellent thermal and impact resistance, high tensile strength, good chemical resistance and outstanding insulating properties<sup>[6]</sup>. They can be tailored to create different types of glass fibers. Therefore, they are used in high performance applications in the industry<sup>[7]</sup>. These properties result in nonwovens with good fire resistance, electrical insulation and dimensional stability to temperature and humidity and impact force. Some typical industrial applications include asphalt-roofing products, flooring, battery separators, fillers, fire barriers and radiant heat barriers. Glass fiber mats give the advantage of damage tolerance and crack resistance that is needed for roofing shingles<sup>[8]</sup>. They are also used as carpet backings and substrates for vinyl flooring products<sup>[9]</sup>. Other uses include electrical wraps and insulation, high efficiency filtration, duct linings, surfacing veils, facings and reinforcement for composites such as printed circuit boards. Glass nonwovens are also used in a number of automotive applications such as headliners, gaskets and battery separators.

The Figure 2.1 shows the process of making fiberglass. There are different types of glass fibers like E-Glass, S-Glass, C-Glass, etc. and they are manufactured by varying the composition of the constituents.



**Figure 2.1 Process of making fiberglass**

<http://www4.esm.psu.edu/academics/courses/emch471/Notes/Chapter3.pdf>

The different types of glass fibers are <sup>[40]</sup>:

**1) E-Glass:**

E-Glass has good strength properties at low cost. It is used in circuit boards of computers to provide stiffness and electrical resistance. Because of electrical resistance it is suited for applications where radio-signal transparency is desired as in aircraft radomes and antenna. It has a specific gravity 2.54 g/cc and a melting point 1555 °F (846 °C). Its refractive index is 1.547.

## 2) S-Glass:

It is named for its good strength. When better strength and low weight are required then such glass fiber is selected. It is often known as R-Glass in Europe and T-Glass in Japan. The high strength glass has appreciably high silica oxide, aluminum oxide and magnesium oxide content than the E-Glass. It has a specific gravity 2.49 g/cc, a melting point 1778 °F (970 °C) and a refractive index 1.523.

## 3) C-Glass:

It is named for its good corrosion resistance. It has high chemical resistance. Usually a 10-micron diameter E-Glass filament typically loses 0.07% of its weight when left in hot water for 24 hours. It has a specific gravity 2.49 g/cc and a melting point 1380 °F (749 °C). The composition of different glass fibers is discussed in the Table 2.1.

**Table 2.1 Composition of Glass Fibers**

<b>Materials</b>	<b>E-Glass Range %</b>	<b>S-Glass Range</b>	<b>C-Glass Range %</b>
Silicon dioxide	52 to 56	65	64 to 68
Aluminum oxide	12 to 16	25	3 to 5
Boric oxide	5 to 10		4 to 6
Sodium oxide and potassium oxide	0 to 2		7 to 10
Magnesium oxide	0 to 5	10	2 to 4
Calcium oxide	16 to 25		11 to 15
Barium oxide			0 to 1
Titanium dioxide	Up to 1.5		
Iron oxide	0 to 0.8		0 to 0.8
Iron	0 to 1		

The glass fibers used normally have diameter in the range of 6.5 micron to 16 micron and are wet chopped. The chop lengths range from 3mm to 25mm with a moisture content of 10% to 20%. The shelf life is about nine months from the date of manufacture<sup>[10]</sup>. Glass fibers are strong, inert, high dielectric strength fibers with elastic modulus of 75 GPa (Approx). But they are hard to disperse, brittle and hard to bond.

## **2.2 Polyester and Bicomponent fibers**

The binder fibers were chosen according to their inherent properties that were desired in the composite. Polyester and Bicomponent (PE/PET sheath/core) were used as binder fibers. PET homopolymer is an adhesive fiber with round cross section and low cost level. It does not bond with glass fiber on application of heat and air. On the contrary, it bonds with glass fiber in presence of heat and pressure. Polyester fiber is somewhat stiff and low strength fiber as compared to other thermoplastic fibers<sup>[11]</sup>.

Bicomponent fiber is a PE/PET sheath core fiber. The sheath core structure allows more expensive adhesives in the sheath and less expensive polymers in the core. It has high bulk and is soft with high strength. It bonds well with glass fibers in presence of heat and air and in presence of heat and pressure. Bicomponent fibers simultaneously provide both a structural element and a thermo-bonding capability. Low melting point bicomponent fibers are more expensive, since they are made from expensive raw materials, and their market is too small to allow economies of scale to be fully realized. More expensive handling and cutting required<sup>[11]</sup>.

The glass and binder fibers can be blended in different proportions. Both the fibers prove advantageous to one another. Higher amounts of polyester along with very less amount of glass, give higher aesthetic quality of web, good handling characteristics and high production line shrinkage. However, higher amount of glass fiber content along with very less amount of polyester, result in higher tear strength and flexibility<sup>[12]</sup>.

### **2.3 Wet Lay Process (Nonwoven Mat Production)**

Wet lay is the major process for converting glass fibers into nonwovens. Wet laid nonwovens are nonwovens made by the papermaking process, or some variation of it. <sup>[10]</sup>

Wet laying involves uniformly dispersing the right type and quantity of fiber in water, transporting onto a continuous moving fine mesh screen and then forming a mat as a result of filtration. The mat or a wet-laid sheet thus formed still contains 80% water and 20% fiber. <sup>[13]</sup>

For a stable dispersion the process may require adding surfactants and viscosity modifier into the water. The consistency of the suspension is also critical and a standard mixture contains 0.3% by weight of fiber. The fiber length/diameter (L/D), stiffness of fiber, kind/amount of crimping, fiber wettability and mechanical agitation of mixture are important parameters for uniform fiber dispersion in the wet lay process. The typical weight of a wet-laid mat is 200-600 lb/3000 ft<sup>2</sup> (90.7-272.1 kg/279m<sup>2</sup>) and density of 0.6-0.8 g/cm<sup>2</sup>.

Structural composite applications require a higher volume fraction of high performance fibers. The fiber volume fraction in nonwoven webs is less than those used in structural applications. But the nonwoven webs can incorporate the better properties of advanced fibers like electrical conductivity, temperature and chemical resistance into the nonwoven

fabric with less effort and time. The first 100% glass-fiber paper was made from filaments with diameters of approximately 0.75  $\mu$  on conventional papermaking equipment at the National Bureau of Standards in September 1950<sup>[14]</sup>. The wet-formed fiberglass mats industry is constantly searching for product improvements and manufacturing economies<sup>[15]</sup>.

In reviewing the wet-laid systems, Dow Chemical's random fiber composite process is a good example of a flocculated wet-laid system. The end product of the process is a glass fiber or other high performance fiber reinforced plastic in a roll<sup>[1]</sup>.

Below are a few advantages of wet-lay process:

- Easy adjustment of sheet basis weight.
- Wet laid yields fiber-reinforced plastics (FRP) composites possessing excellent physical properties.
- Wet lay factors out the large effects associated with variations in web construction for dry-laid webs<sup>[12]</sup>.
- Wet lay process is used in the preparation of circuit board substrates containing additives that improve various electrical properties. The additives are easier to add in wet-lay process as compared to resin impregnated woven glass fabrics. Hence, the circuit board composites can be tailored for specific applications using wet-lay process. The process is adaptable to many resin and fiber combinations<sup>[16]</sup>.

Fibers that are typically wet-laid are cellulosic, either wood pulp, or natural fibers such as hemp, cotton, sisal or flax. But synthetic fibers provide uniformity and consistency of supply

and are currently used in wet-laid nonwovens. The synthetic and glass fibers used in this project are less flexible than the conventional cellulosic fibers used in papermaking. Glass fibers are difficult to disperse since they are somewhat hydrophobic and tend to flocculate with one another.

Drying usually follows wet laying. The drying is done by pressure, vacuum or heat application. In drying, the web is passed through steam-heated cylinders, air dryers, infrared heaters or calendars. Other in-line treatments include aperturing, needle punching and water-jet entanglement<sup>[10]</sup>. This project uses water-jet or hydroentanglement technique after manufacturing the wet-laid sheet.

Summarizing the wet-laid process, we can say that it combines high productivity, control of orientation properties, high uniformity at low basis weight, ability to blend fibers and flexibility in chemical and binder addition.

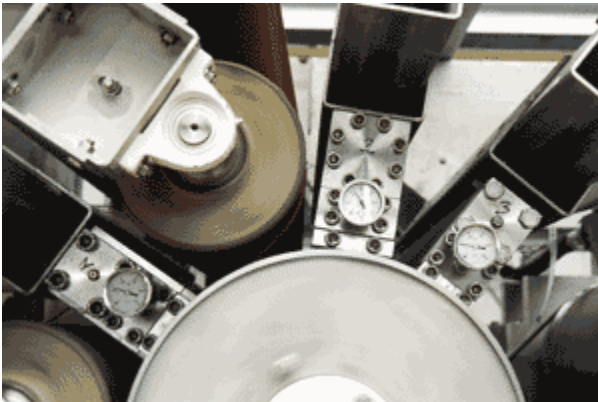
### **2.3.1 Why wet lay?**

Fiberglass has a very smooth surface, which produces a tremendous level of interfiber friction. This makes carding of fiberglass difficult. Glass fibers do not have crimp and are not at all flexible. Because of lack of crimp, fibers do not entangle, which is necessary for web cohesion, during carding. Special sizes need to be applied to the fiberglass if they are to be carded<sup>[10]</sup>. Glass fibers used in this research disperse well in water in presence of certain surfactants and a viscosity booster. The wet lay sheet produced is much more uniform and oriented isotropically.

By wet lay process, webs from fiberglass and binder fibers can be produce at high production rates. The challenge is to achieve desired result through effective mat composition.

## 2.4 Hydroentanglement

The origin of hydraulic entanglement technique dates back to the late 1960's when DuPont showed samples of their proprietary work done in their research center. In 1974 DuPont launched their first hydroentanglement production line in Tennessee. Later a Johnson and Johnson division, Chicopee, introduced their version of hydraulic fiber entangler in 1981 and Kendall corporations brought their hydroentangling process in 1985. Today the major suppliers of hydraulic entangling systems are Honeycomb Systems, Reiter (PerfoJet), Fleissner, Unicharm and Spunlace Technologies<sup>[17]</sup>.



**Figure 2.2 Hydroentanglement machine manifolds**

[http://www.fleissner.de/aj\\_e.htm](http://www.fleissner.de/aj_e.htm)

The Figure 2.2 shows the Fleissner hydroentanglement machine manifolds with pressure controllers. The water-jet pressures can be varied and controlled at each jet manifolds.

Hydroentanglement uses high-speed jets of water to strike a web so that the fibers knot about one another and provide fabric integrity. Hydroentanglement is the generic term for a nonwoven process that can be used for either web consolidation or fabric surface texturing

purposes or both<sup>[18]</sup>. In either case, the mechanism is one of fiber rearrangement and entanglement within a preformed web by means of fluid forces. The fabrics produced have soft handle and drape and they are free from chemical binders or process residues.

