The Influence of Fiber Hybridisation on Dynamic Mechanical Behavior of Natural Based Composites

Jie Cheng

Master of Engineering

Mechanical Engineering

Victoria University of Technology

2000

The Influence of Fiber Hybridisation on Dynamic Mechanical Behavior of Natural Based Composites

Jie Cheng

A thesis submitted to Victoria University of Technology for the degree
of Master of Engineering by Research in Mechanical Engineering

2000

Declaration

The thesis contains no material which has been accepted for the award of any other degree or diploma in any university or institution. It contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

Jie Cheng

March 1998

Acknowledgments

There are many people who I would like to thank for their willing and cheerful help, without whom I could not have completed this work.

My thanks to my supervisors; Dr. Mark Hodge, Dr. Ozden Turan and Dr. Benjamin Tobias for their valuable guidance and helpful suggestions throughout the period of my candidature. I consider myself to have been extremely lucky to have had such diligent and expert supervisors.

Sincere thanks also to Mr. Vincent Rouillard, with whom it has been a pleasure to work, and who helped me with the operation of Instron Model 8500 Testing System.

Special thanks go to my colleagues David Ip and Vu Nguyen for their constructive advice in fabrication and testing of composite materials, for their concern and assistance on this work.

Finally, for their encouragement, for their constant support and for their contribution, my love and gratitude go to my wife, Qiwen Xu, and my family. It is to them that I dedicate this thesis.

Abstract

The relatively higher costs of synthetic fibres (glass, carbon, kevlar fibre) used in fibre reinforced composite materials make it desirable to investigate natural fibres as a source of possible reinforcement in low-cost applications. Natural fibres are abundant and represent a significant cost reduction compared to wholly synthetic composite materials. It is possible to make hybrid natural and synthetic fibre reinforced composites by using fewer amounts of expensive reinforcements with larger amounts of natural fibres, thereby reducing the cost of the material.

Hybrid synthetic and natural fibre composite materials are attractive structural materials because of natural fibres' resource and lower cost. Their advancement is a relatively young and dynamic one. Composites manufactured with these fibres have specific advantages compared with conventional composites for low cost industry applications.

There is growing interest in the development of hybrid fibre composites, which enhances optimal utilization of natural fibre resources. This work presents a detailed investigation of the dynamic and static mechanical properties of hybrid natural and synthetic fibre composites observed over a range of glass fibre and banana fibre contents.

This thesis describes the methods used in composite fabrication and material characterization. The techniques and principles employed in the fabrication of hybrid banana fibre and glass fibre reinforced composite materials are reported. The principles of composite design and other research relevant to hybrid fibre composite materials are critically reviewed.

Dynamic and static mechanical properties were tested under both dry and wet conditions. The effect of hybrid fibre contents and glass/banana fibre volume fractions has been investigated. The moisture effect is an important aspect of this work, because natural fibres are very hygroscopic. This work indicates the variation of dynamic and static properties in these materials in response to water absorption.

The results indicate that banana fibre can be used as reinforcement in polyester composites combined with glass fibre for a specific application, such as providing an inexpensive building material. Although these hybrid composites have lower strength compared to all-glass fibre composites, the material cost and weight are reduced, thereby enhancing the usefulness of these materials in developing countries and regions requiring rapid erection of dwellings, such as areas affected by natural disasters. The use of low modulus and low cost matrix materials such as polyester and the addition of natural fibres produces hybrid composites, maintaining flexibility, lightness and ease of fabrication of complicated shapes with reasonable economy.

Based on the investigations contained herein, it is expected that these composites could find suitable applications in the following areas:

- Low cost housing,
- Emergency shelter materials following natural disasters,
- Packaging for transportation purposes,
- Manufacturing of consumable goods.

Table of Contents

List of Tables

List of Figures

Chapter 1

Introductory Remarks

1.1 BACKGROUND INFORMATION TO THE INVESTIGATION

Fibres probably represent the most important class of reinforcement for composite materials, due to their ability to transfer strength to matrix materials and greatly influence the properties of composites. Many types of fibres are combined with metal, resin and ceramic matrices to form useful fibre reinforced composite materials. Fibre reinforced composites are produced from a wide range of constituents and have evoked a lot of interest among engineers concerned with various applications such as aerospace and automotive.

Fibres are usually classified as either natural or synthetic fibres. Natural fibres are further divided into vegetable, animal, or mineral origin and exist in reasonably large quantities all over the world. In particular, they are abundantly available in developing countries, but are not usually optimally utilized. Due to their relative abundance and ease of handling and processing, natural fibres show considerable potential as a valuable source of raw material for use as reinforcement for low-cost composite materials in developing countries and elsewhere throughout the world.

Currently, there is growing interest in the development of new materials, particularly renewable resources that facilitate utilization of natural materials. Natural fibres such as bamboo, jute, banana, abaca, coir and sisal belong to this category. Although natural fibres generally have poor mechanical properties compared with the synthetic fibres currently available, they have the advantages of low density, low cost and low energy demand during manufacture.

Natural fibres have been employed in various applications and have been used in the cordage industry for a long time. Natural fibre reinforced cement composite materials have also been made for low cost construction materials. *Al-Qureshi (1997)* presented the development and manufacture of automotive body skins of jute fabric reinforced composite, and hybrid composites made from jute/fibre glass composite panels.

According to American Society for Testing Materials (ASTM) standard D123-52, banana fibre is classified as leaf fibre of natural vegetable fibre. Actually, it has also been used for composite materials and packaging materials as a valuable source of raw material. *Satyanarayana et al. (1990)* reported that banana fibres incorporated in a low-modulus matrix such as polyester would yield materials with properties adequate for incorporation into specialized building construction materials.

Glass fibre is a typical synthetic inorganic fibre whose wide use as reinforcement in applications ranging from fishing rods to storage tanks and aircraft parts is well known. At present, the most important grades of glass are:

1. **E-glass**, named for its electrical properties. E-glass has a low alkali content and is the most common glass fibre on the market, as well as being the most widely used in the construction industry. E-glass is now widely used with polyester and epoxy resins for fibre reinforced composites.

2. **S-glass**, a stronger and stiffer fibre than E-glass, was originally developed for military applications. It is not widely used outside the military and other related specialty industries (e.g. aviation, automotive) because of its higher cost.
3. **R-glass**, a civil version of the S-glass fibre, is used for high technology application.
4. **C-glass** is a special mixture used for chemical resistance, mainly against acid attack.

Hybrid fibre reinforced composites are attractive structural materials and their advancement is a relatively young and dynamic one. Hybrid fibre composites contain more than one class of fibre. Fibre hybridization presents new opportunities for tailoring the composite material to specific cost-effective applications and achieving properties that cannot be realized in one single class of fibre reinforced composites. In the development of hybrid fibre reinforced composite materials, one of the major problems that needs to be addressed is reduction in cost of expensive composites with reinforcement by incorporating a proportion of cheaper fibre. The use of a low cost matrix material such as polyester, and the hybridization of natural fibres and synthetic fibres produce hybrid fibre reinforced composites with appreciable lightness and ease of fabrication of complicated shapes. The hybrid composites have significant economical advantages over wholly synthetic composite materials.

Fibre-reinforced composite materials are being increasingly employed to manufacture structural components which are designed to be used successfully in dynamic environments under various temperatures in many diverse industries, such as the aerospace, transportation and sporting goods industries. As these engineering applications further diversify, the necessity for experimental data and analysis of the proposed design methodologies becomes more important. This is especially so when composite materials are subjected to dynamic mechanical loading under changing ambient conditions. When the temperature and moisture change, so does the dynamic mechanical behavior of the structural component fabricated by a composite material. The dynamic mechanical properties have a major influence on the response of the material and the structural integrity of the component.

1.2 SCOPE OF THE PRESENT WORK

In this study, banana fibres are used in conjunction with glass fibres in a polyester resin matrix to produce a series of hybrid fibre-reinforced composite materials. As the hybrid of natural and synthetic fibres, a reinforced composite material has been developed and characterized. Through the use of a hybrid natural/synthetic fibre system, it is possible to achieve significant savings in terms of weight and cost while improving mechanical properties for a specific application such as cheap building material in developing tropical countries.

The main aim of this study has been to develop and characterize a hybrid natural and synthetic fibre reinforcement composite lamina. The specific objectives are as follows:

1. To develop a design procedure to manufacture hybrid natural and synthetic fibre composites.
2. To fabricate laboratory scale hybrid fibre composite laminates with random fibre orientation.
3. To determine the bulk effect of water absorption in each laminae group.
4. To investigate possible mechanical behavior in both dry and wet conditions under time/temperature dependent functions as predicted by dynamic mechanical analysis.

5. To investigate static strength and thereby determine the rigidity of hybrid fibre composite laminae.
6. To monitor the influence of glass fibre and banana fibre volume fraction on the properties of laminae.

1.3 LAYOUT OF THESIS

It is the intention of this work to describe the properties of banana fibres, glass fibres and fibre reinforced composite materials, the methods of manufacturing hybrid banana and glass fibre reinforced composite materials, and the dynamic mechanical properties of these hybrid composite materials.

The scientific literature on fibre reinforced composite materials is reviewed in Chapter 2, including an introduction to current applications of banana fibre and glass fibre reinforced composites. An overview on the aspects of composite manufacture and composite testing is also presented.

Chapter 3 focuses on the fabrication and experimentation of banana fibre and glass fibre hybrid composites. A design procedure is developed to manufacture different fibre volume fractions. Water absorption is also considered due to moisture absorption encountered in tropical regions. The composite experimental investigations are carried out under both dry and wet conditions.

The dynamic mechanical analysis with 10%, 25% and 40% hybrid fibre content is given in Chapter 4. These data illustrate the variation in flexural storage modulus and loss tangent of hybrid composites with temperature in both dry and wet conditions. The effect of hybrid fibre contents and banana and glass fibre volume fractions is presented. With water absorption, it has been found that the effects of interfacial bond strength between fibres and matrix dominates over the gain in fibre properties. The static mechanical properties are also included in Chapter 4.

Conclusions are drawn and recommendations are made for future work in Chapter 5 and Chapter 6, respectively.

Chapter 2

Literature Review

2.1 STRUCTURE AND PROPERTIES OF FIBRES

Fibres are the major constituent in a fibre – reinforced composite material in terms of volume fraction and load-bearing capacity. In structural applications, fibres occupy large volume fractions in a composite laminate and share the major portion of the load on a composite structure. According to commercial and domestic use, fibres are broadly classified as natural fibres and synthetic (man-made) fibres. Natural fibres are plant, animal or mineral products. It is interesting to note that natural fibres such as jute, coir, banana, sisal, etc, are abundantly available in developing countries like India, Sri Lanka and some of the African and Southeast Asian countries. Traditionally, these fibres are used in a conventional manner for the production of yarn, ropes, mats and matting, as well as in making pattern articles like wall hangings, table mats, handbags and purses. Fibres such as cotton, banana and pineapple are also used in making cloth in addition to being used in the paper industry.

In the last fifty years, however, synthetic fibres, the macromolecular structure of which is made up of relatively simple compounds, rapidly found industrial uses and challenged natural fibres. A whole new range of synthetic fibres has been developed. The classification of fibres is shown in Figure 2.1.

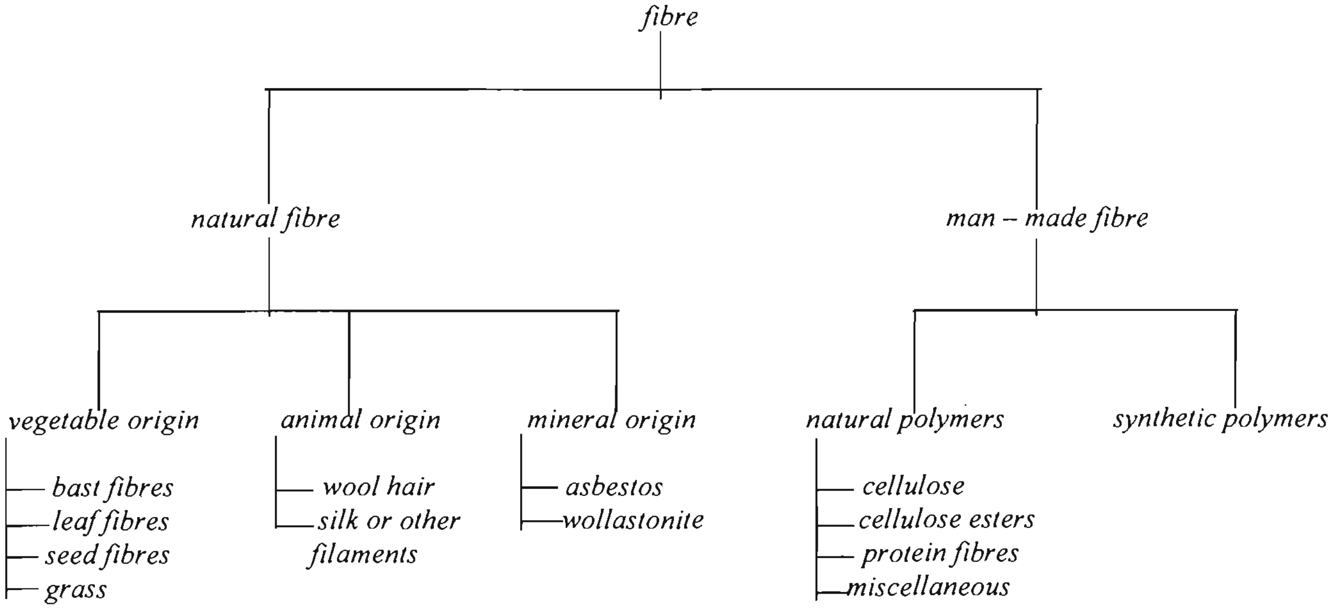


Figure 2.1 The classification of fibres (after *Fordos 1988).*

2.1.1 BANANA FIBRE

Banana plants are now found in most tropical regions. In Australia, they are extensively grown in Queensland and northern New South Wales. As indicated by *Mickels (1990)*, the banana plant has a tree-like appearance and a trunk-like stalk, although it contains no woody material and can grow from 3.0 *m* to 9.0 *m*. The stalk, which ranges in diameter from 200 *mm* to 370 *mm*, consists of layers of overlapping leafstalk surrounding a hollow core. At the end of each stalk is a dark-green oblong leaf, measuring about 3600 *mm* by 600 *mm*. The stalk contains long multi-celled fibres extending length-wise through the pulpy tissues of long leaves or leaf-stems.

Banana fibres are obtained from the pseudo stem of the banana plant. The pseudo stem is called stalk, and is surrounded and supported by leaf sheaths which contain many fibres. A normal stalk is 1.8 *m* to 3.0 *m* long and 0.2 *m* to 0.3 *m* wide, and each leaf contains fibres in the outer layers. The processes of obtaining banana fibre typically involve manual or mechanical scraping.

2.1.1.1 Composition and structure of the banana fibre

According to the American Society for Testing Materials (ASTM) Standard D123-52, banana fibres are still classified as leaf fibre of natural vegetable fibre, even though they are extracted from pseudo stem. Under close examination, the banana stalk reveals fibres extending longitudinally along the entire length of the leaf, reinforcing the leaf structure and keeping it rigid. The fibres are embedded in the pulp tissue of the leaf and are distributed throughout the leaf cross section.

According to *Himmelfarb (1957),* Banana fibres are multiple-celled structures. The long fibre is composed of a bundle of fine hair-like fibres (fibrils) cemented together with the natural gummy materials of the plant tissue. Each fibril, in turn, is made up of a number of cells, which may appear as tubes of irregular polygonal cross section with enclosed pointed ends when greatly magnified. These cells lie side-by-side with overlapping ends and are cemented together to make up the long fibril. A hollow canal in the center of the cell is called the lumen, which is the space previously occupied by the protoplasmic material forming the cell. The cell represents the ultimate in division of the fibre. Four types of cells have been found, namely, xylem, phloem, Sclerenchyma and parenchyma arranged in a particular fashion *(Kulkarni et al. 1983).*

Generally, the fibres are composed of carbohydrate cellulose with the associated gummy binding and encrusting materials. The gummy binding materials, designated the pectic substances, are associated with the fats and waxes inherent to the plant. The woody tissue contains the lignin. The cell is primarily cellulose and the related carbohydrate xylan. There is a little inherent mineral matter related to the plant growth. The typical chemical analysis of banana fibres is shown in Table 2.1. However, it should be mentioned that this analysis of a fibre varies with the source and grade of the fibre. From Table 2.1, it can be seen that the banana fibres are moderately hygroscopic.

Table 2.1 Major chemical constituents of the banana fibre *(Satyanarayana et al. 1986).*

Constituents	**Percentage**
Cellulose (%)	63 – 64
Lignin (%)	5
Hemicellulose (%)	19
Moisture content (%)	10 – 11
Ash (%)	1.02

2.1.1.2 Physical and mechanical properties of the banana fibre

Normally, banana fibres have a natural white color and bright lustre and are finer than sisal fibre when properly extracted and dried. Some physical properties of banana fibre, such as the observed density, range of diameter, elongation and cell dimensions are listed in Table 2.2.

Table 2.2 Physical properties of banana fibres *(Satyanarayana et al. 1986).*

Properties	
Density (kg/m^3)	1350
Elongation (%)	1.8-3.5
Apparent density	0.62
Cell width or diameter (μm)	12-30
Cell length (mm)	2.0- 4.8
Cell length to diameter ratio	150
Size of cell wall (μm)	1.25
Fibre porosity (%)	35-53

Figure 2.2, from *Kulkarni et al. (1983)* shows a typical stress-strain curve for banana fibre. Figure 2.3, from *Satyanarayana et al. (1990)* shows stress-strain curves for some of the natural fibres compared with banana fibre.

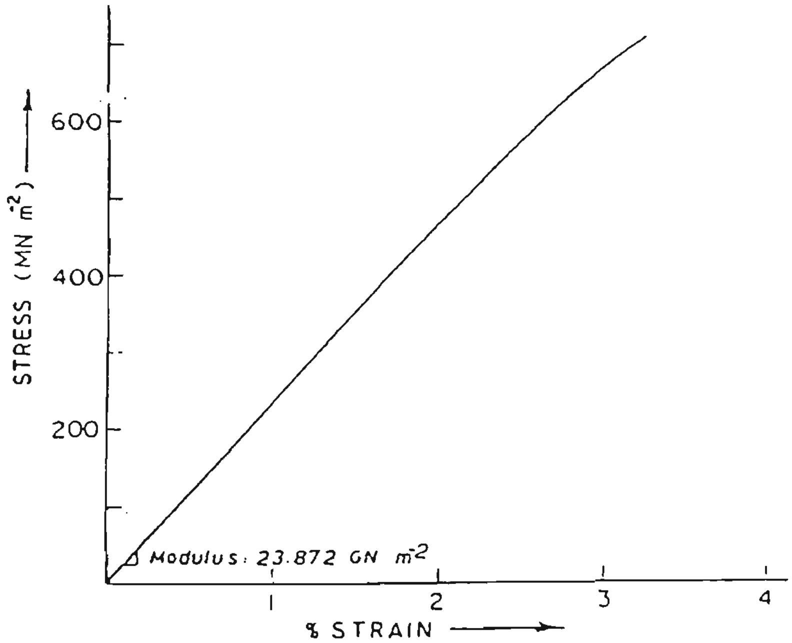


Figure 2.2 Stress-strain relationship of banana fibre *(Kulkarni et al. 1983).*

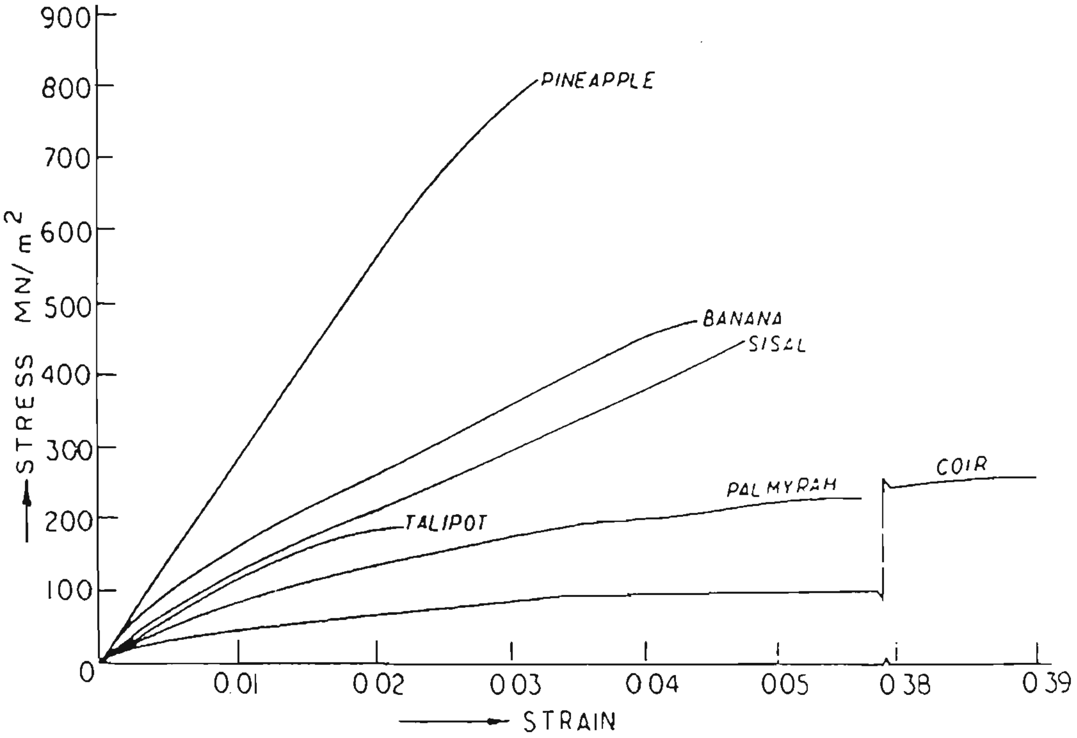


Figure 2.3 Stress – strain curves of other natural fibres *(Satyanarayana et al. 1990).*

Satyanarayana et al. (1984) reported that the strength of banana fibre varies along the stem. Fibres in the lowest portions of the stalk are strongest and the strength decreases with increasing height. Also the fibre, if aged for a short period, gains strength to the extent of 1.05-1.10 times the original strength. When dried at 100°*C* for 2 days or to 70°*C* for 20 days, the fibres exhibited a decrease in stiffness and strength, along with evidence of mechanical embrittlement as the water content in the fibres decreased. Although somewhat counter-intuitive, this data indicates that the hygroscopic nature of the banana fibre is critical to its mechanical performance, as the fibre is stiffened to some degree by water absorption. X-ray analysis shows that banana fibre has a high degree of crystallinity with good alignment of crystallites parallel to the fibre axis. It is proposed that increased water content may enhance molecular mobility to the point where some molecular alignment is possible in the amorphous regions of the fibres, thereby enhancing the physical properties as observed. Some of the mechanical properties of banana fibre are shown in Table 2.3.

Table 2.3 Mechanical properties of banana fibres *(Satyanarayana et al. 1986).*

Initial modulus (GN/m^2)	20-51
Ultimate tensile strength (MPa)	520-750
Torsional rigidity (GN/m^2)	0.3-1.2
Flexural rigidity (N/m^2)	2-5

2.1.2 GLASS FIBRE

Glass fibres are probably the most common of all reinforcing fibres for polymeric matrix composites. The major type of glass fibre is E-glass, which is a borosilicate glass with a little alkali present in its composition. E-glass represents one of the lowest costs of all commercially available reinforcing synthetic fibres, which is the major reason for its widespread use in the fibre-reinforced composites industry.

In general, the principal advantages of glass fibres include high tensile strength, high chemical resistance and good insulating characteristics. On the other hand, the disadvantages are low modulus compared to other high performance fibres such as carbon and kevlar fibres, relatively high specific gravity (among the commercial fibres), high cost (compared to natural fibres), sensitivity to abrasion with handling which frequently decreases tensile strength, low fatigue resistance and high hardness.

2.1.2.1 The composition of glass fibre

Glass fibres are amorphous (noncrystalline) materials. Their internal structure consists of a three dimensional long network of silicon, oxygen, and other atoms arranged in a random fashion. They have no distinctive micro structure. The principal constituent in all glass fibres is silica (SiO_2). Other oxides, such as B_2O_3 and Al_2O_3, are added to modify the network structure of SiO_2 as well as to improve its workability *(Matthews and Rawlings 1994).*

The E-glass is named because of its electrical properties. It is based on the eutectic in the ternary system CaO - Al_2O_3 - SiO_2 with some B_2O_3 substituting for SiO_2 and some MgO for CaO. The main chemical composition of E-glass and S-glass is shown in Table 2.4.

