EFFECT OF FIBER LENGTH AND VOLUME FRACTION ON THE MECHANICAL PROPERTIES OF JUTE FIBER REINFORCED POLYPROPYLENE COMPOSITE

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Dedicated

To

My Parents

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ABSTRACT

This research work comprises of experimental determination and theoretical prediction of the effect of reinforcing fibre volume fraction and the mean reinforcing fibre length on the mechanical properties of short jute fibre reinforced polypropylene composite. Jute fibre reinforced polypropylene composites were prepared with extrusion compounding and injection moulding techniques. Moisture removal or drying was done at different stage of composite fabrication. In the present research, Mechanical behaviour (fracture resistance, tensile properties, critical reinforcing fibre length and the mean interfacial shear strength) of short-jute-fibre reinforced polypropylene composites was studied as a function of fibre volume fraction and fibre length. The values of the tensile strength, tensile modulus, failure strain and notched charpy impact energy were obtained from each group of ten specimens. To predict the tensile behaviour of short jute fibre reinforced polypropylene, the effect of the variation of reinforcing fibre length and volume fraction on the tensile strength, young's modulus and failure strain was investigated. Tensile tests were conducted following ASTM Standard and each test was preformed until tensile failure occurred except 100% polypropylene. The addition of jute fibres effectively enhances the ultimate tensile strength and modulus. The tensile strength of the composites increases with the increase of fibre loading up to the fibre volume fraction 25%, beyond which tensile strength decreased or no significant improvements were observed. A maximum of 11% increase in strength and 163% increase of tensile modulus was observed. The highest tensile strength (33.733 MPa) is obtained from 25% jute fibre loaded polypropylene composite and the reinforcing fibre length is 2 mm. Tensile strength showed an increasing tendency with longer reinforcing fibre length. Fracture resistance being given by the specific work of fracture (WOF) or fracture toughness, here viz the Notched Charpy Impact Energy of the composites were investigated with a charpy impact tester on specimens with V-notches according to ASTM Standard. Introduction of reinforcement effectively enhance the impact strength of the composite but increasing reinforcement is insignificant. Matrix material and single fibre properties were investigated. Tensile modulus showed a decreasing tendency with the increasing reinforcing fibre length.

But results showed that with the increase of reinforcing fibre length the notched charpy impact energy increases (slightly). Fibre morphology and the effect of the different fibre volume fraction on the fracture surface of selected tensile test specimens were observed using a Scanning Electron Microscope (SEM). Fibre orientation was also investigated using SEM and found that the fibres are aligned preferentially along the direction of loading in the whole specimen thickness. The density of each composite was calculated by dividing the specimen mass by the volume. Composite specific properties were determined, which is important for any comparative study. Highest specific tensile strength among all the fibres reinforced composites was 34.35 Pa.m^3/g, and obtained from composite with 8% jute fibre volume fraction with a mean reinforcing fibre length 1 mm and highest specific Young's modulus was 2.952 KPam^3/g and obtained from composite with 40% (volume fraction) jute fibre and mean reinforcing fibre length 1 mm. Jute fibre reinforced PP composite density was found to be in the range 0.930 – 1.099 gm/cm^3. An effective use of fibre strength is dependent on both the interfacial adhesion and the critical fibre length. Mean interfacial shear strength obtained for the investigating fibre-matrix combination was 9.7 ± 1.5 MPa. The strength of composites were theoretically predicted using the modified rule of mixtures. The fibre efficiency factors, respectively, for composite strength (λ_σ) and composite modulus (λ_E) have been studied for short jute fibre reinforced polypropylene composite.

A comparative study of the properties of different natural fibres and manmade fibres along with jute, reinforcing fibre of the current research were presented. Values of mechanical properties of Jute fibre reinforced polypropylene composites obtained in the current investigation were compared with other natural fibre (such as, hemp, Kenaf, slabwood, Luaan, thinning, etc.) reinforced polypropylene composites. A comparative study of mechanical properties were also presented in the current research work between jute reinforced PP composite, short glass fibre reinforced PP composite and short carbon fibre reinforced PP composites.

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Chapter One

INTRODUCTION

1.1 Introduction

Composites are comprised combinations of two or more materials with different composition or form. The constituents retain their identities in the composite and do not dissolve or otherwise merge, but act together [1]. Fibre reinforced composite materials offer a combination of strength and Young's modulus that are either comparable to or better than, many traditional metallic materials. The specific strength and specific Young's modulus of some composite materials are markedly superior to metallic materials. For these reasons, fibre reinforced composites are used or being considered as substitutions for metals in many weight-critical components in industry. Fibre-reinforced composite materials commonly consist of one or more discontinuous phases embedded in a continuous-phase polymer matrix. The discontinuous phase is usually harder and stronger than the continuous phase, and is called reinforcement. These reinforcements (fibres) of high strength and Young's modulus embedded in or bonded to a matrix with a distinct interface (boundary) between them. In this form, both fibres and matrix retain their physical and chemical identities, yet they produce a combination of properties that cannot be achieved with either of the constituents acting alone. In general, the fibres are the principal load bearing members, while the matrix keeps them in the desired orientation and location [2].

A composite may have a ceramic, metallic or polymeric matrix. As a generalization, polymers have low strengths and Young's modulus, ceramics are strong, stiff and brittle, and metals have intermediate strengths and modulus together with high ductility. Polymers are widely used in composites as matrix materials because they are cheap, easy to produce and their densities are low. The polymer matrix may be classified as thermoplastic (capable of being separately hardened and softened by the decrease and increase of temperature respectively) or as thermoset (changing into a substantially infusible and insoluble material when cured by the application of heat or through chemical means) [3]. Metals and ceramics are primarily considered for high temperature applications, ceramics having the potential for the highest working temperatures. The matrix only plays a minor role in the tensile load-carrying capacity of polymer matrix composite structure. The matrix in a fibre reinforced polymer matrix composite transfers stress between fibres, provides lateral support to prevent fibre buckling under compression loading, acts as a barrier against environmental degradation due to elevated temperature and humidity, and protects the fibres from mechanical abrasion. The process ability and defects in a composite material also depend strongly on the physical and thermal characteristics of the matrix (e.g. viscosity, melting point, or curing temperature of the matrix) [4].

The second constituent may be referred to as the discontinuous phase, or reinforcement. In most cases, the reinforcement is harder, stronger and stiffer than the matrix, although there are some exceptions, for example, ductile metal reinforcement in a ceramic matrix and rubber reinforcement in a brittle polymer. The geometry of the reinforcing phase is one of the major parameters in determining the effectiveness of the reinforcement. The mechanical properties of composites are a function of the shape and dimensions of the reinforcement. Proper selection of the type, amount and orientation of fibres is very important, since this influences characteristics of the composite such as specific gravity, tensile strength, compressive strength, Young's modulus, fatigue strength, failure mechanisms, electrical and thermal conductivity as well as cost [4]. A number of fibres are commercially available including glass fibre, carbon fibre, aramid fibre, boron fibre, alumina fibre, and silicon fibre [2]. Recently natural fibres such as jute, wood, hemp and flax have attracted increasing attention for use with polymer composites because of the advantages that these fibres provide [5]. Bangladesh is an agriculture based country. It produces huge amount of jute every year. Jute is the cheapest lignocellulosic, long vegetable bast fibre and abundantly available here. It was called as the 'Golden fibre' of Bangladesh as it earned huge foreign currency for the economic growth of the country by exporting jute and jute products. Jute (including kenaf) was an important foreign exchange earner of the then Pakistan during '60s. Even during the '70s, jute was an important commodity of Bangladesh. However, during the '80s, bulk handing techniques and synthetic substitutes entered the market and jute started losing its predominant position in the market. In Bangladesh jute is traditionally used for making hessian clothes, rope, gunny bags, shoppings bags, baking of carpets, floor mats etc. Nevertheless jute fibres have many drawbacks. Jute fibres are woody, coarse, contain high percentage of lignin and are not spinable to fine fabrics. Its elasticity and compressibility are quite low. The colour of jute and jute products changes from yellow to brown on exposure to light. It has poor crease resistance, lack of thermoplasticity and poor dimensional stability which are requirement for manufacturing fabrics. For these drawbacks jute and traditional jute products are gradually replaced by artificial fibre and synthetic products. In order to overcome the declining market of jute products, new technologies has been developed for bulk use of jute, as a raw material in the production of high value added and price competitive products. These products for new, alternative and non-traditional use of jute are generally termed as diversified jute products. Among the various diversified jute products, jute reinforced composites have high potential for wider use and application. The interest in using jute fibres as reinforcing agent in plastic composites has increased dramatically during the last few years. Production of jute reinforced composites using thermosets and themoplastics can replace a variety of products including carbon- and glass-fibre composites. Processing system of jute-based composites is highly cost effective. So the diversified use of jute in composites has a bright future to increase the economic stability and growth of our country. It can be used for such products as doors, windows, furniture, gaskets, ceiling tiles, partition boards, automotive interior parts, packing, molding etc. So the aim of this present research is to find out a cost effective technology of using of jute fibre as a reinforcing material in thermoplastic composites. The used jute fibres in this research were collected from BJRI, known as "Tossa jute". Its scientific name is *Corchorus olitorius*, genus Corchorus and family Tiliaceae. The scheme shown below gives possible use of different fractions of jute plant.

The fibre-matrix interface also plays a major role in the behaviour of composite materials. The nature of the components determines the wetting and bonding between the constituent phases. Externally applied forces are transferred to and distributed among the fibres. The transfer of load is achieved through the matrix materials and across the fibre-matrix interface. The nature of the interface controls the effectiveness of load transference and the properties of the composite [2].

Although fibre reinforced composites with the best mechanical properties are those with continuous fibre reinforcement, such materials cannot be adapted easily to mass production and are generally confined to products in which the property benefits outweigh the cost penalty. Short fibre reinforced composites are finding ever increasing applications in engineering and in consumer goods. They can offer attractive combinations of properties or may be used simply because they are more economical than competing materials. Short fibre reinforced composites can be processed in a manner similar to the non – reinforced matrix. In the case of thermoplastics, this means that methods such as injection moulding are available, allowing mass production of composites with intricate shapes. The properties of short fibre-polymer composites are strongly dependent on the fibre volume fraction and on fibre orientation, and partly dependent on the processing. As a result, wide ranges of properties including cost are possible. In short fibre composites, the fibre orientation is generally less controlled than in continuous fibre composites and is often quite random. Processes such as injection moulding can cause a degree of fibre alignment, which is often beneficial. However, fibre orientation and distribution changes when moulding conditions change, which is difficult to control. The degree of anisotropy is generally less than in continuous fibre composites, but is often significant [2, 6].

Commercial and industrial applications of fibre-reinforced composites are too numerous to list. However, the major application areas of fibre-reinforced composite include aerospace, automotive, sporting goods, and marine engineering.

In recent years, growing worldwide waste disposal problems have raised environmental awareness among consumers, manufacturers, and governments. In response, governments in many countries have established laws to encourage the use of recycled and/or bio-based sustainable products to deal with this [7]. Societal concern, a high rate of depletion of petroleum resources, concepts of sustainability, and new environmental regulations have together generated the search for new products and processes that are compatible with the environment [8].

Composite materials are no exception to this concept. In fact, most major manufacturers have planed to make their products recyclable to the maximum possible extent and are working vigorously towards that goal. It appears that environment friendly, fully biodegradable reinforced plastic composite materials will play a major role in greening the products of the future [8].

1.2 Historic background of natural fibre reinforced composites

Natural as well as synthetic fibres have been and are both being used as reinforcements in composites. They are used alone in lines, ropes, and other one dimensional products because of their strength [9]. The first composite material known in history was made in ancient Egypt some 3,000 years ago, which was clay reinforced with straw to build walls [10]. As early as 1896, aeroplane seats and fuel tanks were made of natural fibres with a small content of polymeric binders. In 1908, composite materials were applied in the fabrication of large quantities of sheets, tubes and pipes for electronic purposes (paper or cotton to reinforce sheets, made of phenol-or melamine-formaldehyde resins) [11]. In the late 1930s, cellulose fibres such as flax, as well as asbestos and glass fibre with phenolic resin as matrix materials were used to minimise the structural load of aeroplanes [9]. The research effort in the 1950s was generally focussed on strong, stiff, and light fibres, and new fibres appeared such as high-strength glass fibres (E-type), whiskers based on ceramics and inorganics, carbon/graphite fibres, and later polyaramid fibres. The increasing development and use of composites based on polymer matrices and synthetic fibres have dominated the period since the 1960s. Relating to the non-uniform characteristics of natural fibres, relating to plant type, growth conditions, weather, and handling after harvesting, research efforts for better reinforcement fibres were not directed towards natural fibres but rather towards the less variable and structurally simpler inorganic materials previously mentioned.

1.3 Advantages of natural fibre reinforced composites

Glass, carbon, and aramid fibre reinforced thermosetting resins are difficult to recycle and hard to dispose of. They do not degrade naturally and could remain in landfill sites for generations. Production of glass, carbon, aramid, fibres releases CO_2 into the atmosphere, along with NO_x and SO_x gases and dust, which can be a health hazard. Dust and fragments are generated when recycling conventional plastic composites by grinding them down, and remain an issue during disposal either to landfill or by incineration [11].

A solution could be to combine recyclable thermoplastic (polypropylene or PP, polyolefin, polyethylene, polyurethane, and polyamide are some of those already used in composites), with plant-based fibres.

Plant fibres have a number of advantages over glass fibres including that they are renewable, abundant, biodegradable, lightweight, non-abrasive to processing equipment and CO_2 neutral (when burned). They are cheap and will have an increasing price advantage as synthetic fibres become increasingly costly due to the increase in oil prices. They also have favourable accident performance (high stability, no splintering), occupational health benefits (no skin irritations), positive effects on agriculture, good acoustics and are thermally insulating. They can be incinerated with energy recovery and there is no emission of toxic compounds during processing [12]. They can be produced using one-step manufacturing, in complex shapes similar to glass fibre composites. These benefits are not likely to be ignored by the plastic/composites industry for use in the automotive, building, appliance, and other applications.