The impinging of the water jets on the web causes the entanglement of the fibers. The water needling pressure generally increases from the first to the last injectors. Pressures as high as 3000 psi are used. Usually the fiber sheet is hydroentangled on both sides in a step-wise manner. A vacuum within the roll removes used water from the product, preventing flooding.

The pressure and type of water jet depends on the type of injector hole. The injector hole diameter range from 100-120  $\mu$  m and the holes are arranged in rows with 3-5 mm spacing with one row containing 30-80 holes per 25 mm<sup>[39]</sup>.

Whether the fabric surface is visibly smooth or openly patterned depends on the forming wire design and surface geometry. With a very fine forming wire supporting the web through the entangling zone, a non-apertured fabric that is both strong and drapable can be formed. With an open forming wire, an apertured fabric rearranged in the mirror image of the forming wire is formed. Stronger the fabric is produced with finer web support system. The water required for hydroentanglement must have nearly neutral pH, low amount of metallic ions such as Ca, no bacteria or other organic materials<sup>[19]</sup>.

Some properties of hydroentangled fabrics <sup>[19]</sup>:

- High drape, softness and comfortable handle

- More fiber entanglement leads to increased strength.
- Shear modulus remains low and is virtually independent of the degree of entanglement.
- Tensile strength of the fabric increases initially with increase in water pressure until a certain limit depending on the fiber type and then it reduces.
- Generally the water jet is perpendicular to the fabric. If the angle is changed slightly, the strength increases.

## **2.5 Composite Basics**

A material created from fibers (or reinforcement) embedded in an appropriate matrix material in order to enhance specific performance properties is referred to as a composite<sup>[1]</sup>. The constituents do not dissolve or merge completely but retain their identities as they act in concert. For a glass fiber composite, the primary ingredients are usually the reinforcing glass fiber and a plastic resin. This research focuses on use of low melt thermoplastic fibers instead of resin. Composites structures have high strength to weight properties and design flexibility. Due to its high strength and lightweight, aerospace and high performance sporting goods utilize premium composite materials. Most of them have electrical insulation properties due to which they are used in electrical appliances and tools. A chopped strand mat is most widely used form of glass reinforcement. Composites can be classified as particulate composites, short and long fiber reinforced composites, and sandwiched composites<sup>[20]</sup>.

Lee and Springer<sup>[21]</sup> have modeled the consolidation process of unidirectional composites. The flow of resin along the fiber length is modeled as laminar flow. Radial flow is modeled using Darcy's law.

Powder impregnation during wet-laying stage or during consolidation stage has been studied in earlier researches done by Dr. Drzal<sup>[22]</sup>. He also studied the model resin flow. It has been concluded that the major contribution to time of consolidation is from heating and cooling regimes of the composite. For ideal consolidation each fiber is equally spaced apart and wetted completely by the matrix. The powders used were of different shapes viz. spherical, cubic, regular parallelepiped and irregular. Polymer particles are charged either by an electric field or by surface charging. The glass fibers are charged with an opposite polarity and passed through a fluidized medium. The various powder impregnation processes differ mainly in the way of particle deposition on fibers and adhesion of particle fiber surfaces<sup>[23,24]</sup>.

### **2.5.1 Resins and matrices**

Resins can be thermosetting or thermoplastic resins. Thermoset resin requires addition of a curing agent or hardener and impregnation onto a reinforcing material, followed by a curing step to produce a cured or finished part. Thermoset resins "cure" into an irreversible state because the molecular structure gets cross-linked. Examples of thermoset resins for composites are: unsaturated polyester, vinyl ester, epoxy, urethane and phenolic. Thermoplastic resin has a linear molecular structure that will repeatedly soften when heated to its melt temperature and harden when cooled. Examples of thermoplastic resins for composites are: polypropylene, polyethylene, polystyrene, ABS (acrylonitrile-butadiene-

styrene), nylon, polycarbonate, thermoplastic polyester, polyphenylene oxide, polysulfone and PEEK (poly-ether-ether-ketone). Composites are classified according to their matrix phase. There are polymer matrix composites (PMC's), ceramic matrix composites (CMC's), and metal matrix composites (MMC's). Materials within these categories are often called "advanced" if they combine the properties of high strength and high stiffness, low weight, corrosion resistance, and in some cases special electrical properties. This combination of properties makes advanced composites very attractive for aircraft and aerospace structural parts<sup>[25]</sup>.

Bureau and Denant<sup>[26]</sup> showed that matrix type affects the behavior of glass fiber/polypropylene composites. They found that a composite with a thermoplastic matrix has 2-stage fatigue damage and that with a thermoset matrix has 3-stage fatigue damage. They characterized the fatigue behavior by the spherulitic regions formed within the composite.

Impact studies on discontinuous glass fibers with polypropylene matrix have suggested that a thermoplastic matrix gives tougher composite than a conventional thermoset epoxy matrix<sup>[27,28]</sup>.

### **2.5.2 Reinforcement**

Fiber reinforcement materials are added to the resin system to provide strength to the finished part. The selection of reinforcement material is based on the properties desired in the finished product. These materials do not react with the resin but are an integral part of the composite.

There are three basic types of fiber reinforcement materials used and they are aramid fibers, carbon/graphite fibers and glass fibers. Other fibers are also used but these three fibers are most commonly used.

Four main factors govern the reinforcing fiber's contribution in the composite:

- i. The basic mechanical properties of the fiber.
- ii. The surface interaction of fiber and resin.
- iii. The amount of fiber in the composite ('Fiber Volume Fraction').
- iv. The orientation of the fibers in the composite.

### **2.5.3 Methods of Making Composites** <sup>[29]</sup>

The characteristics of composites depend on the method in which they are fabricated. The various methods of fabrication using nonwoven as a preform are given below. Diagrams of these methods can be seen in Appendix A. Figure 2.3 shows the various methods that can be employed for composite fabrication.

#### **i. Resin Transfer Molding**

In this process, the fibers are enclosed in a die. A pre-catalyzed resin is injected into the mold at relatively low pressure. Curing occurs within the mold, often along with application of heat. Relatively large molds like automotive body parts are made this way.

ii. Liquid Resin impregnation routes

The fibers in the form of a mat are impregnated with resin by rolling or spraying. The resin and curing agent are mixed immediately prior to its application. The curing usually takes place at ambient temperature and virtually any shape can be produced by this method.

iii. Vacuum molding

This involves enclosing a pre-preg (sheet of fibers impregnated with resin) with a flexible membrane. This enclosure is vacuumed. Because of the vacuum, the pre-preg is compressed due to atmospheric pressure. This way the composite is produced.

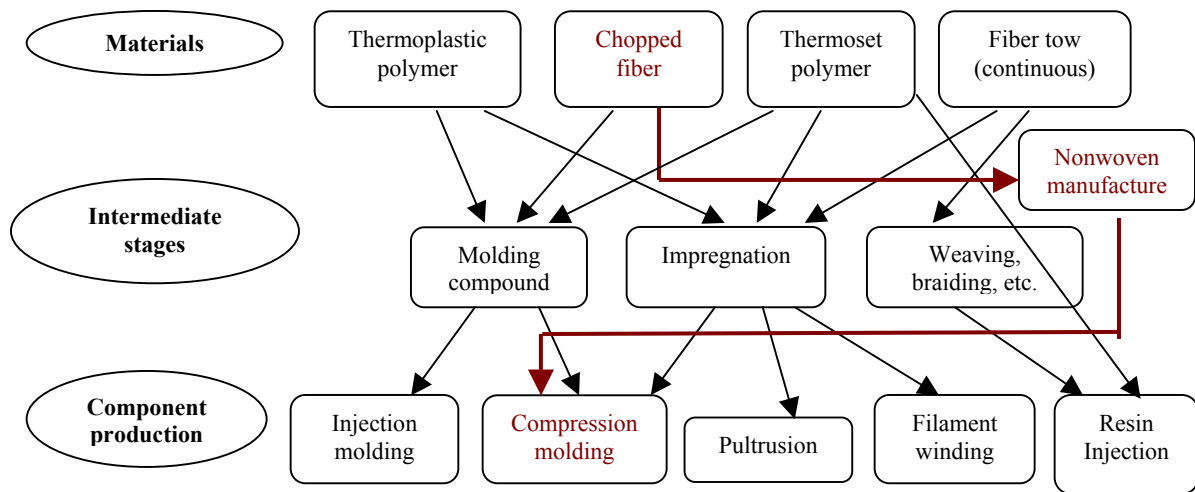


Figure 2.3 Schematic overview of the approaches employed in fabrication of polymer matrix composites [29]

iv. Autoclave molding

Autoclave molding is similar to vacuum molding, but the enclosure is a very large chamber, which can be pressurized along with heat application.

v. Sheet molding

To make a sheet molded compound, resin containing thickening agent and particles of  $\text{CaCO}_3$  is mixed with chopped fibers. This slurry is then passed through films and rolls to produce a consolidated sheet.

vi. Hot Press/Compression molding

In compression-molding process with heat application, a male-female compression tool mounted in a press is loaded with a stack of square cut sheets of material composed of reinforcing fiber and binder. The mold is closed and heat pressurized at a temperature near to the melting temperature of the binder fiber or resin. The composite sample thus formed is allowed to cool so that the resin rapidly cures. The shape and size of the composite depends on the preform and mold used<sup>[7]</sup>.

#### **2.5.4 Benefits of fibrous and polymeric composites**<sup>[11]</sup>

- Processing speeds are high
- Cheaper to use than chemical bonding
- Lower energy requirement
- Fewer concerns regarding environment
- Ease of production of nonwovens with better performance.

End use:

- Apparel interlinings, automotive applications, geotextiles, industrial goods like wall coverings, sports applications, laminates, special shoe parts, filters etc.

### 2.5.5 Glass Fiber Composite Properties and Applications

Glass fibers are preferred for composite manufacture. One of the essential properties of glass fibers is its insulation. Fiberglass insulation products play a significant role in energy conservation by reducing energy use in homes, office buildings, businesses and manufacturing plants. Strong and stiff glass fibers carry loads imposed on the composite while the resin matrix spreads the load across the fibers. Glass fibers exhibit outstanding thermal and impact resistance, high tensile strength, good chemical resistance and extraordinary insulating properties. They are capable of meeting stringent design standards while at the same time provide major cost benefits. Fiberglass mats when impregnated with suitable resins have excellent dielectric strength. Due to their temperature resistance and low density, they serve as an efficient electrical insulating material<sup>[14]</sup>. Chopped glass fiber sheets are useful in applications where moderate reinforcing fiber volumes are necessary<sup>[7]</sup>.