Table 2.4 Typical chemical composition of E-glass and S-glass *(Matthews and Rawlings 1994).*

Glass fibre type	**Oxides in weight fraction (%)**				
	SiO_2	Al_2O_3	CaO	B_2O_3	MgO
E-glass	54	14	18	9	5
S-glass	65	25	-	-	10

2.1.2.2 Common forms of glass fibres

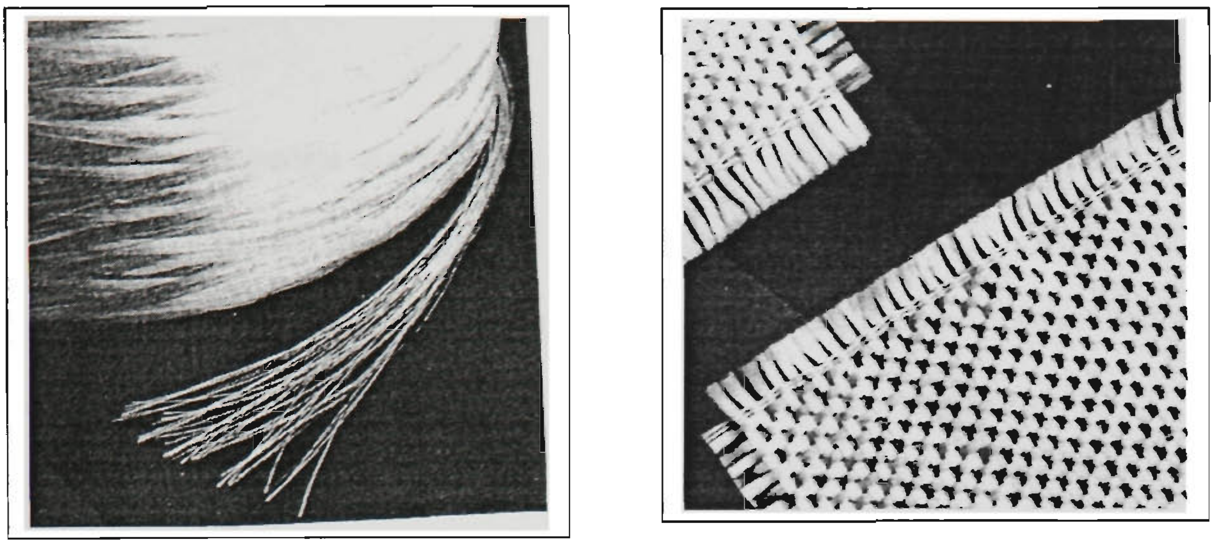
The basic commercial form of continuous glass fibres is a strand, or collection of individual fibres also known as a tow. The strands may be brought together to form an untwisted bundle of fibres called a roving. Both strands and roving can be woven into a variety of cloths.

The roving may be chopped into strands or into strand mats, which form random arrays of fibres. The common forms of glass fibres include continuous strand roving, chopped strands, chopped strand mat, woven roving and woven roving mat *(Mallick 1988)*. Figure 2.4 shows the common forms of glass fibres.

Chopped strands are formed by cutting continuous strands into short lengths. Their length ranges from 3.2 *mm* to 12.7 *mm*. Chopped strand mat is manufactured from chopped strands, which are bonded together in a randomly oriented two-dimensional manner. The strand mat is normally 50mm in length. This type of reinforcement is considerably cheaper than woven fabric when measured on a weight basis and is typically used as a reinforcing material in a laminate by itself or in conjunction with a woven fabric. Chopped strands are often used in injection molding operations.

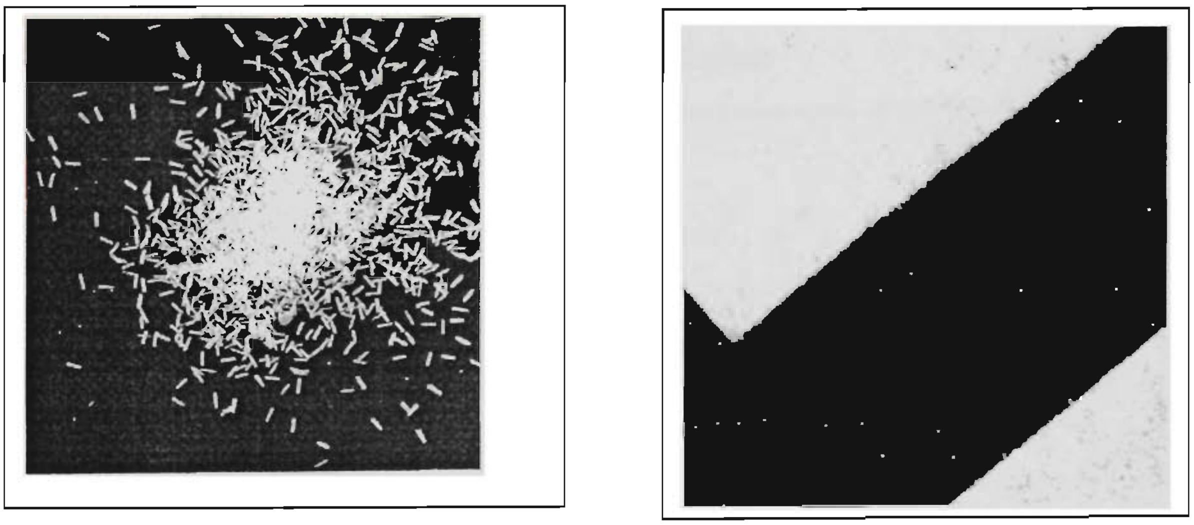
Glass fibres are also available in woven form. Woven roving is a coarse fabric and used in moulding and laminates to produce highly directional strength characteristics. A layer of woven roving is sometimes bonded with a layer of chopped strand mat to produce a woven roving mat *(Mallick 1988)*. The woven forms are suitable for hand lay-up moldings.

All forms of glass fibre must have a surface treatment called a “sizing”, which enhances the surface properties of the glass, allowing them to bond to a matrix material in composite applications and allowing relatively easy movement across one another without adverse mechanical damage or other adverse effects, such as static charge buildup and entanglements. It is very important to choose the correct sizing from both processing and mechanical performance points of view.



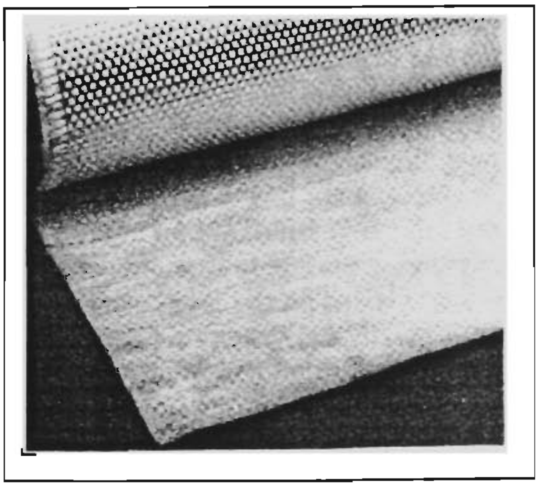
Continuous strand roving

Woven roving mat



Chopped strands

chopped strand mat



Woven roving

Figure 2.4: The common forms of glass fibres *(Mallick 1988).*

2.1.2.3 General properties of glass fibres

Glass fibre properties are not strongly dependent on the chemical composition of fibre. The mechanical properties are isotropic. Processing parameters during fibre forming have a significant effect on fibre properties. Furthermore, fibres of the same composition and same diameter but made under different forming conditions show differences in properties. Table 2.5 shows some properties of the E-glass fibre and S-glass fibre.

Table 2.5 Typical properties of E-glass and S-glass *(Potter 1997 and Mallick 1988).*

Properties	**E-glass**	**S-glass**
Diameter (μm)	7	7
Specific gravity	2.54	2.49
Tensile modulus (GPa)	70	88
Tensile strength (GPa)	1.7	4.6
Strain to failure (%)	2.2	5.2
Density (g/cm^3)	2.56	2.49

2.2 FIBRE REINFORCED COMPOSITE MATERIALS

In engineering practice, the modern composite materials have had a significant impact on the technology of design and construction. It is a common principle that two or more components may be combined together to be tailor-made advanced composite materials, which are lighter, stiffer and stronger than any other structural material that may otherwise have been used. According to the different constituent forms, composite materials may be classified into the following five types *(Bunsell 1988)*:

- *fibre-reinforced composites*: composed of continuous or chopped fibres,
- *particulate composites* : composed of particles dispersed in a matrix. The particles are distinguished from the filamentary type, and may be round, square or even triangular, but the side dimensions are approximately equal. Ceramic and metal composites that are made up of particles with one phase dispersed in the other phase are known as particle reinforced composites. The material properties are dependant on not only the constituent, but also the interfacial properties and geometric shapes of the array.
- *flake composites* : composed of flat flakes, or platelets. Flakes can be more tightly packed than other type composites. Metal flakes touching each other in a polymer matrix can conduct heat or electricity. In some cases, flakes are easier and less expensive to produce than fibres. However, flakes may be difficult to line up parallel to one another in a matrix resulting in uneven strength and other properties. The disadvantages of flake composites are the quality control of the sizes, shape and distribution flaws in the final product. Aluminum flake composites are used in metallic automobile paints to provide decorative color effects and various degrees of transparency. Glass flakes are applied to printed circuit boards for computers *(Agarwal and Broutman 1980).*
- *filled composites*: filler materials are added to a plastic matrix to replace part of the matrix or to add to or to change the overall properties of the composite. In some cases, the fillers actually offer an increased strength of the composite, a reduction in weight and the quantity of plastic used. However, fillers also have disadvantages, and may

limit the method of fabrication or inhibit curing of certain resins.

- *laminar composites*: composed of two or more layers or lamina constituents held together by the matrix binder. There are as many possible laminar composites as there are combinations of materials, such as metal/metal, metal/plastic, metal/ceramic laminates etc. At present, the greatest emphasis is on structural laminates or laminates with useful mechanical properties *(ASM 1990)*.

Within the above classification of composites, one of the most important of the composite material types cited from an application point of view is fibre-reinforced composites. Although fibre-reinforced composites have been used only for a relatively short period of time among the modern structural materials, there has been a dramatic advancement in the technology of fibre composites. Fibre composites have evoked the most interest among engineers concerned with structural applications. It has been pointed out by *Tobias (1987)*, that synthetic fibres play an important role in the development of new composite materials.

In fibre-reinforced materials, high strength fibres are surrounded by a relatively weak matrix. The functions of the matrix are to bond the fibres together, to transfer the load from one fibre to another and to protect them from damage. Thus, the fracture toughness properties of fibre reinforced materials are enormously affected by interfacial bonding between matrix and fibres. Fibre composites which have a weak interface have low strength and stiffness but have high resistance to fracture. On the other hand, fibre composites which have strong interface have high strength and stiffness but are very brittle. The most important fibre parameters are diameter, length, volume fraction and alignment.

According to the fibre placement in different directions, the fibre composites may be classified into the following four types *(Gibson 1994)*:

- *Continuous fibre composites:* The fibre may be arranged either in a unidirectional orientation or in a multi axial orientation. A laminate formed by continuous fibres has the highest strength and modulus in the longitudinal direction of the fibres, but in the transverse direction, its strength and modulus are relatively low.
- *Woven fibre composites:* The delamination or separation of the laminates is still a major problem due to the fibres not being so straight as in the continuous fibre laminate. Hence, strength and stiffness are sacrificed. However, the woven fibre composites are not relevant to delamination because they do not have dependent laminae.
- *Chopped fibre composites:* With random orientation of fibres, it is possible to obtain nearly uniform mechanical and physical properties in all direction. Chopped fibre composites are used extensively in high-volume applications such as building materials, because of low manufacturing cost.
- *Hybrid fibre composites:* Mixed chopped and continuous fibres, or mixed different fibre types such as glass/carbon fibre and natural/synthetic as well. Hybrid fibre composites provide the chance of achieving a balance of mechanical properties and cost.

Fibre composite types are shown schematically in Figure 2.5 below.

Continuous fibre composite ***Woven fibre composite***

Chopped fibre composite ***Hybrid composite***

Figure 2.5 The classification of fibre reinforced composite materials *(Gibson 1994).*

The commercial and industrial applications of fibre composites are varied and widespread. A significant structural application is in the field of commercial and military aircraft. Composite materials reinforced with carbon fibre, either alone or in hybridization with kevlar fibres, have become the primary material in many wing and fuselage components in aerospace applications. The aim of this is to improve performance while reducing weight.

The principal advantage of using fibre-reinforced composites is weight reduction. For instance, in the field of sporting goods applications, weight reduction achieved by substituting carbon fibre-reinforced epoxy for metal has led to higher speeds and improved maneuvering in competition, such as bicycle or canoe racing. Weight reduction in the golf club shaft results in a faster swing as well as a longer drive *(Cahn 1990)*.

Fibre-reinforced composite materials also have found wide use in the automotive industry. Great emphasis is being placed on the development of light weight automobiles, fuel economy, and cost-effectiveness issues. The high cost of carbon or kevlar fibre reinforced epoxies have paved the way for lower cost E-glass fibre reinforced polyesters or natural fibre-reinforced polyesters in key automotive applications. In marine applications, glass fibre-reinforced polyester laminates are used in areas such as hull, deck, mast, bulkheads and frames. Weight reductions made possible by using composite materials have increased boats' cruising speeds, maneuverability and fuel efficiency.

2.2.1 NATURAL FIBRE COMPOSITES

The history of natural fibre composites can be dated back thousands of years. The ancient Chinese, Egyptians and Israelites all made bricks by mixing straw with clay. Bamboo used so often in structures by the Chinese is in fact a typical fibrous composite material. The principle of natural composite materials can be found in numerous naturally occurring substances. Wood is an interesting example of a natural fibre composite composed primarily of cellulose fibre chains bonded together with lignin matrix. The bond between the fibres and lignin is exceedingly strong. The high strength and stiffness of wood, along with its well-known versatility and attractiveness provide a ready indication of the effectiveness of natural fibre reinforced composite materials. Bone is another type of natural composite material composed primarily of organic collagen fibres, small inorganic crystals, water and fats. These inorganic crystals are bound tightly to the collagen fibres and show good resistance in compressive loading.

Natural fibres such as jute, coir, sisal, banana and abaca fibres have been used to reinforce with common matrices such as polyester. Natural fibres make this kind of material with specific properties suitable for proper applications. Some plant and vegetable fibres were used in commercial high performance composites in early aircraft and automotive timing gears *(Grayson 1983)*. Successful trials carried out in Germany have illustrated the possibility of using the lighter banana fibre-polyester composite laminates to replace heavy and brittle glass fibre-polyester laminates to produce reinforced molded parts for the automotive industry *(Satyanarayana et al. 1990)*. Also, it has been reported by *Satyanarayana et al. (1990)* that banana fibre substituted for asbestos with bitumen can be used for roofing. *Coutts and Warden (1985)* reported that air-cured wood fibre reinforced cement composites have yielded materials with flexural strengths close to 30MPa and fracture toughness values of approximately 2kJ/m^2 with a density of about 1.6 g/cm^3 (when the composite contains 8% fibres by mass). In research conducted at CSIRO *(Coutts 1990)*, Australia, 8% by weight of banana fibre was fabricated with autoclave cement mortar, air-cured cement and air-cured plaster. The composite products had adequate mechanical and physical properties for building applications. Selected properties of banana fibre reinforced materials are shown in Table 2.6.

Table 2.6 The properties of banana fibre-reinforced composites *(Coutts 1990).*

Matrix	Cement	Cement mortar	Plaster
Curing	air-cured (28 days)	autoclaved (125 p.s.i.)	air-cured (1 day)
Modulus of rupture (MPa)	20.0 ± 1.3	18.4 ± 1.0	22.1 ± 1.9
Fracture toughness (kJ/m^2)	0.83 ± 0.09	0.55 ± 0.05	1.02 ± 0.05
Modulus of elasticity (GPa)	8.12 ± 0.70	9.39 ± 1.53	8.47 ± 0.96
Density (g/cm^3)	1.54 ± 0.02	-	1.55 ± 0.03
Water absorption (%)	22.93 ± 0.57	-	-

In general, natural fibre reinforced composites have the following advantages for industral applications:

- Low cost and low energy consumption compared with synthetic fibre composites due to the fact that natural fibres are abundantly available.
- Low density. Natural fibre composites can be used in the development of light weight automobiles thereby leading to fuel economy.
- Natural fibre composites can improve the strength and impact resistance of the resin.
- Natural fibres are non-toxic to work with.
- The use of natural fibres helps in extending the utilization of one of the abundantly available natural resources in developing countries which otherwise go to waste and create pollution problems.

Nevertheless, the natural fibre composites have the following disadvantages:

- Natural fibres are generally very hygroscopic thus causing poor bonding between fibre and matrix and resulting in loss of mechanical properties of composites. Degradation of composite materials based on natural fibre is one of the major limitations for durability.

- Currently, since natural fibres are not available in the required length and form, the process should be firstly to obtain the required natural fibre form.
- Suitable inexpensive resins should be developed for better performance and better compatibility with natural fibres.

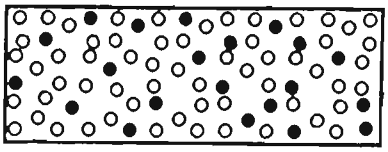
2.2.2 HYBRID FIBRE COMPOSITES

Hybrid fibre composites contain two or more kinds of fibres, which are incorporated into a single matrix. Although individual types of fibres may contribute some desirable property, the particular interest in composite material systems lies in optimizing the different contributions from different types of fibres, whilst at the same time, paying attention to optimizing cost effectiveness. Hybrid fibre composites therefore provide researchers an opportunity for tailoring composites to achieve desired properties *(Kretsis 1987)*.

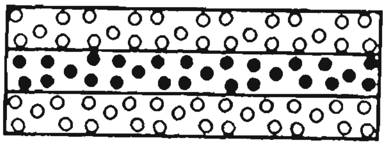
According to the arrangements of fibres and layers, hybrid fibre composites can be generally classified into the following types *(Chou 1992)*:

- *Intermingled:* Different fibre materials are mixed together and passed through a matrix simultaneously,
- *Interlaminated:* Each separate laminate containing just one type of fibre. The laminae are bonded together in a matrix,
- *Interwoven:* Composed of fabric reinforcements where each fabric contains more than one type of fibre.

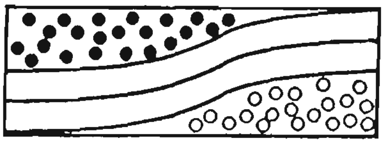
The Figure 2.6 shows the three types of hybrid fibre composites.



Intermingled



Interlaminated



Interwoven

Figure 2.6 The schematic for types of hybrid fibre composites *(Chou 1992)*.

One of the advantages of hybrid fibre composites is flexibility in the choice and disposition of reinforcements *(Hancox 1981)*. Fibre hybridization can be a very useful way of balancing mechanical properties (such as requirements for strength and stiffness) in various directions at minimum cost. In general, the hybrid effects are likely to be dominated by the properties of each individual fibre and their law of mixture (such as fibre volume fraction). Hybrid composites made with a high performance fibre and another lower performance fibre or a high cost fibre and a cheaper fibre, may have adequate properties for a specific application. It may be possible to save weight and reduce cost while getting improved mechanical and thermal properties, compared with an individual fibre reinforced system.

Applications of hybrid fibre composites have grown rapidly in the last decade or so *(Hancox 1981)*. At present, the most popular fibre hybridizations are glass-carbon and kevlar-carbon fibres. The growth of hybrid fibre composites has been encouraged by the demand for high-performance engineering material and economy issues, especially where light weight is of great importance. Turning to specific applications, hybrid fibre composites have been used in aerospace industry, such as helicopter rotor and drive shafts. Also, hybrid fibre composites are attractive for commercial transportation and building industries.

Overall, effective hybrid fibre combinations have simply taken the composite material approach one step further than individual fibre laminates. Fibre hybridization improves the possibilities for total optimization of costs and properties. However, the negative aspects of fibre hybridization are an increase in the complication of material responses and analytical complexity. The reason is that, in the case of layered hybrids, it is hard to distinguish between the two or more fibres, especially for hybrids of high-performance. Thus, processing errors may easily be made.

2.2.3 SHORT FIBRE COMPOSITES

For various applications, many fibre composite materials are not reinforced by continuous fibres but by short fibres. Composites reinforced with discontinuous fibres are referred as short fibre composites. Short fibres have no constant definition of fibre length. Depending upon the dispersion of fibres in the matrix, the fibre aspect ratio (length/diameter) is usually a measurement of fibres relative length *(Chou 1992)*. Although short fibres have been used to reinforce metals and ceramics, the majority of short fibre composites are based upon polymeric matrices.

In some applications the stress distribution can be exactly determined. In these situations unidirectional fibre composites have strong advantages, because they have high strength and modulus in the direction of the fibre axis, but are general very weak in the transverse direction. However, if the stress state is not readily predictable, or the expected service stresses are approximately equal in all directions, the unidirectional fibre composites lose this advantage. With short fibre composites, it is possible to obtain nearly equal mechanical properties in all directions, by virtue of the random nature of fibre orientation within the composite material. An effective way of producing an isotropic laminate is to use randomly oriented short fibres as the reinforcement. The moulding compounds consisting of short fibres that can be easily moulded by injection or compression, and they are also economical and can produce generally isotropic composites. In general, short fibre composites are less expensive for mass production techniques than continuous fibre composites *(Folks 1982)*.

2.3 COMPOSITES MANUFACTURE

There are many differences between composites and metallic materials on the choice of manufacturing method. With composite materials, processing technique has a direct influence on fibre volume fractions, fibre distributions, fibre orientations and details of laminate lay up. Many of the main issues, which affect component performance, are linked with manufacturing method. Composite products of the same form, but of different fabrication methods, could have markedly different properties. This not only affects mechanical properties such as strength and modulus, but also other properties such as the interface between fibre and matrix, thermal and electrical, chemical resistivity and internal damping. A cost-effective and reliable manufacturing method is also a key issue in the successful production application of composite materials. The effect of manufacturing process on cost components between equipment, tooling, labor and materials varies greatly. The balance between achieving the maximum level of performance and minimising processing costs should satisfy the requirements of a particular application. For example, in the automotive industry, there is more emphasis on the development of manufacturing methods that can support mass production rates. Unit costs and production rates commensurate with large volumes are needed.

Currently, there are many manufacturing processes for composite materials. Brief characteristics of major manufacturing processes are described as follows *(Eckold 1994)*:

- **Continuous reinforcement processing**

  - *Filament winding:* A band of continuous fibres impregnated with resin is wrapped around a rotating mandrel and cured to produce axially symmetric hollow parts. The applications are strong, stiff shell structures such as automotive drive shafts and pipe lines.

  - *Pultrusion:* Pultrusion is effective for producing long, straight structural components of constant cross-sectional area. The common pultruded products are solid rods, hollow tubes, flat sheets and various types of beams.

- **Hand lay up processes**

  In these processes, components are normally produced on a mould, coated with a suitable release agent. Hand lay up processes have the advantage of low cost and versatility. The details will be described in the following section 2.3.1.

- **Molding processes**

  - *Matched - die molding:* Matching steel male and female dies are to be used to form a cavity of the shape of the component. Advantages of matched -die molding are high dimensional control and good surface finish.

- *Vacuum bagging:* The procedure involves the use of a flexible plastic membrane that is molded over the surface of the lay up to form a vacuum-tight bag. It is used in aerospace industry.

- *Autoclave molding:* It is similar to the vacuum bag process except that greater pressures are used in the lay up.

- **Resin injection process**

  - *Resin - transfer molding (RTM):* Several layers of dry continuous strand mat or woven roving are placed in the bottom half of a two-part mould, and a catalyzed liquid resin is injected into the mould via a centrally located sprue when the mould is closed. The RTM process has a low tooling cost compared with molding process. It has been successfully used in molding such parts as cabinet wall , water tanks and boat hulls.

  - *Reaction injection molding (RIM):* RIM uses relatively low pressures to produce large moldings principally in polyurethane elastomer. The major difference from RTM is that the RIM brings two fast-reacting components together and mixes them just prior to injection into the mould.