Natural fibres have the potential to reduce weight (up to 40% compared with glass fibre, which accounts for the majority of automotive composites), while satisfying increasingly stringent environmental criteria. Less energy is used in growing, harvesting, and preparing natural fibres than in producing glass fibre, which has to be drawn from a melt at several hundred degrees Celsius, using raw materials obtained through energy-intensive mining [11].

1.4 Limitations of natural fibre reinforced composites

Despite the ecological advantages of natural fibres over glass fibres, natural fibres also possess a number of disadvantages. The major disadvantage of cellulose fibres is their highly polar nature, which makes them incompatible with non-polar polymers. Other disadvantages of plant fibre composites are:

- development of cost-effective (re)processing methods required [13]
- lower strength, and lower durability, however, these can be improved with fibre treatments
- variable quality depending on plant type, growth conditions and handling after harvesting
- moisture absorption, which causes swelling of the fibres
- limited maximum processing temperature
- potential fibre degradation, something that can occur during compounding and moulding as well as in service
- poor fire resistance, although developers in Bremen are currently testing ramie as a possible replacement for interior fittings for the Airbus and it is fireproof [14]
- price can fluctuate by harvest results or agricultural politics

It is believed that by accessing the limitations however, in general the benefits of these fibres are not likely to be ignored by the plastic/composites industry for use in the automotive, building, appliance, and other applications.

1.5 Prospects of jute fibre reinforced composites

Due to an occurrence of a wide variety of natural fibres in the subcontinent, Bangladeshi and Indian researchers have directed efforts for quite some time in developing innovative natural fibre composites for various applications. Development of diversified composite materials as wood substitutes is being considered an attractive solution with a view to conserve forest resources. The existing wood substitute materials such as particle/fibre board and other materials cannot meet the increasing demand of wood without renewed efforts.

The jute composites can be very cost-effective material especially for building and construction industry (panels, false ceilings, partition boards etc.), packaging, automotive and railway coach interiors, helmets and storage devices. Wood fibre composites are widely used for building applications such as outdoor decking, fences, window and door frames figure 1.1. These can also be the application areas of jute fibre reinforced composites.

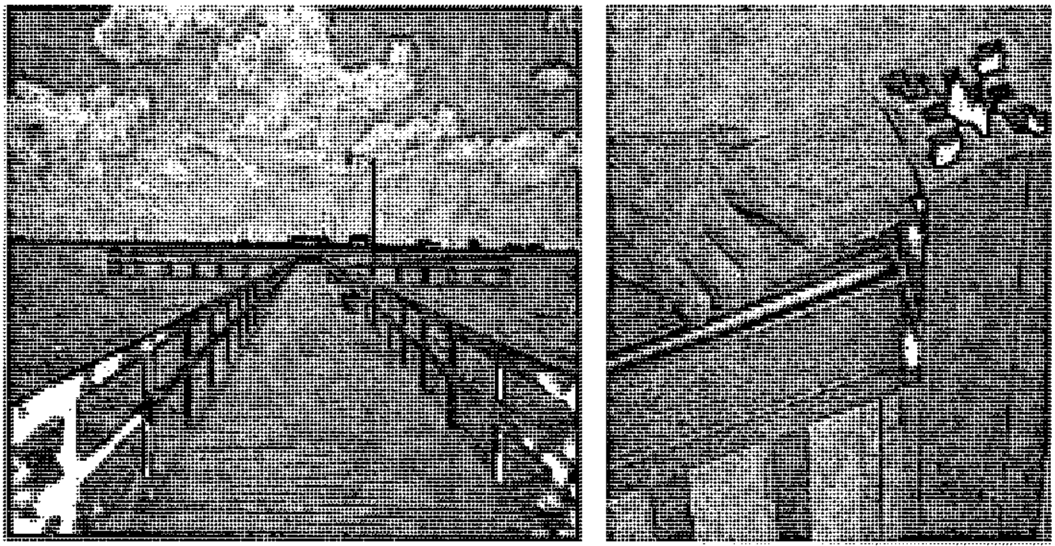


Figure 1.1: Composite lumber made from recovered wood and recycled plastic combines a wood tone appearance with the process ability and durability of plastics [5].

In a recent US patent [US Patent 5985429, November 1999] by Plummer et al., the project innovation relates to a natural fibre composite for fabrication of structural components such as rails, sills, tracks, stops and non-structural members such as grid, cove, bead etc. for residential and commercial architecture. The composite material, extruded in the form of pellets, comprises thermoplastic matrix (polyester, polyvinyl alcohol, PBT, nylon, spandex etc.) and short/long fibre reinforcements. A variety of fibres has been tried out by the inventor. A large array of natural fibre such as jute, flax, hemp, ramie, cotton, palm leaf, coir etc. can be used. The composite material is pelletized and the pellets are further extruded or injection moulded as per the desired shapes/profiles.

In a US Patent [US Patent 5285957, 1994], The Mead Corporation Dayton, Ohio, USA described the use of jute mesh as the intermediate reinforcing material for a corrugated container such as bulk storage bins. The reinforcing material may be replaced in between the outer and inner lines of two-faced corrugated board construction.

A US Patent [US Patent 5037690, 1991] M/s. De Groot Automotives BV of Netherlands describes the process of fabricating a sheet material. The sheet comprises polyurethane resin reinforced with binder free natural fibres such as jute, flax, hemp, coir, ramie, cotton etc. possibly combined with polypropylene, polyethylene and/or glass fibre. The preferred natural fibre is jute in the form of needled jute felt. The application lies in fabricating a sandwich panel with two outer walls made of jute composite sheets.

M/s. Care Inc., N.Y., USA patented [US Patent 3819466, 1974] double-wall reinforced and insulating building panel with a combination of glass and jute composites. The panels comprises of an inner skin of woven jute layers saturated in polyester resin and an outer skin of woven jute with an exterior coating of chopped glass fibre both impregnated with polyester resin. The intermediate layer bonding inner and outer skin is made of corrugated woven jute composite. The panel is of lightweight and has high durability even in extreme temperature conditions.

The project on 'Jute-based Composites – An Alternative to Wood Products' has been launched in collaboration with M/s Duroflex Limited, Bangalore. The project activities involve the production of coir-ply boards with oriented jute as face veneer and coir plus waste rubber inside. A very thin layer of jute fibres impregnated with phenolic resin is used as the face veneer for improved aesthetics and to give a wood like finish. The orientation and uniformity of jute fibre improve with carding and this also helps in better penetration of resin into the fibre. In this project, 80% of the material used in the composite are renewable natural fibres such as jute and coir.

1.6 Prospects of natural plant fibre reinforced composites

Plant fibres like jute, flax, hemp and kenaf are currently being evaluated as environmentally friendly and low-cost alternatives for glass fibres in engineering composites. The combination of interesting mechanical and physical properties together with their environmentally friendly characteristics has generated various activities in the area. In July 2002, the European Union Council of Ministers approved the EU end-of-life vehicle directive, which will have huge impact on the materials and processing methods used to produce motor vehicles in the future. The European automotive industry is trying to make every component recyclable and is looking into the possibility of using natural fibres reinforced thermoplastics as a way to serve the environment and at the same time save weight and cost [5].

The development of a door module for motor vehicle has been described by Neuhauser et al. in the European patent [European Patent DE19725176, December 1998]. The module comprises an internal lining component, which accommodates a side air bag and gas generator. The internal lining component is made of plastics or PU foam with synthetic or natural fibre reinforcing inserts.

In a European Patent [European Patent EP0872383, October 1998] by Ulrich Josef from Denmark had described a composite interior lining for vehicle. The inner cladding material for a vehicle consists of a natural fibre (jute, flax or sisal) based thermoplastic composite; the decorative layer is made of leather or synthetic leather (wool or cotton fibres with polyurethane) component. The intermediate layer is made of PP or PE foam or non-woven PET/PP as sheet or rolled material.

The process of making a multilayer composite body comprising a thermoplastic layer and layers of natural fibre bonded to thermoplastic resin was patented in US by a German company [US Patent 9836900 A1, 1998].

A US Patent [US Patent 9831626 A1, 1998] granted to a US company describes the method for fabricating wet-laid non-woven webs using jute fibre as reinforcement. Composites of the unpulped fibre webs with cellulosic and spun bonded sheets find applications as thermoformed trim products for vehicle interiors.

The quality German manufacturers, Daimler/Chrysler (Mercedes), BMW, and Audi/Volkswagen are proactive in the specification of natural fibre substrates. Daimler/Chrysler and BMW have initiated in house research into short fibre/polypropylene granulation processes for injection moulding applications. All BMW and Mercedes models now use natural fibres as the basic for components such as door liners, boot liners and parcel shelves [12]. In one large research programme, Daimler-Chrysler has evaluated flax and hemp fibres as potential candidates to replace glass fibres in engineering composites and has developed a number of automotive products replacing glass-mat-reinforced thermoplastics [15]. Until recently, most of the use of natural fibres in automotive applications has been limited to interior components. However, current research at the Daimler-Chrysler research centre in Ulm, have developed a number of natural fibre reinforced exterior parts. Products include not only prototype parts such as under body panels for the A-Class (see figure 1.2) but also a flax fibre-reinforced polyester engine and transmission cover with improved sound insulation for the new Travego travel coach [5]. This part, which is manufactured by resin transfer moulding (RTM), is an important innovation since it is the first exterior component made from natural fibre composites on a commercial vehicle and must be able to withstand extreme environmental conditions such as wetness and chipping [5]. In addition, other car manufacturers are actively looking into natural fibre composites and currently some 25,000 tons of natural fibres are used in the European automotive industry [5].

Figure 1.2: Flax fibres have been evaluated by a number of car manufacturers as an environmentally friendly alternative for glass fibres (A-Class showing prototype parts made from flax/PP based NMT, photo courtesy Daimler-Chrysler, Germany) [11].

Audi for example have developed interior door trim panels made from polyurethane (PUR) reinforced with mixed flax/sisal non-woven mats for their new A2. Fiat, which is an Italian car manufacturing company, has developed gaskets, seat parts, dashboards and handles produced by gas-assisted injection moulding [5]. Ford's materials engineering department in Cologne has done considerable development work in the area of injection mouldable flax/PP grades for radiator grills, front ends and engine shields for the new Ford Focus. Parts are 30% lighter than current glass fibre reinforced parts. Kafus Environmental Industries, a company that grows kenaf in Texas, and Visteon, one of Ford's component subsidiaries involved with the development and production of compression moulded parts based on non-woven mats of commingled fibres of kenaf, hemp and PP. Components that are manufactured for the Ford Mondeo include door panels and trunk liners. Such components were manufactured in the past from Woodstock®, a material based on wood flour and PP. It is expected that in the near future more of these wood fibre composite applications will change to natural fibre composites because of their better impact characteristics, which allows for higher weight savings [5, 13].

The following overview covers some recent car models (see Table 1.1) and illustrates the establishment of natural fibres for serial parts in the automotive industry.

Table 1.1: Use of natural fibres for serial parts in the automotive industry (1997-2001) [12].

Manufacturers/Customers	Model / Application (dependent on model)
Audi	TT, A2, A3, A4, A4 Avant (1997), A4 Variant (1997), A6, A8 (1997), Roadster, Coupe Seat back, side and back door panels, parcel tray, boot lining, rear flap lining, rear storage panel, spare tire lining
BMW	3, 5 and 7 Series and others Door inserts/door panels, headliner panel, boot lining, seat back
Citroen	C4 (2001) Door inserts
DaimlerChrysler	A-Klasse, C-Klasse, E-Klasse, S-Klasse Door inserts, windshield/dashboard, business table, column cover
Fiat	Punto, Brava, Marea, Alfa Romeo 146, 156, Sportwagon
Ford	Mondeo CD 162 (1997), Cougar (1998), Mondeo (2000), Focus Door inserts, B-column cover, parcel tray, in the future also motor protection (cover undershield)
MAN	Bus (1997) Headliner panel
Mitsubishi	Miscellaneous models (since 1997)
Nissan	Miscellaneous models
Opel	Astra, Vectra, Zafira Headliner panel, door inserts, column cover, instrument panel, rear shelf panel
Peugeot	New model 406
Renault	Clio, Twingo
Rover	Rover 2000 and others Insulation, rear storage panel
Saab	Coupe (1998) Door inserts
FEAT	Door inserts, seat backs
Toyota	Miscellaneous models
Volkswagen	Golf A4, Golf 4 Variant (1998), Passat Variant, BoraDoor inserts, seat backs , rear flap lining, parcel tray
Volvo	C70, V70, Coupe (1998) Door inserts, parcel tray

From all these development programmes, it has become apparent that natural fibres as a reinforcement material for plastic composites in automotive applications have a great potential and the European market is expected to require over 50,000 tons of natural fibres by the year 2005. At this moment, the most important fibres for the automotive industry are flax and hemp. Another fibre which is recently attracting attention is kenaf fibre from the US and Bangladesh. Other natural fibres such as sisal and jute have also been used for many years in the automotive industry but their market share is currently decreasing because of less reliable supply and less competitive pricing compared to flax and hemp. Ramie fibres are also being examined, because of their specific properties along with fire resistance giving potential for use in the aeroplanes [5].

From the above discussion it is clear that the opportunities for Bangladesh grown jute fibre reinforced composites is immense. Characterisation of the fibre and composite properties will encourage increased use in composites and hence capture an ever-growing market share, boost the agricultural based economy and help the world to make it more environmental friendly.