**Table 2.2 Properties of glass fiber composites**

<b>Property</b>	<b>In chopped strand mat</b>
Glass content	25-45
Softening or melting point °C	750-800
Specific gravity	1.4-1.6
Tensile strength, MPa	76-160
Tensile modulus, MPa	5.6-12
Flexural strength, MPa	140-260
Flexural modulus GPa	6.9-14
Compressive strength, MPa	120-180

The properties, specifically, the strength of a fiber-reinforced composite depends on the volume fraction of the composite.

**Volume Fraction <sup>[30]</sup>:**

The volume fraction of the composite formed by any consolidation technique is the amount of fiber in the volume of the composite. A fiber volume fraction can be calculated by the formula:

$$W_g = \rho t V_f \dots\dots\dots(1)$$

Where,

$W_g$  = Relative areal density of glass (g/cm<sup>2</sup>)

$\rho$  = Specific gravity of glass (g/cc)

$t$  = Thickness of fiber

$V_f$  = Fiber volume fraction

True areal density is calculated by multiplying weight percent of glass with the relative areal density. The number of layers necessary to produce a desired fiber volume fraction can be given as:

$$N = W_g / W_{g(\text{true})} \dots\dots\dots(2)$$

When the two materials are combined to make a composite, the mechanical properties depend not just on those of the two materials being mixed, but also on the relative amount of each material (the term volume fraction is used to describe the relative volume occupied by the fiber

or reinforcing material), the shape and size of the reinforcement and its orientation with respect to the loads that are to be applied to the composite.

**Applications** of fiberglass composites <sup>[7]</sup>:

Because of flexibility in manufacturing, they can be used to design complex parts.

1. Bumpers, fenders and hoods
2. Radiator end caps, intake manifolds
3. Car interiors, and components with ignition systems
4. Door structures
5. Sound and thermal barriers
6. Circuit boards and other electrical appliances
7. Aerospace applications (they show 20% weight reduction)

In helicopter rotor blades, they increase the life of blades by 100% and also the speed performance is improved [Appendix B]. Composites have use in bridges where they show 80% weight reduction of the materials.

**2.5.6 Why are glass fibers used in Automotives?** <sup>[31]</sup>

- Production rate in aerospace is much higher than that in automotives. Therefore nonwoven performs are preferred. Cost to reduce weight is much higher in aerospace industries but still they can afford it. While, automobile industries demand less weight at low cost. Hence the challenge is to produce cost-effective, high volume and light weight composites. Glass fiber nonwovens are a solution to this.

- Less weight is necessary for aircraft for obvious reasons. For automobiles, low weight gives more power in engine pick-up with less emission and less fuel waste. Corvette has fiberglass epoxy composite body with fatigue life of more than 5 times that of steel (for example leaf spring). They give more rapid responses to stress. 8% by weight of automobile parts today are made of composites<sup>[6]</sup>.
- Composites have high energy absorbing characteristics due to their complex failure behavior (Fiber break, matrix failure or delamination). This allows much of the energy to be absorbed during a crash, which is essential in automobiles.
- Glass fiber composites give other advantages like high stiffness and strength at low density, good fatigue performance and corrosion resistance.
- Lotus Elite was one of the first composite cars. BMW company's Z1 sports car also used composite in its flooring.

Low temperature impact behavior study is essential in automotive applications, since many plastic parts may undergo severe conditions in an automotive exposed to impact loading. The impact behavior of short glass fiber reinforced thermoplastic polyurethane was studied by Jancar J<sup>[32]</sup>.

### **2.5.7 Composites in Printed Circuit Boards**

Nonwoven composites have a potential in the manufacture of Printed Circuit Boards. Glass fiber composites give the advantage of high strength, surface resistance, electrical stability and many more as stated in the earlier paragraph. For these advantages, such composites are preferred for the manufacture of printed circuit boards. Usually glass fibers or glass fabric is

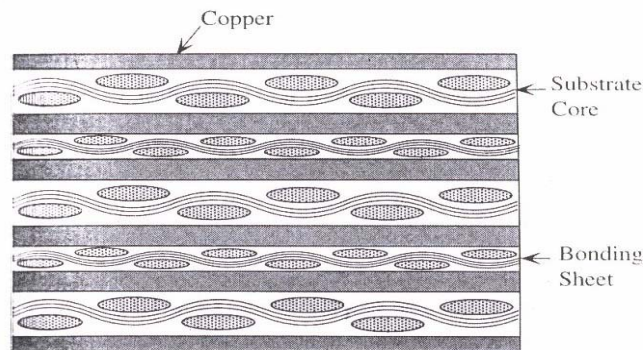
used for producing the printed circuit boards. But some thermoplastic fibers can also be used for the production of flexible printed circuit boards.

Printed circuit boards are manufactured in different ways from glass cloth. There is one way in which water is squirted out under pressure from fine holes, which separate the glass cloth thread into independent filaments. These are then reacted with silicone bonding agents to give surface treatments followed by impregnation in the epoxy resin to form composite circuit boards<sup>[33]</sup>. Circuit boards must have low dielectric constant so that high-speed signals can propagate with shorter delay. The circuit boards include glass fiber to strengthen the board and reduce its thermal expansion. Glass exhibits low value of dielectric constant K and it softens at low temperature. Glass/ceramic composite circuit boards are manufactured by placing ceramic material within the glass body. Ceramic inhibits curling of the formed sheet and strengthens the body<sup>[34]</sup>.

For PCB's, the interfacial properties of E-glass fiber reinforced composites is essential in predicting the long-term reliability, because of the detrimental effects of interfacial moisture. The presence of moisture can cause delamination as well as corrosion due to reaction of water with metal oxides present in glass. A study of moisture absorption and waterborne epoxy resins has been conducted by Jensen, Johnson and Ward<sup>[35]</sup>. They concluded that in order to reduce the moisture absorption of E-glass fibers, they should be treated with a silane-coupling agent<sup>[35]</sup>.

There are some circuit boards that are called flexible printed circuit boards. For manufacturing of flexible printed circuit boards, a nonwoven is produced from aramid fibers and then is impregnated in resin, which is an acrylonitrile and styrene copolymer. The prepreg is allowed to dry for preliminary cross-linkages and then laminated with a copper foil followed by curing of the composite. Composite circuit boards made from glass fibers have the advantages like high strength, high electrical resistance, blister formation resistance, lower dielectric constant, low dissipation factor and above all non-flammability. One disadvantage with glass fiber composite circuit boards is that they split when being cut or machined.

An alternative to such composite is a multi-layered composite of resin impregnated outer plies of glass fiber with resin impregnated core plies of flat textiles made from thermoplastic fibers having a dielectric constant less than 5, which is needed for circuit boards.



**Figure 2.4 Multi-layer Circuit Board Schematic**

Multi-layer circuit boards are used extensively in electronic packaging assemblies. Stresses are produced during processing and these stresses are large enough for causing dimensional changes like shrinkage of one layer with respect to another. For this, residual deformation and

warping problems in multi-layer circuit boards were studied by Shrotriya et al<sup>[36]</sup>. A schematic of multilayer circuit board is shown in Figure 2.4.

Multilayer circuit boards are manufactured in several stages: First stage is that the glass fiber bundles are woven into fabric and impregnated with epoxy resin to form a prepreg called a B-staged prepreg. After this a number of B-staged prepreps are stacked between two layers of copper foil in a hot press to for obtaining a core called C-staged core. These cores are passed through etching and screening processes. Multilayered circuit boards are then prepared by alternating B-staged and C-staged prepreps<sup>[36]</sup>.

### **2.5.8 Copolymerization of PP on glass fiber**

The adhesion between matrix and fibers is an essential factor in determining the properties of thermoplastic matrix polymer composite materials. Weak adhesion at interfaces causes deterioration of mechanical properties. Considerable progress is made in improving the durability. But breakdown in the glass resin interface result in fiber pop-out and surface micro-cracking of the matrix. These are the two main types of surface deterioration that may affect the mechanical properties. To improve resin-fiber adhesion, the glass fibers are treated with silane coupling agents. This treatment causes the surface modification of glass fibers and hence provides more anchorage to the resin<sup>[37]</sup>.

### 2.5.9 Other Nonwoven Composites

Apart from glass fibers, various other fibers are used for nonwoven composites. Some of the examples include:

**Battery separator:** These are wet-laid nonwovens made from Polyvinyl alcohol fibers. The polyvinyl alcohol fibers have properties like mechanical stability, high uniformity of fibrous structure, electrolyte resistance along with wettability and adsorption capacity of electrolyte that are needed for proper functioning of battery separators.

**Cable industry:** Nonwoven composites are used as a conductive buffering material in shield area of plastic insulated power cables or as water blocking tapes. For the water blocking tapes, a swelling powder, which is a mixture of synthetic super absorber plus chemically pure cellulose pulp, along with a polyester backing is used.

Glass fiber nonwovens are extensively used in Japan for various applications. One such application is glass fiber paper used as a filtration material. Glass nonwovens are used in floorings, printed circuit boards, battery electrode separators, filters, glass mats for roofing materials and composite materials for thermo-formable products with excellent stiffness and strength<sup>[9]</sup>.

# CHAPTER III

## EXPERIMENTAL APPROACH

### 3.1 Raw Materials

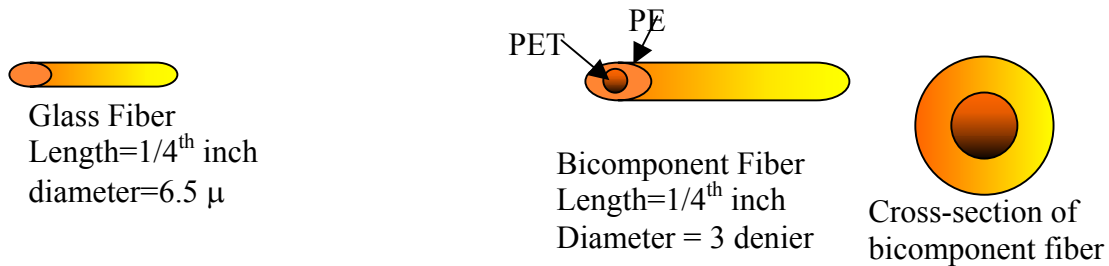
This research addresses the manufacturing of glass and binder fiber blend composites. The glass fibers used for composite manufacture were supplied by Owens-Corning Company. The type of glass fiber was an E-Glass fiber. Each glass fiber had 6.5 $\mu$  diameter, ¼-inch length. Some of the general properties of glass fibers are given in Table 3.1 below.

**Table 3.1 General Properties of glass fibers**

Typical Properties	E-Glass	S-Glass
Density(g/cm <sup>3</sup> )	2.6	2.5
Young's modulus(GPa)	72	87
Tensile Strength (GPa)	1.72	2.53
Tensile Elongaion	2.4	2.9

Low cost and high strength of glass fibers were the driving concerns in fiber selection. Apart from these, glass fibers have other advantages such as good impact strength, good chemical and corrosion resistance and good dimensional stability. The glass fibers were blended with binder fibers during the dispersion process discussed below. The binder fibers are used so that after heat pressing the blend sample, they melt and adhere to the glass fibers and hence give strength to the composite formed. The binder fibers used in this research are polyester (homocomponent) and PE/PET sheath core (bicomponent) fibers. These fibers were supplied

by KoSa Company. The polyester fibers were 1.5 denier and ¼-inch (6.35 mm) length fibers.