2.3.1 HAND LAY-UP PROCESS

Hand lay-up is perhaps the oldest method of fabrication of structural composites, but it still seems to offer a low cost, simple, efficient manufacturing method with no size limitations, and produces a high gloss finish on one surface. Its principal limitations are that there is only one finished surface, and the quality of the product is very much subject to operator skill. Another advantage of hand lay-up is low capital cost. It is particularly suited for one-offs or short production runs and can be used for large components such as hulls of boats and swimming pools.

In hand lay-up, a male or female mould is used. After the mould is prepared with a release agent to prevent sticking, gel coat is used to give a decorative and protective surface. Reinforcing material is placed on or in the mould. The liquid thermosetting resin is mixed with a curing agent and applied with a brush or roller taking care to work it into reinforcement. The most commonly employed resins are polyesters or epoxies, and curing is usually at room temperature. The prime consideration is the viscosity and the working time of resin *(Scwartz 1984)*.

The major disadvantages of hand lay up are the low reinforced volume fractions and the difficulty in removing all of the trapped air, thus, the mechanical properties are decreased. Also, being a labor-intensive technique, provision must be made in the design for the greater degree of variability.

2.4 COMPOSITE MATERIAL TESTING

Material properties are usually determined by conducting mechanical and physical tests under controlled laboratory conditions. Due to the special characteristics of composite materials, such as orthotropic nature, interfacial effects between fibre and matrix and the variety of possible failure modes, the mechanical testing methods that are used for conventional materials are different from those used for composite materials *(Nielsen 1994)*. The development of these unique test methods has been a major challenge for the experimental mechanics field. The experimental techniques, which are used for this project, are discussed in the next section.

2.4.1 DYNAMIC MECHANICAL ANALYSIS (DMA)

Polymers are often viscoelastic in nature. Viscoelasticity implies that a material will exhibit mechanical behavior with characteristics representative of both a viscous liquid and purely elastic solid. A viscous liquid in a non-hydrostatic stress condition has a capacity for dissipating energy, but none for storing it. Perfectly elastic materials have the capacity to store mechanical energy with no dissipation of energy. When composite structures are subjected to dynamic loads, many exhibit an elastic solid and a viscous fluid behavior. The deformation and the corresponding strain may be decomposed into elastic and viscous components. It is this dual nature of composite materials which makes their behavior so complex and interesting. The balance between elasticity and viscosity varies with temperature, fibre type, fibre amount, fibre volume fraction and degree of cross-linking*(Ferry 1980)*.

The investigation of the dynamic mechanical behavior over a wide temperature, frequency, and dynamic stress range is useful in studying the structure of polymers and variations in properties. These parameters have been used to determine the glass transition region, relaxation spectra, degree of crystallinity, molecular orientation, crosslinking and to measure the damping properties. For any application of polymers, the stiffness variation and thermal expansion must be taken into account whenever a component is subjected to a wide range of temperature in service *(Haddad 1995)*.

A DMA (Dynamic Mechanical Analysis) instrument operates on the principle of applying stress in a periodic, cyclic fashion (typically with sinusoidal character) at controlled frequency. Dynamic mechanical properties are usually described in terms of a complex modulus E^*, which is divided into storage modulus E' (expressing a material's ability to store energy), and the loss modulus E'' (expressing a material's ability to dissipate energy). The DMA measures a strain that is in phase with the applied stress in elastic portion, while viscous portion will exhibit a strain that is 90°C out of phase. DMA resolves the complex modulus into an elastic modulus and viscous modulus *(Campbell and White 1989)*:

$$E^* = E' + iE'' \quad \text{and} \quad |E^*| = (E'^2 + E''^2)^{\frac{1}{2}} \qquad (2.1)$$

The ratio of loss modulus and storage modulus is called tanδ (the 'loss tangent'):

$$tan\,\delta = \frac{E''}{E'} \qquad (2.2)$$

Tan δ gives the relative ability of the material's ability to store and dissipate energy. High Tan δ indicates more viscous behavior and low Tan δ indicates more elastic behavior.

T_g is glass transition temperature. T_g values depend on the chemical structure, processing conditions, molecular weight and compositional changes. Amorphous polymers are relatively hard and rigid below T_g, in the so-called glassy region. Above T_g, however, the amorphous polymers are soft and flexible. T_g is important to understand the properties of polymers. It can be considered as one of the important material characteristics. Polymer mechanical and physical properties change rapidly with temperature in the glass transition region. The storage modulus decreases rapidly, and the loss modulus and tangent delta increase to peak.

T_g measurements may be made by many different methods, such as Differential Thermal Analysis (DTA), Differential Scanning Calorimetry (DSC) and Dynamic Mechanical Analysis (DMA). Different values of T_g are often obtained from different measuring techniques. Moreover, even within a given technique, for example, DMA, there are many variations on detecting and calculating T_g. For example, the T_g region can be taken as storage modulus onset, loss modulus peak or onset, or Tanδ peak *(Cassel and Twombly 1991)*.

One of the simplest results available from a DMA instrument is a curve of storage modulus versus temperature. Temperature regions are encountered where the storage properties decline rapidly. The loss modulus rises to a local maximum as the storage modulus declines. Another important graphical result, is that Tan δ, follows the loss modulus *(Sepe 1997)*, although the two properties do not exhibit transitions at exactly the same stages of a test. DMA instruments may employ many different geometries and apply the stress in various modes under temperature/time, stress, frequency, creep-recovery and the constant force scan modes.

2.4.2 STATIC FLEXURE TESTING

Static flexure testing is performed to determine the rigidity of the hybrid fibre composites, and it is done under bending loads. Three point bending flexural tests are usually used in the composite material tests, because the sample preparation and fixtures are very simple *(Chang 1995)*.

According to ASTM D790, the flexural strength in a three-point flexural testing is given by:

$$\sigma = \frac{3PL}{2bt^3} \qquad (2.3)$$

Flexural modulus is calculated by:

$$E = \frac{mL^3}{4bt^3} \tag{2.4}$$

where:

σ: flexural strength (MPa)

E: flexural modulus (GPa)

P: maximum load at failure (N)

b: sample width (mm)

t: sample thickness (mm)

L : sample length between the two support points. (mm)

m: initial slope of the load deflection curve. (mm)

The three point bending is shown in Figure 2.7.

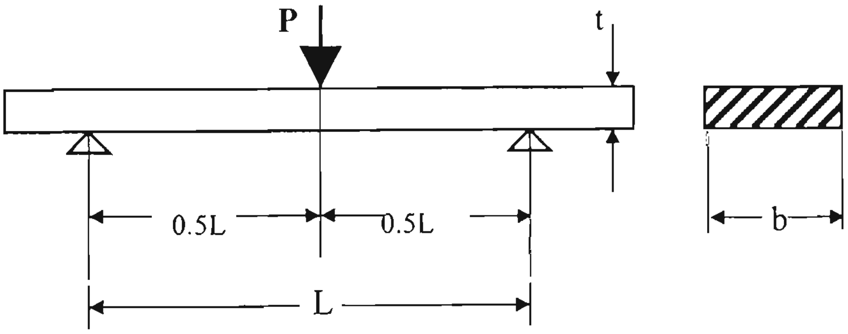


Figure 2.7 Schematic illustration of 3-point bending test.

Chapter 3

Material Fabrication and Experimental Methods

3.1 MATERIALS

3.1.1 BANANA FIBRE

The banana fibre used in the study is 10 *mm* long chopped banana fibre. The banana stalk was supplied from a banana plantation in Woolgoolga, N.S.W, Australia.

Banana fibres were obtained from the pseudo stem of the banana plant. The pseudo stem, which is surrounded and supported by leaf sheathes, is called the stalk. The leaves were separated from the pseudo stem and cut into 1 *m* length and 0.02 *m* width. The extraction of the fibre from the stripped leaf sheath (cleaned well) was done by hand scraping using a soft wooden plank. The pith was then removed continuously until the fibres appeared clean. These strands were dried and then used for fibre preparation by cutting the strands into ~10 *mm* in length.

The equilibrium water content (EWC) of banana fibres is defined as the percentage amount of water absorbed under ambient conditions and can be calculated from the difference in mass before and after exposure to ~110°C for about an hour (this will drive any water away). The EWC of banana fibers used in this investigation was determined to be 12%.

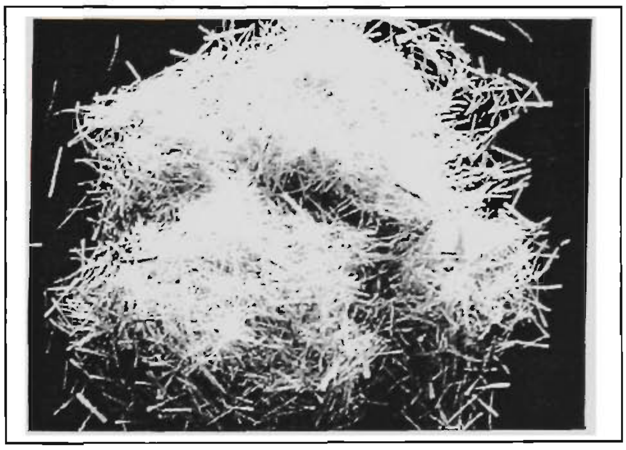


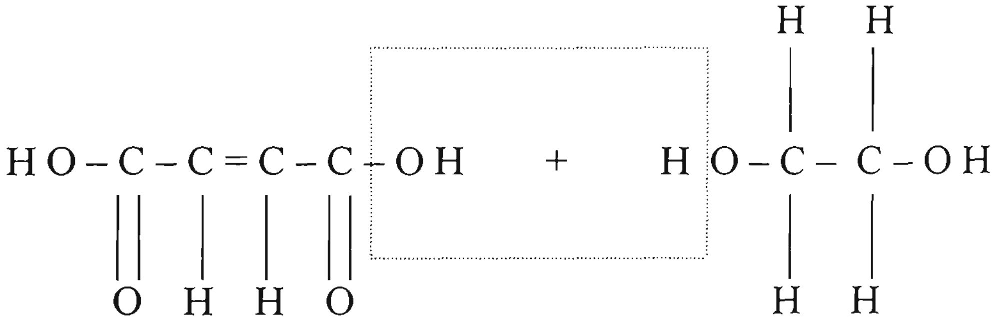
Figure 3.1 10 *mm* long banana fibres

3.1.2 GLASS FIBRE

The glass fibre used in this study is circular cross-section E-glass chopped strand mats from Resin and Fibreglass Services Pty. Ltd., Australia. Longer chopped fibreglass strands (up to 50 *mm* in length) are mixed with a resinous binder (a polyester powder) and spread in a random two-dimensional fashion to form chopped strand mats. These mats are typically used for hand lay-up molding and provide equal properties in all of the in-plane directions of the structure.

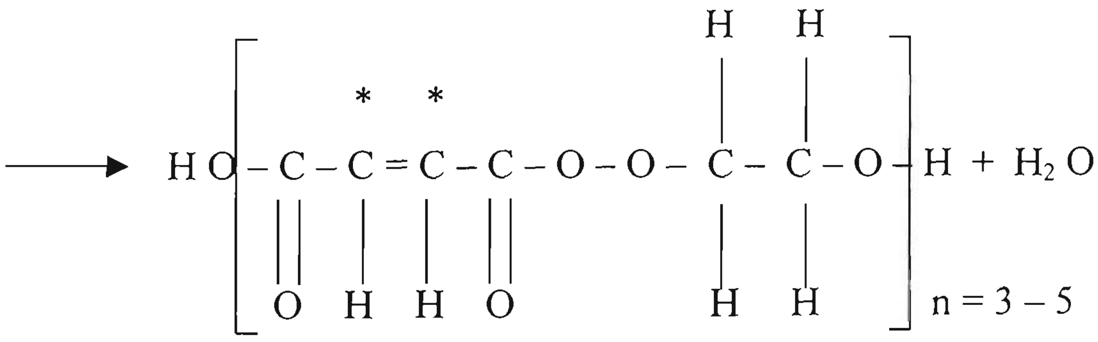
3.1.3 MATRIX

The resin used in this work was unsaturated polyester resin (resin number: 837E) from Resin and Fibreglass Services Pty. Ltd., Australia. It is one of the commercial thermoset polymers which contain a number of carbon, C=C double bonds. Unsaturated means that the resin is capable of being cured from a liquid to a solid state. A typical unsaturated polyester may be prepared by reacting an unsaturated dibasic acid, *maleic anhydride*, with a glycol, *ethylene glycol.* The resulting molecule chain has the following general formula.



$$HO-\underset{O}{\underset{\|}{C}}-\underset{H}{\underset{|}{C}}=\underset{H}{\underset{|}{C}}-\underset{O}{\underset{\|}{C}}-OH \quad + \quad HO-\overset{H}{\overset{|}{\underset{H}{\underset{|}{C}}}}-\overset{H}{\overset{|}{\underset{H}{\underset{|}{C}}}}-OH$$

Maleic Anhydride ***Ethylene Glycol***



$$\longrightarrow H\left[O-\underset{O}{\underset{\|}{C}}-\underset{H}{\underset{|}{\overset{*}{C}}}=\underset{H}{\underset{|}{\overset{*}{C}}}-\underset{O}{\underset{\|}{C}}-O-O-\overset{H}{\overset{|}{\underset{H}{\underset{|}{C}}}}-\overset{H}{\overset{|}{\underset{H}{\underset{|}{C}}}}-O\right]H + H_2O \quad n = 3-5$$

Unsaturated Polyester Molecule

Figure 3.2 Unsaturated polyester molecule *(Mallick 1988).* The asterisk (*) denotes the saturation points (reactive sites) in the unsaturated polyester molecule.

The curing reaction for polyester resin will start immediately upon addition of a suitable catalyst and accelerator. The polyester resin used in this work is normally pre-accelerated. The accelerator proportions are already adjusted to give the most suitable gelling and hardening characteristics. Once the catalyst is added, the curing reaction starts immediately at room temperature. The proportions of catalysts are recommended ranging between 1% and 4 % of the resin weight, depending on the type of the catalyst. In this work, the catalyst is *Methyl – Ethyl –*

Ketone – Peroxide (MEKP), produced as a liquid (40% in *Dimethyl phthalate* solution). The proportion of catalyst was chosen on a 2% scale (20 *ml* per litre polyester resin).

The setting reaction of polyester resin occurs in four stages:

- ***Pot life time:*** during which the resin still remains in a workable liquid form although it continues to thicken.
- ***Gel time:*** the time taken for the resin to set to a soft gel.
- ***Hardening time:*** further time taken for the resin to become hard enough for the part to be removed from its mould.
- ***Maturing time:*** further period of time over which the molding will continue to gain hardness and eventually, complete stability. When fully matured the molding will have its maximum strength, hardness, chemical resistance and stability.

These four stages are illustrated in Figure 3.3

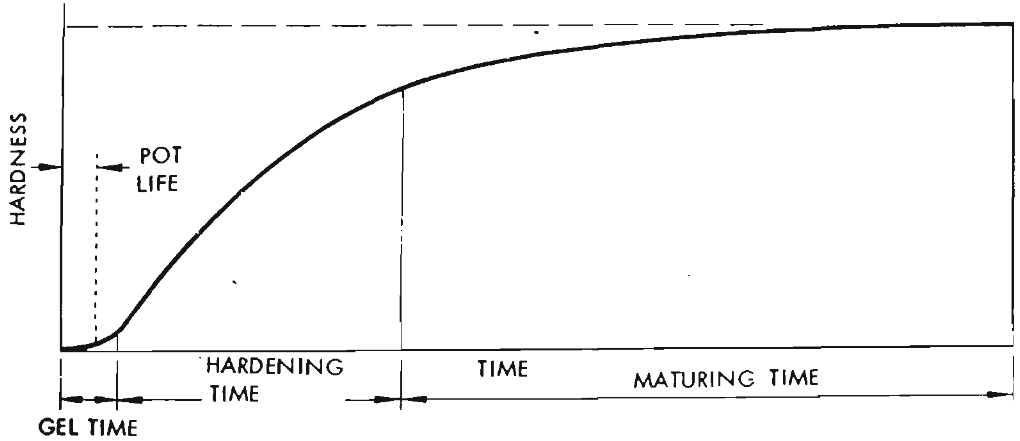


Figure 3.3 Four stages of setting action of the resin *(Warring 1993).*

The curing time for polyester resin depends on the proportions of catalyst. An increase in catalyst content will result in a more rapid increase in hardening. Also the working time of resin should be mentioned here. The working time means the speed of reaction between resin and catalyst, which is dependent on both temperature and catalyst quantity. The polyester resin normally has a pot – life in the 20 to 30 minutes range at room temperature and should not normally be used below 15 $^{\circ}C$ or above 35 $^{\circ}C$.

3.2 COMPOSITION OF HYBRID FIBRE COMPOSITES

3.2.1 RULE OF MIXTURES

The rule of mixtures has been used to calculate the relative volume or weight contents of the various constituent materials. In hybrid fibre composites, the three constituents in the fabricated lamina are glass fibres, banana fibres and polyester resin. Fibre volume fraction is usually used in theoretical calculations for properties such as strength, modulus etc. However, the rule of mixtures is not suitable to measure the volume fractions of these three constituents, since it assumes volume additivity and does not take account of synergistic volume interactions. In order to calculate the volume fractions, they are converted into the weight fractions. The fibre weight fractions can be determined directly from the given proportions *(Sheldon 1986)*.

The following formulae were applied to calculate the glass fibres, banana fibres and polyester resin volume fractions:

$$v_g = \frac{(w_g / \rho_g)}{(w_g / \rho_g) + (w_b / \rho_b) + (w_m / \rho_m)} \tag{3.1}$$

$$v_b = \frac{(w_b / \rho_b)}{(w_g / \rho_g) + (w_b / \rho_b) + (w_m / \rho_m)} \tag{3.2}$$

$$v_m = 1 - v_g - v_b \tag{3.3}$$

$$w_m = 1 - w_g - w_b \tag{3.4}$$

where:

w_g : the weight fraction of glass

w_b : the weight fraction of banana fibres

w_m : the weight fraction of matrix

v_g : the volume fraction of glass fibres

v_b : the volume fraction of banana fibres

v_m : the volume fraction of matrix

ρ_g : the density of glass fibre (kg/m^3)

ρ_b : the density of banana fibre (kg/m^3)

ρ_m : the density of polyester resin (kg/m^3)

The density of composite lamina ρ_c also can be calculated according to equation (3.5).

$$\rho_c = \frac{1}{(w_g / \rho_g) + (w_b / \rho_b) + (w_m / \rho_m)} \tag{3.5}$$

The composite weight W_c is the multiplication of the composite volume V_c and ρ_c.

$$W_c = V_c \times \rho_c \tag{3.6}$$

The glass fibre weight W_g:

$$W_g = W_c \times w_g \tag{3.7}$$

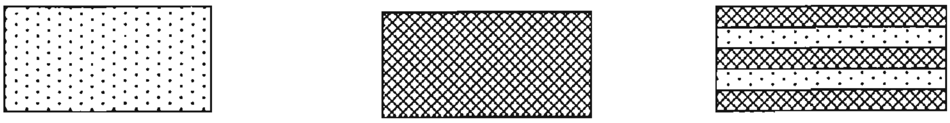
The banana fibre weight W_b:

$$W_b = W_c \times w_b \tag{3.8}$$

3.2.2 CONSTITUENTS OF HYBRID FIBRE COMPOSITE LAMINAE

The composite laminae were made with different fibre weight fractions which are defined in three groups including 10 wt%, 25 wt%, 40 wt% hybrid fibre weight fractions. Each group was subsequently divided into five samples of different glass fibre and banana fibre fractions as shown in Tables 3.1, 3.2 and 3.3.

The Figure 3.4 shows the cross-sectional view of fibre composites, which were used in this project. The all glass fibre reinforced composites (GP1005, GP2505 and GP4005) are referred as B type, the all banana fibre reinforced composites (BP1004,BP2504 and BP4004) are referred as A type, the hybrid glass-banana fibre composites are referred to as C type.



(A) All Banana ***(B) All Glass*** ***(C) Hybrid***

Figure 3.4 Cross – sectional schematic view of lay-up sequences of glass and banana fibre in a polyester matrix.

Table 3.1 The composition of 10wt% hybrid fibre composites. Data presented is average of 3 samples.

Sample ID	W_f ±0.5 (g)	W_g ±0.5 (g)	W_b ±0.5 (g)	W_c ±0.5 (g)	V_c ±2.5 (cm^3)	w_g ±1.0 (%)	w_b ±1.0 (%)	v_g ±2.0 (%)	v_b ±2.0 (%)	ρ_c ±0.05 (g/cm^3)
GP1005 (All glass)	7.56	7.56	0	73.75	64.85	10.31	0	5.11	0	1.13
GBP1001	7.58	5.61	1.97	75.85	66.99	7.39	2.59	3.62	2.39	1.13
GBP1002	7.92	3.96	3.96	71.25	65.52	5.56	5.56	2.71	5.08	1.09
GBP1003	7.27	1.82	5.45	70.45	66.36	2.58	7.74	1.24	6.98	1.06
BP 1004 (All banana)	7.25	0	7.25	67.85	65.10	0	10.68	0	9.54	1.04

Where: W_g : The weight of glass fibres.
W_c : The weight of composites
w_g : The weight fraction of glass fibres
v_g : The volume fraction of glass fibres
ρ_c : The density of composite lamina
W_b : The weight of banana fibres
V_c : The volume of composites
w_b : The weight fraction of banana fibres
v_b : The volume fraction of banana fibres
W_f: The weight of total fibres

Table 3.2 The composition of 25wt% hybrid fibre composites. Data presented is average of 3 samples.

Sample ID	W_f ±0.5 (g)	W_g ±0.5 (g)	W_b ±0.5 (g)	W_c ±0.5 (g)	V_c ±2.5 (cm^3)	w_g ±1.0 (%)	w_b ±1.0 (%)	v_g ±2.0 (%)	v_b ±2.0 (%)	ρ_c ±0.05 (g/cm^3)
GP2505 (All glass)	20.55	20.55	0	80.15	64.68	31.77	0	13.91	0	1.24
GBP2501	17.30	12.25	5.05	71.25	64.89	17.19	7.09	8.94	6.94	1.10
GBP2502	18.30	9.45	8.85	61.85	56.70	15.28	14.30	7.94	13.99	1.09
GBP2503	19.20	5.15	14.05	64.55	61.01	7.98	21.77	4.02	20.59	1.06
BP 2504 (All banana)	18.45	0	18.45	66.45	65.14	0	27.77	0	25.31	1.02

Table 3.3 The composition of 40wt% hybrid fibre composites. Data presented is average of 3 samples.

Sample ID	W_f ±0.5 (g)	W_g ±0.5 (g)	W_b ±0.5 (g)	W_c ±0.5 (g)	V_c ±2.5 (cm^3)	w_g ±1.0 (%)	w_b ±1.0 (%)	v_g ±2.0 (%)	v_b ±2.0 (%)	ρ_c ±0.05 (g/cm^3)
GP4005 (All glass)	36.24	36.24	0	81.15	61.29	44.66	0	27.44	0	1.32
GBP4001	34.32	25.74	8.58	72.45	60.88	35.53	11.84	20.87	13.11	1.19
GBP4002	33.68	17.12	16.56	70.95	62.42	24.13	23.34	13.39	24.38	1.14
GBP4003	31.44	7.86	23.58	67.75	60.29	11.62	34.85	6.06	34.26	1.12
BP 4004 (All banana)	30.15	0	30.15	64.25	63.72	0	46.93	0	43.79	1.01

3.3 FABRICATION OF BANANA/GLASS POLYESTER COMPOSITE LAMINAE

3.3.1 FABRICATION FACILITY

A hydraulic press was used for fabrication of banana fibre/glass-polyester hybrid composite lamina. This machine was designed to manufacture composite material boards with a maximum dimension of 450 *mm* × 300 *mm*, and a thickness up to 50 *mm*. It provided control of temperature, and featured an auxiliary air boost compressor and a pedal to facilitate pressure control. The hydraulic platen press had the capacity in excess of 200 bar applied pressure.

The composite lamina was formed in a mould. This mould was composed of aluminum of rectangular bars and two flat plates, as shown in Fig. 3.5. The press set up is also shown schematically in Fig. 3.5.