1.7 Objective of the study

The main objectives of the present research can be summarised as follows:

i. To fabricate short-jute-fibre reinforced polypropylene composite material.
ii. To measure different mechanical properties of the fabricated samples of short-jute-fibre reinforced polypropylene composite.
iii. To summarise the variation of mechanical properties of the jute fibre reinforced polypropylene composites as a function of reinforcing fibre volume faction.
iv. To summarise the variation of mechanical properties of the jute fibre reinforced polypropylene composites as a function of reinforcing fibre mean length.
v. To find out jute fibre reinforced polypropylene composite's density, specific properties (specific tensile strength and specific tensile modulus), mean interfacial shear strength, critical reinforcing fibre length and theoretical tensile strength prediction of the composite using modified rule of mixtures.

vi. To calculate fibre efficiency factor for composite strength and composite modulus using the modified rule of mixtures.

vii. To compare properties and some physical parameters of different natural fibres.

viii. To compare the mechanical properties of the short-jute-fibre reinforced polypropylene composites against those of the short-glass-fibre and short-carbon-fibre reinforced polypropylene composites from the literature [9,10].

Chapter Two

LITERATURE REVIEW

2.1 Introduction

For the optimisation of natural fibre reinforced plastic composite properties characterisation of fibres according to their source, availability, cost, chemical properties, dimensional properties and mechanical properties is essential. Matrix selection according to cost, recyclability and processability are similarly important. Strong composites cannot be produced by using strong fibre only. A natural fibre reinforced plastic composites properties also depend on factors such as incompatibility between the fibre and matrix, moisture content and volume fraction. In addition, the fibre/matrix interface plays a crucial role in controlling composites properties. Methods of improving the interfacial property both physical and chemical are available.

2.2 fibres

Fibre properties including chemical composition, surface properties, dimensions, defects, strength, and stiffness are important in selecting suitable natural fibres for use in plastic composites. Cost and availability of the natural fibres are similarly important, for their consideration [16].

2.2.1 Lignocellulosic fibres

Lignocellulosic fibres refer to those agro based substances which contain cellulose, hemicelluloses and lignin as their structural molecules. Lignocelluloses include wood, agricultural residues, water plants, grasses and other plant substances.

2.2.2 Classification of lignocellulosic natural fibres

Natural organic fibres can be derived either from animal or plant sources. The majority of useful natural textile fibres are plant derived with the exceptions of wool and silk. All plant fibres are composed of cellulose, whereas fibres of animal origin consist of protein. Natural cellulose fibres tend to be stronger and stiffer than natural protein fibres and are therefore more promising for use in composite materials. Depending on the origin of the fibre, natural cellulose fibres can be classified into the following categories [17, 20]:

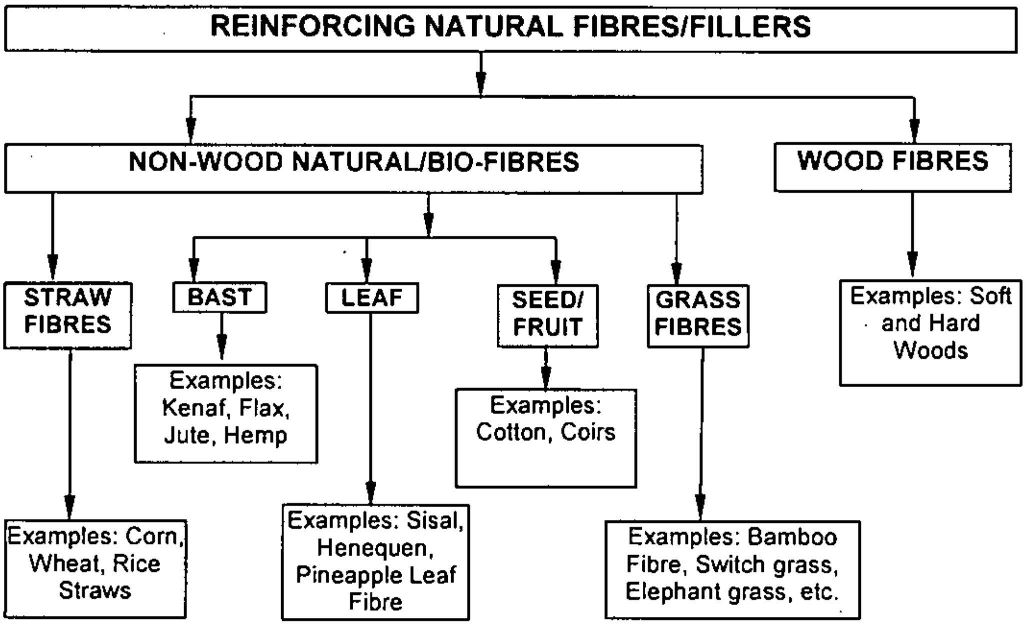


Figure 2.1: Classification of natural fibres

Bast fibres: Situated in the inner bark (phloem) of the stems of dicotyledonous plants. Common examples are jute, flax, hemp and kenaf.

Leaf fibres: Run lengthwise through the leaves of most monocotyledonous plants such as sisal, henquen and abaca.

Seed and fruit fibres: Come from seed-hairs and flosses, which are primarily represented by cotton and coconut.

Wood fibres: Found in the xylem of angiosperm (hardwood) and gymnosperm (softwood) trees. Examples are pine, eucalyptus, maple and spruce.

Grasses: Found in the stems of monocotyledonous plants such as bamboo and sugar cane.

2.2.3 Availability and price of natural fibre

Jute (Corchorus capsularis & Corchorus olitorius), Kenaf (Hibiscus cannabinus), Flax and Hemp are vegetable bast fibre plants next to cotton in importance. Jute usually two different trade names: White and Tossa. Corchorus capsularis is called White Jute & Corchorus olitorius is called Tossa Jute. The genus of jute is corchorus and the family is Tiliaceae. The natural fibre colour of white jute is creamy white and that of tossa jute is golden. Depending on demand, price and climate, the annul production of jute and allied fibres in the world remains around 3 million tonnes. [18]

Jute and wood fibres are the most abundantly used cellulose fibres in our country. Extensive use of wood fibre is in pulp and paper industries. Other fibre types are becoming increasingly important due their better strength and stiffness properties (see Table 2.5). Commercially important fibres sources and world production are listed in Table 2.1.

Table 2.1: Commercially important fibre sources and production [19]

Fibre Source	**Species**	**World Production (10^3 tonnes)**	**Origin**
Wood	(>10,000 species)	1,750,000	Stem
Bamboo	(>1250 species)	10,000	Stem
Cotton lint	Gossypium sp.	18,450	Fruit
Jute	Corchorus sp.	2,300	Stem
Kenaf	Hibiscascannabinus	970	Stem
Flax	Linum usitatissimum	830	Stem
Sisal	Agave sisilana	378	Leaf
Roselle	Hibiscus sabdariffa	250	Stem
Hemp	Canabis sativa	214	Stem
Coir	Cocos nucifera	100	Fruit
Ramie	Boehmeria nivea	100	Stem
Abaca	Musta textiles	70	Leaf

The cost of the fibres is an important factor for fibre selection. Natural fibre prices tend to fluctuate considerably and are dependent on a number of factors, such as supply, demand, quality and exchange rate [21]. A comparison of the relative costs of a number of fibres can be seen in table 2.2. The costs of cellulose fibres are considerably lower than that of glass and carbon.

Table 2.2: Natural plant fibre costs

Fibre type	Price ($US/Kg)
Jute	0.4 – 0.7
Hemp	0.5 – 1.5
Flax	0.4 – 0.8
Sisal	0.6 – 1.1
Wood	0.2 – 0.4
Glass	1.5 – 2.5
Carbon	10 – 100

2.2.4 Structure and constituents of natural fibres

To understand the properties of plant fibres, it is necessary to understand the fine structure and constituents of the cell wall. The following constitutes a brief review of the plant fibre cell's wall structure and chemical composition [16]. The basic information is derived from studies of wood fibres. As much as possible, any contrasting properties of bast fibres will be highlighted.

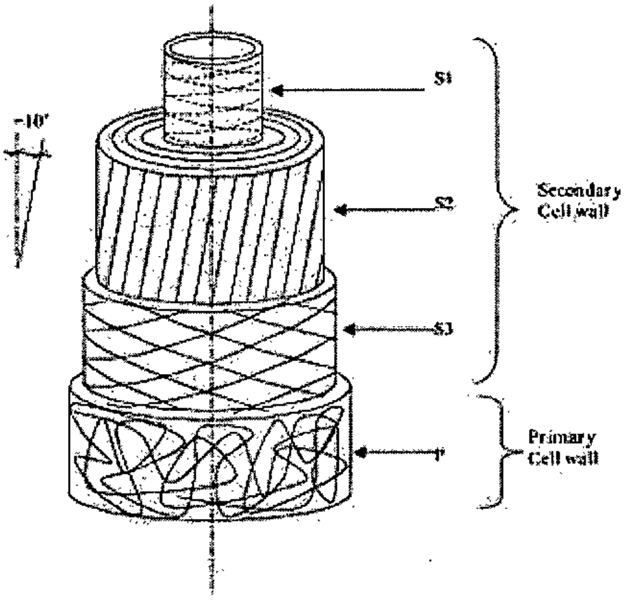


Figure 2.2: The structure of cellulosic fibre cell [22].

Natural lignocellulosic fibres can themselves be considered as composites because they consist of helically wound cellulose microfibrils in an amorphous matrix of lignin and hemicellulose. The fibre cell wall is divided into two distinct parts, namely the primary cell wall and the secondary cell wall (see Figure 2.2). The primary cell wall is located on the outside of the fibre and relatively thin (0.2 μm) consisting of pectin, some lignin and cellulose. The secondary cell wall is composed of two or three layers, known as S1, S2, and S3, respectively (Figure 2.2). The secondary cell wall makes up most of the fibre diameter, and consists of oriented, highly crystalline cellulose microfibrils and amorphous hemicellulose [16]. The microfibrils are packed together and oriented spirally at approximately 10° to the major axis of the fibre. The fibrils are are generally considered to be glued together with hemicellulose rich phase [16].

The bast fibres from jute, are the long, strong fibres used in textiles, ropes and composites. Bast fibres are found in the bark layer of the stem, generally solid in cross-section but a small lumen (void) can sometimes present. Elementary bast fibres are glued together by an interface, which consists mainly of pectin, lignin and hemicellulose.

Within the bast cells found in jute the secondary wall is less thick than that of wood cells, wherein extensive secondary wall thickening replaces almost all of the pectin with lignin. The other components namely cellulose, hemicellulose and lignin are universal to plant fibres [16].

The constituents of natural fibre vary according to origin, the area of production and the maturation of the plant. Percentage content of constituents of available plant fibres are listed in table 2.3.

Table 2.3: Comparative chemical composition of available plant fibres [16]

Fibre/fibre bundle	Type	Cellulose content (%)	Lignin content (%)	Pectin content (%)
Flax	Bast	65–85	1–4	5–12
Hemp	Bast	60–77	3–10	5–14
Jute	Bast	45–63	12–25	4–10
Kenaf	Bast	45–57	8–13	3–5
Sisal	Leaf	50–64	–	–
Abaca	Leaf	60	12–13	1
Coir	Seed	30	40–45	–
Cotton	Seed	85–90	–	0–1
Softwood	Wood	40–45	26–34	0–1
Hardwood	Wood	40–50	20–30	0–1
Wheat straw	Cereal stem (grass)	38–41	12–16	0–1

The major constituents of plant fibre: cellulose, hemicellulose, lignin and pectin are discussed briefly.

Cellulose

Cellulose is a linear polymer consisting of D-anhydroglucose units joined together by β-1,4-glycosidic linkages. The long thin crystalline microfibrils that dominate the secondary cell wall are made of cellulose. Cellulose is the reinforcing material within the cell wall and is responsible for the high tensile strength of the fibre. It is defined chemically as a highly crystalline segments alternating with regions of amorphous cellulose (non-crystalline) [16, 43].

Plant-based celluloses are highly crystalline and can be as much as 80% crystalline cellulose [43]. The rigidity and strength of cellulose-based materials is a result of extensive hydrogen bonding both between chains and within chains. The amorphous cellulose regions have a lower frequency of inter-chain hydrogen bonding, thus exposing reactive inter-chain hydroxyl groups (OH) to bond with water molecules. Amorphous cellulose can therefore be considered hydrophilic due to their tendency to bond with water. Crystalline cellulose is far less hydrophilic than amorphous cellulose due their extensive hydrogen bonding. Crystalline microfibrils have tightly packed cellulose chains within the fibrils, with accessible hydroxyl group present on the surface of the structure. Only the very strong acids and alkalis can penetrate and modify the crystalline lattice of cellulose.

Hemicelluloses

The hemicellulose fraction of the fibre contains a collection of polysaccharide polymers containing mainly the sugars D-xylopyranose, D-glocopyranose, L-arabinofuranose, D-manopyranose, and D-glucopyranosyluronic acid with minor amounts of other sugars. Hemicelluloses cover the surface of the microfibrils by hydrogen bonding with outer cellulose chains. In many plant and wood species, the hemicelluloses tend to interface between the cellulose and the lignin, thus permitting the effective transfer of shear stresses between the cellulose microfibrils and the lignin [23, 24]. Unlike cellulose, hemicelluloses chains are rarely crystalline as a result very hydrophilic and are largely responsible for the water absorption behaviour exhibited by plant fibres (along with pectins when present). Hemicelluloses are of lower molecular weight than cellulose, heavily branched, and are much less ordered than cellulose [16]. Hemicellulose have a greater solubility in solvents compared to cellulose, and can be broken down in high temperature environments.

Lignin

Lignin is distributed throughout the primary and secondary cell walls. Lignin is generally regarded as the adhesive within the cell wall and is the final polymer to be laid down between the hemicellulose zones surrounding microfibrils, conferring rigidity, and decay resistance to the cell wall [16]. Lignin is essentially a disordered, polyaromatic, and cross-linked polymer arising from the free radical polymerization of two or three monomers structurally related to phenylpropane [25]. Free radical coupling of the lignin monomers gives rise to a very condensed, reticulated, and cross-linked structure. The lignin matrix is therefore analogous to a thermoset polymer in conventional composite terminology. The dissolution of lignin using chemicals, aids fibre separation, as is commonly used in the pulp and paper industries. When exposed to ultraviolet light, lignin undergoes photochemical degradation [16].