**Figure 3.1 Raw materials used**

Figure 3.1 shows the glass and binder fibers used in this research. The bicomponent fibers were sheath-core structure fibers with core of polyester and sheath of low melt polyethylene fibers. They were 3 denier and ¼-inch (6.35 mm) length fibers. The thermal properties of these fibers were determined by using a Differential Scanning Calorimeter (DSC).

### **3.2 Dispersion and composite perform formation**

The first step of this research was to obtain a uniformly dispersed web. Thus, optimal dispersion times for various fibers were determined.

- 100 % glass
- 100 % polyester and 100% Bicomponent
- Glass/Polyester blend and Glass/Bicomponent blend

There are many different variables that influence dispersion. These variables can be classified into independent and dependent variables:

**Independent Variables:**

- Speed of agitation
- Time
- Amount of Fiber (consistency)
- Type and amount of surfactant and antifoaming agent

**Dependent Variables:**

- Log defects
- Ropes

Taking these variables into consideration, the optimum time of dispersion was to be established. Fibers were dispersed in a stirring tank for about ½-hour. Hand sheets were used as a product development tool for chopped fiber composites and hand sheets were taken every 5 minutes. First only glass fibers were dispersed and their optimum time for dispersion was determined. To check the uniformity of dispersion, the hand sheets were analyzed by image analysis. After analyzing these images, the number of logs per 100 sq. cm and number of ropes per 100 sq. cm were counted. Graphs of time of dispersion vs. defects (logs and ropes) were plotted.

The same procedure was followed for 100 % Polyester, 100 % Bicomponent fiber dispersion and glass/binder blend dispersion and the optimum time of dispersion was decided after analysis of these graphs. Optimum time of dispersion is the time when there is least amount of both log and rope defects. This way, a proper dispersion recipe and time was established.

### 3.3 Chemicals for dispersion

Various chemicals were added to the water so as to get a uniform dispersion of the fibers.

The chemicals added were:

- Surfactant: Nalco 8493. It is an alkyl amine surfactant product of Nalco Company. 50-100 ppm of this surfactant was added.
- Antifoaming agent = Nalco PP04-3804. 5-10 ppm of this petroleum-based agent is to be added.
- Viscosity Booster. This is a polyacryamide chemical of the Nalco Company with viscosity of 1.8 cp

This recipe was obtained after a personal discussion with Owens Corning Company on May 15<sup>th</sup> 2001. After adding these chemicals, fibers were added and dispersed. The total amount of fiber added was 0.03 % by volume of water. Different blend percentages of glass/polyester and glass/bicomponent fibers were used. The Glass/ Binder percentages used are given in the Table 3.2 below.

**Table 3.2 Glass/Binder percentages**

<b>Glass/Bicomponent</b>	<b>Glass/Polyester</b>
20/80	20/80
30/70	30/70
40/60	40/60
50/50	50/50

The 60/40 (glass/binder) was tried, but it gives a very low strength as a composite sheet because of less binder fibers.

Wet laid sheets are formed after getting a uniform dispersion. The belt speed in the wet lay machine was kept at its lowest speed (1m/min), to get a high weight per unit area of the nonwoven sheet. 6 such layers of wet-laid sheet were stacked and hydroentangled to get a goal basis weight ( $>100 \text{ g/m}^2$ ) hydroentangled sheet. This sheet was used as a prepreg for the making of composites.

The hydroentanglement machine, in the Cotton Inc. laboratory, College of Textiles, has three jet manifolds. The pressures used to hydroentangle are 300 psi (20bar), 500 psi (35bar), and 600 psi (41bar) respectively on the three jets. Lower pressures of 300, 400 and 400 psi on the three jet manifolds respectively were tried, but it resulted in a hydroentangled sheet with insufficient entanglement. Higher pressures of 500, 700, 1000 psi on the three jet manifolds were also tried. At these higher pressures, the hydroentangled sheet tore apart due to higher water jet force. The fiber orientation distribution was determined in the hydroentangled sheet formed.

### **3.4 Orientation Distribution Function**

Fiber orientation, caused by processing, has a serious influence on the final mechanical properties of reinforced components. To study the fabric's anisotropy, the orientation distribution function (ODF) was measured. When the samples are tested in different directions, the relative contributions to the total deformation would be different. This is

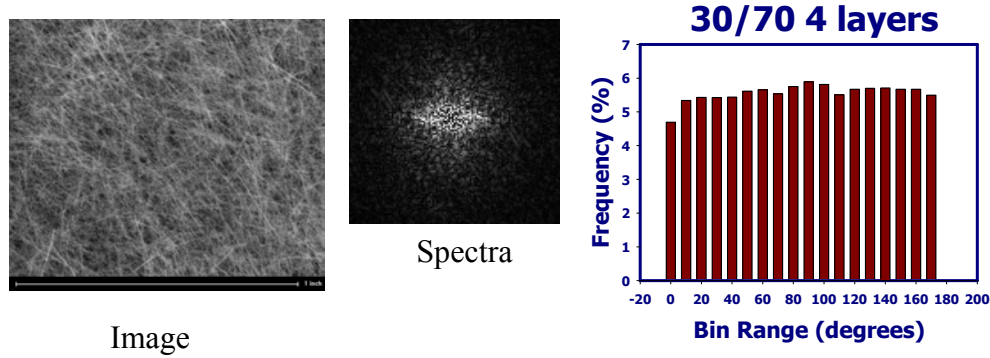
because of the anisotropy of the structure. The orientation distribution function [ODF]  $f(\theta)$  is a function of the angle  $\theta$ . The integral of the orientation distribution function  $\psi(\theta)$ , from an angle  $\theta_1$  to  $\theta_2$ , is equal to the probability that a fiber will have an orientation between the angles  $\theta_1$  and  $\theta_2$ .

The function  $\psi(\theta)$  must additionally satisfy the following conditions:

$$\begin{aligned} \psi(\theta + \pi) &= \psi(\theta) \\ \int_0^{\pi} \psi(\theta) d\theta &= 1 \end{aligned} \quad \dots\dots\dots (3)$$

The orientation angle is angle between the sample axis and the loading direction (machine direction (MD) in our case).

The ODF program captures an image of the object and then scans it for orientation distribution. The ODF for each sample set was calculated by digitizing each image using the LED back lighting system disclosed previously [38]. After scanning it, a median filter is applied to eliminate noise and then the program gives a spectrum of fiber orientation and also the statistics. Five images for each sample were captured. The results of the orientation distribution function are discussed under the results and discussion topic. Figure 3.2 is an example of a captured image (glass/PET=30/70, sample 2), its spectra and its orientation distribution graph:



**Figure 3.2 Orientation Distribution Function of 30/70 Glass/PET sample**

From the ODF graphs, the cosine squared anisotropy parameter was measured for the samples. This parameter can be defined using the ODF function.

$$f_p = 2 \left[ \frac{\int_0^\pi \psi(\theta) \cos^2(\theta_{ref} - \theta_i) d\theta}{\int_0^\pi \psi(\theta) d\theta} \right] - 1 \quad \dots\dots\dots(4)$$

This parameter varies between -1 to 1. Here, a value of -1 signifies orientation of fibers parallel to the reference direction while 1 signifies fiber orientation perpendicular to the reference direction. An anisotropy parameter near to zero signifies a random distribution.

### 3.5 Differential Scanning Calorimeter (DSC)

Composite was to be manufactured by heat pressing the hydroentangled sheet. In order to proceed, the proper melt temperatures of the binder fibers need to be known. To find out the melting curve (melting behavior) of the binder fibers (polyester and bicomponent fibers), differential scanning calorimeter (DSC) was used. The DSC was used to find the onset and peak temperatures of polyester and bicomponent fibers.

The DSC measures temperatures and heat flow associated with thermal transitions in materials. These measurements can be utilized to determine the melting point and glass transition temperatures of materials, as well as heats of fusion, specific heat capacities, crystallinity, purity, degree of cure, and reaction kinetics.

**Principle of working:** DSC is based on the thermal response of an unknown specimen as compared to a standard, when both of them are heated under identical conditions at a constant rate. The DSC contains a furnace having two identical crucibles each resting on a thin plate. Directly below the center of each plate is the junction of the differential thermocouple (Pt--Pt-Rh). Any difference in temperature caused by difference in masses, heat of reaction, specific heat or phase transaction is recorded.

To determine the specific heat capacity, a baseline is established by measuring the temperature difference between two empty crucibles at constant rate of change in temperature. Thermal response records are then acquired for a standard material and an unknown under identical conditions. The ratio of the departure of the standard and the unknown from the baseline is then calculated to determine the specific heat of the unknown.

### **3.6 Composite Manufacture**

After knowing the melt temperatures of the binder fibers, samples of composites were manufactured. The samples included:

- Single hydroentangled sheets (prepregs) compression molded

- 4 layers of hydroentangled sheets stacked and then compression molded
- 8 layers of hydroentangled sheets stacked and then compression molded.

For the 4-layered samples, the samples were made at 10 minute, 15 minute and 20 minute residence time. It was seen that the polyester fiber in the sample degrades at 20 minutes. Hence the residence time was decided as 15 minutes. The residence time was decided as 25 minutes for the 8-layered samples. Below are the machine settings on the molding machine:

Pressure applied on the two hot plates = 6000 psi

Hot plate Temperature = 480°F (for polyester fiber),

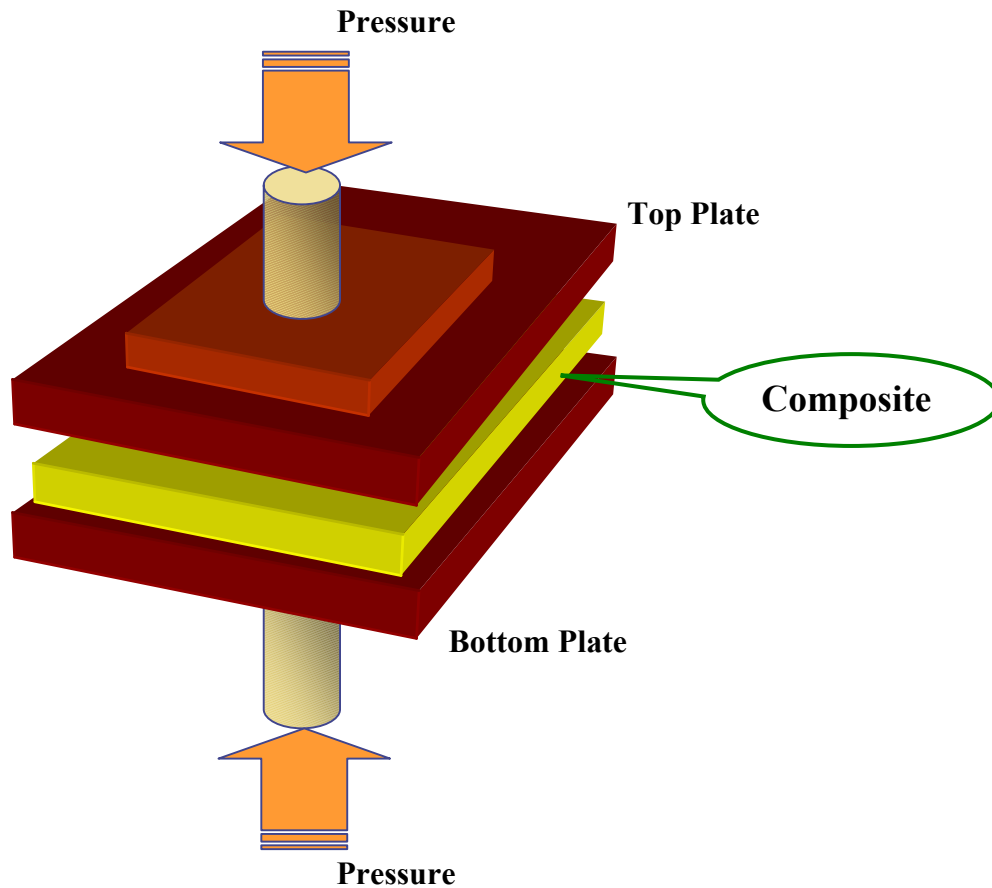
430°F (for bicomponent fiber)

Optimum residence time = 15 minutes (for 4-layered samples)

25 minutes (for 8 layered samples)

Release film = Release Film from Airtech Company

Figure 3.3 below shows the schematic of the compression-molding machine used.



**Figure 3.3 Schematic for the compression-molding machine**

## **3.7 Tests Performed**

### **3.7.1 Tensile Tests**

The composites thus formed, were tested for tensile strength on the Instron machine. The test was done in the machine direction of the sample tested. Strip test was carried out for measuring the tensile strength of the composite. 5 x 1 inch samples were cut and tested with the below mentioned machine settings.

The Instron machine settings were as follows:

Load cell = 50 kg (for single layer sheets), 1000 lbs (for 4 and 8 layered sheets)

Gauge length = 3 inches

Sample length = 5 inches

Principal Used = Constant rate of extension (300 mm/min)

The thickness of the samples was measured. The values of stress were calculated and stress strain graphs plotted for each sample. Toughness and stiffness of the samples were calculated from these curves. The area under the curve, in units of  $\text{MJ/m}^3$ , is a measure of a material's toughness. The greater this area, the tougher the material, and the greater the amount of energy required to break it. For stiffness, the secant modulus at breaking strain was calculated. Secant modulus is the ratio of stress to corresponding strain at a specified strain level. It is usually employed when the stress-strain curve for a material does not exhibit linearity of stress to strain.

### **3.7.2 4 – Point Bending Test**

4 – Point Bending Test was employed on the glass/binder fiber composites made using the Instron machine. The results obtained were compared with the glass/resin samples. The glass/resin samples were manufactured by making a composite from 100% glass fiber hydroentangled sheet and epoxy resin (DER 331 epoxy resin & DEH 26 hardener). The resin was applied within the layers of 100 % glass fiber for each of the 4 and 8-layered composite samples.

The Instron machine settings for the 4-point bending test are given below:

Samples tested in Machine Direction

Span length = 2 inch

Sample size = 5 inch x 1 inch (12.7 cm x 2.54 cm)

Load Cell = 50 kg (for Glass/ Binder fiber blends)

1000 lb (for Glass/ Resin samples)

After testing the samples, the stress strain curves were plotted.

# CHAPTER IV

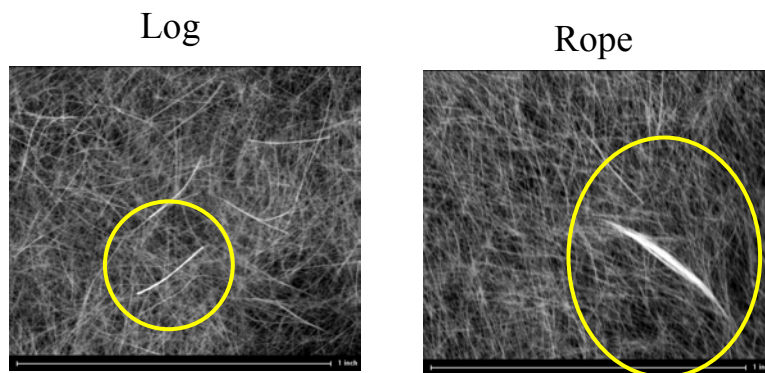
## RESULTS AND DISCUSSIONS

### 4.1 Dispersion

The uniformity of the dispersed sheet was checked through imaging and the defects counted. Graphs of time of dispersion vs. defects were plotted. Logs and ropes were the defects, which were counted. Here is a brief definition of these defects:

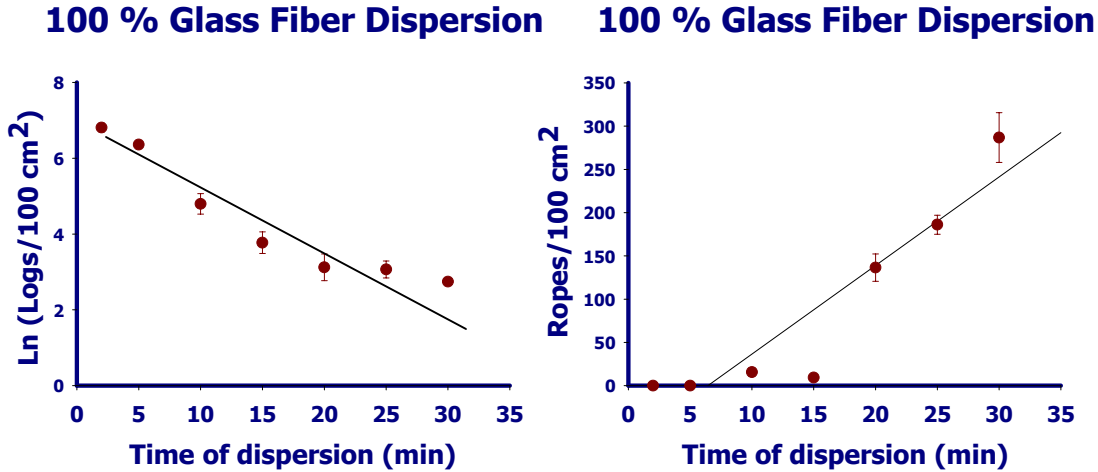
**Logs:** Logs are a bunch of fibers grouped together. The diameter of the log is  $n$  times the diameter of a single fiber ( $n$  being the number of fibers in a log), while its length is same as that of a single fiber.

**Ropes:** Ropes are a bunch of fibers entangled with each other. The diameter of a rope is more than that of a single fiber, but it varies throughout the length of the rope. The length of the rope is usually greater than the length of the original single fiber. Figure 4.1 shows their images.



**Figure 4.1 Images of logs and ropes defects**

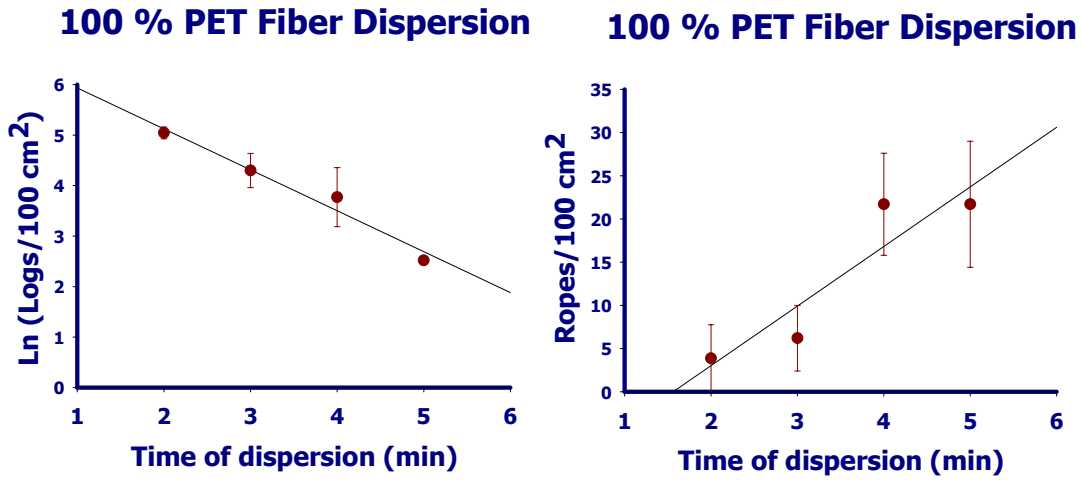
The graphs for the time of dispersion vs. defects are shown in Figure 4.2 for 100% glass fiber dispersion.



**Figure 4.2 Glass Fiber Dispersion**

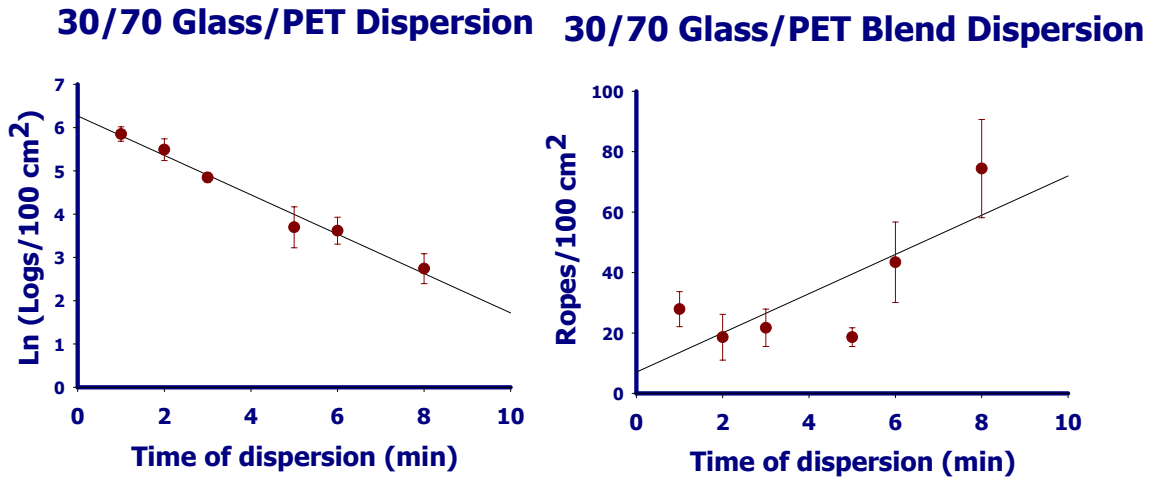
Figure 4.2 shows that the glass fibers take 15 minutes to disperse. The number of logs is minimum at 20-minute dispersion time, however, at this time, the amount of ropes increase markedly. 15-minutes is decided because at this time the amount of logs and ropes, both are optimum. The logs, generally, decrease with increase in dispersion time while the ropes increase with increase in dispersion time.