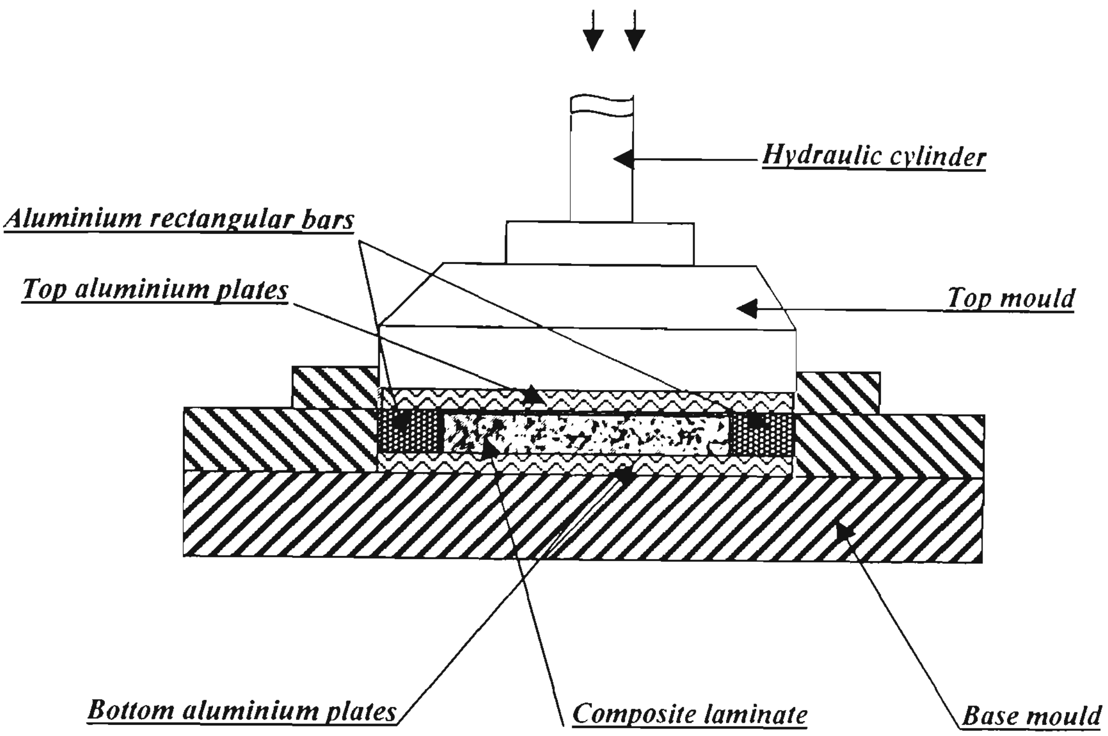


Figure 3.5 Schematic of composite materials pressed mould.

3.3.2 FABRICATION PROCEDURES

The mould for fabrication of composite lamina was completely cleaned (removing any remaining parting agent if the mould has been used before). It was free from surface damage, along with grease or dust, in order to obtain good surface finish of composite lamina. Then the mould was treated with release agent to promote sample removal after curing. The release agent was applied sparingly either by spray or brush, otherwise it took too long to dry. The release agent must be left to dry thoroughly; otherwise, it would not form a proper skin, and the moulding would stick.

Ideal air temperature had to be at least 15 °C. If the temperature was lower than this, more than 2% catalyst had to be used to compensate for the decrease in thermal activation. If the temperature was below about 10 °C, however, it was best to leave laying-up until conditions improved. It was also important that the air should be dry or reasonably dry. Laying-up must not be attempted in damp or excessively humid conditions, due to inhibition of the curing reaction by the moisture in the air.

Chopped glass fibre strand mats were cut to 150 *mm* × 100 *mm*. After weighing the glass fibres, glass strand mat, banana fibres and polyester resin, the first layer of glass strand mat, was put on the bottom of the mould. The polyester resin was prepared by adding approximately 2% catalyst of total polyester resin by weight.

The matrix then was poured over the first glass mat layer and distributed with a wide, soft brush, in order to obtain an even distribution of resin with a continuous application. In the meantime, the mixture consisting of banana fibres and resin was mixed carefully in a beaker with a stirrer bar. Mixing of the glass and banana fibres took approximately 10 minutes. The mixture was then evenly distributed on the first glass layer by rolling or brushing. The second glass mat layer was put on the top and the matrix was brushed on surface of layer again. Successive layers were added in a similar fashion.

Uniform distribution of the fibres and resin is important but also difficult to achieve. Care was taken at all times to minimize the potential for formation of defects. Brushing with a dabbing motion was used to avoid sweeping or ‘painting’ strokes. Dabbing down was followed by rolling to ensure proper consolidation.

The plate, which contained hybrid fibres/resin mixture was placed on the press. A second flat plate was put on top of the mixture. The fibres/resin mixture was then pressed by the top mould until the desired thickness of 4 *mm*. Pressure up to 200 bars was applied to the top mould. The fibres/resin mixture was compressed at a constant pressure of 200 bars, at room temperature and for 24 hours of curing.

3.4 SPECIMEN TESTING

3.4.1 WATER ABSORPTION

The water absorption values were obtained in accordance with ASTM C220. The samples were dried in an oven at 100 ± 5 °C for a period of 24 hours. After cooling down in a dessicator to room temperature, the dry weight of each was determined and recorded.

Samples were then immersed in distilled water at room temperature for a period of 24 hours. Surface water was quickly removed from each sample using a towel prior to the measurement and the wet weight in air was recorded. All masses were recorded to the nearest 0.01g.

The water uptake was then determined relative to the dry weight of the sample using following equation:

$$W_m = \frac{W_w - W_d}{W_d} \times 100\% \qquad (3.9)$$

where: W_m: Water absorption value, W_w: Wet weight, W_d: dry weight.
The water absorption results are summarised in Table 3.4

Table 3.4 Water absorption of hybrid composites (24 hours at room temp.)

Sample	*Water absorption (%)*	*Sample*	*Water absorption (%)*	*Sample*	*Water absorption (%)*
GBP1001	1.72	GBP2501	1.69	GBP4001	4.17
GBP1002	3.46	GBP2502	3.17	GBP4002	4.82
GBP1003	3.76	GBP2503	7.86	GBP4003	9.82
BP1004	6.86	BP2504	15.74	BP4004	20.13
GP1005	1.28	GP2505	1.45	GP4005	2.94

3.4.2 DMA TESTING

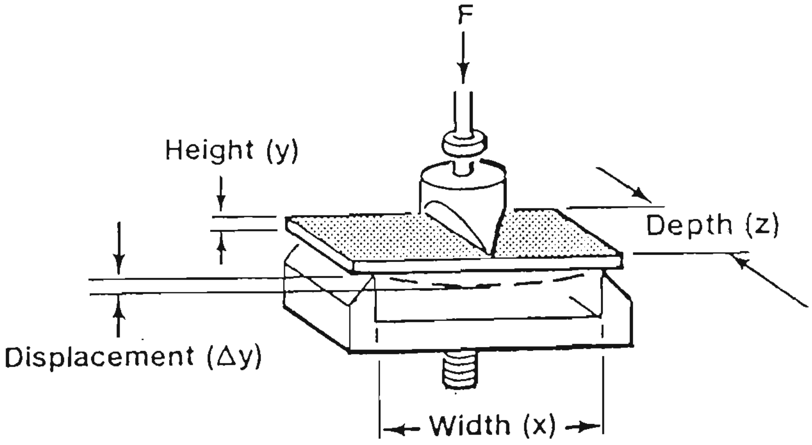
The temperature/time scan mode was used in this work for both wet and dry specimens.

3.4.2.1 Facility

The dynamic mechanical analysis system used was a Pekin-Elmer 7-series thermal analysis system, consisting of a TAC 7/DX thermal analysis instruments controller and a DMA7 dynamic mechanical analyzer. With this analyzer the specimen could be analyzed by DMA parameters versus temperature and stress without changing the furnace and sample mounting system. This system contains a software which is needed to control the system, perform experiments and analyze experimental data.

3.4.2.2 Sample preparation

Each sample was cut by high speed bandsaw for temperature/time and stress mode. Three-point bending dimensions of each sample are shown in Figure 3.6:



x=14.5 mm *y=2.0 mm* *z=3.5 mm*

Figure 3.6 Three-point bending dimensions *(DMA manual 1995).*

3.4.2.3 Temperature scan mode

In the temperature/time scan mode, the temperature is programmed and the oscillation frequency and stress are held constant. Temperature-dependant behavior is characterized by monitoring changes in strain and phase. Modulus and viscosity, as well as other standard reporting variables may be readily quantified for these materials as a function of temperature/time. Flexural storage modulus and the loss tangent were determined during heating over the temperature range $25^{\circ}C-180^{\circ}C$ at a rate of 5 °*C/min*.

3.4.3 STATIC FLEXURE TESTING

Static flexural strength and modulus were measured by a three point bonding method. The samples for testing were cut by band saw with a dimension of ~70 *mm* × 30 *mm* × 4 *mm*.

The testing was performed on Instron Model 8500 Plus Testing System. The system applies load, using a hydraulic actuator, to a specimen of the material under test. The test speed used in this work was 0.25 *mm/second.*

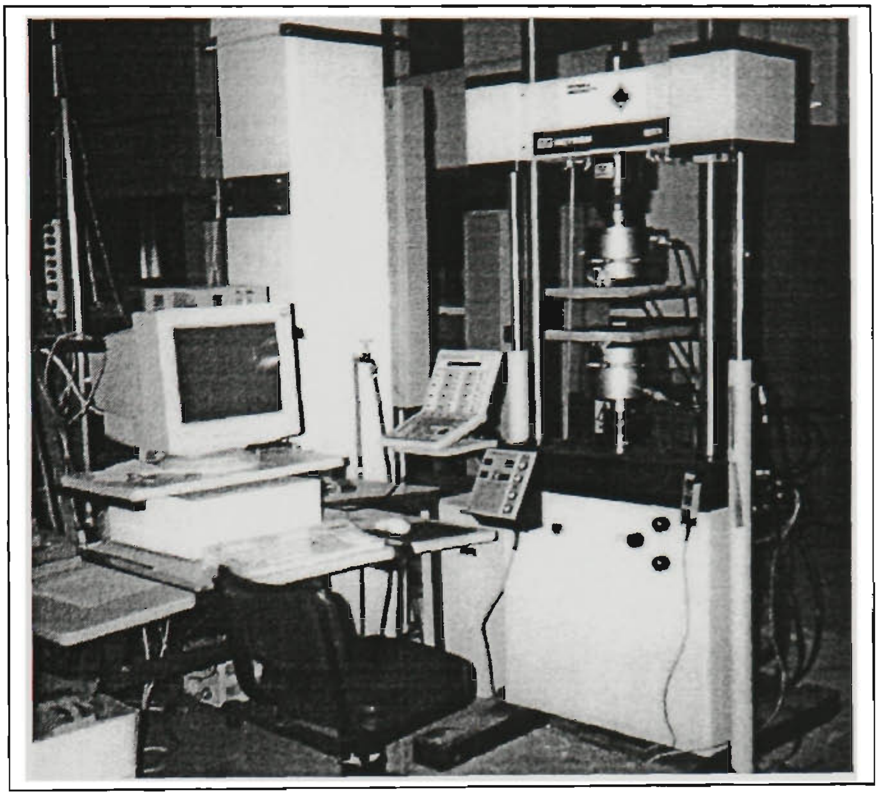


Figure 3.7: The Instron Model 8500 Plus Testing System.

Chapter 4

Results and Discussion

4.1 DYNAMIC MECHANICAL ANALYSIS

4.1.1 FLEXURAL STORAGE MODULUS VERSUS TEMPERATURE

Figures 4.1, 4.2 and 4.3 show the variation in dynamic flexural storage modulus with temperature for 10%, 25% and 40% banana-glass hybrid fibre composites, respectively, under dry conditions. These plots are distinguished by three distinct zones, which are called glassy, transition, and rubbery. The glassy zone is characterized by a region where no significant change in the storage modulus is evident until the onset temperature of glass transition is reached. The onset temperature of glass transition indicates the temperature at which the material's stiffness begins to decrease such that the material is no longer able to bear a load without undergoing a large deformation. In the second region, known as the transition region, the flexural storage modulus drops quite significantly and the material loses its rigidity. This zone is located in the temperature range of approximately $35^{\circ}C$ - $100^{\circ}C$. With further increase in temperature, the storage modulus continues to decrease quickly until it reaches the beginning of the third region also known as the rubbery region, which extends beyond 100 °C. All tests were stopped at 150 °C, when the materials were well into the rubbery region.

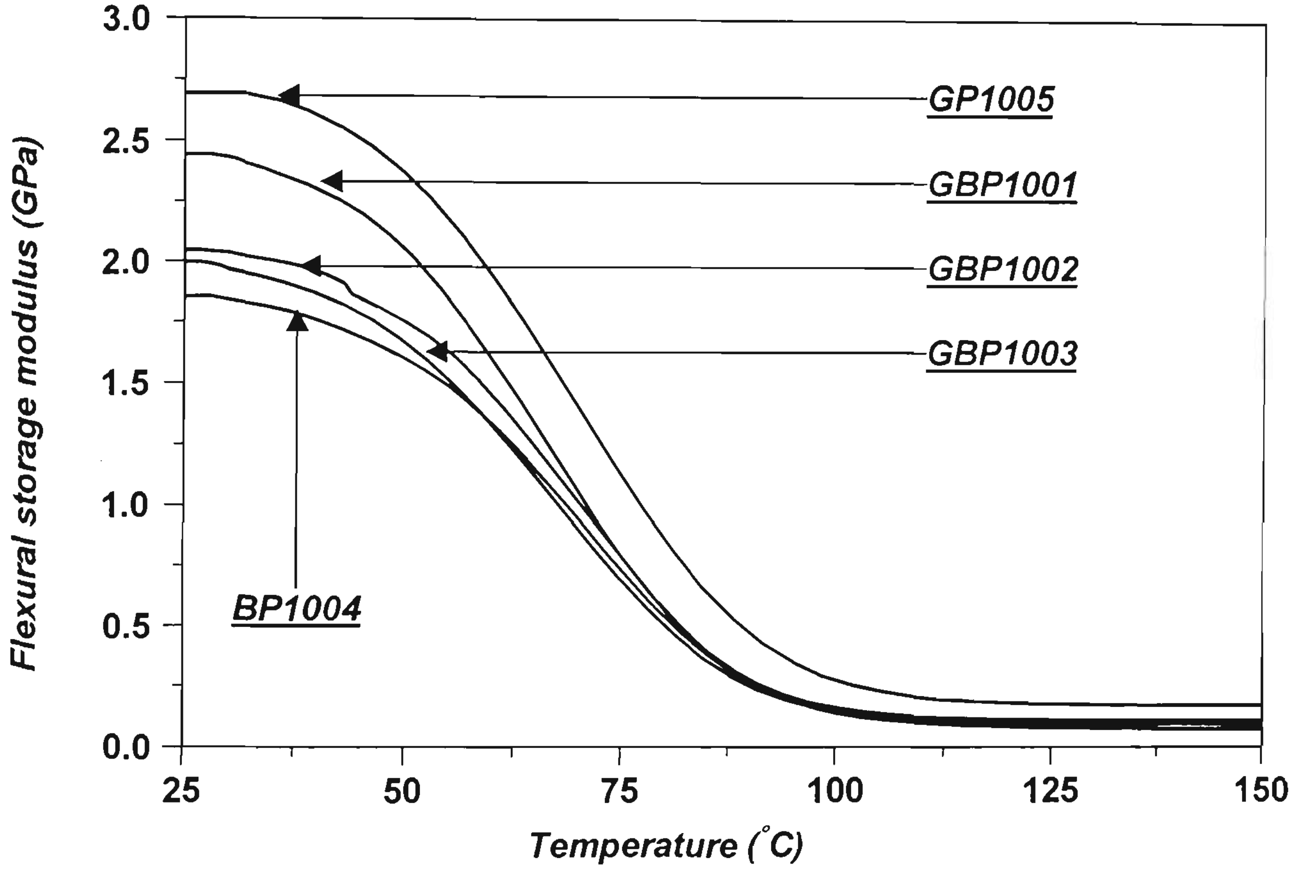


Figure 4.1: The variation in flexural storage modulus with temperature for 10% hybrid composites (dry condition).

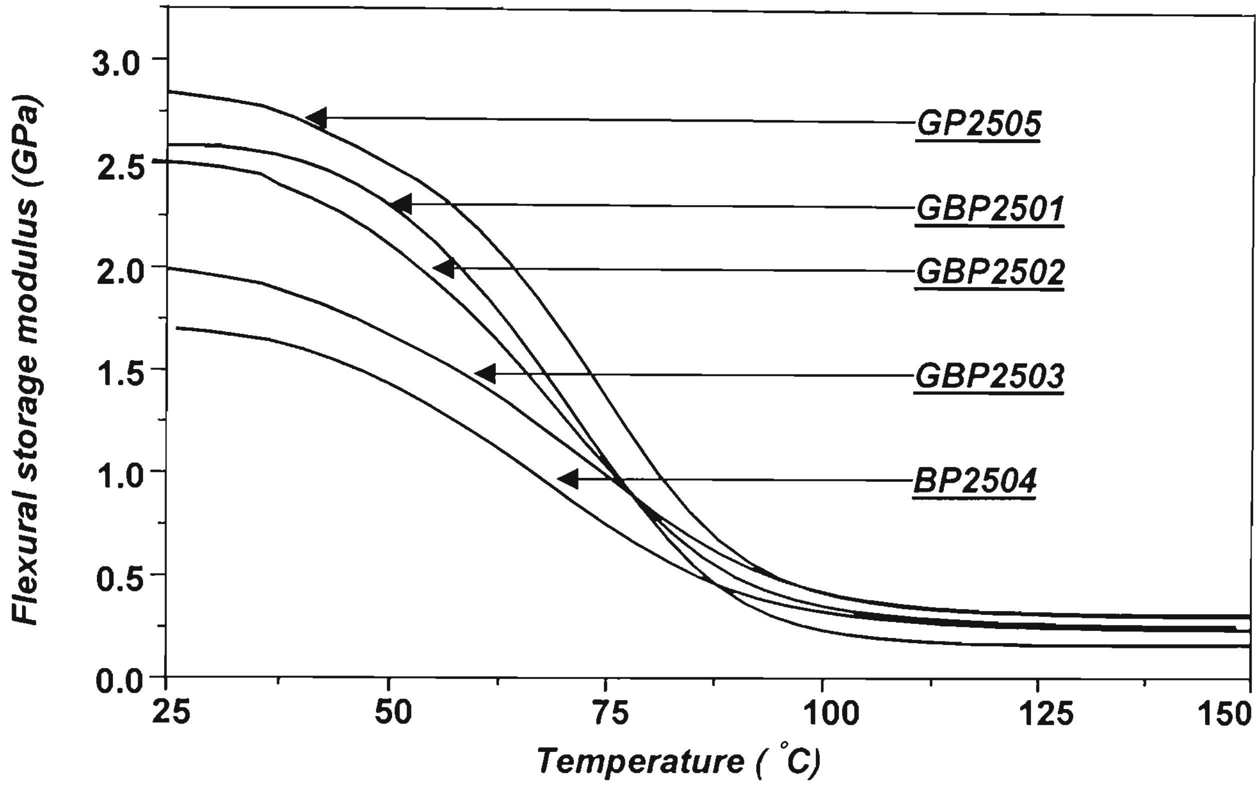


Figure 4.2: The variation in flexural storage modulus with temperature for 25% hybrid composites (dry condition).

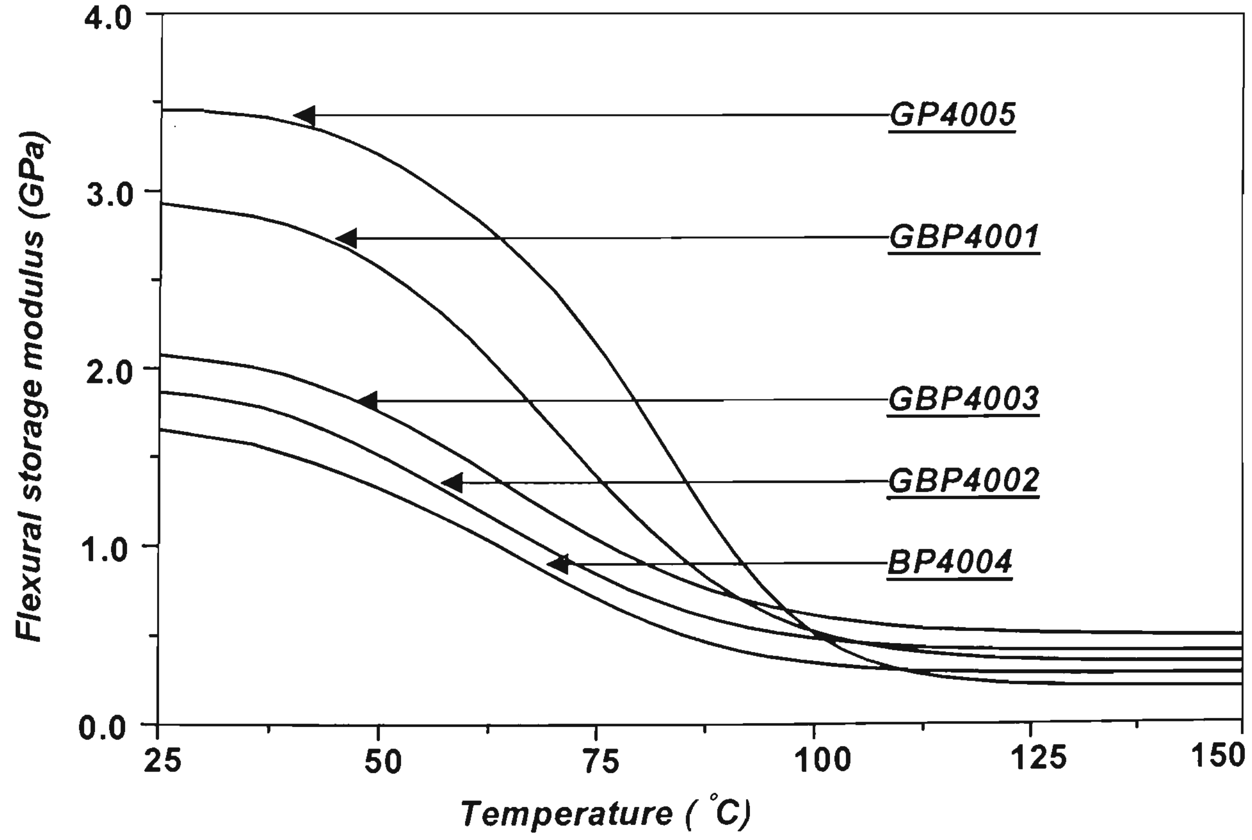


Figure 4.3: The variation in flexural storage modulus with temperature for 40% hybrid composites (dry condition).

Figures 4.4, 4.5 and 4.6 show the variation in flexural storage modulus with temperature for 10%, 25% and 40% hybrid fibre composites, respectively, under wet conditions. As in the case of the dry condition, curves can be demarcated into three distinct zones, which are glassy, transition, and rubbery. The variation in flexural storage modulus of the hybrid composites under wet conditions follows the same trend as that observed in the dry condition, but at a reduced magnitude due to water absorption causing loss of mechanical properties. There is no discernable variation in the transition temperature for equivalent samples from the wet condition to the dry condition.