Pectin

In most non-wood fibre cells, pectin is a major matrix component within the primary cell wall. Pectins are polysaccharides and can have complex branched structures. The main chain is a polymer of (1–4)-α -D-glucuronic acid, in which the acid groups are partially esterified with methanol. At frequent intervals, residues of the sugar units of a variety of compositions are included in the main chain and side chains. In addition, acid groups between adjacent pectin chains are often cross-linked by calcium ions. This confers a degree of structural integrity and rigidity to regions of the cell wall rich in pectin. Pectin is an important component of non-wood fibres, particularly the important bast fibres from flax, hemp, and jute [16]. Pectin, along with lignin and hemicellulose present in natural fibres can be hydrolysed at elevated temperature.

2.2.5 Dimensional characteristics of natural fibre

The dimension of a fibre, especially the fibre aspect ratio (length/diameter) is a critical parameter in a composite material. For each short-fibre composite system, there is critical fibre aspect ratio, which may be defined as the minimum fibre aspect ratio in which the maximum allowable fibre stress can be achieved for a given load. This will ensure maximum stress transfer to the fibres before the composite fails [26]. The dimensions are listed in table 2.4 as length, diameter, and aspect ratio.

Table 2.4: Dimensions of natural fibres [16]

Vegetable Fibres	Average length (mm)	Average diameter (mm)	Aspect ratio
Bast fibres			
Flax (single)	33.0	0.019	1700
Hemp (single)	25.0	0.025	1000
Jute (single)	3.0	0.020	150
Stem fibres			
Straw	1.4	0.015	90
Seed fibres			
Cotton (single)	18.0	0.020	900
Grass fibres			
Babmboo	2.7	0.014	200
Wood fibres			
Soft	3.3	0.033	100
Hard	1.0	0.020	50

The wide range of natural fibres used in composites, ranging from aligned fibre high-strength composites to random fibre moderate-strength composites. The possibility of shortening the long fibres for specific processing requirements is also an option. The potentially very high aspect ratios for some of the natural fibres such as hemp and flax make them suitable for continuous fibre handling, such as filament winding or pultrusion.

2.2.6 Mechanical characteristics of natural fibre

To achieve strong composites, it is important to start with strong fibres; but these themselves are not sufficient to achieve strong composites, because good bonding to the matrix and good orientation are also needed. Nevertheless, strong fibres are a prerequisite to strong composites, and it is therefore of considerable interest to elucidate the potentials and limitations of strong natural organic fibres [16]. The fundamental characteristics, which qualify fibres as reinforcements, are density, strength and stiffness [16]. The often rather large range for stiffness and strength values of natural fibres reflect both the natural variation of plant type, growth conditions, and harvest procedures. Specific sets of properties have not yet been developed for efficient use of natural fibres for industrial products. Stiffness is often as important as strength because many engineering structures are limited by the allowable deflection [16]. For natural fibre reinforced composite another important property is density. Density is used for the calculation of tensile specific properties (tensile properties/density), and these specific properties consequently give a better indication of the benefits achievable with the material. Typical values for both synthetic and natural fibres are presented in table 2.5.

Table 2.5: Mechanical properties of available plant fibres [16]

Fibre	**Density (gcm^{-3})**	**Tensile Strength (MPa)**	**Young's Modulus (GPa)**	**Specific strength (Pam^3/g)**	**Specific Young's modulus ($KPam^3/g$)**
Glass	2.54	3530	72	1390	28.35
Flax	1.4–1.5	500–900	50–70	357 – 600	36 – 47
Hemp	1.48	300–800	30–60	203 – 541	20 – 41
Jute	1.3–1.5	200–500	20–55	154 – 333	15 – 37
Sisal	1.45	100–800	9–22	69 – 552	6 – 15
Banana	1.4	500–700	7–20	357 – 500	5 – 14
Pineapple	1.44	400–1600	35–80	278 – 1111	34 – 56
Cotton	1.50	300–600	6–10	200 – 400	4 – 7
Softwood	1.4	100–170	10–50	71 – 121	7 – 36
Hardwood	1.4	90–180	10–70	64 – 129	7 – 50

From table 2.5 it is observed that the densities of all natural fibres are less than that of glass fibre. Natural fibres, such as flax, hemp, pineapple and wood can easily compete with glass fibres in terms of specific Young's moduli. However, the specific strengths, of natural fibre composites are relatively low compared to glass fibre composites.

2.2.7 Factors controlling mechanical properties of plant fibres

The mechanical performance of natural lignocellulosic fibres are the result of complex interactions between a number of external variables and inherent structural parameters that originate at the molecular, macro-molecular, and microscopic levels. Among the most important of these are crystallinity/amorphousness, orientation of the cellulose, lignin and hemicellulose content, microscopic and molecular defects in the fibre and, the presence of moisture or other introduced chemicals [27].

The fibre structure may and most likely will, contain various imperfections and defects (e.g., pits, nodes etc.); cracks will formally cause local stress concentrations, which will reduce the strength [28].

Lignin and hemicellulose play an important part in determining the characteristic properties of natural fibres. Removal of lignin and hemicellulose affects the tensile characteristics of the fibres. Literature reports on the variation of tensile characteristics on lignin and hemicellulose demonstrate competing influence of lignin removed. When hemicelluloses are removed, the inter-fibrils region is likely to be less dense and less rigid and thereby makes the fibrils more capable of rearranging themselves along the direction of tensile deformation. When fibres are stretched, such rearrangements among the fibrils would result in better load sharing and hence in higher stress development in the fibre [29]. Alternatively, softening of the inter-fibrilar matrix adversely affects the stress transfer between the fibrils and, thereby, the overall stress development in the fibre under tensile deformation [30]. A gradual decrease in strength, stiffness and extensibility of the fibre with lignin removal has been reported in the literature for jute, sugarcane and hemp [28, 30]. It is also reported that relatively mild treatments used did not allow complete removal of lignin in the literature [28]. In comparison, it has been reported in another study using a mild alkali treatment (5% aqueous solution at 28°C for 72–76 h) that the tensile strength and Young's modulus of the fibres were increased by 15% and 40%, respectively [30].

Purification processes can significantly alter the crystalline structure of the plant fibre [28]. These preparation methods routinely involve the use of water or mild alkaline solutions that strongly interact with the cellulose components, swelling the fibre and increasing molecular mobility. As a result, the relative ratio of the crystalline to amorphous phase can be altered as well as the orientation of the crystallites, thereby modifying the mechanical properties of the fibre. Fibres like hemp, jute, flax, and ramie have their cellulosic chains oriented nearly parallel to the fibre axis (in the range 7-12^{o}), and they exhibit higher strength than other natural fibre like cotton fibres, whereas cellulose chains are oriented approximately 30° to the fibre axis [28]. It is reported in the literature that the moisture tends to disrupt the crystalline structure of the cellulose [28].

2.3 Matrix selection

The mechanical properties of composites based on the fibres depend not only on the characteristics of the fibres but also on the matrix itself as well as on the fibre-matrix interface. The matrix in a polymer composite serves both to maintain the position and orientation of the fibres and to protect them from potentially degrading environments.

2.3.1 Thermosetting and Thermoplastic Polymer

The matrix plays a crucial role in the performance of natural fibre reinforced plastic composites. One of the main concerns is whether to use a thermoset or thermoplastic matrix.

Thermosetting polymers are normally chemically cured to a highly cross–linked, three dimensional network structure. These cross–linked structures are highly solvent resistant and creep resistant [31]. Thermosets includes such polymers as epoxy, phenols and polyesters.

Thermosets are the most commonly used matrices due to the following advantages:

- Chemical constitution of thermosets being the most similar to natural fibres
- Production is lot simpler, as resin moulders can be used allowing the matrix and the reinforcing agent to be cured under mild processing conditions
- Thermosets have a highly cross linked chain structure which does not allow the chains to slide and rotate easily
- Chain structure gives thermosets high strength and good stiffness properties but ductility reduces, with thermosets generally showing a brittle form of failure.

Thermoplastics are comprised of flexible linear chains. Thermoplastics offer many advantages over thermoset polymers. The advantages of the thermoplastic matrix composites are:

- Low cost of processing than thermoset.
- Design flexibility and ease of moulding complex parts, simple methods such as extrusion and injection moulding are used for processing these composites [32].
- They are flexible, tough, and exhibit good mechanical properties.
- They generally have a lower weight than conventional thermosets resulting in a more straightforward and safer handling of the materials.
- Thermoplastics such as polypropylene have the lowest level of moisture absorption.
- Recycling is possible with thermoplastic reinforced natural fibre composites (see section 2.4.5).

The only major disadvantage of using thermoplastics is that they have a different chemical structure compared to natural fibres as they have high non–polar nature, so often a method of improving the interfacial region between the two materials needs to be investigated [33]. However, after assessing the limitations and the benefits of thermoplastic and thermoset in the present study, thermoplastics were chosen in preference to thermoset for natural fibre reinforcement.

The primary drawback when using lignocellulosic fibres is the lower processing temperature permissible due to the possibility of lignocellulosic degradation that could affect composite properties. The processing temperature is therefore limited to 200° C, although it is possible to use higher temperatures for short period of time. Therefore, the types of thermoplastic that can be used in natural fibre composites are limited to polypropylene (PP), high-density polyethylene (HDPE), low-density polyethylene (LDPE) and polyvinyl chloride (PVC). These thermoplastics have lower melting temperature generally less than 180° C.

Natural fibre composites need to be lightweight, and therefore require a thermoplastic matrix with low density. Density is often used for the calculation of specific properties, and these specific properties consequently give better indication of benefits achievable with the material. Polypropylene and low-density polyethylene have the lowest densities and are therefore most suitable for natural fibre. Water absorption in the matrix is a great disadvantage in composites, as water can migrate through the polymer to the fibre/matrix interface, resulting in the reduction in strength of composites. A matrix with low level of moisture absorption is thereby desirable, and polypropylene and low-density polyethylene are suitable as they have the lowest level of moisture absorption. Polypropylene happens to have the best combination of tensile strength and stiffness compared to low and high density polyethylene [34]. It can therefore be concluded that polypropylene is appropriate thermoplastic to use in natural fibre composites as it has the lowest density, absorbs less amount of water, has the best mechanical properties and is the cheapest among polypropylene, low density polyethylene and high density polyethylene.

2.3.2 Polypropylene (PP)

The most common polyolefin used to prepare composites is polypropylene, a commodity polymer that has been in commercial production for the last 40 years following its controlled polymerisation by Natta in 1954. [36] Natta used a Ziegler catalyst consisting of titanium tetrachloride and an aluminum alkyl to produce isotactic polypropylene directly from propylene.

Polypropylene is available with many different reinforcing agents or fillers such as talc, mica or calcium carbonate; chopped or continuous strand fibre. Glass is the most common reinforcing agent used for composites. Many additives have been developed to enhance the thermal stability of polypropylene to minimize degradation during processing. One of the most important requirements of the polypropylene used in the manufacture of composite is that, it should be relatively pure and free of residual catalyst. Recent developments to form copolymers of polypropylene and polyethylene have great promise for relatively inexpensive, tough thermoplastic composite application.

Molecular structure of Polypropylene:

In 1955 Natta first determined the molecular structures of the various types of PP and introduced the descriptive nomenclature universally used today. In isotactic PP, each monomer unit in the chain is arranged in a regular head-to-tail assembly without any branching. Furthermore, the configuration of each methyl group is the same figure: 2.2. This is caused by the template type constraints of the stereospecific catalytic site. Such a regular structure is the hallmark of a good catalyst.

Properties of Polypropylene:

Polypropylene is a linear hydrocarbon polymer containing little or no unsaturation. It is therefore not surprising that polypropylene and polyethylene have many similarities in their properties. [37] Basic mechanical properties are largely influenced by molecular mass and molecular mass distribution (MMD), chain stereoregularity and processing conditions, which introduce orientation, structural strain, etc. Various additive packages must be tailored to the application to achieve good and durable performance. Some typical properties of PP are given in table 2.6. The melting point of commercial PP lies in the range 160-170 °Cand for purified polymer melting point reaches to 176 °C. Within the range of commercial polymers, the greater the amount of isotactic material, the greater the crystallinity and hence greater the softening point, stiffness, tensile strength, modulus and hardness. [37] The crystalline and nonpolar nature of PP confers good resistance to a wide range of aqueous and polar media, including emulsifier solutions with their strong stress cracking abilities. Powerful oxidizing agents, highly aromatic and chlorinated solvents are too aggressive for safe storage in PP containers. [38] One disadvantage of PP is the susceptibility of its methyl groups to thermooxidative degradation. [39]

Table 2.6: Properties of PP

Parameters	Standard used	Values
Specific gravity	ASTM D792	0.90 – 0.91
Crystallinity, (%)	-	82
Melting temperature, (°C)	-	165 – 171
Tensile strength, (MPa)	ASTM D638	31 – 41
Tensile modulus, (GPa)	ASTM D638	1.10 – 1.55
Elongation at break, (%)	ASTM D638	100 – 600
Impact strength, notched Izod, J/m^{-1}	ASTM D256	21 – 53
Rockwell hardness (R-scale)	ASTM D648	90 – 95

2.4 Fibre reinforced polymer composites

The term composite material is used to describe macroscopic combinations of two or more materials. The fundamental goal in the production and application of composite materials is to achieve a performance from the composite that is not available from the separate constituents or from other materials. The concept of improved performance is broad and includes increased strength or reinforcement of one material by the addition of another material. [36] The modern interest in composite materials can be traced in the development of Bakelite, or phenolic resin, which was synthesized by Backeland a Belgium scientist, in 1906. [36] Bakelite was a hard, brittle material that had a very few mechanical applications of its own. However, the addition of a filler, (the earliest applications used short cellulose fibres) yielded Bakelite moulding compounds that were very strong and tough and found several applications in mass produced automobile components. The wood flour additives improved Bakelite's processibility, physical, chemical and electrical properties, as well as reducing its cost. [36]