The same procedure was followed for the polyester fiber dispersion. The graph is as seen in Figure 4.3. It can be concluded from the graphs that 4 to 5 minutes is the optimum time of dispersion of the polyester fibers. For the blend dispersion, glass and polyester fibers were blended in the ratio of 30/70 (glass/polyester). The glass fibers were first allowed to disperse for 10 minutes after which the polyester fibers were added in the dispersion tank.



**Figure 4.3 Polyester Fiber Dispersion**

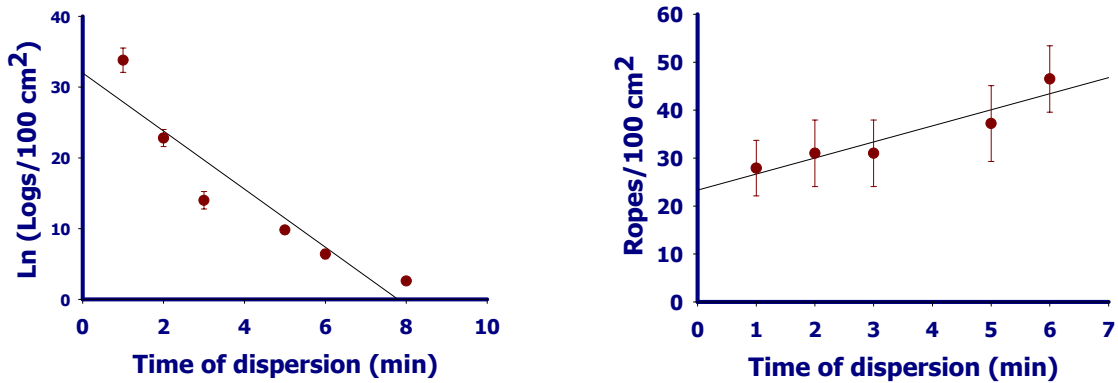
This mixture was allowed to disperse for about 10 minutes and samples were taken after every 5-minute to see the uniformity of the sheet. These samples were again studied for defects. Results are shown in Figure 4.4.



**Figure 4.4 30/70 Glass/Polyester Blend Dispersion**

From the graphs, it can be concluded that the polyester fibers must be added after glass fibers have been dispersed for 10 minutes and this blend must be allowed to stir for 5 minutes. The wet laid sheet thus produced will be a uniformly dispersed sheet. The logs and ropes were also studied in the bicomponent fiber dispersion and the graph obtained is as seen in Figure 4.5.

**100 % Bicomponent Fiber Dispersion      100 % Bicomponent Fiber Dispersion**

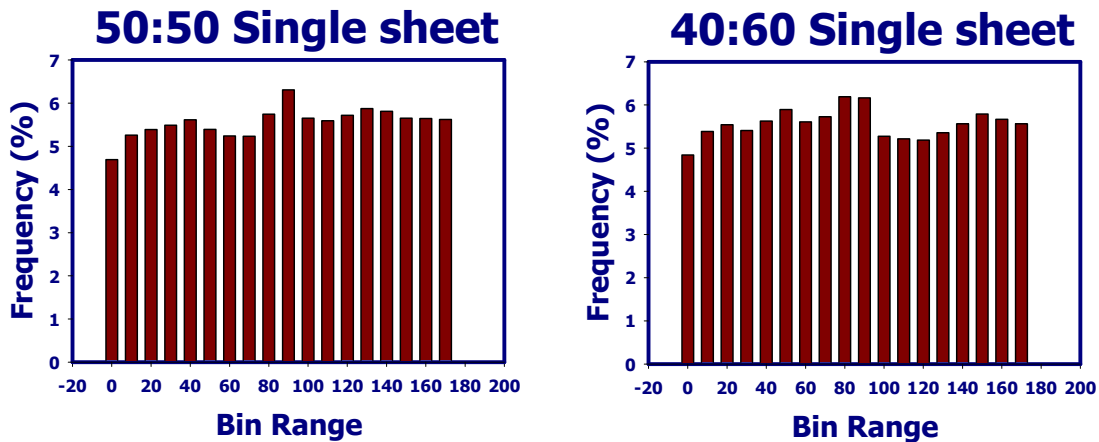


**Figure 4.5 Bicomponent Fiber Dispersion**

Again, the polyethylene sheath polyester core bicomponent fiber follows the same kind of dispersion pattern. It can be seen from the graph that approximately 5 minutes is an optimum time of dispersion for the bicomponent fibers.

**4.2 Orientation Distribution Function (ODF)**

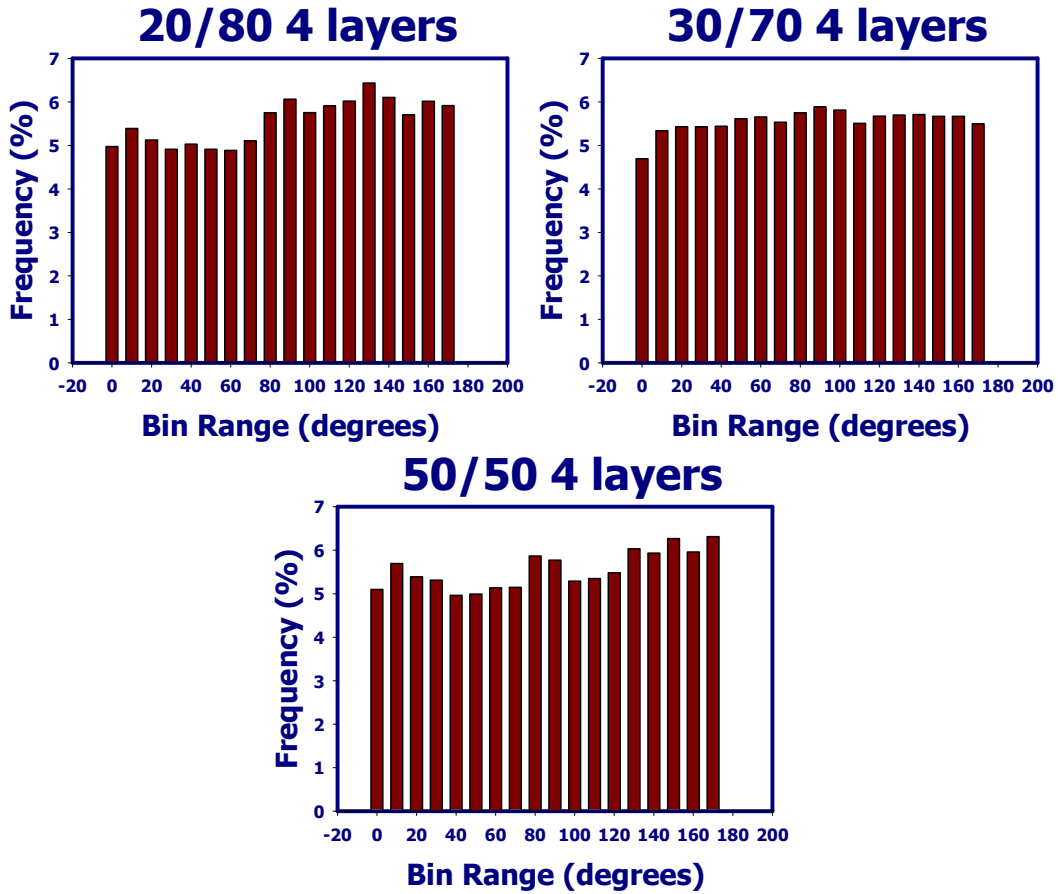
Wet laid sheets were hydroentangled and the hydroentangled sheets were imaged to see the fiber orientation distribution. The ODF was calculated using the LED back lighting system developed by NCRC and disclosed previously <sup>[38]</sup>. The fiber orientation spectra and the graphs for single sheets are shown as under.



**Figure 4.6 Orientation Distribution Function for single layered sheets**

For single sheets, it can be seen that there is almost random distribution in all directions and hence, the sample can be tested in any direction. The same results were obtained for 4 as well as 8 wet laid sheets stacked together and hydroentangled to form a single hydroentangled sheet. Figure 4.7 shows the ODF graphs for the 4-layered sheets.

It can be seen from the graphs that the fibers are uniformly oriented in all directions. However, 30/70 glass/pet shows slightly more orientation in machine direction, but the orientation is not significant. This could be due to some non-uniformity in the fabric. 8-layered samples were also analyzed.



**Figure 4.7 Orientation Distribution Function for 4-layered sheets**

Since the orientation is random in the hydroentangled fabric, it can be concluded that the sample is isotropic and hence behaves isotropically. Moreover, the cosine squared anisotropy parameter was measured for the samples. Figure 4.8 shows the anisotropy parameter values for all the samples tested.

Since all samples have the cosine squared anisotropy parameter value near to zero, it can be concluded that the fibers are randomly orientated in all directions and hence the fabric behaves isotropically.