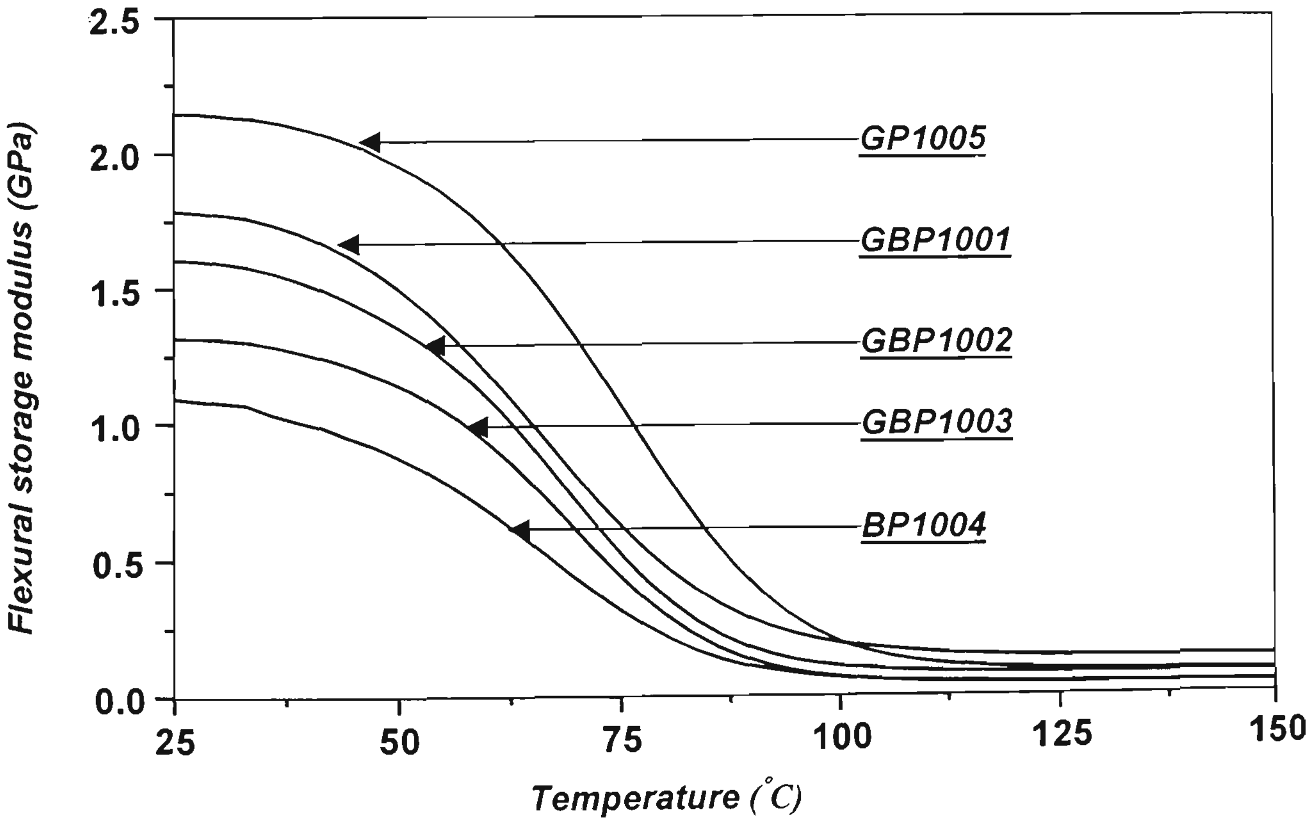


Figure 4.4: The variation in flexural storage modulus with temperature for 10% hybrid composites (wet condition).

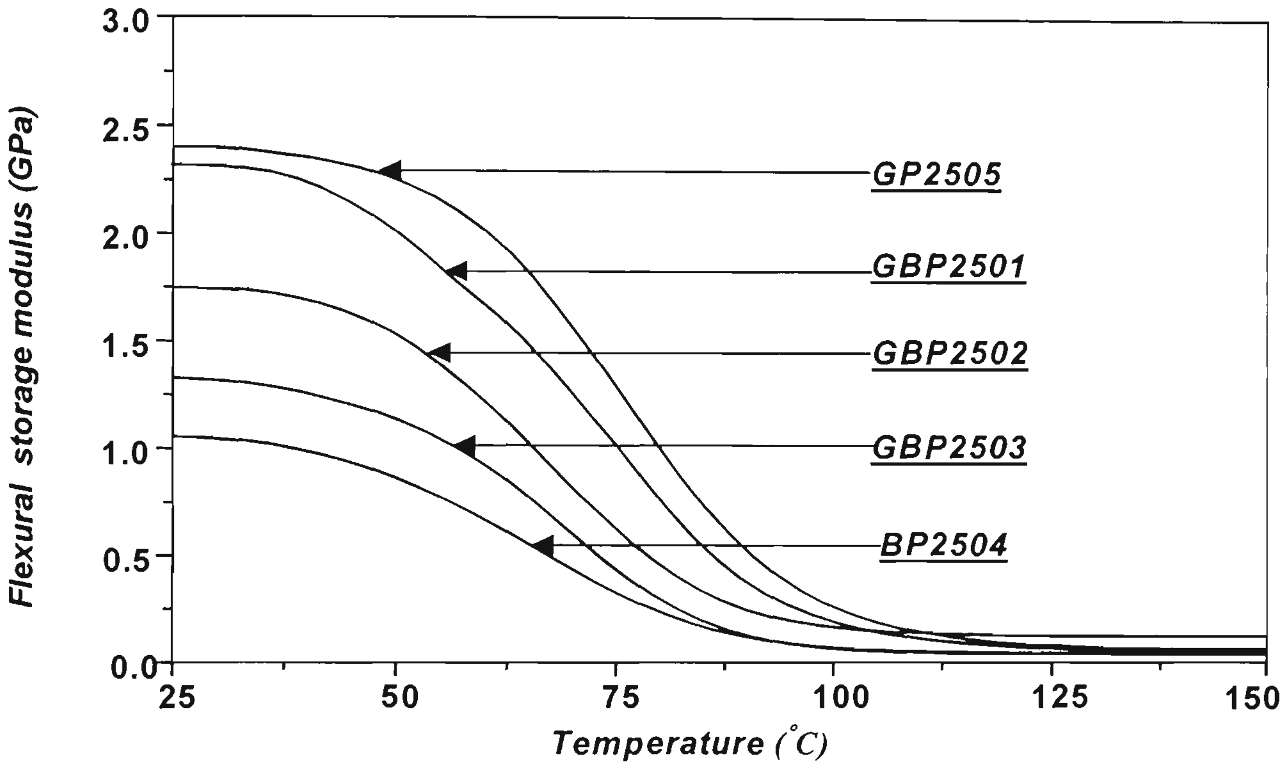


Figure 4.5: The variation in flexural storage modulus with temperature for 25% hybrid composites (wet condition).

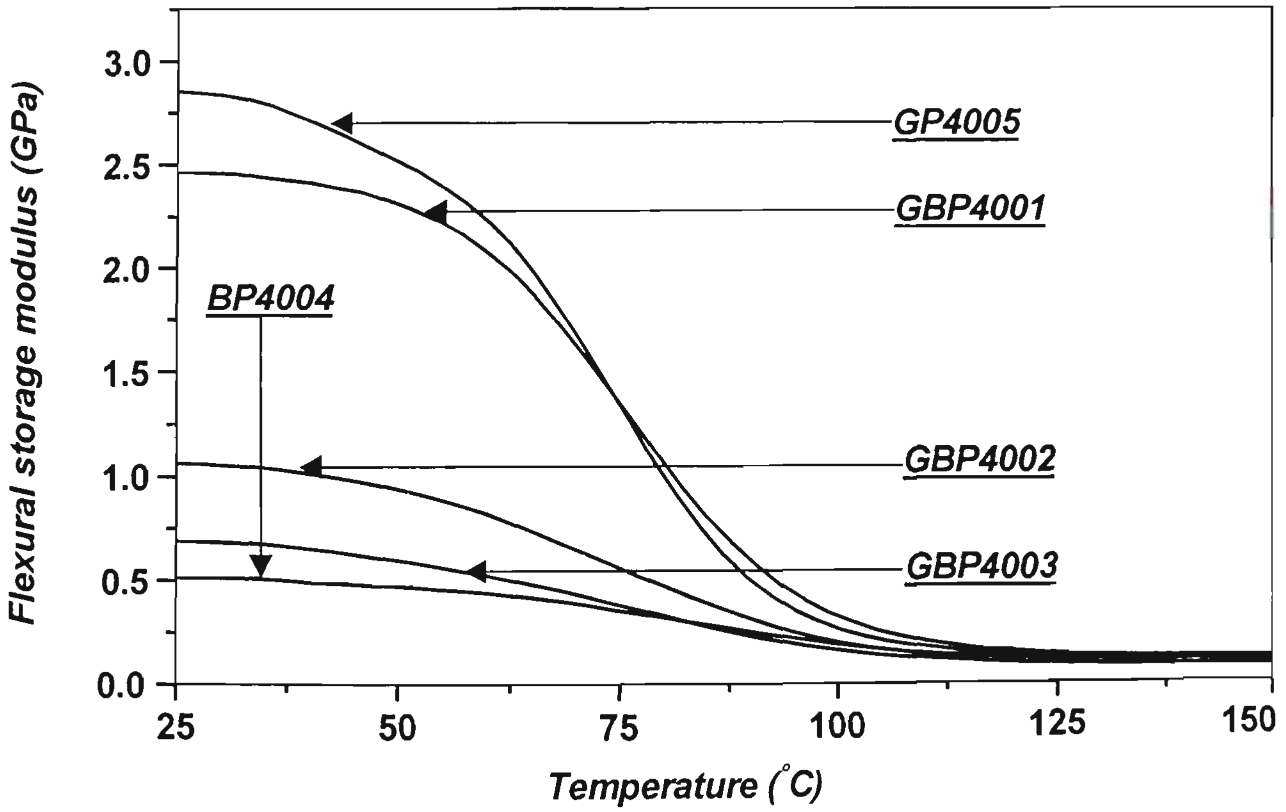


Figure 4.6: The variation in flexural storage modulus with temperature for 40% hybrid composites (wet condition).

Tables 4.1, 4.2 and 4.3 show the value (average of three specimens from each of hybrid samples) of initial flexural modulus of 10%, 25% and 40% hybrid fibre composites along with their onset temperature of transition under dry and wet condition.

Table 4.1: Characteristics of 10% hybrid fibre composites.

Sample ID	**Initial flexural storage modulus *(GPa)***		**Onset temperature *(°C)***	
	Dry	**Wet**	**Dry**	**Wet**
GBP1001	2.41	1.79	35	35
GBP1002	2.08	1.62	33	31
GBP1003	1.98	1.31	32	31
BP1004 (all banana)	1.86	1.12	32	31
GP1005 (all glass)	2.73	2.19	37	36

Table 4.2: Characteristics of 25% hybrid fibre composites.

Sample ID	Initial flexural storage modulus *(GPa)*		Onset temperature *(°C)*	
	Dry	**Wet**	**Dry**	**Wet**
GBP2501	2.58	2.31	38	34
GBP2502	2.49	1.73	37	36
GBP2503	1.97	1.28	35	33
BP2504 (all banana)	1.71	1.06	33	33
GP2505 (all glass)	2.81	2.42	40	38

Table 4.3: Characteristics of 40% hybrid fibre composites.

Sample ID	Initial flexural storage modulus *(GPa)*		Onset temperature *(°C)*	
	Dry	**Wet**	**Dry**	**Wet**
GBP4001	2.93	2.42	41	40
GBP4002	2.11	1.07	34	33
GBP4003	1.87	0.71	34	34
BP4004 (all banana)	1.65	0.52	33	31
GP4005 (all glass)	3.48	2.86	44	37

As expected, the all-glass-reinforced composites have the highest initial flexural storage modulus (at room temperature) compared to any other hybrid specimen. In contrast, the all-banana fibres reinforced composites have the lowest initial flexural storage modulus. This can be attributed to the higher stiffness of glass fibres compared to banana fibres. The flexural storage modulus of other banana-glass hybrid composites lies in between these two extremes, with the addition of glass fibres promoting a gradual enhancement of the flexural stiffness. This can be observed in the hybrid samples GBP1003 and GBP1001, where the glass fibre content is increased from 2.58% to 7.39%, causing the flexural storage modulus to rise approximately 22% with a 5% increase in the glass fibre content. Also, in the hybrids samples GBP2503 and GBP2501 having glass fibre content 7.98% and 17.19% respectively, the flexural storage modulus rise is about 31% with a 10% increase in the glass fibre content.

The all-banana fibre reinforced composites have the lowest initial flexural storage modulus value (at room temperature) compared to any other samples. With an increase in banana fibre content in composites, the flexural storage strength is reduced, but not significantly. In fact, there were no significant changes in flexural modulus, such as for samples GBP1001, GBP1002, GBP2501 and GBP2502, but the density and cost of hybrid composites are reduced with the addition of banana fibre. This indicates that low cost banana fibres can be readily used as replacement materials (in limited amounts) in glass fibre composites without significant impact on as-received mechanical properties, thereby decreasing component mass and enhancing cost effectiveness of the composite materials.

Zhu (1994) reported that the strength of short (10 *mm*) random banana fibre reinforced polyester composites decreased with the increase of fibre contents. This can be attributed to weak interfacial bonding between fibre and matrix and probably indicates that the 10 mm fibres are less than the critical fibre length required for optimum stress transfer across the fibre/matrix interface. Indeed, with longer banana fibre strand (100 *mm* length), the flexural strength is enhanced with the increase of banana fibre content.

With further rise in temperature the flexural storage modulus starts decreasing quickly, beginning at the onset temperature of transition. From Tables 4.1, 4.2 and 4.3, it can be observed that the onset temperature ranged from about $30^{\circ}C - 45^{\circ}C$ depending on the composition of hybrid fibre. The onset temperature of the all-banana fibre composites (BP1004, BP2504 and BP4004) was around $33^{\circ}C$ whereas it was at about $37^{\circ}C$ for all-glass fibres composites. The onset temperature of all the other hybrid composites was in between the two extremes. The hybrid composites containing more banana fibres generally exhibit lower onset temperature of glass transition.

Moisture generally decreases bonding strength between fibre and matrix and results in loss of mechanical properties of composites *(Wolff 1993)*. *Satyanarayana (1981)* however, reported that the banana fibres from lower stalk (more water) were actually stronger than from higher portions of the stalk, and furthermore, that banana fibre strength increases with water absorption. So, there are two competing mechanisms; fibre strength and interfacial bonding strength, both of which affect the properties of hybrid fibre composites. From Tables 4.1, 4.2 and 4.3, it can be noticed that the initial flexural storage modulus of all samples decreases with water absorption. This can be attributed to the decrease in interfacial bonding strength between fibre and matrix. Therefore, the effect of interfacial bond strength between fibre and matrix dominates over the gain in fibre properties.

T_g for all samples was observed to decrease with water absorption. The rate of drop in flexural modulus in the second zone, which signifies the slope of the curve in this zone, also decreased with water absorption. The higher the drop rate, the steeper is the curve. From figures 4.4, 4.5 and 4.6, it can be seen that the slope of the curve in the wet condition is lower than in the dry condition.

4.1.2 LOSS TANGENT VERSUS TEMPERATURE

Figures 4.7, 4.8 and 4.9 show the variation in the position of the loss tangent with temperature for 10%, 25% and 40% banana-glass hybrid fibre composites under dry condition, respectively. It is clear from the figures that in general, for all the samples tested, there is practically no change in the loss tangent at the temperature below the onset temperature of glass transition. This indicates glassy behaviour. At temperatures near the glass transition, the loss tangent rises rapidly until it reaches a peak. The peak temperature is indicative of the glass transition temperature (T_g) *(Campbell and White 1989)*. After reaching the peak, the loss tangent falls. At the end of this glass transition region, around 125 $^{\circ}C$, the loss tangent stabilizes indicating rubbery behaviour.

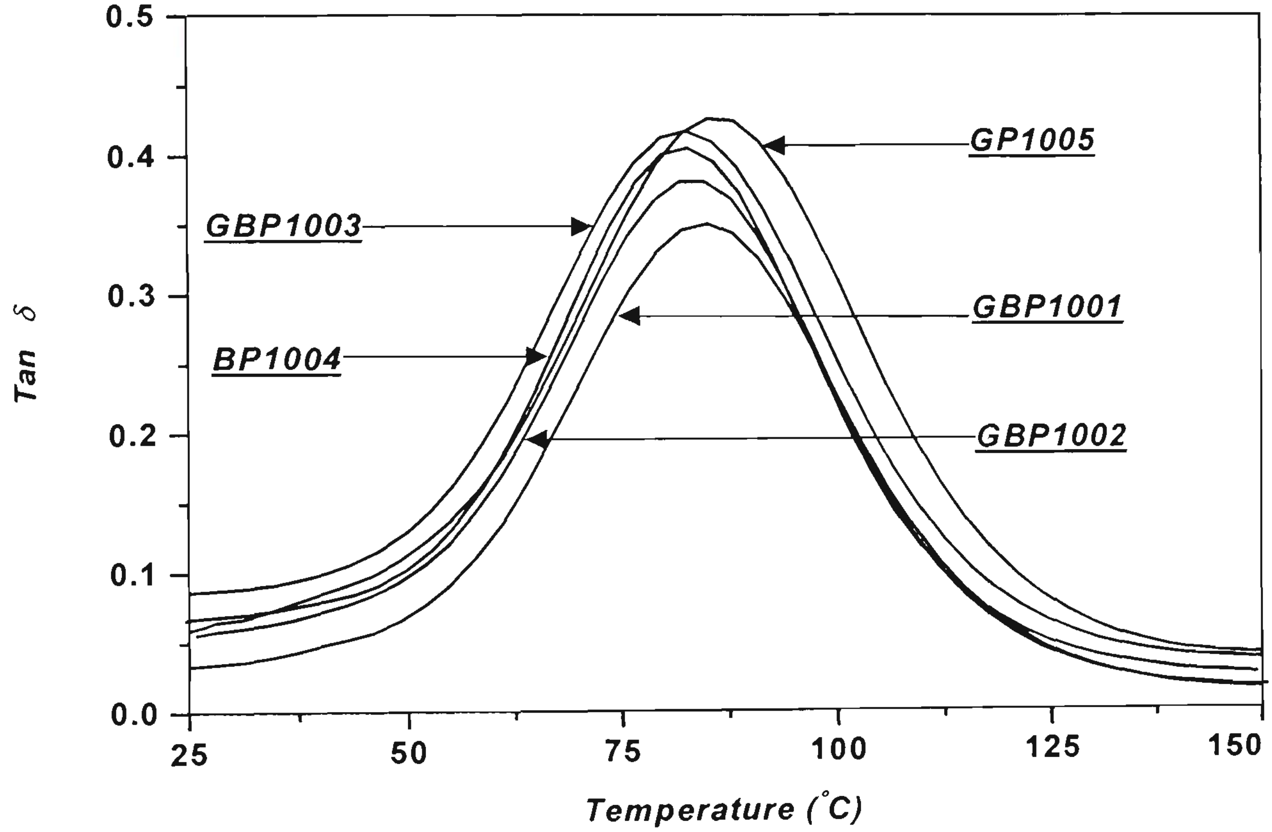


Figure 4.7: The variation in loss tangent with temperature for 10% hybrid fibre composites (dry condition).

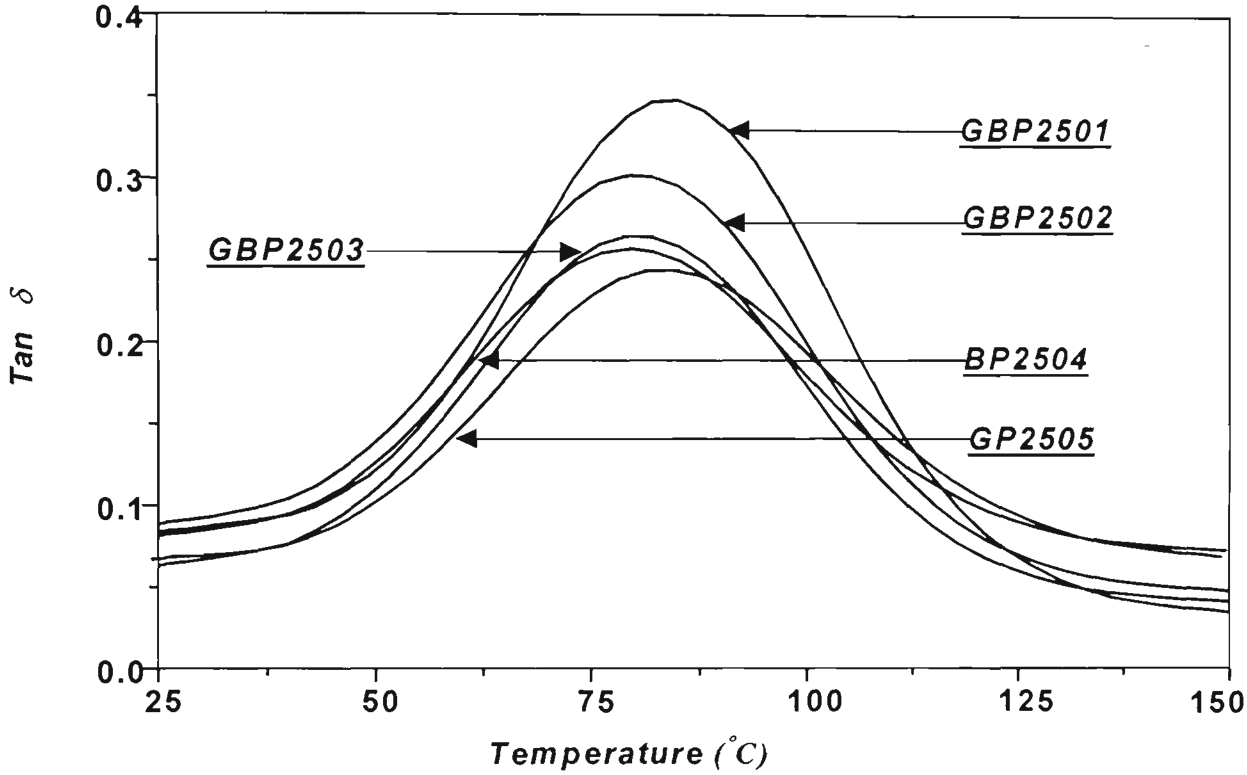


Figure 4.8: The variation in loss tangent with temperature for 25% hybrid fibre composites (dry condition).

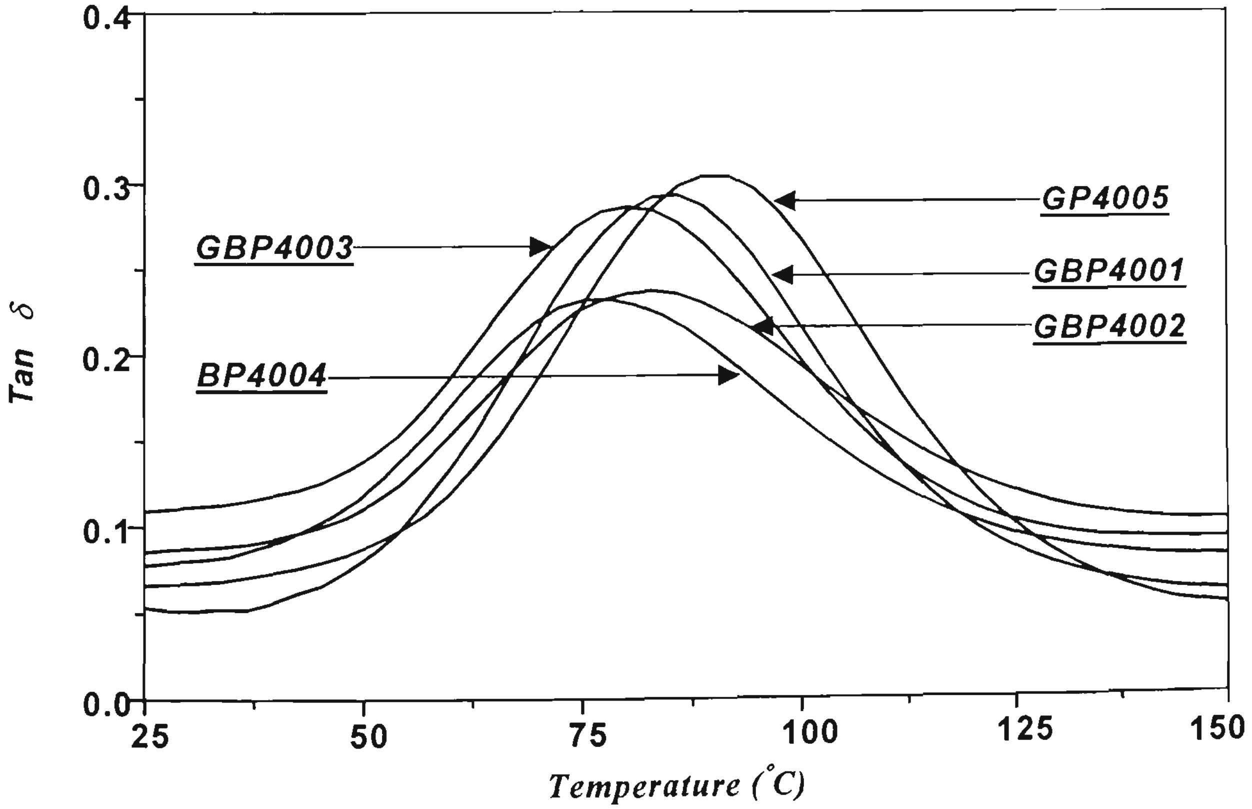


Figure 4.9: The variation in loss tangent with temperature for 40% hybrid fibre composites (dry condition).