Polymer composites are now an important class of engineering materials. The properties of composites are largely influenced by the properties of their constituents and the distribution and interactions among them. The constituents usually interact in a synergistic way, providing properties that are not accounted for by a simple volume-fraction sum of components. Along with the volume fraction and the distribution of discrete units in the discontinuous phase, the interfacial area plays an important role in determining the extent of interaction between the reinforcement and the matrix and – in this way – the final properties of the composite. The fabrication technology of composites, as well as some of their physical properties, is dominated by the chemistry and theology of the matrix resin and by the type and physical form of the reinforcement. [3]

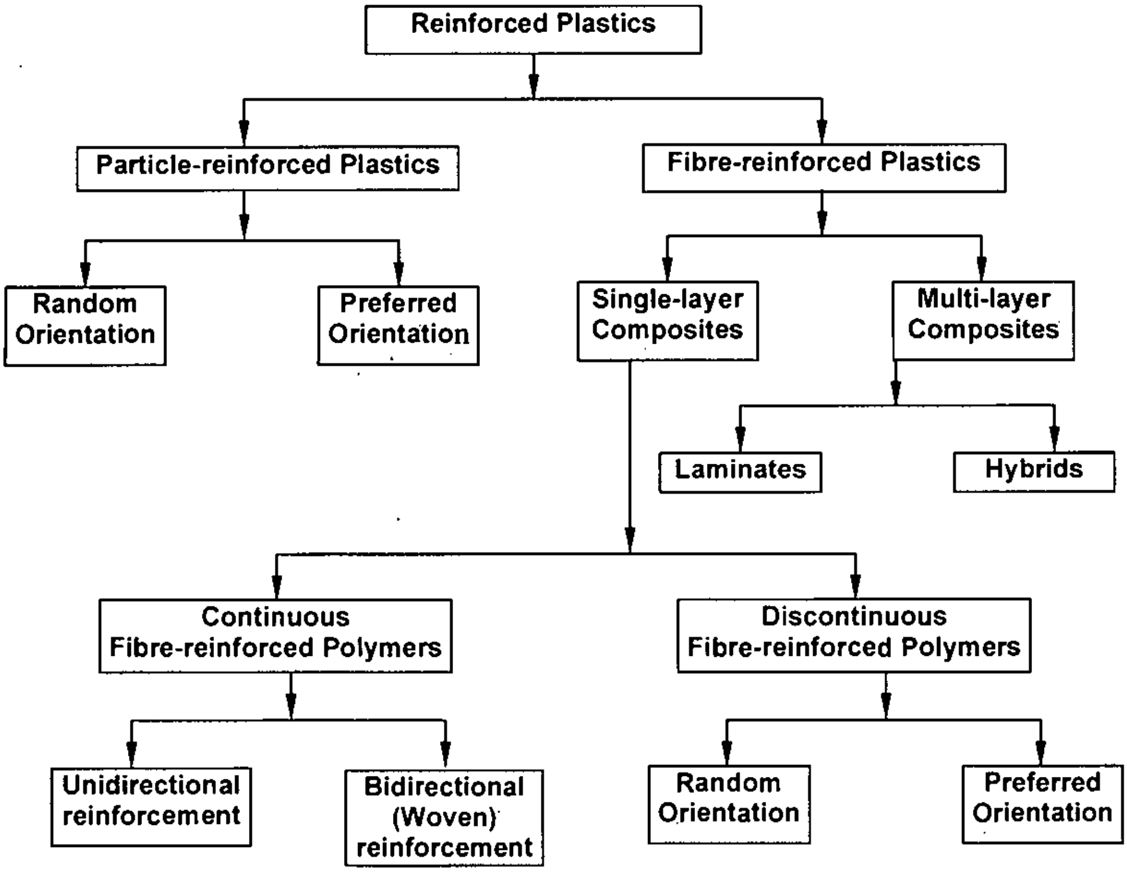


Figure 2.3: Classification of polymer composites.

The use of reinforcing agents makes it possible for any thermoset or thermoplastic matrix property to be improved or changed to meet varying requirements. Thus most polymer composites have been developed or fabricated to improve mechanical properties such as strength, stiffness, or toughness. The strengthening efficiency of the discontinuous phase plays the most important role in these products and the strengthening mechanism depends strongly on the geometry of the reinforcements.

Therefore, polymer composites can be classified according to geometry of reinforcement materials. The three major classes of polymer composites are fibrous, laminar and particulate. The commonly accepted classification scheme for polymer composites is presented in figure 2.3. [3]

2.4.1 Factors controlling the performance of natural fibre reinforced composites

The performance of a fibre–reinforced composite depends largely upon the strength of the interfacial bond between the fibre and the matrix. A major concern for thermoplastic materials, therefore, is incompatibility between natural fibre and thermoplastic [35].

Poor surface wetting and interfacial bonding:

The surface adhesion between the fibre and the polymer plays an important role in the transmission of stress from matrix to the fibre and thus contributes towards the performance of the composite. Poor surface wetting is the main reason for the formation of an ineffective interface between the fibre and the polymer. Most polymers, especially thermoplastics, are non–polar (hydrophobic) substances that are not compatible with polar (hydrophilic) fibres, preventing efficient fibre-matrix bonding. Therefore, the result is poor adhesion between polymer and fibre. This leads to problem of poor stress transfer, small voids in structure and de-bonding of the composite material [40]. In order to improve the affinity and adhesion between fibres and thermoplastic matrices in composite production, chemical coupling agents have been employed [31]. Grafting chemical series on to the fibre surface has also been reported to improve the interaction properties between the fibres and the matrix. Although grafting can improve properties of the composites to a significant extent, this process increases the materials cost of the system. The use of dispersing agent and/or coupling agents is a cheaper route to improve properties and makes practical sense for high volume, low cost composites systems [24].

Limited thermal stability of the fibre

The primary drawback of the use of Natural fibres is the lower permissible processing temperature due to possibility of lignocelluloses degradation and/or the possibility of volatile emissions that could affect composites properties. The processing temperatures are thus limited to about 200^0 C, although it is possible to use higher temperatures for short periods of time. This limits the type of thermoplastics that can be used with natural fibres [24].

The hydrophilic nature of organic fibre

Moisture absorption can result in swelling of the fibres and raises concerns about the dimensional stability of the agro-fibre composites. It affects the mechanical properties of composites. The absorption of moisture by the fibre is minimised in the composites due to encapsulation by the polymer. It is difficult to eliminate the absorption of moisture totally without using expensive surface barriers on the composite surface. The moisture absorption of fibres can be dramatically reduced through the acetylation of some of the hydroxyl groups present in the fibre, but with some increase in the cost of the fibre [41]. Good fibre-matrix bonding can also decrease the rate and amount of water absorbed by the composite [42].

Dispersion of the fibre in the matrix

The incorporation of fibres in thermoplastics leads to poor dispersion of the fibres. To obtain a satisfactory performance from the composite, it is necessary to have a good fibre distribution within the matrix. A good distribution implies that the fibres are fully separated from each other, and each fibre is fully surrounded by the matrix. Insufficient fibre dispersion can lead to clumping and agglomeration of the fibres, resulting in an inhomogeneous mixture of thermoplastic rich and fibre rich areas. This segregation is undesirable, as the thermoplastic rich areas are weak, while the fibre rich areas (clumps) are susceptible to micro cracking. Micro cracks contribute to inferior mechanical properties for composites. It is therefore necessary to ensure a homogeneous fibre distribution in order to achieve better composite tensile properties.

Two major factors that affect the extent of fibre distribution and dispersion in a composite are the strong hydrogen bonding between the fibres and fibre length [43]. To separate the fibres from their fibre bundles, it is necessary to dissolve the pectin and lignin joining the individual fibre together. Fibre separation can easily be performed by digesting the fibres with a strong alkali [24]. Fibre separation also occurs during compounding with the thermoplastic matrix. Several factors contribute to this fibre attrition, such as the shearing forces generated in the compounding equipment, residence time, temperature and viscosity of the mix [24]. The use of dispersing agent such as stearic acid, or pre-treating the fibre with acetic anhydride can also improve a composites properties as fibre clumping is not as severe a problem with treated fibre as it is with untreated fibre [44]. The length of the fibres used in the composites is a critical factor. They should not be too long; otherwise, they may entangle with each other resulting in clumping and reduced composites mechanical properties such as strength. If the fibres are too short, the stress transfer area will be too small for them to offer effective reinforcement. As fibre lengths reduce during composites processing, the ultimate fibre lengths present in the composite are dependent on the type of compounding and moulding equipment used. To produce efficient composites with well-dispersed fibres, it is therefore necessary to make careful selection of the initial fibre lengths, processing aids, processing techniques and processing conditions.

Biodegradability

The biodegradability of natural fibre reinforced composite materials is often put forward as a positive advantage justifying the use of these materials. However, for many applications, outdoor performance for a number of years is required of composite components. Natural cellulose fibres degrade easily when exposed to nature. Some of these methods of degradation include biological, thermal, aqueous, photochemical, chemical and mechanical degradation processes [45]. In order to produce cellulose fibre-based composites with a long service life, it is necessary to retard this natural degradation. One way of preventing or slowing down the natural degradation process is by modifying the cell wall chemistry. Undesirable natural fibre properties such as dimensional instabilities, flammability, biodegradability, and chemical degradation can be eliminated or slowed down in this manner [47]. Chemical treatments can reduce the water uptake in the fibres, and can therefore reduce the amount of fibre swelling and biological degradation by blocking the available OH group on the fibre surface [48]. It is reported in the literature that encasing in thermoplastic reduced water uptake [48].

Critical fibre length (aspect ratio)

The fibre aspect ratio (length/diameter) is a critical parameter in a composite material. For each short fibre composite system, there is critical fibre aspect ratio, which may be defined as the minimum fibre aspect ratio in which the maximum allowable fibre stress can be achieved for a given load [46]. If the fibre aspect ratio is, lower than its critical value, insufficient stress will be transferred and reinforcement of the fibre will be insufficient (i.e. the fibres are not loaded to their maximum stress value). By contrast, if the fibre aspect ratio is too high, the fibres may get entangled during mixing resulting in poor fibre dispersion. An aspect ratio in the range of 100 – 200 after composite processing is recommended for high performance short fibre composites [48].

Fibre orientation

Orientation of fibres related to one another plays an important role in the study of composites. The strength of the unidirectional aligned composites normal to the fibre alignment (transverse) is less than that of the randomly oriented fibre composite. When the fibres are aligned perpendicular to the direction of force (transverse), fibres are not reinforcing the matrix to increase the strength of the composite in the direction of applied load [48]. Short fibre composites rarely consist of fibres oriented in a single direction. During extrusion and injection moulding, the polymer melt will undergo both extensional and shear flow. There will be rotation of the fibre during shear flow and alignment during elongation flow. Thus, it is possible to achieve some degree of fibre alignment using extrusion and injection moulding [28].

Fibre volume fraction

One of the most significant factors determining the mechanical properties of composite material is the content of reinforcing fibre. Changes in a composite's properties with variations in fibre content, particularly tensile strength and Young's modulus can be predicted using failure prediction models such as the "Modified rule of mixtures".

$$\sigma_c = \left(V_m \times \sigma_m^*\right) + \left(V_f \times \sigma_f \times K_1 \times K_2\right) \quad \text{………………………………………} (1)$$

Where,

σ_c = the tensile strength of the composite
σ_f = the tensile strength of the fibre
V_m = the matrix volume fraction
V_f = the fibre volume fraction
K_1 = orientation factor
K_2 = a factor dependent on the stress transfer between the matrix and the fibres
σ_m* = the tensile contribution of the polymer matrix at the failure strain of the composite

The mechanical properties of short fibre composites are more difficult to predict than continuous fibre composites. This is due to the complexity of determining parameters such as fibre dispersion, orientation and geometry (aspect ratio) of the fibres within the composite, fibre and matrix volume fractions, and the interfacial shear strength between the fibre and the matrix [43].

At low fibre volume fractions, a decrease in tensile strength is usually observed. This is due to the introduction of flaws created by the fibre ends. These flaws act as stress concentrators, and cause the bond between fibres and matrix to break. At higher volume fractions, the matrix is sufficiently restrained and the stress is more evenly distributed. This results in the reinforcement effect outweighing the effects of the stress concentrations.

As the fibre volume fraction is further increased, the tensile properties gradually improve until they surpass those of the matrix. The corresponding fibre volume fraction at which the strength properties of the composite cease to decline and start to increase is known as the critical fibre volume fraction. At very high fibre volume fractions, the strength of the composite starts to decrease due to insufficient filling of the matrix material. From the literature [30], it was found that the strength increase with an increase in fibre volume fraction was linear up until 40% fibre (by volume), after which there was reduction in strength for kenaf fibre reinforced poly-L-lactic acid composites. Another explanation for the decrease in composite mechanical properties at high volume fractions has been mentioned in the literature [49]. During the processing (extruding and injection moulding) of short fibre reinforced polymers, fibre damage take place as a result of fibre polymer interaction, fibre-fibre interaction, and fibre contact with the surface of the processing equipment. At high volume fractions, there is an increase in fibre-fibre interaction and fibre equipment contact, resulting in reduction of fibre length and fibre efficiency. A high fibre content therefore leads to reduction in the mean fibre length, and if the mean fibre length is very different than the critical fibre length, the reinforcement efficiency is reduced.

Modification of interfacial region

The stiffness and strength of the fibres are the basis for reinforcement, but also the interfacial strength (bonding) is important for efficient reinforcement. For strength properties, where the interface is loaded directly in shear and/or tension, interfacial strength enters directly as controlling parameter (e.g. off axis loading, shear loading, transverse tensile loading and axial compressive loading). Weak interfaces act as internal defects or cracks and are thus generally detrimental and lead to early crack development and growth. It may not always be an advantage for a composite to have a strong interface, since this could render the composite as a whole brittle because the cracks will not be deviated from their main path by branching and/or interfacial delamination. It is therefore not only of interest to develop strong interfaces but rather to develop interfaces of controlled strength [16]. To improve interfacial bonding, modification can be made to the fibres, the matrix or both the fibre and matrix. Fibre treatment performed to achieve one or more of the following objectives.