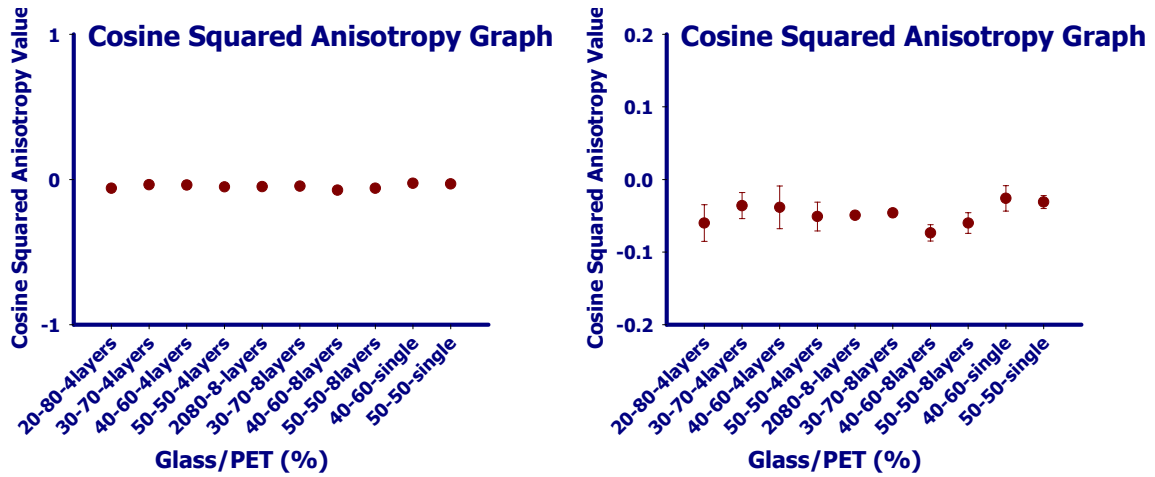


Figure 4.8 Cosine squared anisotropy ratio for Glass/Polyester blend samples

### 4.3 Differential Scanning Calorimeter

The results obtained after testing polyester and bicomponent fibers on the DSC are shown below in Figure 4.9 and Figure 4.10:

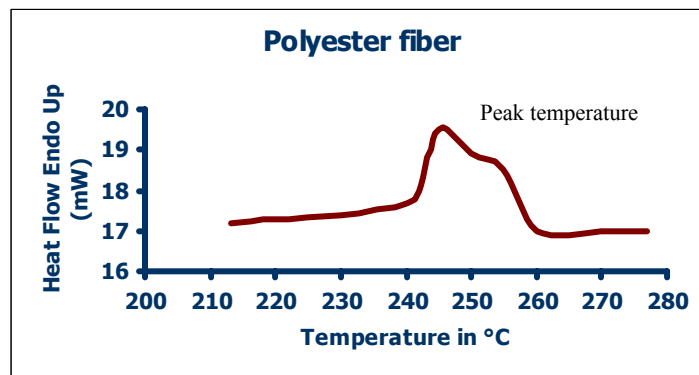
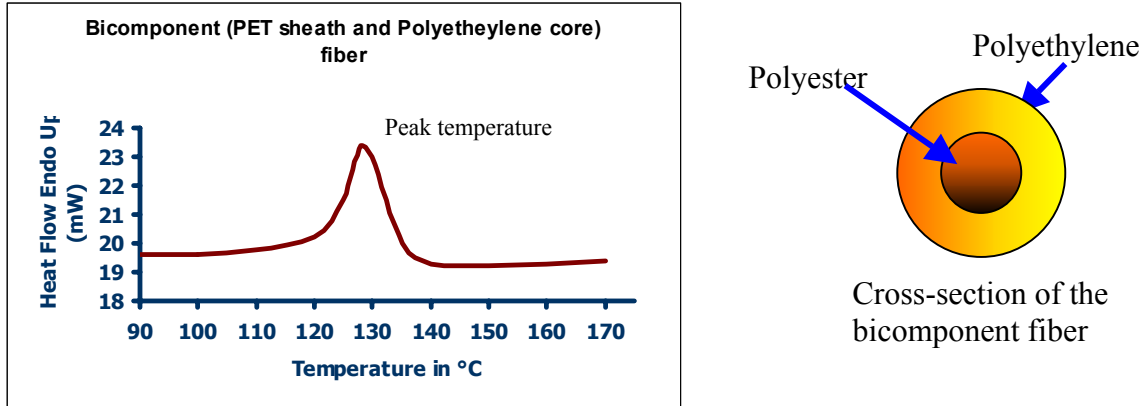


Figure 4.9 DSC results for Polyester fiber



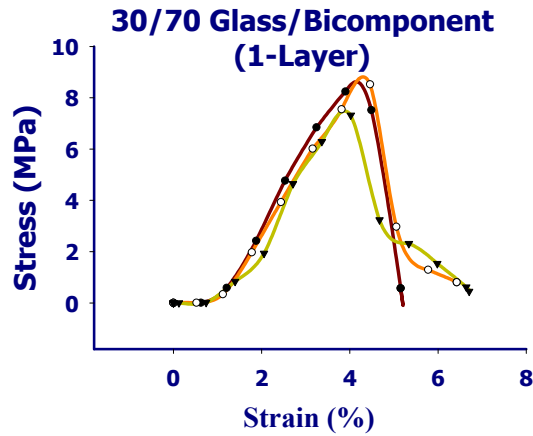
**Figure 4.10 DSC results for Bicomponent fiber**

These results showed that the onset melting temperature of polyester was about 240°C and that for the bicomponent fiber (polyester core and polyethylene sheath) was about 110°C. The peak temperatures for polyester and bicomponent fibers were 245°C and 128°C respectively. The onset temperatures would decide the temperature of the heat plates on the compression-molding machine.

#### **4.4 Tensile Tests**

The effect of the addition of different contents of binder fibers on the tensile properties of binder/glass fiber composite was studied. Figure 4.11 is a stress-strain curve for 30 % glass/ 70 % Bicomponent fiber 1-layered composite.

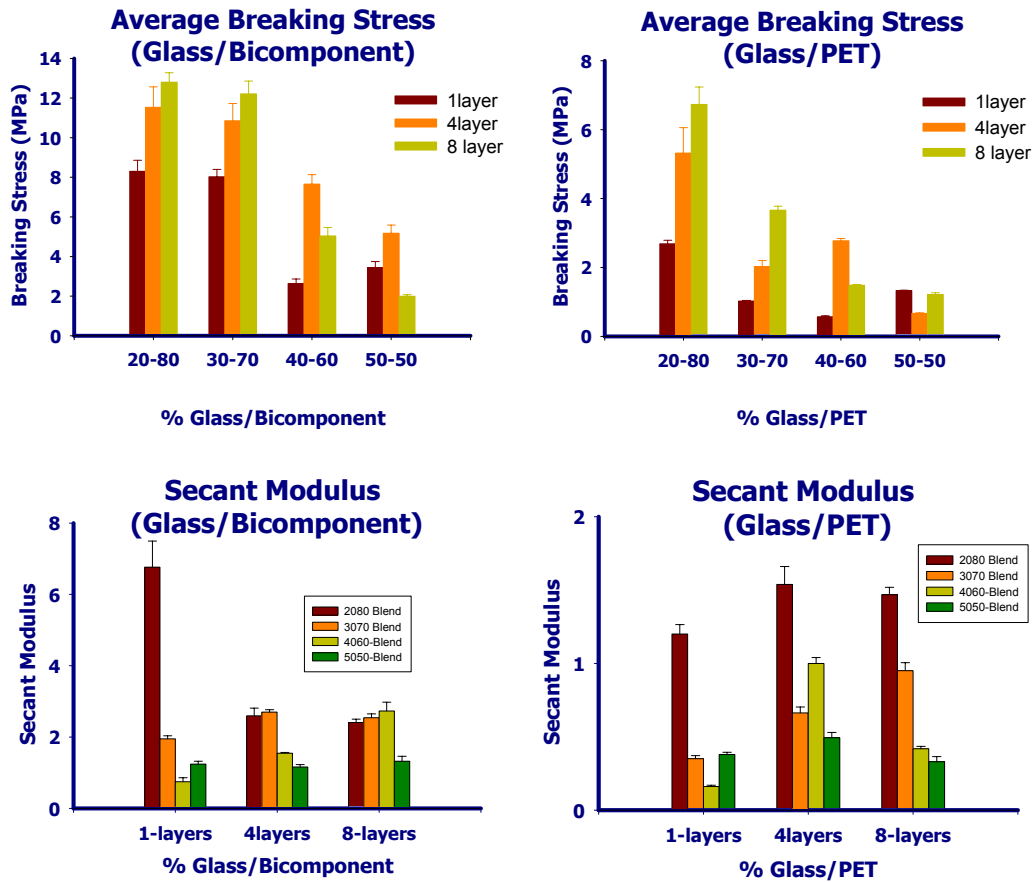
Figure 4.11 shows that all the three tested replicate samples in each case have almost the same tensile strength. Hence the samples are uniform in strength.



**Figure 4.11 Stress strain graph for 30/70 Glass/Bicomponent single layer sample**

Figure 4.12 is a graph showing the average of peak breaking stress for all the layers. It can be seen from the graph that as the number of layers increase, the strength increases. The graph also shows that as the percentage of bicomponent fiber decreases, the strength shows a significant decrease. Reduction in binder fibers apparently leads to less adhesion within the glass fibers, resulting in low strength.

The secant modulus of the Glass/Bicomponent blend was also determined and plotted as shown in Figure 4.12. 20/80-Glass/Bicomponent blends depicted a high value of the secant modulus for each of the 1,4 and 8 layers. Same is the case with 30/70 and 40/60 blends. However, the 50/50 blends showed very low values, the reason being less adhesion of glass fibers with binder fibers.



**Figure 4.12 Average breaking Stress and Secant modulus for glass/pet and Glass/Bicomponent samples**

For each stress-strain graph, the area under the curve was calculated. The area under the curve signifies the toughness of the material. Figure 4.13 shows the average result of area under the curve (toughness) of each sample for glass/bicomponent and glass/polyester blend.

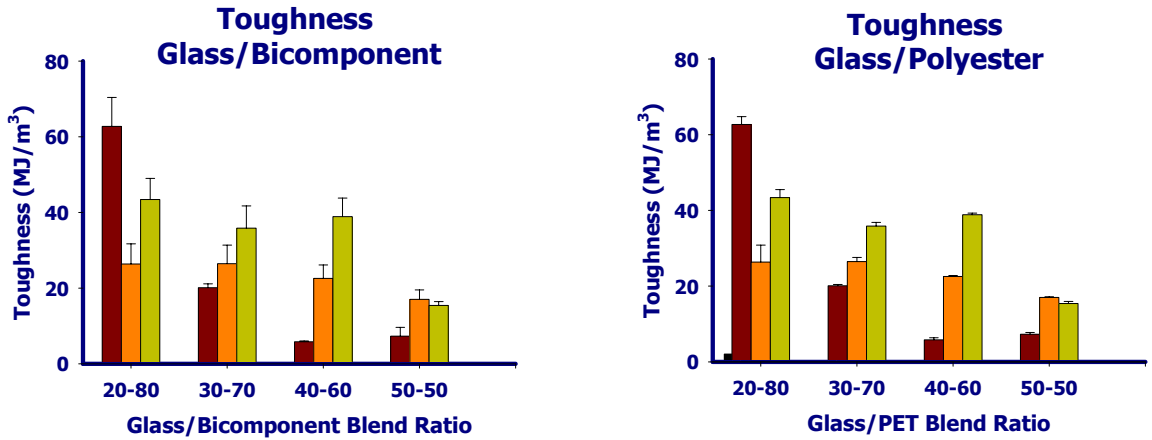


Figure 4.13 Toughness for Glass/Bicomponent and Glass/Polyester samples

An analysis of these graphs gives us the same conclusion as the breaking stress graphs. The toughness increases with an increase in the number of layers, while it reduces with reduction in the binder fiber (polyester or bicomponent fiber) content.