The tan δ data for each sample illustrated in Figures 4.7, 4.8 and 4.9 in the dry condition reveal no systematic variation in glass transition temperature in each series. Composites containing all glass fibres have a higher T_g than those containing any amount of banana fibre. No significant variations in T_g are observed as the banana fibre content is changed in each series. Although T_g behaviour in composite materials is generally thought to be largely controlled by the matrix material, the data collected in the current work indicate that the type of fibres also plays a role in determining the thermal behaviour of the composite materials.

Similar trends are apparent in Figures 4,10, 4.11 and 4.12, which represent tan δ vs temperature data for the samples tested under wet conditions. Variations from the dry condition to the wet condition will be discussed at the end of this section.

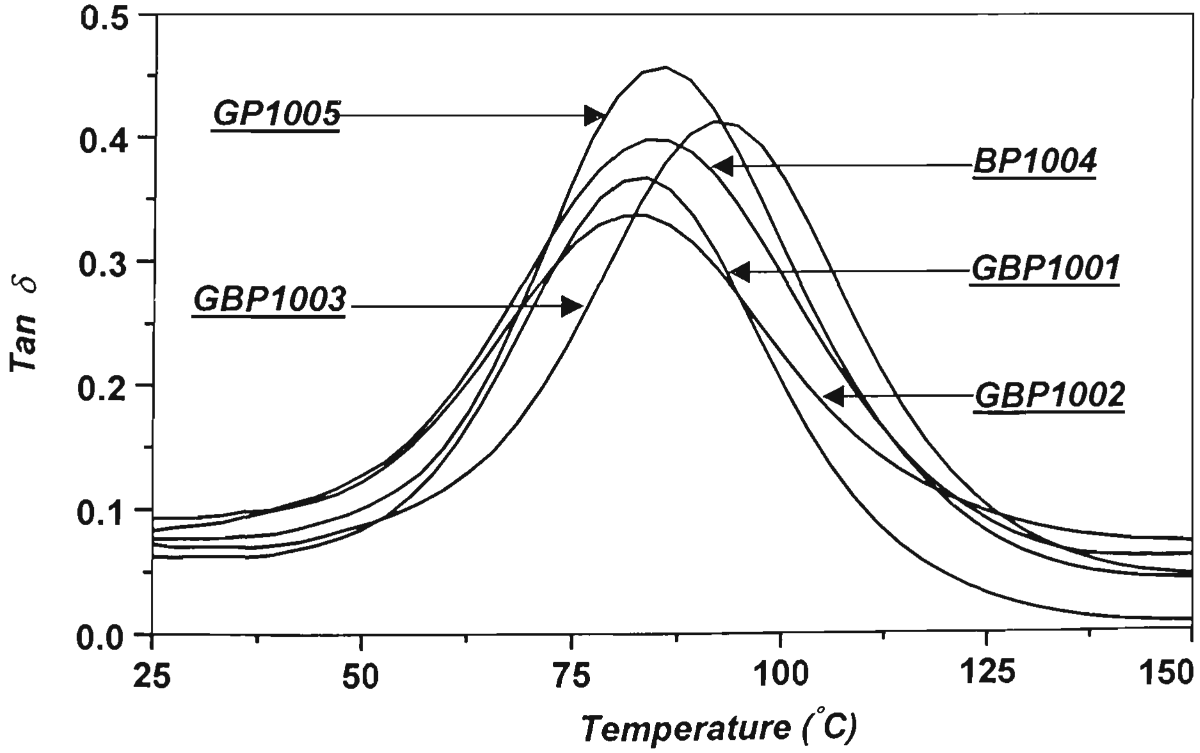


Figure 4.10: The variation in loss tangent with temperature for 10% hybrid fibre composites (wet condition).

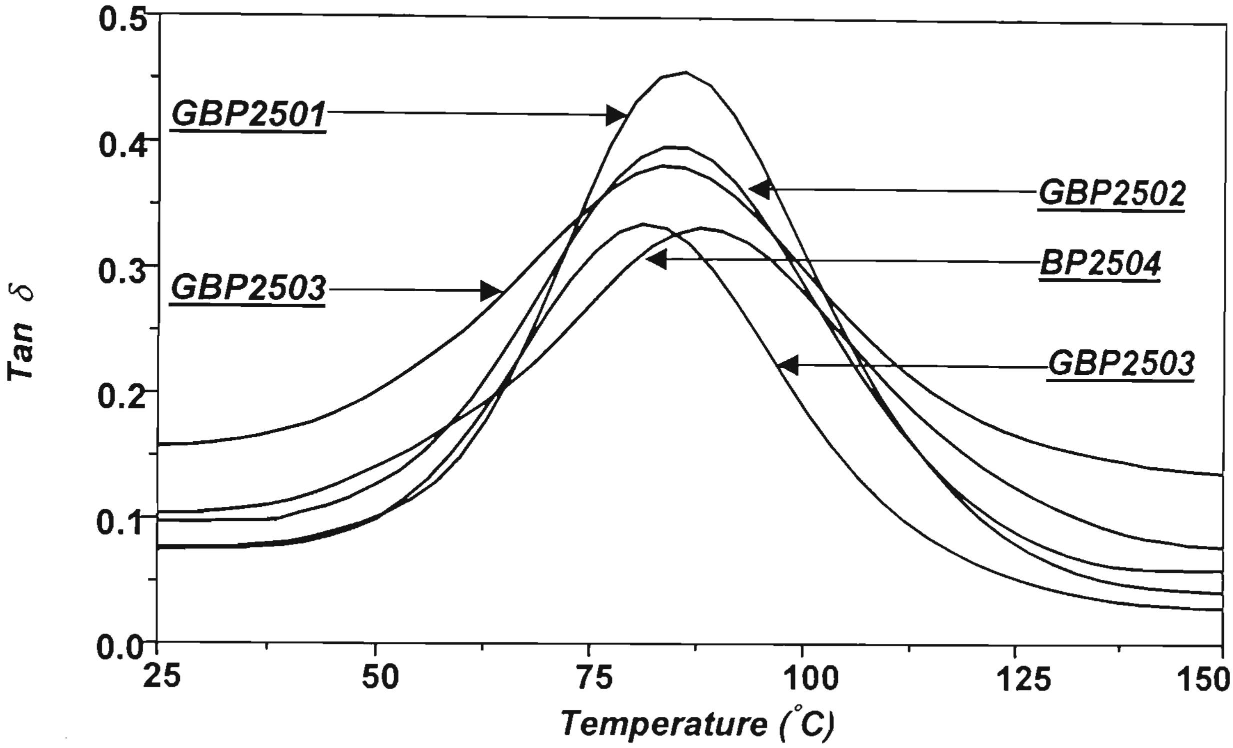


Figure 4.11: The variation in loss tangent with temperature for 25% hybrid fibre composites (wet condition).

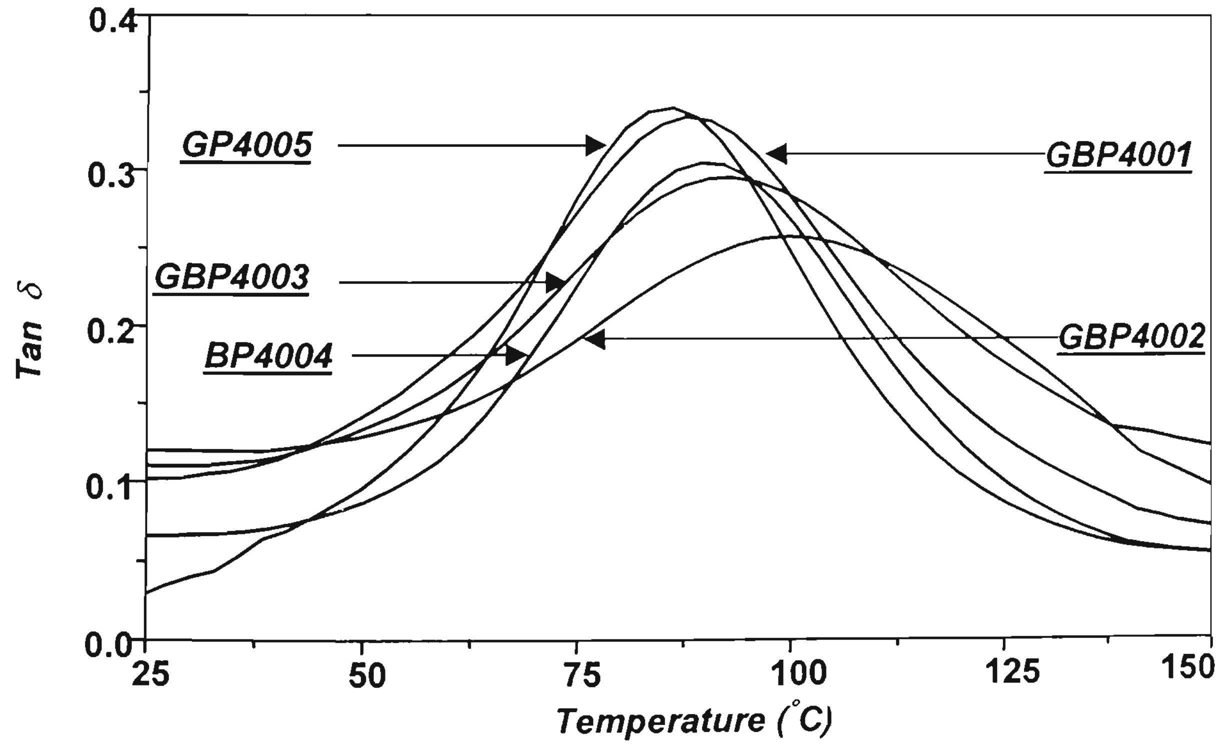


Figure 4.12: The variation in loss tangent with temperature for 40% hybrid fibre composites (wet condition).

The rate of increase in the loss tangent (in the glass transition zone) of all samples is given in Tables 4.4, 4.5 and 4.6 along with their glass transition temperature (T_g) in both the dry and wet condition. T_g data were based on the average of three measurements, accurate to ±3°C.

Table 4.4 Comparison of T_g and the rate of loss tangent variation between dry and wet condition for 10% hybrid composites.

Sample ID	T_g *($^\circ C$)*		**Rate of increase in loss tangent in the glass transition zone** *($/ ^\circ C \times 100$)*	
	Dry	**Wet**	**Dry**	**Wet**
GBP1001	84	84	0.75	0.86
GBP1002	82	83	0.81	0.90
GBP1003	83	89	0.84	0.64
BP1004 (all banana)	82	85	0.85	0.84
GP1005 (all glass)	86	84	0.72	0.91

Table 4.5 Comparison of T_g and the rate of loss tangent variation between dry and wet condition for 25% hybrid composites.

Sample ID	T_g *($^\circ C$)*		**Rate of increase in loss tangent in the glass transition zone** *($/ ^\circ C \times 100$)*	
	Dry	**Wet**	**Dry**	**Wet**
GBP2501	85	83	0.72	0.86
GBP2502	83	83	0.75	0.87
GBP2503	82	82	0.78	0.82
BP2504 (all banana)	79	87	0.87	0.81
GP2505 (all glass)	86	81	0.65	0.86

Table 4.6 Comparison of T_g and the rate of loss tangent variation between dry and wet condition for 40% hybrid composites.

Sample ID	**T_g (°C)**		**Rate of increase in loss tangent in the glass transition zone (/ °C × 100)**	
	Dry	**Wet**	**Dry**	**Wet**
GBP4001	86	85	0.69	0.72
GBP4002	81	88	0.81	0.77
GBP4003	79	87	0.82	0.71
BP4004 (all banana)	77	86	0.89	0.80
GP4005 (all glass)	89	81	0.63	0.68

Figures 4.13, 4.14, and 4.15 show the variations in T_g with banana fibre volume fractions of 10%, 25% and 40% hybrid fibre composites in both the dry and wet conditions, respectively.

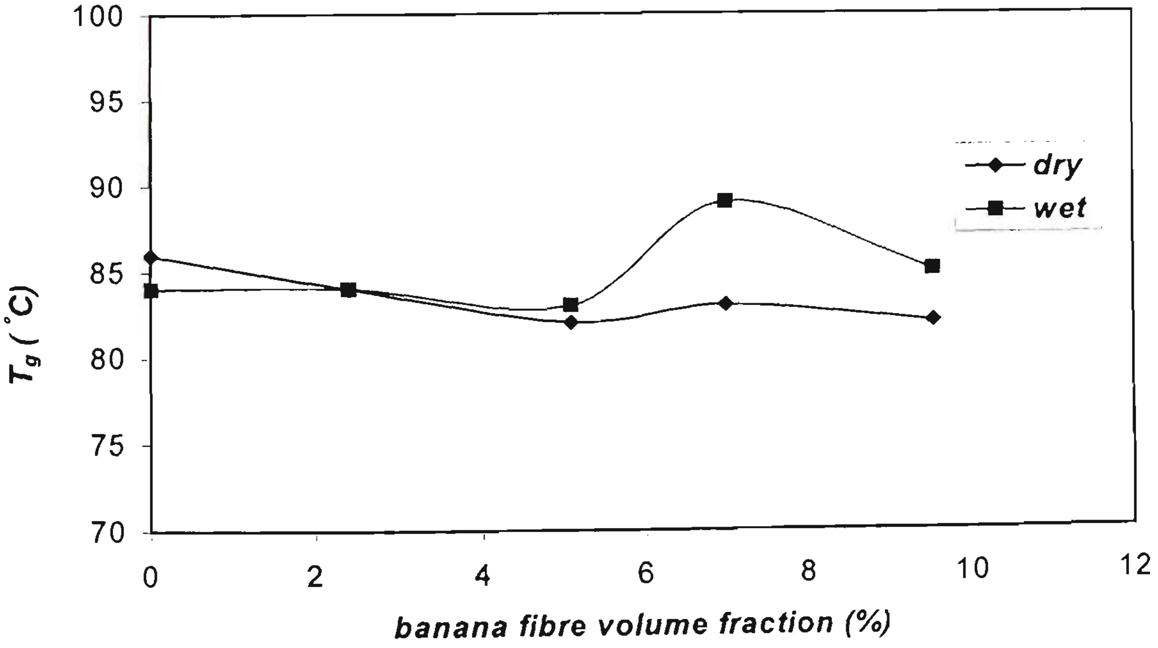


Figure 4.13: Tg vs banana fibre volume fraction (10% hybrid fibres)

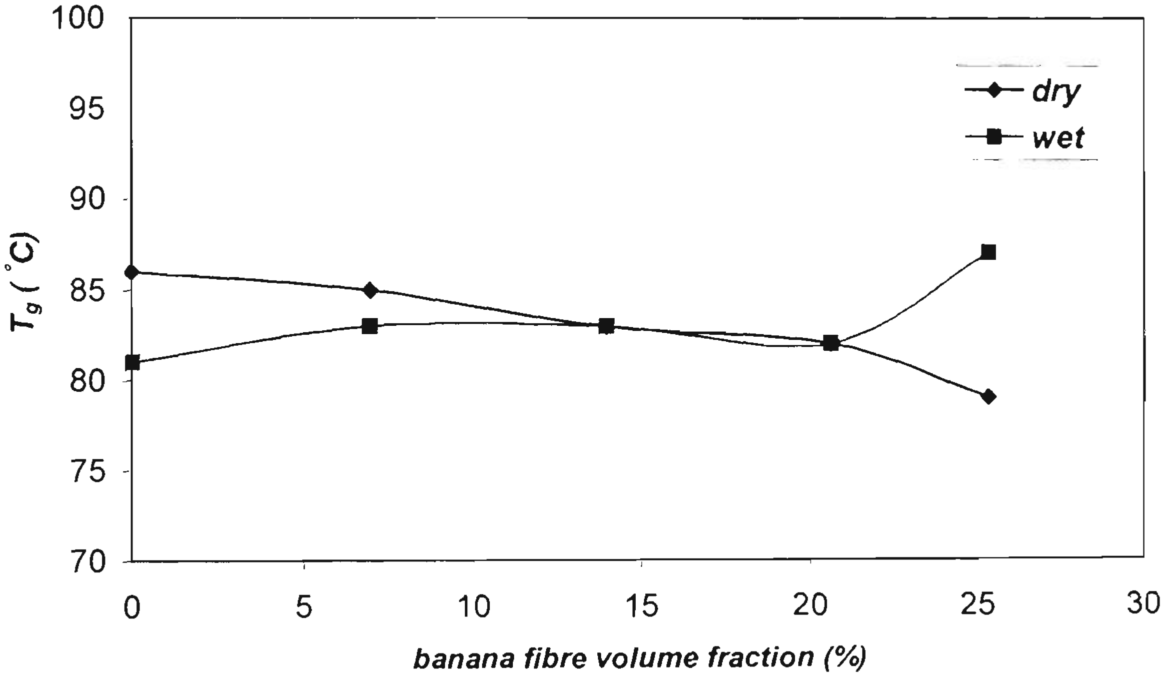


Figure 4.14: Tg vs banana fibre volume fraction (25% hybrid fibres)

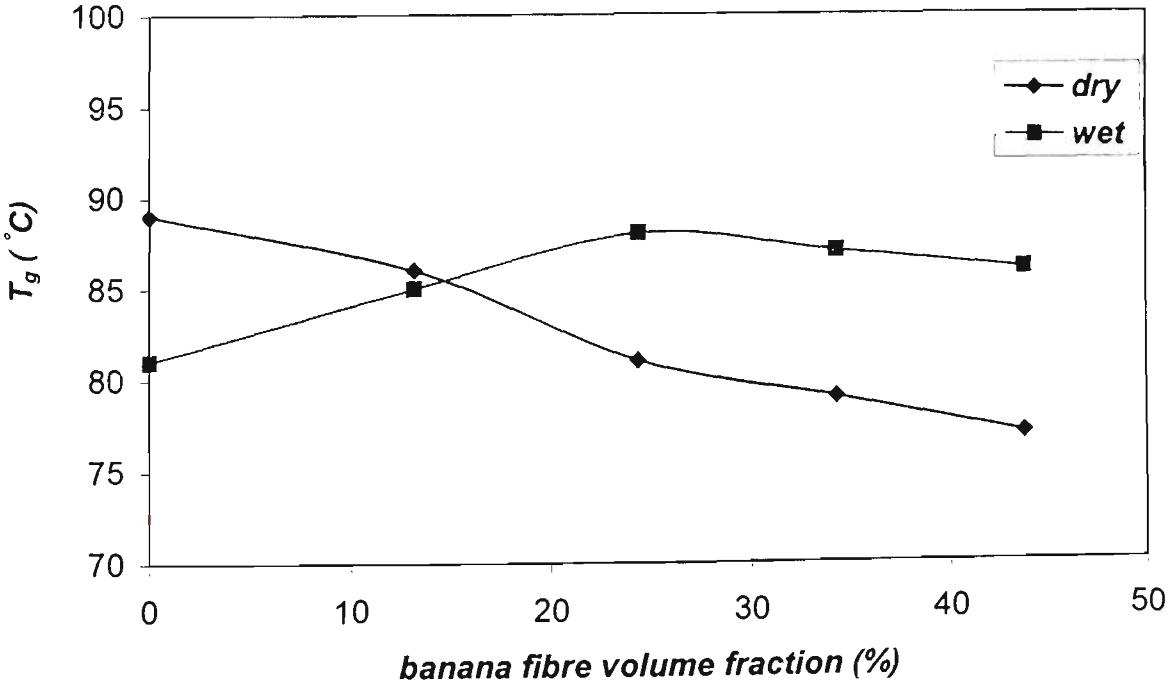


Figure 4.15: Tg vs banana fibre volume fraction (40% hybrid fibres)

From Tables 4.4, 4.5 and 4.6, in dry condition, it can be noticed that the all-glass fibre composites have the highest initial (dry) T_g compared to any other hybrid composites. With increasing glass fibre content, T_g increases, from that of GP1005 (10% all glass) to that of GP4005 (40% all glass). In contrast, the all-banana fibre composite having 40% fibre content, BP4004, has the lowest initial T_g. In Figures 4.13, 4.14 and 4.15, the other hybrid composites lie in between these two extremes. No significant change in the T_g is observed with different banana and glass hybrid volume fractions, among the GBP1000, GBP2500 and GBP4000 series samples. It is interesting to note a general trend of increasing T_g with increasing banana fibre content in the wet composites. This is presumably due to the phenomenon reported earlier by *Satyanarayana (1981)* where the banana fibre stiffness increases over the initial stages of water absorption. Although possibly counter-intuitive, it is proposed that this effect plays a significant role in the wet-behaviour of the hybrid composites. As discussed briefly, although the glass transition behaviour is normally thought to be controlled primarily by the matrix material, different T_g behaviour exists between the all-glass and all-banana fibre reinforced materials. It is reasonable to assume therefore, that any changes in mechanical properties of the banana fibres will be reflected in a change in the overall T_g behaviour. In this case, the observed behaviour is likely explained by the increased fibre stiffness in the wet state leading to greater reinforcement and causing glassy behaviour to be maintained to higher temperatures than in the dry state.

The glass transition temperature of most of the hybrid composites fell in the narrow temperature range of $81^{\circ}C$-$85^{\circ}C$. Composites fabricated from hybrid fibres may therefore be expected to perform adequately in service conditions of high ambient temperature and high humidity, such as those encountered in tropical regions. The data indicate that the materials tested will remain glassy and stiff, even when wet, provided the temperature does not reach ~$81^{\circ}C$-$85^{\circ}C$.

The rate of increase in loss tangent of the hybrid composite is dependent on the glass/banana fibre volume fraction. It can be observed that the rate of increase in loss tangent of the all-banana fibre specimens is higher when dry than the other hybrid specimens. With the addition of glass fibres the rate of increase in loss tangent decreases. When wet, the same conclusion is true for most of the samples. *Satyanarayana et al. (1984)* reported that the banana fibres are hygroscopic, and they are stiffened by water absorption to some degree. In fact, the banana fibres or the fibre/matrix interfaces are influenced more by the presence of water than the glass fibres. Therefore, when there are no glass fibres to damp out this effect, the influence is most greatly felt.

Water absorption may generally decrease the glass transition temperature of fibre reinforced composites *(Springer 1982 and Selzer 1997 and Friedrich)*. From Tables 4.4, 4.5 and 4.6, it can be seen that T_g of all-glass reinforced composites (GP1005, GP2505 and GP4005) decreases by 2 to $8\,^{\circ}C$ with water absorption. T_g of hybrid composites having more glass fibres (GBP1001, GBP2501 and GBP4001) either remains the same or increases with water absorption. With increasing banana fibre volume fraction, T_g of wet samples is higher than that of dry samples for the GBP4000 series.

4.2 STATIC MECHANICAL PROPERTIES

The flexural strength and flexural modulus of hybrid composites are given in Table 4.7. The flexural strength was calculated using equation (2.3) after obtaining experimental values of P_{max}. The flexural modulus was calculated using equation (2.4).

Table 4.7 Static mechanical properties of hybrid composites.

Sample ID	**Density** *(g/cm³)*	**Water absorption** *(%)* **(24 hours at room temperature)**	**Flexural strength** *(MPa)*		**Flexural modulus** *(GPa)*	
			Dry	**Wet**	**Dry**	**Wet**
GBP1001	1.13	1.72	81.40	62.88	2.76	2.69
GBP1002	1.09	3.46	37.40	42.03	2.47	2.27
GBP1003	1.06	3.76	34.79	30.85	2.04	1.72
BP1004	1.04	6.86	34.49	25.18	1.59	1.58
GP1005	1.13	1.28	108.89	95.44	3.41	3.10
GBP2501	1.10	1.69	135.69	134.2	4.34	3.39
GBP2502	1.09	3.17	102.40	75.94	3.48	2.67
GBP2503	1.06	7.86	74.31	63.12	2.13	1.20
BP2504	1.02	15.74	19.35	18.48	0.90	0.90
GP2505	1.24	1.45	169.54	168.20	4.71	4.08
GBP4001	1.19	4.17	114.08	119.43	5.97	4.23
GBP4002	1.14	4.82	74.44	59.65	2.41	1.29
GBP4003	1.12	9.82	49.23	24.05	1.59	0.70
BP4004	1.01	20.13	13.81	10.52	0.56	0.20
GP4005	1.32	2.94	165.54	125.47	6.18	4.35

Figures 4.16, 4.17 and 4.18 show the variation in flexural strength with banana fibre volume fractions of 10%, 25% and 40%, respectively, in both dry and wet conditions. The variation in flexural modulus with banana fibre volume fractions is given in Figures 4.19, 4.20 and 4.21. Again, the influence of the increased stiffness observed with wet banana fibres as reported by *Satyanarayana (1981)* is seen. This is particularly prevalent in the case of the high fibre content composites in Figure 4.21, where the initial gap in stiffness between wet and dry materials is less pronounced for higher banana fibre contents. The water absorption vs. banana fibre volume fraction is illustrated in Figures 4.22, 4.23 and 4.24 over 10%, 25% and 40% hybrid fibres in both dry and wet conditions.