- Removal of undesirable fibre constituents
- Roughening up of fibre surfaces
- Separation of individual fibre from their fibre bundles
- Modification of the chemical nature of the fibre surface
- Reduction in the water uptake of the fibre

There are a number of ways in which the interface can be enhanced as shown in Figure 2.4.

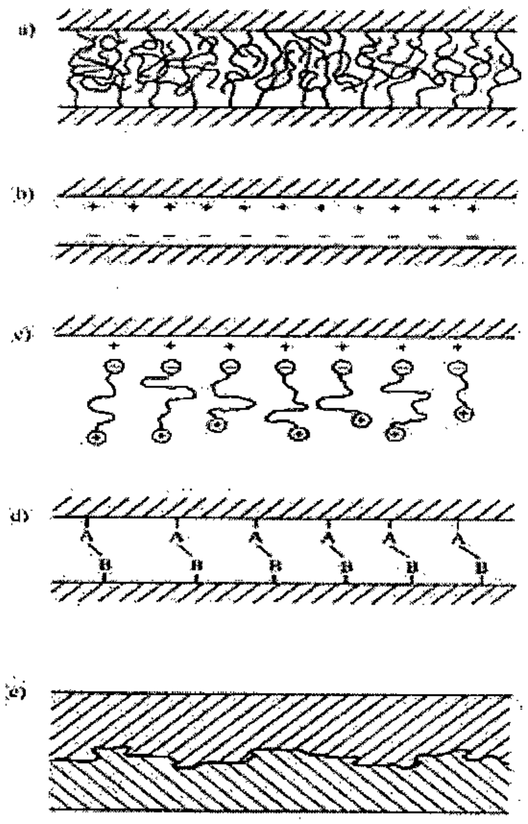


Figure 2.4: Ways to increase interfacial adhesion [50].

Figure 2.4 (a) shows the diffusion of free chain ends at the interface between two polymers, which leads to chain entanglements and an increase in adhesive strength. Figure 2.4 (b) represents two surfaces that carry net electrical charges of opposite signs, while figure 2.4 (c) shows how these two surfaces can be attracted due to cationic and anionic functional groups. Figure 2.4 (d) shows how a simple chemical reaction can aid interfacial forces, while figure 2.4 (e) represents how a contribution to the strength of the interface can be due to the surface roughness of the fibres [51]. Fibre treatment for interfacial modification can be physical, biological or chemical.

Physical methods of modification

Physical modification methods involve surface fibrillation or electric discharge (corona, cold plasma). Physical treatments change structural and surface properties of the fibre and thereby influence the mechanical bonding with the matrix. Physical methods of modification include low temperature plasma, oxygen plasma, electrical discharge and corona treatment, which are of great interest in the relation of improvement in functional properties of plant fibres [50].

Biological treatment

One method of fibre treatment involves the use of naturally occurring micro-organisms, namely bacteria and fungi. In the future, enzyme-based processes could lead to efficient fibre processing for natural fibre reinforced composites. The potential for environmentally friendly efficient lignin removal encouraged research that led to the discovery of lignin-degrading enzymes in the early 1980s and to extensive investigations into their activities up to present. Development of Microbial enzyme applications in pulp and paper began with studies of the use of cellulases (an enzyme that hydrolyses cellulose) to facilitate fibre beating, and progressed through to current efforts to apply lignin-degrading enzymes [52]. Enzymes such as xylanases reduce the amount of chemicals required for bleaching; cellulases smooth fibres, enhance drainage, and promote ink removal; lipases reduce pitch; lignin degrading enzymes remove lignin from pulps [53]. White-rot fungi is extensively used in degradation of lignin [54]. The white-rot fungi Ceriporiopsis subvermispora grows on wood aggressively and is suitable for biopulping of both soft and hardwoods [55]. Although extensive work on biologically treated natural fibre reinforced plastic composites was not evident from the literature but it is a potential environmentally friendly natural fibre modification process for increasing the interfacial strength and composite's mechanical and environmental properties.

Chemical modification

Chemical modification can be classified as fibre pre-treatments and treatment with coupling agents. Pre-treatments include the use of chemicals that remove undesirable and non-strength contributing fibre constitutes such as lignin, pectin, and hemicellulose. The most popular chemical pre-treatment is alkali treatment. Another most extensively used chemical treatment is chemical coupling. Coupling agents improve the adhesion between the reinforcing fibres and the matrix material. Coupling agents can sometimes reduce the water uptake of the fibres and can assist with fibre dispersion as well.

Chemical pretreatment of natural fibres

Pretreatment with NaOH improves adhesion characteristics of natural fibre by removing surface impurities (lignin, pectin and hemicellulose), which then provide the fibre surface with a rough texture, the rough and cleaned surface facilitates mechanical interlocking in addition improves wetting ability of the matrix [56]. NaOH treatment also improves mechanical properties of natural fibre reinforced plastic composites by assisting separation of the elementary fibres, as well as exposure of more active OH sites for interfacial bonding [57]. Furthermore, change in the crystallinity through alkaline treatment is reported in the literature [24]. The removal of the cementing materials (lignin, pectin and hemicellulose) within the fibre wall leads to a better packing of cellulose chains, thus increasing the crystallinity index of the fibre. Additionally, treatment with NaOH leads to a decrease in the spiral angle, i.e. closer to fibre axis, and increase in molecular orientation. Well oriented cellulosic fibres such as hemp and flax have much higher Young's modulus than fibres with medium orientation, such as cotton [28]. Alkali fibre treatment is therefore a suitable pre-treatment process for natural fibre that is to be used in thermoplastic composites.

2.4.2 Chemical modification with coupling agent

Strongly polarized cellulose fibres are inherently incompatible with hydrophobic polymers. When two materials are incompatible, it is often possible to bring about compatibility by introducing a third material that has properties intermediate between those of the other two. Chemical modification method such as chemical coupling method can improve the interfacial adhesion. In this process, fibre and matrix are mixed together with a compound to form a bridge of chemical bonds between them. Coupling agents can sometimes reduce the water uptake of the fibres and can assist with fibre dispersion as well [58].

The important coupling agents for natural fibre reinforced composites are acetic anhydride, maleic anhydride (MA)-grafted polypropylene or maleated polypropylene (MAPP), silanes and some thermosetting resin adhesives. They are briefly discussed below:

Maleated polypropylene (MAPP)

MAPP has been reported to function efficiently in improving the dispersion and interaction between cellulose-based fibres and polypropylene. MAPP consists of long polymer chains with a MA functional group grafted at one end. MAPP acts as a bridge between the non-polar polypropylene matrix and the polar fibres by chemical bonding with the cellulose fibres through the MA groups, and bonding to the matrix by means of chain entanglement. Figure 2.5 shows the reaction mechanism of MAPP with the lignocellulosic fibre surface. It is seen that the MA forms covalent bonds with the hydroxyl group (-OH) present on the natural fibre surface [24]. To create a successful interface between the MAPP and natural fibre-PP composite some important considerations must be taken in to account. One important consideration is that MAPP has to be strongly interactive with the fibre surface through covalent bonding. This means that there must be sufficient functional groups (free anhydride) available to react with the hydroxyl groups (-OH) on the fibre surface. The acid number, which represents the amount of functionality in coupling agent, is therefore very important [24].

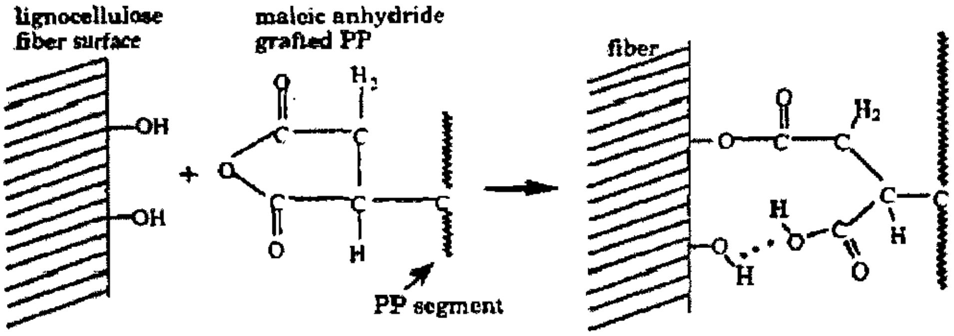


Figure 2.5: Reaction mechanism of maleated polypropylene (MAPP) with the surface of the lignocellulosic fibre (showing potential for both covalent and hydrogen bonding) [24].

Another important consideration when selecting a suitable form of MAPP is the molecular weight of the MAPP. Higher molecular weight ensures longer chain length. Long MAPP chains will form multiple entanglements with polypropylene (PP) chains, hence improving the properties of the composite material (see Figure 2.6).

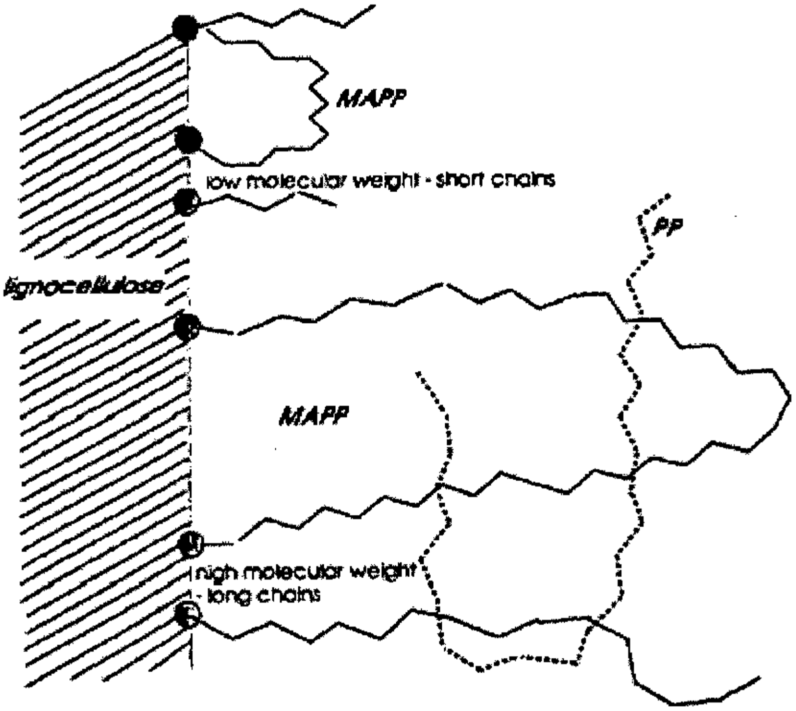


Figure 2.6: Schematic of possible polypropylene (PP) molecules' entanglement with the longer chains of maleated polypropylene (MAPP). Shorter chains of MAPP have less opportunity to entangle with the PP molecules [24].

Whereas, short MAPP chains with low molecular weight will not entangle with PP chains, and hence will not improve properties. Therefore, a minimum chain length ensures entanglement of fibres [24]. However, extremely long chains may reduce the possibility of migration of the MAPP to the fibre surface if the processing time is short.

The amount of MAPP used in the experiments is also an important consideration. The concentration of MAPP determines the coupling effectiveness in the composite. Generally, mechanical properties increase with the increase in concentrations of MAPP up to a certain limit, and then decline or level off at higher concentration. An excess amount of MAPP is detrimental to the coupling action and may inhibit the adhesion. The reason possibly lies in one of the following:

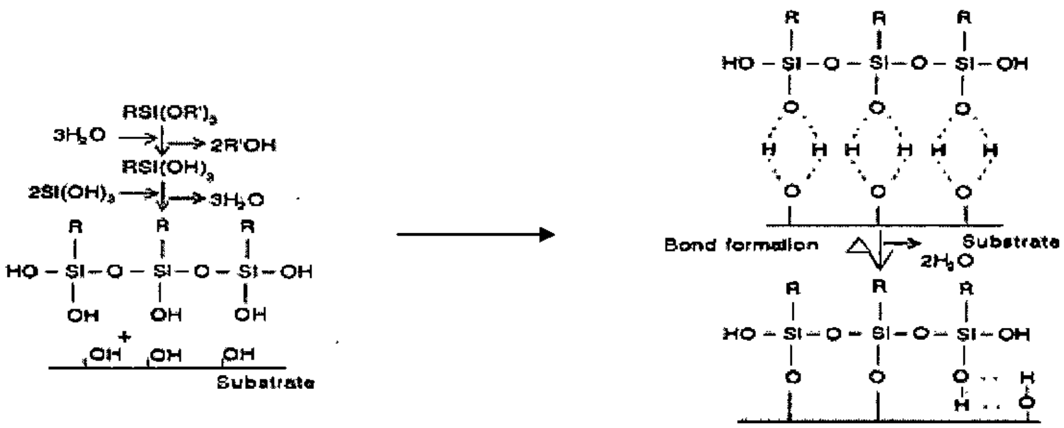
- The formation of different by-products,
- Increase in concentration of non reacting or non grafting coupling agents, and
- Interference with coupling reaction

During the coupling treatment, initiators, organic solvents, antioxidants, stabilizers, and other processing aids are also added to help reaction and improve the physical and mechanical properties of natural fibre composites [59].

Composite with 3 wt% MAPP (Eastman Chemical Epolene G-3002) 50wt % kenaf fibre reinforced polypropylene showed a tensile strength increase of 88% and a Young's modulus increase of 350% [24]. Composites with 2 wt % MAPP (Aldrich A-C 950P) to couple 50 wt% radiate pine fibres with polypropylene reported an increase in tensile strength of 123% and Young's modulus 177% [60].