#### 4.5 4-Point Bending Test

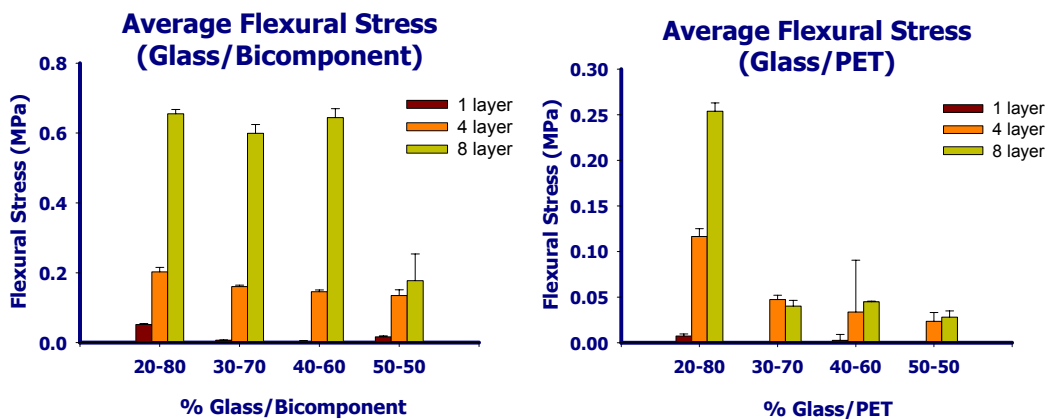
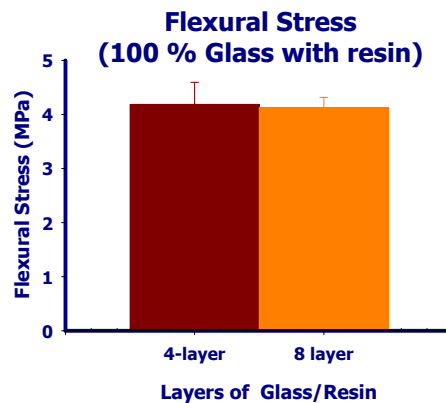


Figure 4.14 Average flexural stress for glass/bicomponent and glass/polyester samples

The consequence of amount of binder fiber on the bending rigidity of material was studied by the 4-point bending test. The average flexural strength of the glass/bicomponent, glass/polyester and glass/resin blend is obtained through this test.



**Figure 4.15 Average flexural stress for glass / resin samples**

As seen from Figure 4.14 and Figure 4.15, the bending rigidity increases with the increase in number of layers of the composite. Also, the resin samples show considerably more strength (4 MPa) when compared to glass/binder fiber blends (strength < 1 MPa). Within the binder fibers, the glass/bicomponent blend shows high values (0.6 MPa) of flexural stress than the glass/polyester samples (0.25 MPa). It is also seen from Figure 4.14 that decreasing the amount of binder fibers decreases bending strength.

# CHAPTER V

## CONCLUSIONS AND FUTURE WORK

### Conclusions

- Strength increases with increasing glass fiber content up to 30-40%, after which the strength of the composite starts reducing.
- Combining more layers of wet laid sheets and hydroentangle them together to make a single hydroentangled sheet improves tensile strength. This behavior is seen in each 20/80 and 30/70 glass/bicomponent 4 and 8 layered sheets.
- The advantage of the wetlay process is that it is possible to achieve a homogenous aqueous dispersion of the reinforcing fiber and the polymer resin fiber. From ODF results it can be seen that the fibers are almost randomly distributed in the hydroentangled sheet and hence the tensile test results are convincing.
- Fiber-reinforced thermoplastic sheets are typically lighter in weight than traditional materials like steel or SMC sheets.
- Fiberglass being cheap and keeping in mind the high production of nonwoven glass: binder fiber mats, polyester/fiberglass or bicomponent (PE/PET sheath core) / fiberglass composites appear to be a promising product design opportunity.

### Future Work

As a future work to this research, different kinds of binder fibers, apart from polyester and bicomponent fibers can be mixed with glass fibers and the composites formed can be analyzed. Different length glass fibers can also be used along with blending of different

(smaller) diameter glass, glass with curl/crimp and different surface finish and make a composite from them. Different surface finish would affect the frictional properties within the blend of fibers. Also, binder powder impregnated glass fiber composites can be manufactured and their properties compared with the composites made in this research.

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# **APPENDICES**

# APPENDIX A

## METHODS OF COMPOSITE FABRICATION

<http://www.netcomposites.com/>

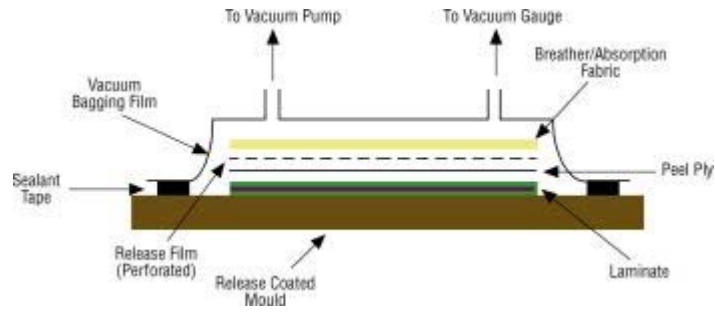


Figure A.1 Vacuum Bagging

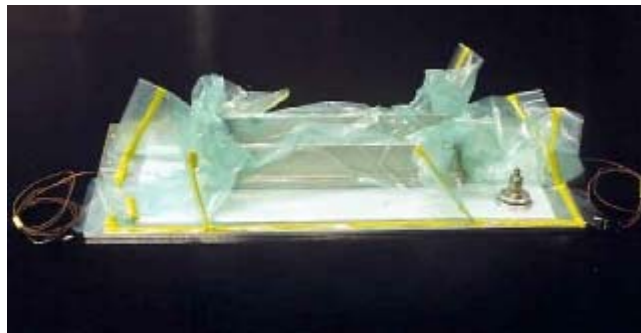


Figure A.2 Vacuum Bagging

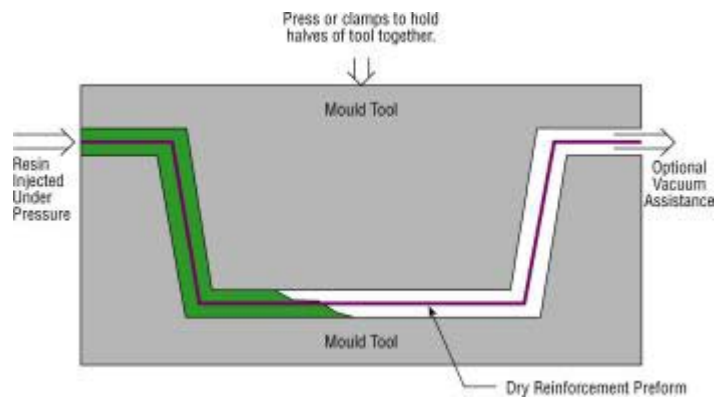


Figure A.3 Resin Transfer Molding

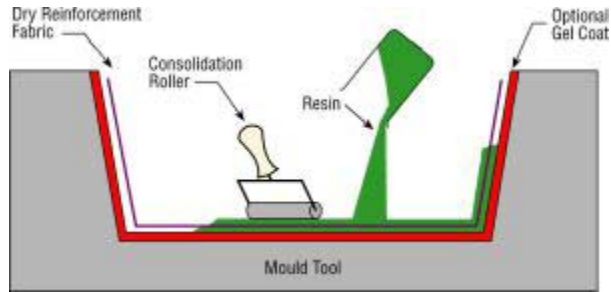


Figure A.4 Hand Lay-up

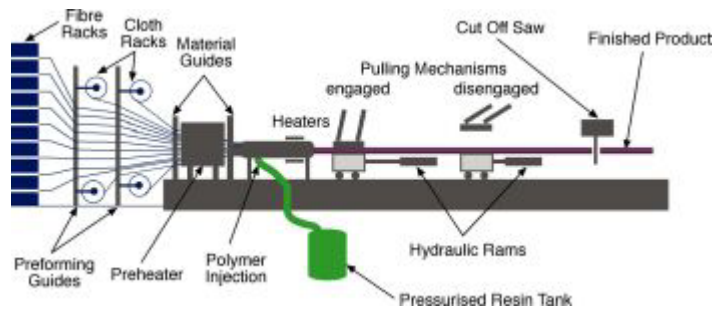


Figure A.5 Pultrusion

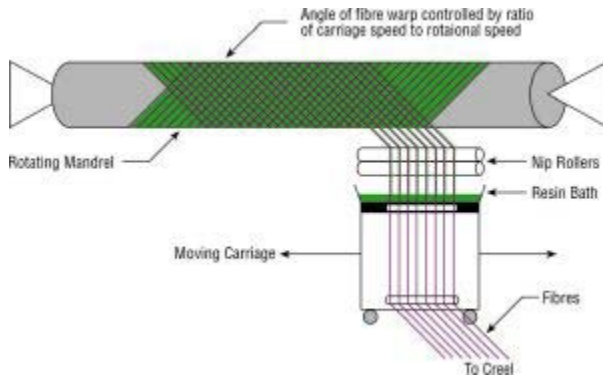


Figure A.6 Filament Winding

## APPENDIX B

### HELICOPTER ROTOR BLADE<sup>[29]</sup>

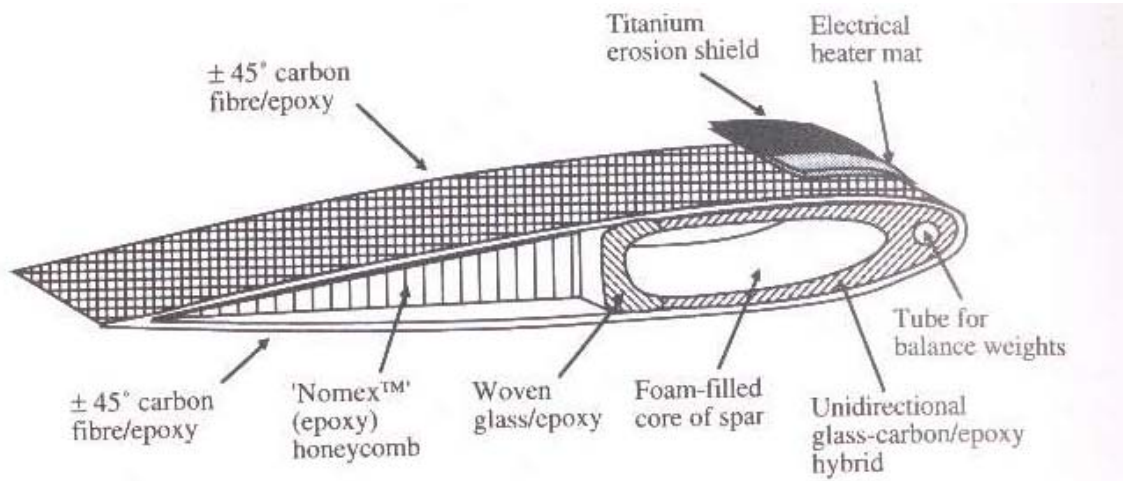


Fig. 12.4 Schematic section through a typical composite construction for a helicopter rotor blade. (Courtesy of Westland Helicopters.)

Figure B.1 Helicopter Rotor Blade