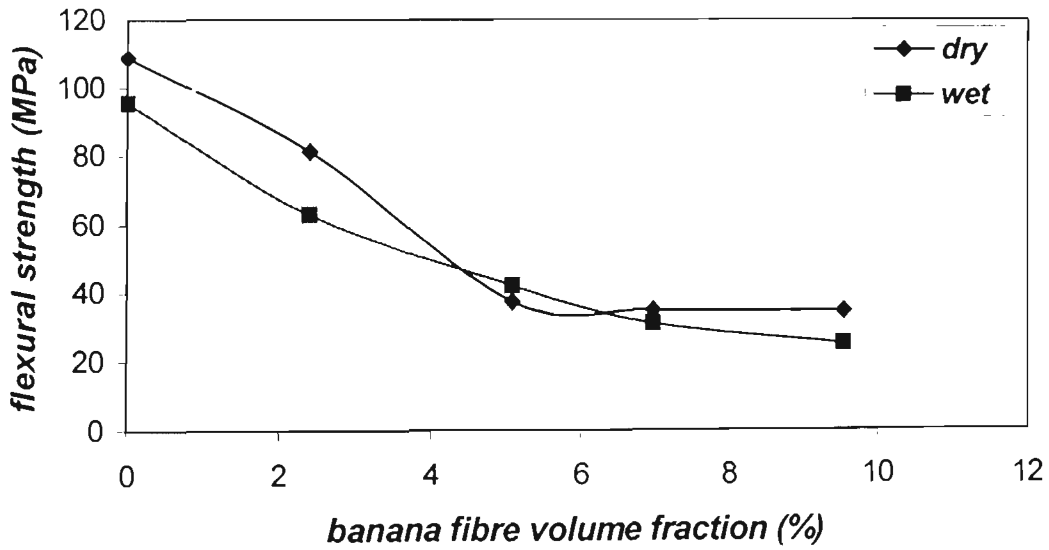


Figure 4.16: The flexural strength vs banana fibre volume fraction (10% hybrid fibres)

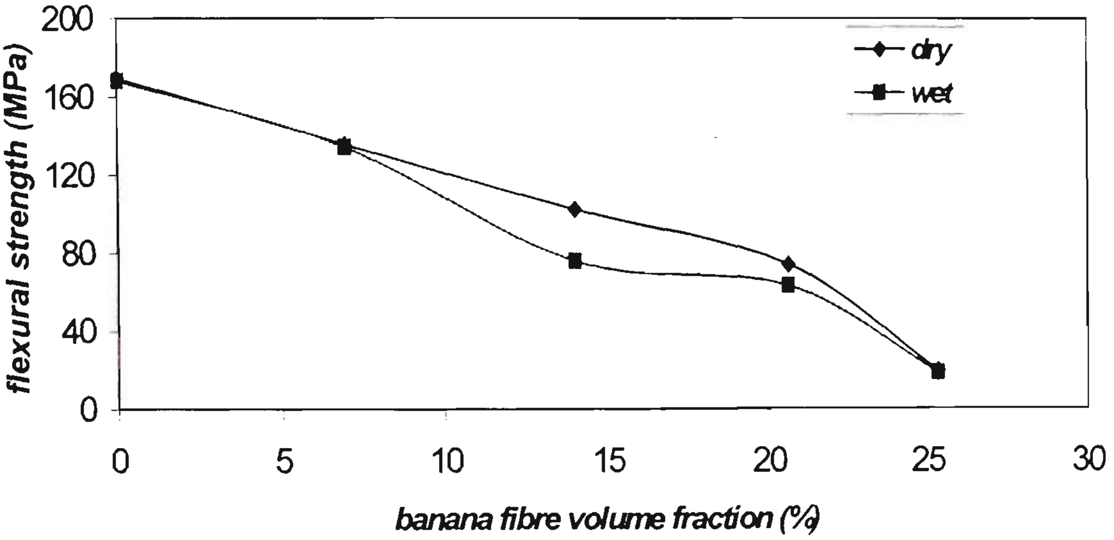


Figure 4.17: The flexural strength vs banana fibre volume fraction(25% hybrid fibres)

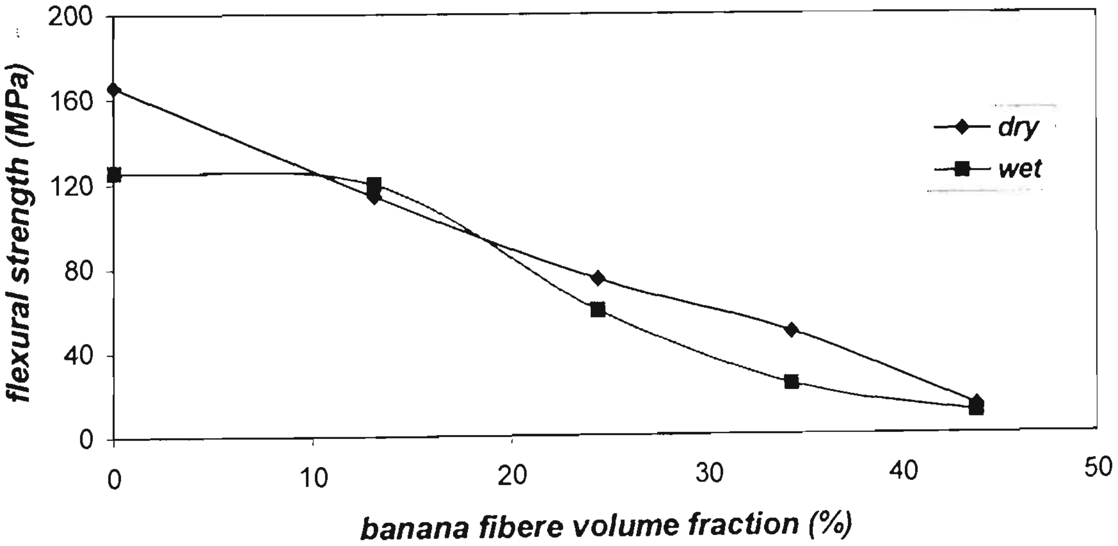


Figure 4.18: The flexural strength vs banana fibre volume fraction (40% hybrid fibres)

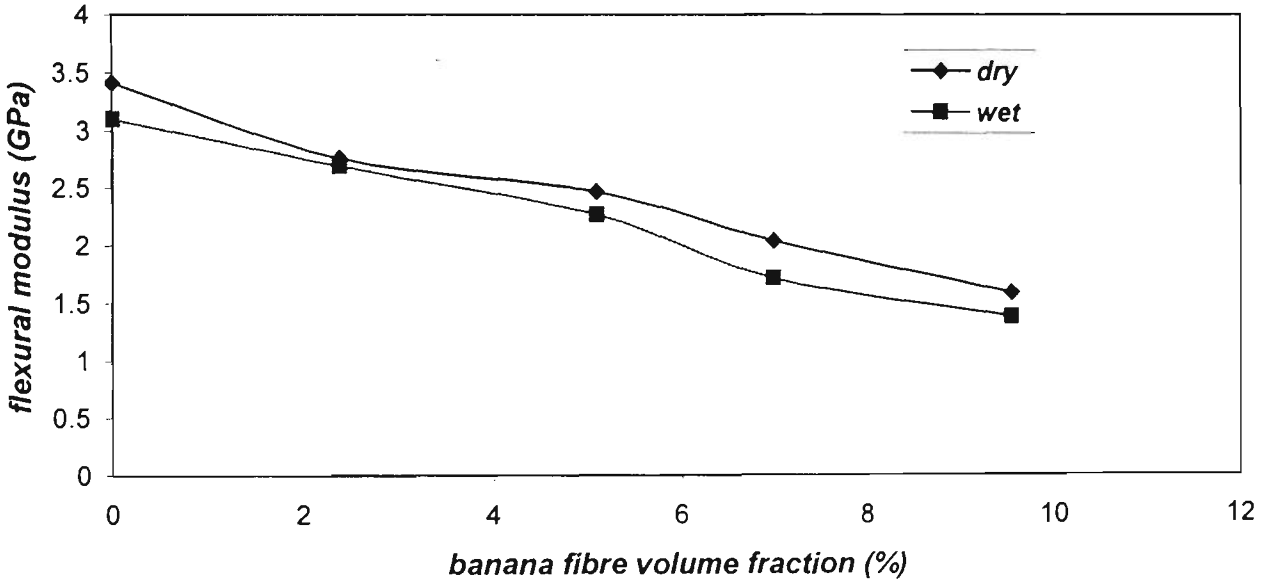


Figure 4.19: The flexural modulus vs banana fibre volume fraction (10% hybrid fibres)

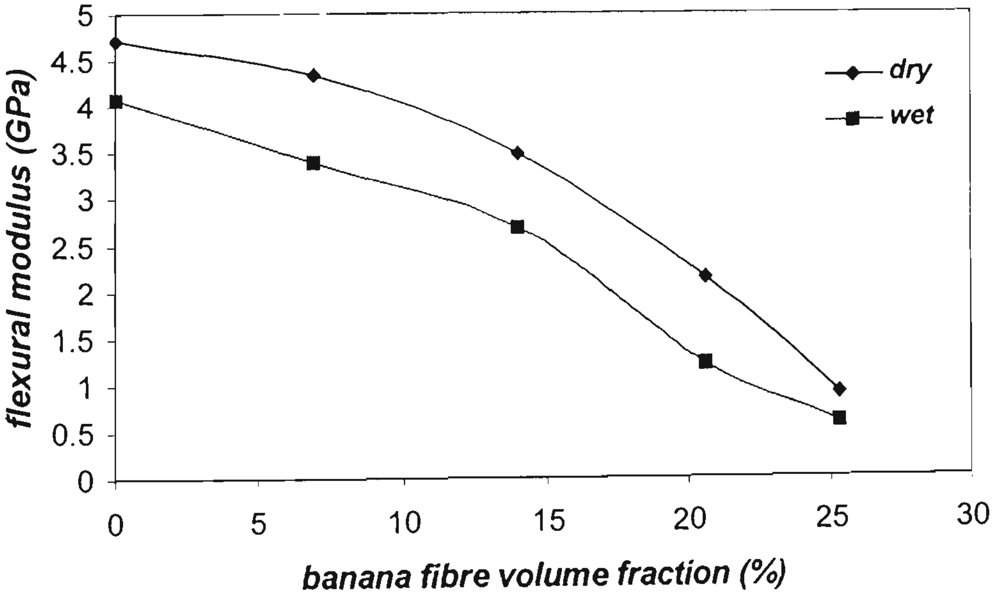


Figure 4.20: The flexural modulus vs banana fibre volume fraction (25% hybrid fibres)

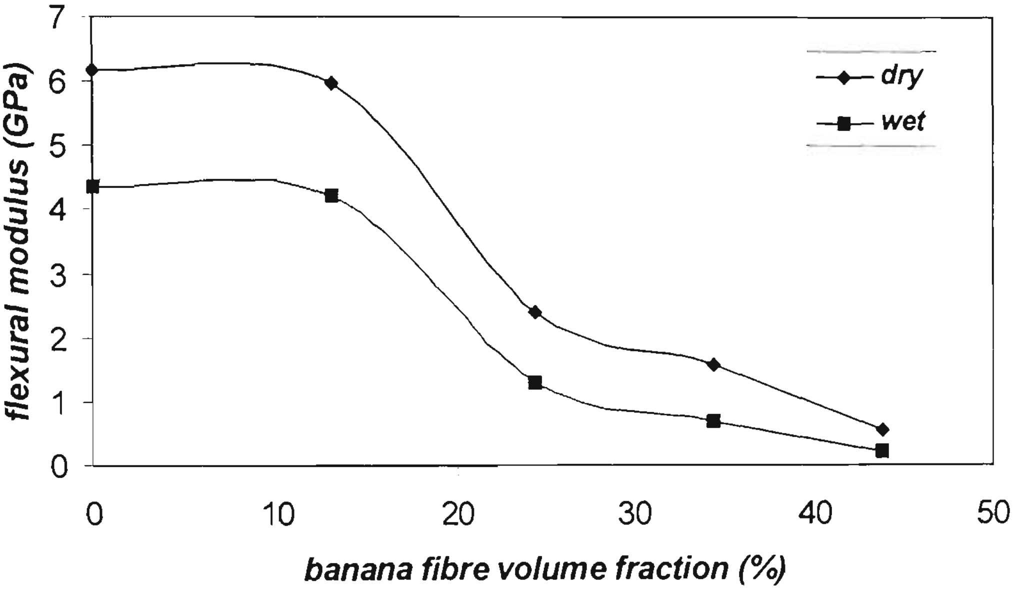


Figure 4.21: The flexural modulus vs banana fibre volume fraction (40% hybrid fibres)

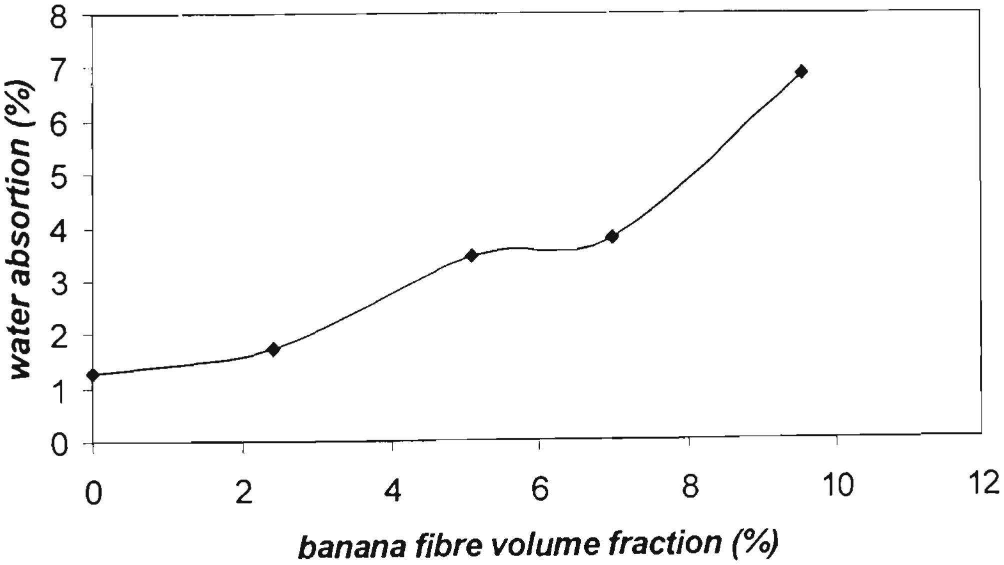


Figure 4.22: Water absorption vs banana fibre volume fraction (10% hybrid fibres)

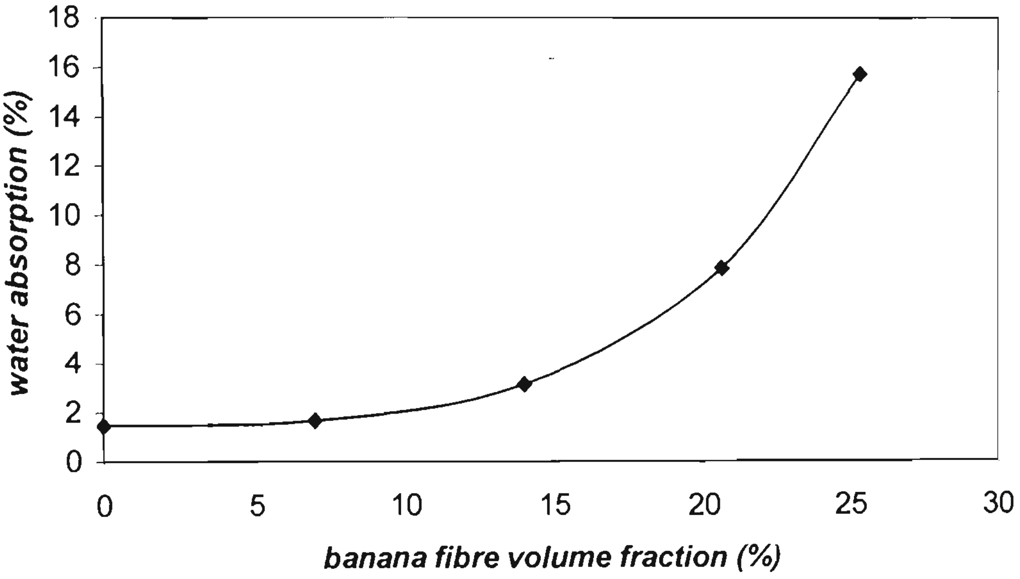


Figure 4.23: Water absorption vs banana fibre volume fraction (25% hybrid fibres)

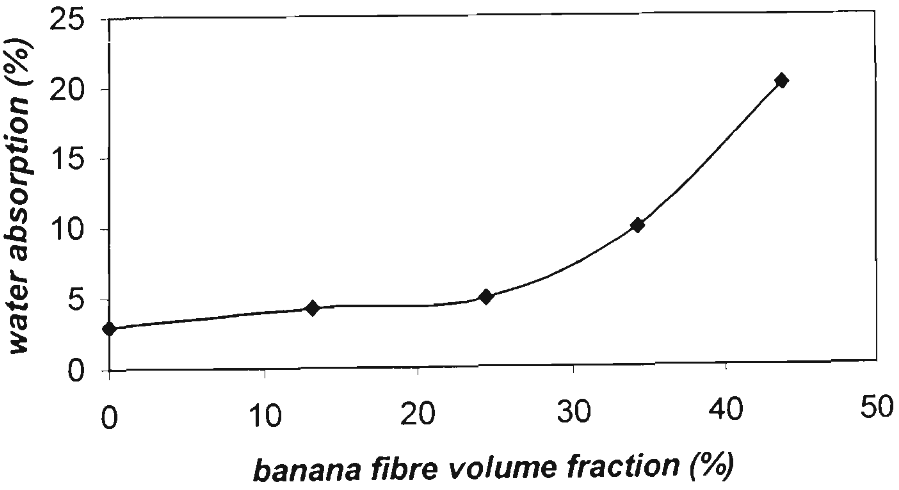


Figure 4.24: Water absorption vs banana fibre volume fraction (40% hybrid fibres)

From Table 4.7, it is seen that the flexural strength and modulus increase with hybrid fibre content from 10% to 25%. All-glass fibre composites have higher value of both strength and modulus. The strength of banana fibres is considerably less than that of glass fibres, so that with addition of banana fibre in hybrid composites, the strength and modulus of hybrid composites decrease. This is most obvious in the 40% hybrid group.

A similar effect of water absorption to that shown in dynamic and static mechanical behavior is also observed with the static properties. The flexural strength and modulus of all hybrid composites decreases with water absorption. The biggest change in modulus value is observed in 40% hybrid fibre composites, as seen in Figure 4.21. From Figures 4.22, 4.23, and 4.24, the amount of water absorption in hybrid composites increases with addition of banana fibres. In Table 4,7, the hybrid composites having more banana fibres have lower density compared with those having more glass fibres.

In Figures 4.25 to 4.30, load deflection curves are given for 10% to 40% hybrid composites. Although the inclusion of banana fibres causes a slight deterioration in properties of hybrid composites, this deterioration is certainly not so significant as to preclude these hybrid composites' use in certain applications, such as inexpensive building materials for developing tropical countries. The addition of banana fibres brings the benefit of low cost and low density(as shown in Table 4.7) for this service condition.

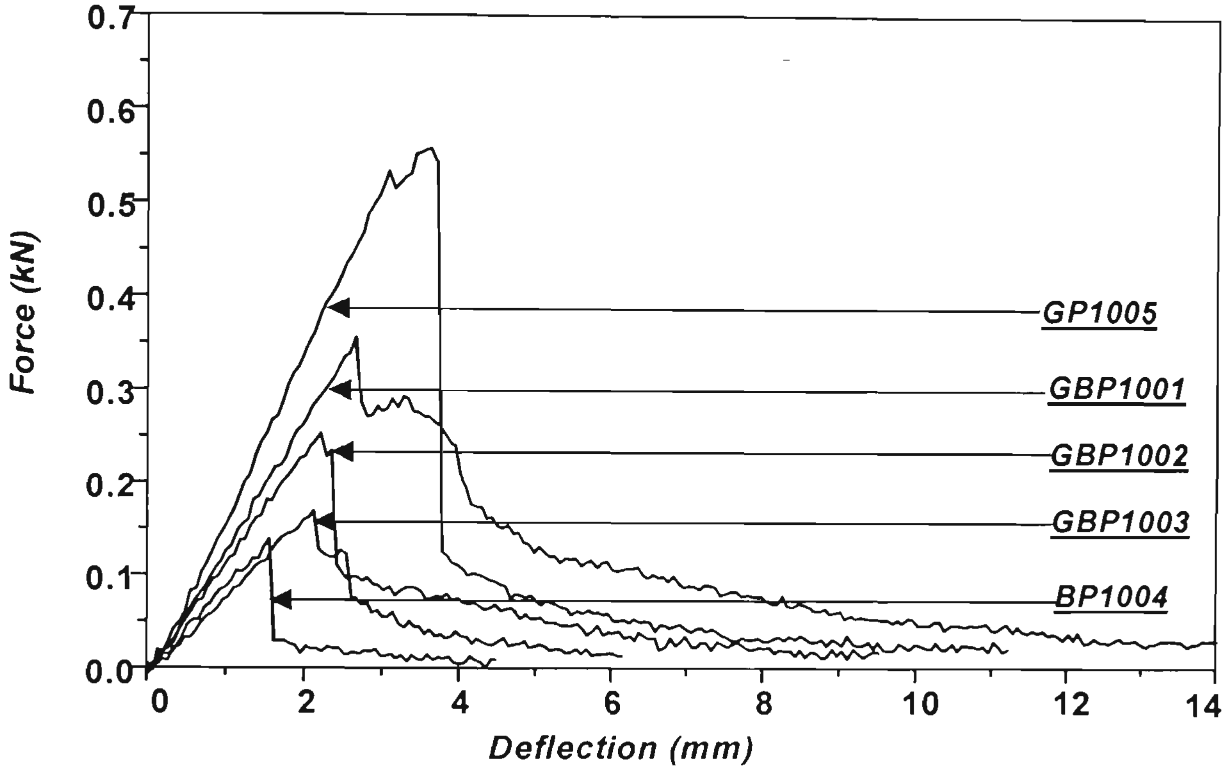


Figure 4.25 Load deflection curve for 10% hybrid composites (dry condition).