Silanes

Silanes, represented as R-Si(OR)$_3$, have been used to couple cellulose fibre with thermoplastic such as polystyrene, polypropylene and polyethylene [61, 47]. The general mechanism of how alkoxysilanes form bonds with the fibre surface, which contains hydroxyl groups, is as follows [48]:



Silane based coupling agents are hydrophilic compounds based on silane molecule with different organic groups attached. One group interacts with the hydrophilic cellulose fibre, while another groups react with the hydrophobic thermoplastic matrix material [62]. The reaction between cellulose material and silane is not simple. It is known that silane coupling agents react with cellulose water (or additional water) to from silane (Si-OH) groups. After hydrolysis, the coupling agent can develop either covalent or hydrogen bonds with the free OH groups on the fibre surface, but the degree of conversion of such OH groups is not well known [63].

Acetylation

Fibre treatment with acetic anhydrite (acetylation) is an effective method of reducing the hydrophilic characteristics of cellulose fibres [64], as well as fibre dispersion within a thermoplastic composite.

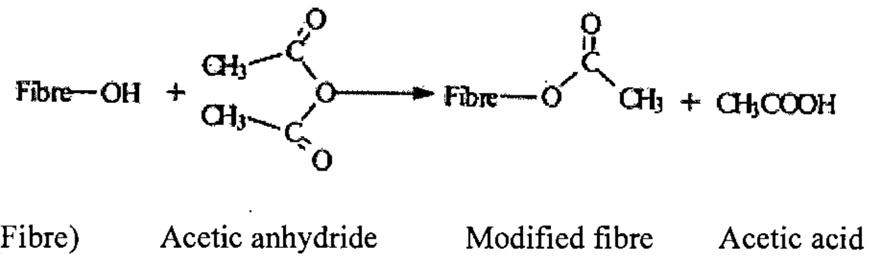


Figure 2.7: Fibre reaction with acetic anhydride.

Acetic anhydride is a compatiblizer that lowers the surface energy of the fibre to make it non-polar and more similar to the thermoplastic matrix [65]. This is achieved by the formation of stable acetate bonds with the reactive OH groups on the fibre surface. Once the acetic anhydrite has bonded with the OH groups of the fibre, they are no longer reactive and are therefore no longer free to bond with other OH groups, water or other chemicals.

Acetylation has been shown to reduce swelling of wood in water [50, 66], and to be beneficial in reducing moisture absorption of natural fibres. Reduction of about 50% of moisture uptake for acetylated jute fibres and of up to 65% for acetylated pine fibres has been reported in the literature [58]. It was reported that acetylation did not significantly affect the single fibre tensile strength of dew rated flax fibres, and that a slight increase in strength was observed for green flax fibres (11.8% increase in strength). It was also reported that acetylation slightly improved the interfacial bonding of dew rated flax reinforced isostatic polypropylene composites, and cause a significant improvement for the green flax composites. A shear strength increase of 2.3% was observed for the acetylated dew-rated flax composites, and a shear strength increase of 83% was observed for acetylated green flax composites [67].

Thermosetting resin adhesives

Some thermosetting resin adhesives, such as phenol-formaldehyde resin (PF) and mono- or dimethylol melamine resin (DMM) have been introduced as bonding agent in plant fibre plastic composites. PF and DMM resins can crosslink wood fibre with methylene ($-CH_2-$) linkage resulting from the condensation reaction between their reactive methylol groups ($-CH_2OH$) and hydroxyl groups ($-OH$) of wood fibre. Although these methylol groups can not react with the thermoplastic matrix. PF and DMM improve the interfacial adhesion through molecular entanglement with the matrix [68].

2.5 Processing methods for short fibre reinforced composites

The processing methods used to fabricate thermoplastic reinforced with short cellulose fibres are generally the same as those used for short fibre synthetic composites. The manufacture of short natural fibre reinforced thermoplastic composites is often a two-step process. The raw materials are first mixed together in a process called compounding, and the compounded material is then formed into a product. Compounding involves the feeding and dispersing of fillers and additives in to the molten polymer. Many options are available for compounding, using either batch, continuous or melt mixers, or single or twin-screw extruder. The compounded material can be immediately pressed or shaped into an end product or formed into pellets for future processing like injection moulding or extrusion to final long product. The most widely used techniques for compounding natural fibres are "melt mixing" with mixer and twin-screw extrusion discussed below. Injection moulding and compression moulding are two of the most commonly used composite forming techniques also discussed briefly below.

2.5.1 Melt mixing

Melt mixing using a radial flow (turbulent) mixer is a commonly used method for combining short reinforcing fibres with thermoplastic matrix materials. The thermoplastic material usually heated up to its melting temperature before the fibre is added. After the mixing has taken place, the composite mix can be rolled, formed or injection mould into the desired shape. From the study of sisal fibre with polypropylene using a Haake Rhecord mixer it was found that ineffective mixing and poor fibre dispersion occurred at short mixing time and low mixing speeds, while low mixing temperatures resulted in extensive fibre breakages [48]. Composite strength loss due to fibre breakage also occurred at high mixing times and high mixing speeds, with high mixing temperature resulting in fibre degradation and poor fibre dispersion. An optimum mixing time 10 min, mixing speed 50 rpm and mixing temperature 170° C was reported.

2.5.2 Extrusion

The process of extrusion is similar to the squeezing of toothpaste or forming of spaghetti. Because the viscosity of most natural fibre reinforced thermoplastic composites melt is high, extrusion requires the production of pressure in order to force the melt through the die. A screw pushes natural fibre with thermoplastic granules or powder through a heated cylinder, changing the feed from solid to liquid and mixing the thermoplastics with natural fibre as it moves through the barrel. The thermoplastic is melted in the barrel by the mechanical energy from the rotating screws and the heat transferred from the high temperature barrels [69].

There are two types of extruder namely single screw extruder and twin screw extruder. For single screw extruders, friction between the plastic and the rotating screw makes the resin rotate with the screw. The friction between the rotating plastic and the barrel pushes the materials forward and generate heat. Single screw extruders are not positive displacement, so they are not effective mixing device. Twin-screw extruder is a compounding device to uniformly blend matrix and reinforcement into the composite melt. Twin-screw extruders have intermeshing screws, the relative motion of the flight of one screw inside the channel of another pushes the material forward with very low friction. Heat is controlled from an outside force and is not controlled by the speed [71, 70].

Extrusion using a twin-screw extruder is often carried out prior to injection moulding because a good fibre distribution within the matrix is achievable [72], and extruded composites can easily be chopped into injection mouldable pellets. In producing fibre reinforced composites using extruding techniques, it is necessary to optimise the extent of compounding. Inadequate compounding causes poor dispersion and poor wetting of the fibres, while excessive compounding causes severe fibre damage and fibre shortening, all of which lead to a reduction in mechanical strength.

Most fibre damage is caused by friction between fibres, or between fibres and thermoplastic melt. One method of minimising fibre breakage is to feed the thermoplastic into the main in-feed port and to feed the fibres into a second port further down the barrel [73]. This enables thermoplastic to melt before coming into contact with the fibres, thus reducing the shear force action on the fibres. A second method of preserving the fibres during compounding is to keep the compounding distance as short as possible and to exclude kneading elements on the extruder screw [74].

Another variable that can affect the composite strength is processing temperature. Insufficient wetting of the fibres can occur if the temperature is very low resulting in a weaker composite. A very high temperature also results in a weaker composite because of fibre degradation.

2.5.3 Compression moulding

Compression moulding is the most common method of processing thermosets. Generally, the bast fibres jute, flax and hemp can all be used to produce thermoplastic press-moulded composites. The most commonly used polymer is polypropylene in a (50:50) blend. In this process, natural fibres are blended with polypropylene (PP) fibres and then pressed under heat into desired shape. Advantages of compression moulding are short cycle time (typically 1-6 minutes), high volume production, and high quality surfaces. Disadvantages are high initial capital investment, labour intensive, slow, automation of production is not possible, secondary operations required.

2.5.4 Injection moulding

Injection moulding is the most promising method for processing of natural fibre reinforced thermoplastic. Some important parts of an injection-moulding machine are the hopper, barrel, screw, and mould (see Figure 2.8).

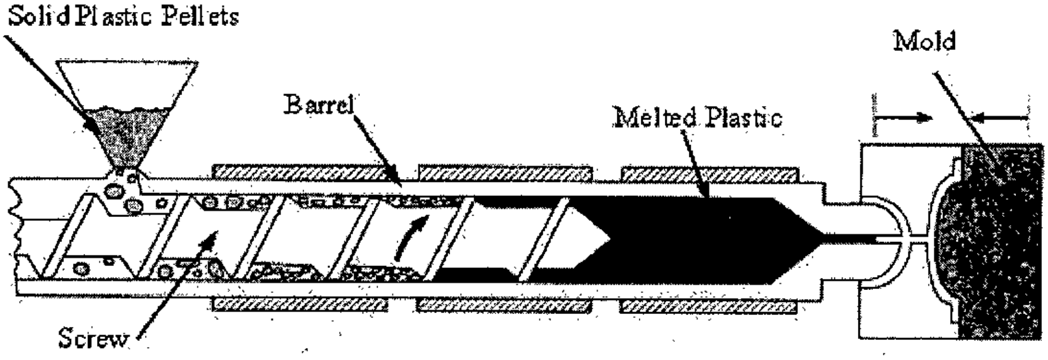


Figure 2.8: Detail of screw and barrel of a injection moulder.

Several steps comprise the injection moulding process: feeding, melting, injecting, cooling, and ejecting. When extruded pellets of the compounded mixture are fed into the hopper in the feeding step, the injection moulding machine rotates the screw, pumping composite material from the hopper towards the front of the barrel, creating a reservoir of melted material. During screw rotation, electric barrel heaters and friction melt the plastic pellets. In the injection phase, the screw moves forward, pushing the molten composite material into the mould. A large force must be used to inject into the hollow mould cavity. Injection-moulding machine pushes melt, under high pressures into the mould. The mould, usually made from steel or aluminium, has the shape of the part desired machined into it. The mould holds the shape of the part as it cools and solidifies; the part is then removed. The cooling water in the mould draws away the heat during the cooling phase. After the part has been held long enough to solidify, the injection-moulding machine opens the mould and ejects the newly formed part.

Advantages of injection moulding are that: complexity is virtually unlimited, sizes can vary and excellent tolerance is also possible. Identical parts are produced through a cycle process involving the compounding of natural fibre reinforced composite material by extruding, followed by the injection moulding of the melted composite material into the mould cavity. Cycle times are relatively lower than other available process such as compression moulding, and many parts can be made from a single mould, making extremely high volumes (millions per year) possible. Injection moulding can be used to form a wide variety of products and is commonly automated. A single operator can run many machines. The incorporation of short fibres in an injection moulded polymer increases the strength, modulus, impact, creep and heat resistance while decreasing the strain to failure [75].

Disadvantages of injection moulding with respect to reinforced composites is that only randomly oriented short fibres can be used in this process, the orientations of the fibres in the composite are determined by the flow of the composite melt during filling of the mould cavity. Large undercuts cannot be formed (such as bottles). Mould cost is high, so low part volumes are not recommended (usually less than 1000 parts is considered low; most volumes for injection moulded parts are well over 10,000 pieces per year) and primary processing is required.

Composites materials, for injection moulding must be capable of flow under pressure and therefore usually short fibre reinforced thermoplastics with a relatively low fibre fraction (typically <50wt% or 30vol%) can be produced. However, too low fibre fraction does not give sufficient property improvements to the moulded composite. At high volume fraction, difficulties in processing can compromise properties such as impact performance [76].

Unlike extrusion and melt mixing, it has been found that injection moulding does not significantly damage cellulose reinforcing fibres [77]. The fibre distribution of an extruded hemp fibre reinforced thermoplastic composite was compared with the same composite that had been extruded and then injection moulded [77]. The results showed that average fibre length after extrusion was 0.53 mm (reduced from 8 mm average length), and that there was no significant reduction in fibre length with the addition of injection moulding process.

The rapidly expanding use of composite components in automotive, construction, sports and leisure and other mass production industries has focused attention on continuous production techniques. Techniques like extrusion and injection moulding definitely suitable for the manufacture of structural profiles from composites on a continuous basis in line processing. Combining the compounding and product manufacturing steps is called in-line processing.

2.6 Natural fibre reinforced polypropylene composites

The property data on natural fibre reinforced polypropylene composites with maleated polypropylene (PP) used as coupling agent published in literatures is shown in table 2.7. The tensile property data of glass fibre reinforced PP composites with MAPP coupling agent also included. Specific sets of properties have not yet been developed for natural fibre reinforced polypropylene composites.

Table 2.7: Mechanical properties of natural fibre and glass fibre reinforced polypropylene (PP) composites with maleated polypropylene (MAPP) coupling agent [78, 58, 79, 80, 81, 82, 83, 84, 85].

Fibre reinforcement (%)	**Density (g/m$^{3)}$**	**Tensile strength (MPa)**	**Tensile Young's modulus (MPa)**	**Specific tensile strength (Pam^3/g)**	**Specific tensile Young's modulus (KPam^3/g)**
Polypropylene (PP)	0.9	23	1.3	25.56	1.44
PP+20% glass	1.04	49.9	4.7	48	4.52
PP+30% glass	1.17	70.8	6.5	60	7.29
PP+40% glass	1.22	78.3	8.9	64	7.29
PP+30% flax	1.05	52	5.7	50	5.43
PP+30% kenaf	1.3	65	8.3	50	6.38
PP+40% kenaf	1.15	55.8	6	48	5.22
PP+50% kenaf	1.2	65.8	8.3	55	6.92
PP+30% jute	1.05	49	4.8	46	4.6
PP+60% jute	1.12	71	10.8	63	9.6
PP+40% bamboo		13	3		
PP+50% bamboo		35	4		
PP+30% hemp	1.03	37	2.93	35.92	2.84
PP+40% hemp	1.10	38	4.02	34.55	3.65
PP+30% thermo mechanically pulped wood		44.11	2.46		
PP+30% bleached kraft pulp of wood		40.86	2.440		
PP+40wt% wood flour		34.8	3.7		

From the table 2.7 it is clear that mechanical properties of natural fibre reinforced PP composites with MAPP compares well with their glass fibre counter part.