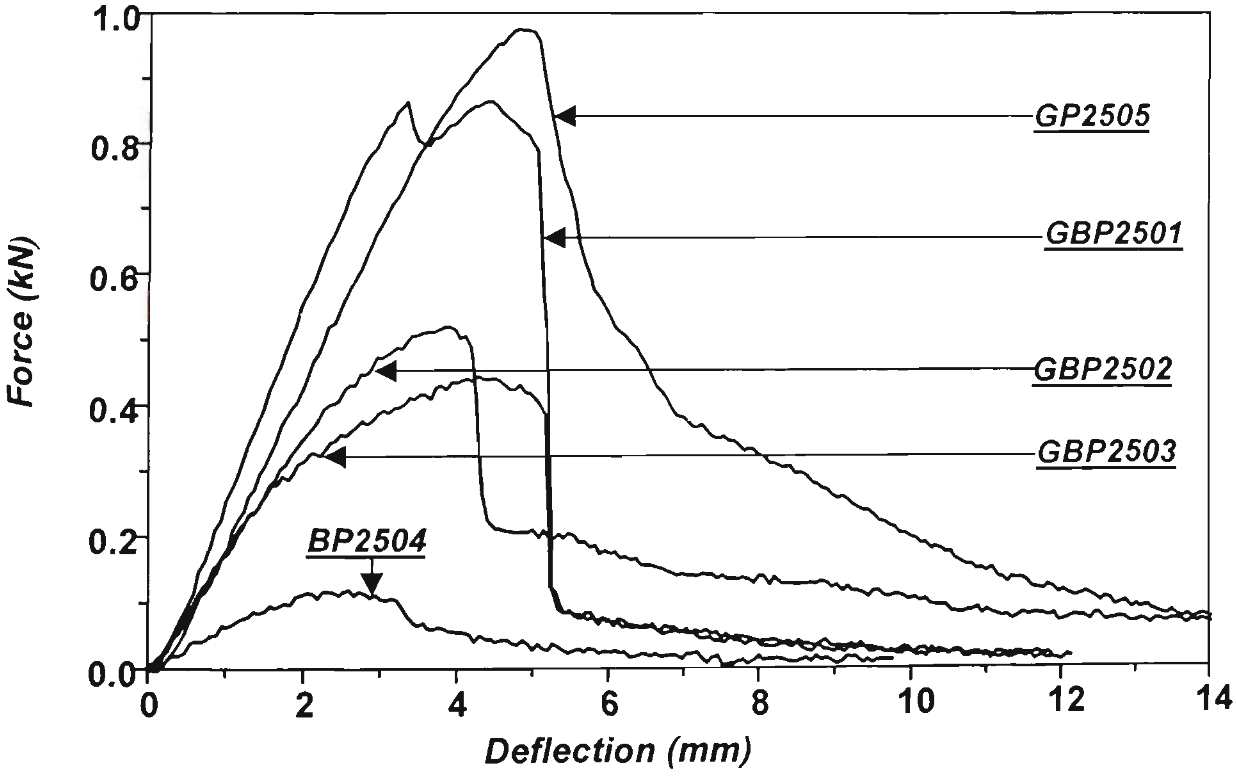


Figure 4.26 Load deflection curve for 25% hybrid composites (dry condition).

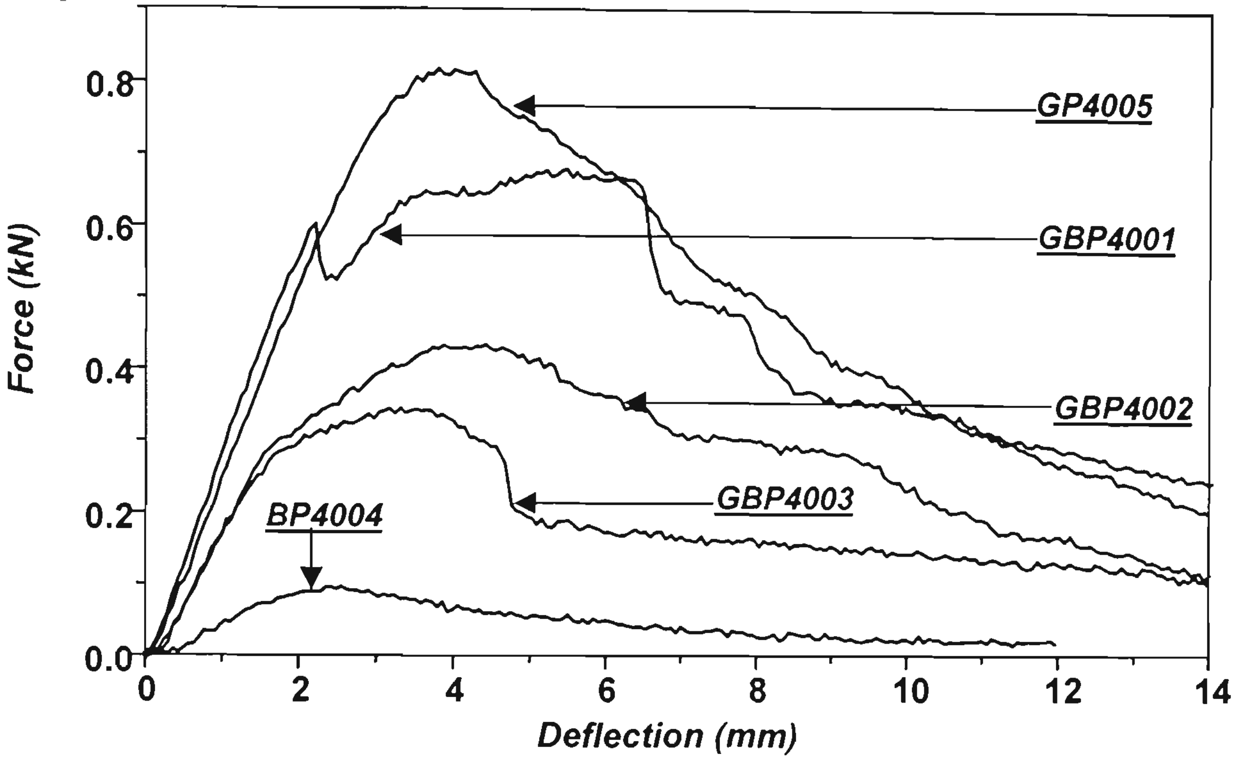


Figure 4.27 Load deflection curve for 40% hybrid composites (dry condition).

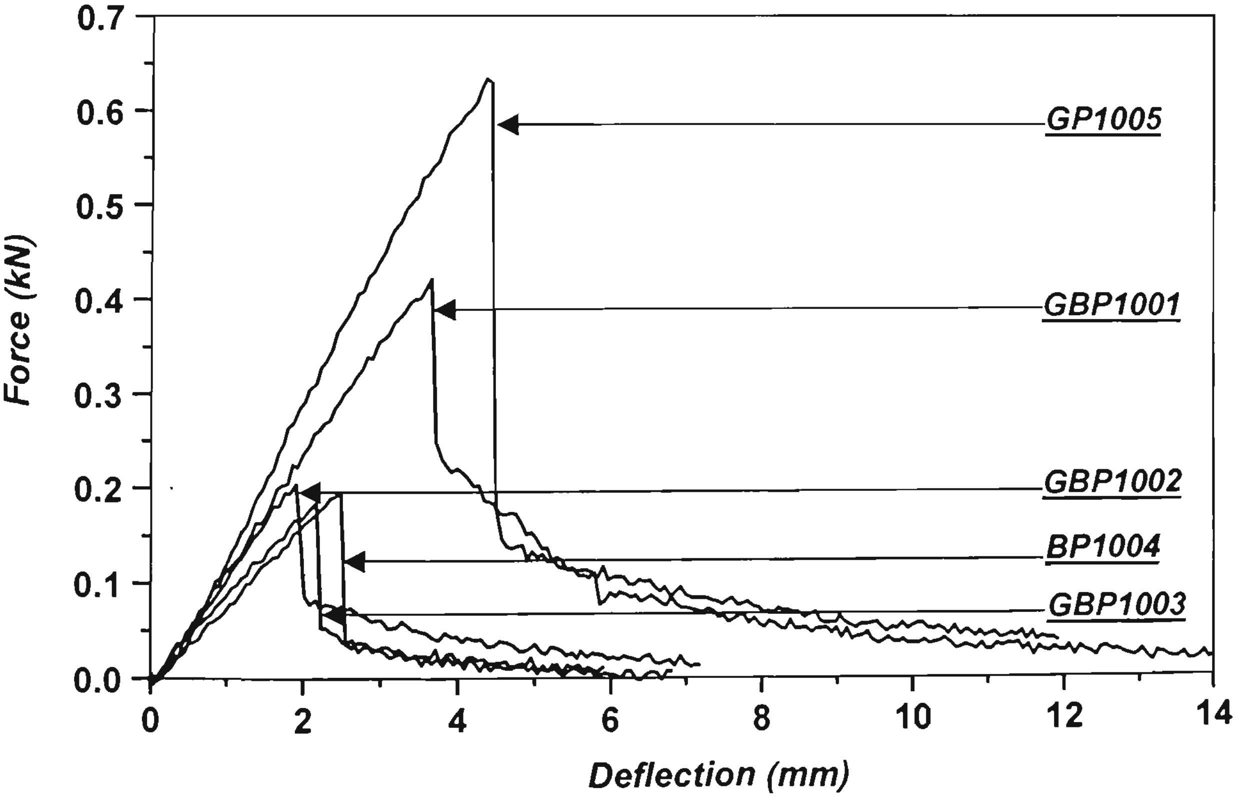


Figure 4.28 Load deflection curve for 10% hybrid composites (wet condition).

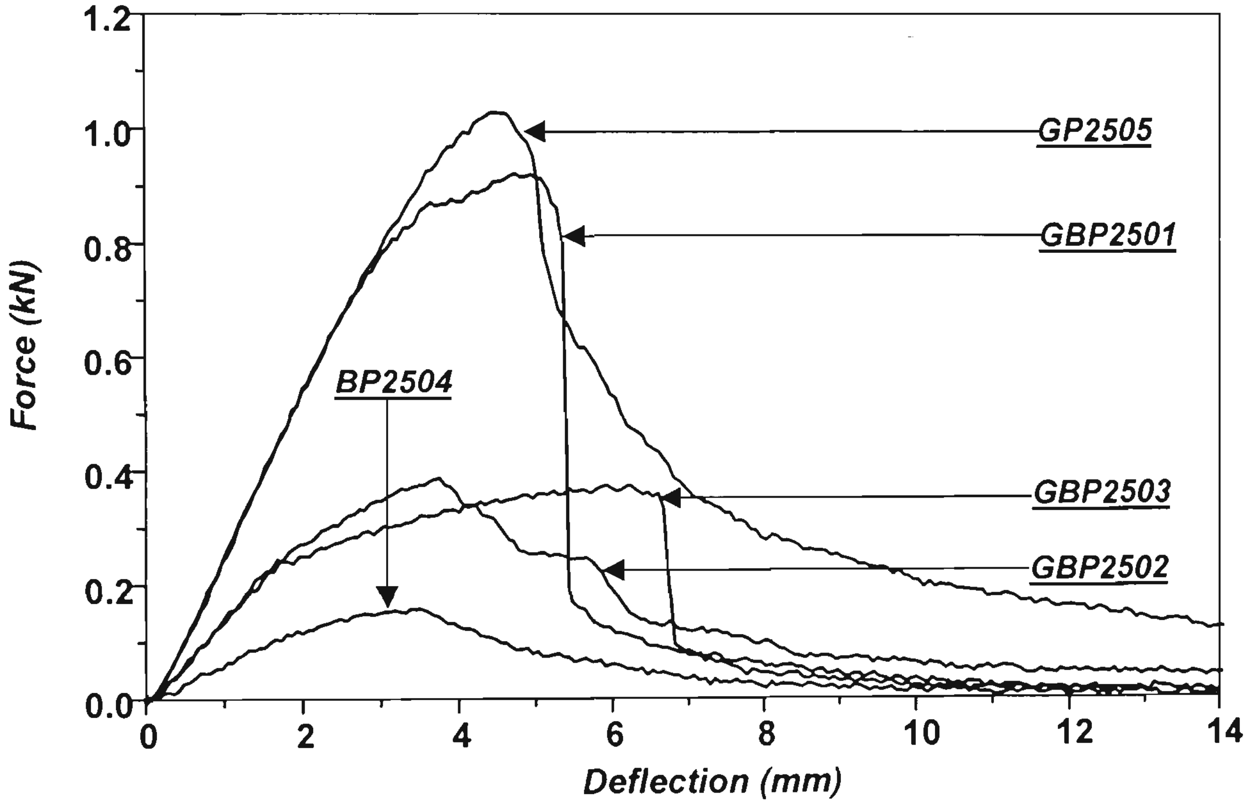


Figure 4.29 Load deflection curve for 25% hybrid composites (wet condition).

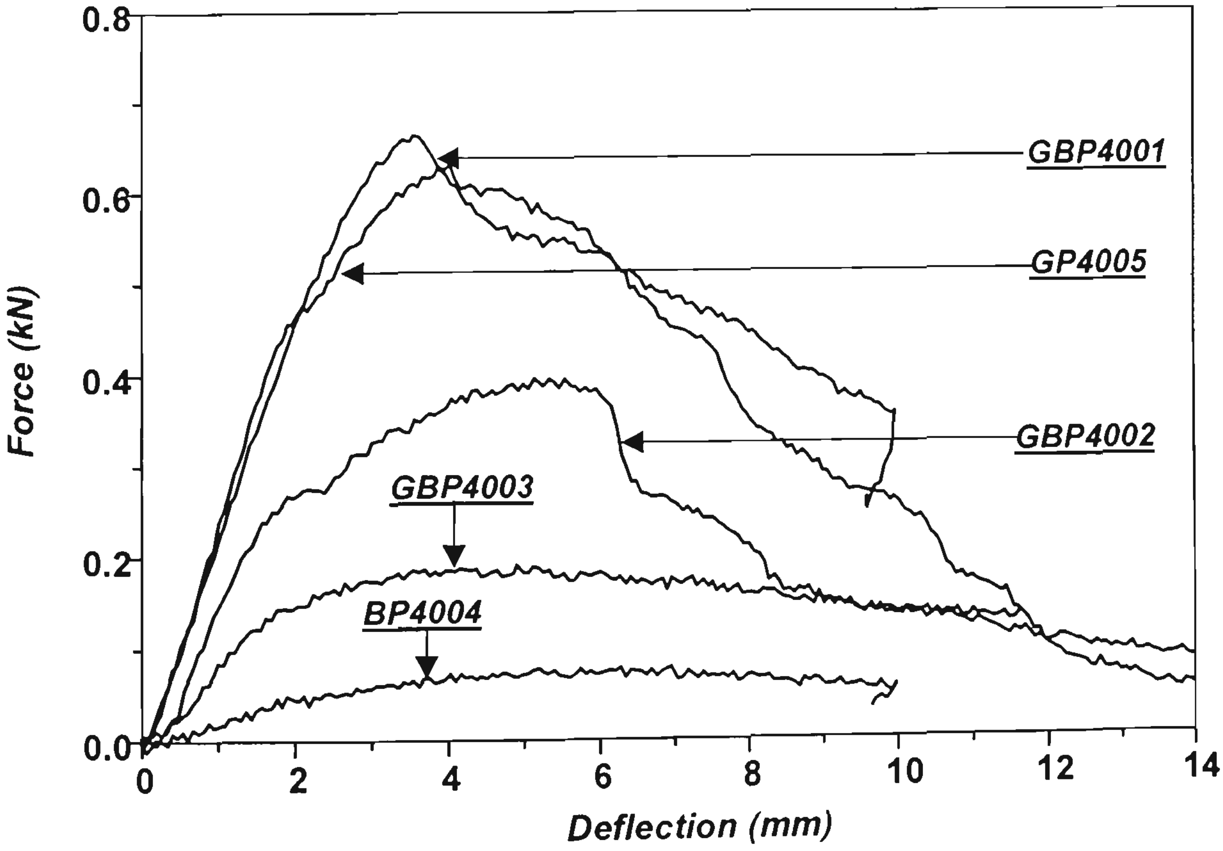


Figure 4.30 Load deflection curve for 40% hybrid composites (wet condition).

Chapter 5

Conclusions

The banana-glass hybrid fibre reinforced polyester composite materials were fabricated. Techniques for the fabrication of hybrid composites have been reported.

The dynamic mechanical analysis techniques have been used to investigate the effect of temperature and absorbed moisture on the dynamic mechanical properties of glass-banana hybrid fibre composites. Dynamic mechanical analysis testing conducted in the temperature scan mode, using a dynamic mechanical analyzer, was effective in characterizing the hybrid fibre composites over a wide temperature range. The following conclusions can be drawn from the data:

1) Dynamic mechanical analysis, which requires small sized samples, can provide sensitive insight into the behavior of hybrid composite materials over a wide temperature range.

2) The dynamic mechanical behavior exhibited by the hybrid fibre composite materials at room temperature is not representative of their characteristics at higher temperature. The degradation in flexural storage modulus with higher temperature is quite apparent. Also, there is significant variation in loss tangent at higher temperatures.

3) The flexural storage modulus exhibited by the hybrid composites is dependent on hybrid fibre volume fraction. With increasing glass fibre content, the storage modulus increases. In contrast, with increasing banana fibre content the storage modulus decreases.

4) In general, the rate of change in flexural modulus and loss tangent (in the glass transition zone) is found to be dependent on the hybrid fibre contents, glass fibre and banana fibre volume fractions.

5) The storage modulus exhibited by the hybrid fibre composites is reduced under the wet conditions. Although the banana fibre stiffness increases by water absorption, the fact that this increase in stiffness is not reflected in the mechanical properties of the composite material leads to the conclusion that the interfacial strength is compromised by the absorption of water. The effect of interfacial bond strength between fibre and matrix dominates over the gains in fibre stiffness brought about by water absorption.

6) Stiffness of the hybrid composite materials decreases with increased banana fibre content, and wet stiffness is generally less than dry stiffness. At higher banana fibre contents, the wet stiffness of the materials does not decrease at the same rate as that in the dry materials with increased banana fibre content, indicating that the wet stiffening effect begins to contribute to an enhancement of mechanical properties.

7) All-glass fibre reinforced composites have the highest glass transition temperature and all-banana fibre reinforced composites have the lowest glass transition temperature. No significant improvement in the glass transition temperature is observed with different hybrid fibre contents.

The investigation of static flexural test was carried out to determine the rigidity of hybrid fibre composite materials. The static properties of hybrid composites do not appear to deteriorate to a significant degree under the wet conditions

This study suggests that it is possible to fabricate natural fibres such as banana fibres and glass fibre hybridization into composites with polyester resin. Although these composites exhibit lower strength and stiffness than all-glass fibre reinforced composites, they possess comparable stiffness, competitive costs and lower overall density. Based on the presented investigation, it is expected that these composites could find applications in the following areas, low cost housing, emergency shelter materials following natural disasters, packaging for transportation purposes and manufacturing of consumable goods that require light weight, such as golf clubs, tennis rackets and kayaks.

Chapter 6

Recommendations for Future Work

Although the aim of this project has been reached to investigate the dynamic mechanical behavior of hybrid composites, some potentially interesting aspects of this work are expected to provide future work and more complete understanding.

Other natural fibres such as abaca, bamboo fibres and rice husk are strongly recommended for hybrid fibre reinforced composite. Dynamic and static mechanical properties can be investigated for comparison between them.

Composites made from continuous natural fibres could have greater strength than those with short fibres. Fibre orientation in the matrix also determines the mechanical strength of the composites and the direction in which that strength will be the greatest. The composites made from shorter fibres, if the fibres could be properly oriented, could have substantially greater strength than those made from continuous fibres. This aspect can be investigated.

The type of hybrid composite material is one of the factors which affects the dynamical and static mechanical behavior of hybrid composites. Only one type of hybrid composite has been tested during the current work. The variation of flexural modulus and loss tangent with temperature probably are dependent on the fibre lay-up sequence. For example, the natural fibre layer may be put as the inner glass fibre layer or outer glass fibre layer.

It is thought that a more thorough theoretical understanding of system behavior would be gained through a more systematic evaluation of the wet and dry performance of the composites tested. The data generated in this study focused on the differences in performance between wet and dry materials, but it did not address issues of dynamic water absorption or the effect of repeated wet/dry cycles. It is thought that a study of the relationship between water absorption and properties across the entire spectrum of water contents possible in this and other systems would prove instructive.

A consideration should be given to the development of theoretical modeling to predict properties of hybrid fibre composites based on an understanding of fibre and matrix and their inter-relationship. Modeling allows the engineer to indicate the direction for future work in achieving optimum system parameters.

References

Agarwal, BH. and Broutman LJ. *'Analysis and performance of fibre composites', New York, John wiley and sons* (1980)

American Society for Metal (ASM), *'Engineer guide to composite materials', OH, USA, Carnes Publication Services* (1990)

Bunsell, AR. *'Fibre reinforcements for composite materials', New York, Elsevier Science Publishers* (1988)

Cahn, RW. *'Structure and properties of composites', Materials Science and Technology*, Volume **13** (1990) 56-67

Campbell, D. and White, JR. *'Polymer characterization: Physical technology', London, Chapman and Hall* (1989)

Cassel, B. and Twombly, B. *'Material characterization by thermomechanical analysis', PA, USA, ASTM* (1991) 108-119

Chang, SC., Tai NH, Chen, C. and Ma, M. *Journal of Materials Science* **30** (1995) 1225-1232

Chou, TW. *'Microstructural design of fibre composites', London, Cambridge University Press* (1992)

Coutts, RSP. and Warden, PG. *'Air-cured, wood pulp, fibre cement composites' Journal of Materials Science Letters* **4** (1985) 117-119

Coutts, RSP. *'Banana fibres as reinforcement for building products', Journal of Materials Science Letters* **9** (1990) 1231-1242

DMA7 Manual, *Perkin Elmer* (1995)

Eckold, G. *'Design and manufacture of composite structures', London, Woodhead Publishing Ltd* (1994)

Ferry, JD. *'Viscoelastic properties of polymers', 3^rd^ editon, New York, John Wiley & Sons* (1980)

Folks, MJ. *'Short fibre reinforced thermoplastics', London, Research press* (1982)

Fordos, Z. *'Natural or modified cellulose fibres as reinforcement in cement composite', Glassgow and London, Blackie and Son LTD* (1988) 173-206

Gibson, RF. *'Principles of composite material mechanics', New York, McGraw-Hill Inc* (1994)

Grayson, M. *'Encyclopedia of composite materials and components', New York, A Wiley-Interscience Publication* (1983) 373-375

Haddad, SM. *'Viscoelasticity of engineering materials', London, Chapman and Hall* (1995)

Hancox, NL. *'Fibre composite hybrid materials', London, Applied Science Publishers LTD* (1981)

Himmelfarb, D. *'The technology of cordage, fibres and rope', London, Leonard Hill Books* (1957)

Kelly, A. *'Concise of composite: concise encyclopedia materials', London, Pergamon Press* (1984)

Kretsis, G. *'A review of the tensile, compressive, flexural and shear properties of hybrid fibre reinforced plastics' Composites* volume **18** NO **1**(1987) 13-22

Kulkarni, AG. Satyanarayana, KG. Rohatgi, PK. Vijayan, K. *'Mechanical properties of banana fibres(musa sepientume)', Journal of Material Science,* **1**(1983) 2290-2296.

Mallick, PK. *'Fibre-reinforced composites-materials, manufacturing and design', New York, Marcel Dekker* (1988)

Matthews, FL. and Rawings RD. *'Composite materials: Engineering and Science', Chapman and Hall* (1994)

Mickels, N. *'Banana collins encyclopedia',* **3** (1990) 540

Nielsen, LE. *'Mechanical properties of polymers and composites', New York, Marcel Dekker* (1994)

Potter, K. *'An introduction to composites products', London, Chapman and Hall* (1997)

Qureshi, HA. *'The design and development of automotive body from natural fibre reinforced composites', 4th international conference on composites engineering* (1997) July 95-96

Satyanarayana, KG., Sukumaran, K., Mukherjee, PS., Pavithran, C. and Pillai, SGK. *'Possibility of using natural fibre composites as building materials', Roorki, India, Proc International Conference on Low Cost Housing for Developing Country on Composite Structure,* (1984) 177-181

Satyanarayana, KG., Sukumaran, K., Kulkarni, AG., Pillai, SGK. and Rohatgi, PK. *Composites* (1986) Volume **17** NO**4** 329-333

Satyanarayana, KG., Sukumaran, K., Mukherjee, PS., Pavithran, C. and Pillai, SGK. *Cement & Concrete Composites* (1990) **12** 117-136.

Scwartz, MM. *'Composite materials handbook', New York, Mcgraw-Hill Book Company* (1984)

Selzer, R. and Friedrich, K. *Composites part A* (1997) **28A** 595-604

Sepe, MP. *'The use of dynamic mechanical analysis in the characterization of composite materials', 4th International Conference on Composite Engineering* (1997) July 871

Sheldon, RP. *'Composite polymeric materials', USA, Applied Science Publishers* (1986)

Springer, GS. *'Developments in reinforced plastics-2', London, Applied Science Publishers* (1982) 43-65

Tobias, BC. *'Development of organic fibre-reinforced composite materials', California, USA, Science of Advanced Materials and Process Engineering Series, book 1 (of 2)* (1987) 211-221

Ward, I.M. *'Mechanical properties of solid polymer', London, A Wiley Interscience Publication* (1971)

Warring, RH. *'The glass fibre handbook', London, Nexus Special Interests* (1993)

Wolff, EG. *SAMPE Journal* (1993) Volume **29** NO **3** 11-19

Zhu, WH. *M.S. thesis, 'Utilisation of banana fibre in composite materials', Victoria University, VIC, Australia* (1994)