2.7 Recycling/Reprocessing

The natural fibres are less brittle and softer than glass fibres and are likely to result in composites that are easier to recycle than mineral-based fibres. Although no post-consumer based recycling studies have been done on natural fibres, a short study of the effect of reprocessing has been conducted at the Forest Products Laboratory and the University of Wisconsin-Madison [24, 77].

Short kenaf filaments were compounded with polypropylene and MAPP using the thermo kinetic mixer. The blend ratio was 50% kenaf to 49%PP to 1% MAPP. All the compounded material was then granulated, dried at 105^0 C for 4 hours and moulded at 190^0 C using the injection moulder. Specimens were selected to evaluate tensile properties. All the non-tested specimens were again granulated and injection moulded. The procedure of granulation and injection moulding was repeated for total nine data points. The highest tensile strength was observed 62.5 MPa for virgin composite and the lowest 50 MPa for nine times recycle composite. The highest tensile stiffness was observed 8 GPa for virgin composite and the lowest 6.7 GPa for nine times recycle composite. The loss of properties is a combination of repeated fibre attrition and oxidative degradation of the polypropylene.

Chapter Three

MANUFACTURE AND EXPERIMENT OF COMPOSITES

3.1 Introduction

Characterisation of single fibre properties such as morphological, physical, chemical and mechanical properties were compared to select the ideal fibre for reinforcing polypropylene composites. Mechanical properties like tensile strength, Young's modulus, failure strain, notched charpy impact energy for jute fibre reinforced polypropylene composite are carried out considering the length and volume fraction of the reinforcing fibre as variables. Comparison of tensile strength, Young's modulus, failure strain, notched charpy impact energy, mean interfacial shear stress for jute, carbon and glass fibre reinforced polypropylene composites were carried out. Comparison of properties like tensile strength, young's modulus, composite density for jute fiber reinforced polypropylene composite with other natural fiber (slabwood, thinnings, luaan, hemp and eucalyptus) reinforced polypropylene composites were also performed. The jute fibre were cut to desired length and then dried to elevated temperature (105 °C) for a certain period of time (6 hours) to remove moisture completely. Single screw extruder and a manual powered injection moulding machine were used to prepare the sample specimens of desired size and shape. The dried jute fibre reinforced composites with different fibre volume percentages and polypropylene volume percentages were used to study the effect of fibre volume percentage and polypropylene volume percentage on composite tensile strength, Young's modulus, failure strain and notched charpy impact energy. Also the effect of fibre length on composite tensile strength, Young's modulus, failure strain and notched charpy impact energy were studied. Calculation of composite density with different fibre volume percentages and fiber lengths were performed. Calculation of specific tensile strength and specific Young's modulus were also performed. Theoretical calculations of composite tensile strength values for different volume fractions of fibre were also carried out to compare with experimentally obtained values. Fibre efficiency factor for the composite strength, fibre efficiency factor for composite modulus and theoretically composite's strength prediction are calculated using the modified rule of mixtures.

3.2 Materials

3.2.1 Natural fibre

The jute fibre were collected from Bangladesh Jute research Institute (BJRI), Dhaka, Bangladesh. The supplied jute fibres were mixture grade of Tossa variety (Corchorus olitorius). The middle parts of jute fibres were taken in this study and to prepare short fibres, the jute fibres were chopped carefully by using scissors into lengths of approximately 1 mm, 2 mm, 3 mm.

3.2.2 Matrix

Polypropylene (PP) was used in this study. It was manufactured by the Polyolefin Company, Pte., Ltd., Singapore. Melting point of this polypropylene was measured and found to be 174°C. The used polypropylene was an isotactic polypropylene and pure. In the literature it is mentioned that the melting point of commercial grade polypropylene lies in the range 160°-170°C but pure PP melts at 176°C [51]. The density of the polypropylene used in this work is found to be 0.903 gm/cm^3.

3.3 Instrument used

The list of instrument used in this study are:

- Chopper or scissor
- Oven
- Desiccators or Conditioning chamber
- Single-screw extruder
- Injection-moulding machine
- Milling Machine
- Universal Impact Testing Machine
  Type: TIT – 30
  Pendulum type impact strength tester
  Tokyo Testing Machine MFG. Co. Ltd.
  Japan.
- Universal tensile testing machine (model:MSC-5/ 500, capacity:5KN, Ogawa Seiki C. Ltd., Japan)
- Scanning Electron Microscope (Philips, Model: XL-30, Netherlands)

3.4 Pre-treatment of jute fibres

The jute fibres were first cleaned manually and chopped using scissors into approximately 1 mm, 2 mm and 3 mm length. The fibres were then washed with distilled water and dried in open air. The air-dried fibres were then oven dried at 105°C for 5 hours until the moisture were fully removed. Then the fibres were placed in desiccators and ready to be fed to the extruder.

3.5 Composite fabrication

Jute reinforced polypropylene composites were prepared using raw jute following the procedure described below:

Polypropylene polymers were dried in oven for 3 hours at 105°C. Jute fibres were mixed thoroughly with polypropylene to prepare composites. Jute fibres of different length (1 mm, 2 mm, 3 mm) are used in the fabrication of the composite. polypropylene matrix and jute fibres were taken in different volume fractions for each reinforcing fibre length (Table 3.1). Weight fractions for desired volume fractions of jute and polypropylene were calculated by multiplying the densities of jute and polypropylene with their volume fractions respectively.

Table 3.1: Relative amounts of reinforcing materials and polymer matrix by volume fraction (%).

Reinforcing fibre Length, mm	Reinforcing fibre volume fraction (%)	Polymer matrix volume fraction (%)	Composites (volume fraction)
-	None	PP: 100	100 (volume fraction %) PP
1	Jute: 08	PP: 92	08 : 92 (volume fraction %) Jute : PP
	Jute: 16	PP: 84	16 : 84 (volume fraction %) Jute : PP
	Jute: 25	PP: 75	25 : 75 (volume fraction %) Jute : PP
	Jute: 32	PP: 68	32 : 68 (volume fraction %) Jute : PP
	Jute: 40	PP: 60	40 : 60 (volume fraction %) Jute : PP
2	Jute: 08	PP: 92	08 : 92 (volume fraction %) Jute : PP
	Jute: 16	PP: 84	16 : 84 (volume fraction %) Jute : PP
	Jute: 25	PP: 75	25 : 75 (volume fraction %) Jute : PP
	Jute: 32	PP: 68	32 : 68 (volume fraction %) Jute : PP
	Jute: 40	PP: 60	40 : 60 (volume fraction %) Jute : PP
3	Jute: 08	PP: 92	08 : 92 (volume fraction %) Jute : PP
	Jute: 16	PP: 84	16 : 84 (volume fraction %) Jute : PP
	Jute: 25	PP: 75	25 : 75 (volume fraction %) Jute : PP
	Jute: 32	PP: 68	32 : 68 (volume fraction %) Jute : PP
	Jute: 40	PP: 60	40 : 60 (volume fraction %) Jute : PP

3.5.1 Preparation of composites by extrusion compounding

Composites were prepared by passing mixtures (jute-polypropylene of different volume fraction combination) through a single screw extruder (Fig. 3.1). The processing temperature of extrusion was controlled at 180°C with the help of a micro-controller based heating system that cover approximately the whole extruder barrel. The switchboard along with the control panel of the extruder is shown in Fig. 3.2. The jute-polypropylene mixtures were continuously fed into an extruder. The composites were delivered through a die of rod shape at a uniform rate. Then the composites were cut into small pieces of 8 - 20 mm length by a scissor. The approximately uniform shaped and sized extruded products were dried in an oven at 105°C for 6 hours and then used in injection moulding machine.

The extruder used in manufacturing composites was designed and manufactured at Bangladesh University of Engineering and Technology (BUET) during a research at BUET [99]. The photograph of the extruder is shown below:

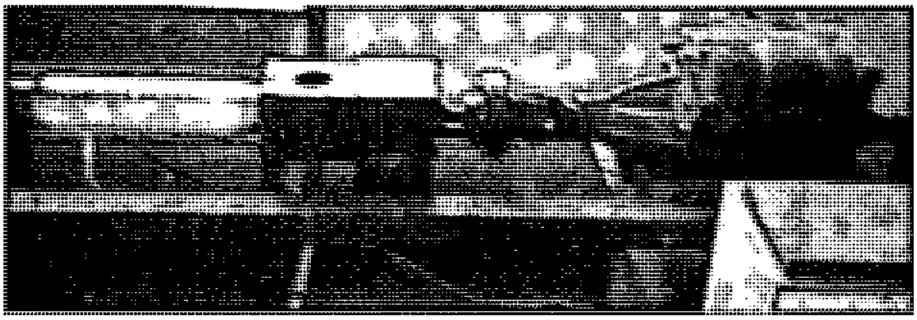


Figure 3.1: Single screw extruder

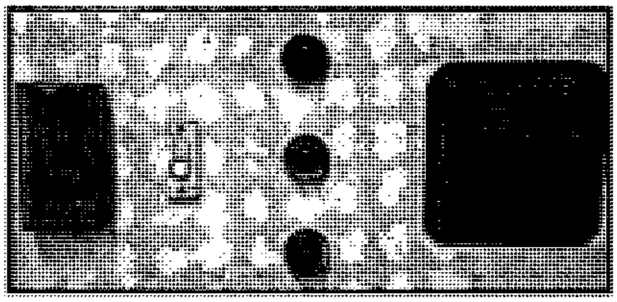


Figure 3.2: switchboard and control panel of the extruder

3.5.2 Preparation of composites by injection moulding

The dried small pieced products of extruder were moulded as per ASTM standard specimens (tensile and impact test bars) (ASTM D 638-01, ASTM D 6110-97 [87, 86]) by an injection moulding machine (Fig.3.3) at a moulding temperature of 180°C. The temperature was controlled by another micro-controller based heating system. Switchboard and control panel for the injection moulding machine is shown in figure 3.4. The pressure, temperature and heating time of the samples were controlled at the same rate to prepare all composites. The used injection-moulding machine is vertical and operated manually. The sample was heated to melt in the heating chamber, then pumped into closed mould die applied by the use of a plunger or ram into the heated cylinder. Pressure (Approx. 2 MPa) was applied for few minutes and then the mould was opened to remove sample. In this way, all the tensile and impact test specimens were prepared by injection moulding technique.

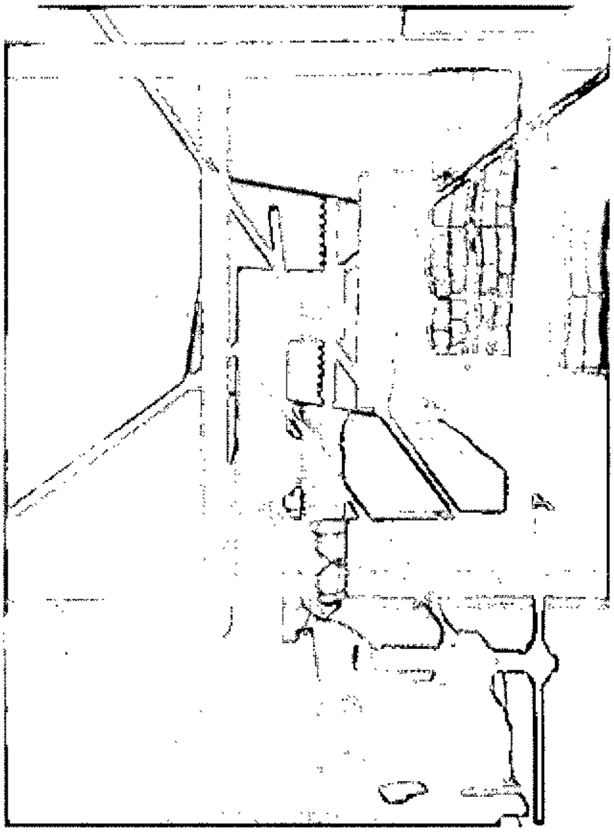


Figure 3.3: Injection moulding machine

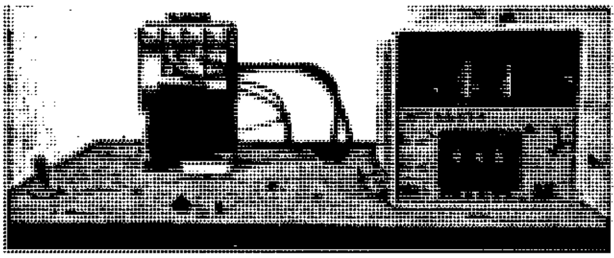


Figure 3.4: Switchboard and control panel of the Injection moulding machine

3.6 Characterization of composites

3.6.1 Scanning Electron Microscopy (SEM)

To investigate the effect of the different fibre volume fraction, the fracture surface of selected tensile test specimens were observed using a Scanning Electron Microscope (SEM) (Philips, Model: XL – 30, Made in Netherlands) and was run at 10 kV. Samples were sputter coated with gold to make them conductive prior to SEM observation.

The SEM analysis was carried out at the SEM Laboratory, Department of Materials and Metallurgical Engineering, Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh. The photographs are presented in the result and discussion section.

3.6.2 Density measurement of composite

Densities of composites were simply determined by weighing each composite test specimen and then submerging the test specimen in a measuring cylinder to determine the volume of water displaced. After measuring the displaced volume of water, specimen was quickly removed to avoid any water uptake. The density of each composite was then calculated by dividing the specimen mass by the volume of water displaced.

3.7 Mechanical properties of the composites

In order to investigate the mechanical properties of the prepared composites the following tests were carried out; (a) tensile test, (b) charpy impact test. For these tests the approximate ASTM methods (ASTM D 638-01, ASTM D 6110-97 [87, 86]) were followed. Specification and picture of the used machines, set-up of the tests, operating conditions and dimension of test specimens are described below.

3.7.1 Tensile test

The static tensile test of the composites were carried out in an universal tensile testing machine, model: MSC-5/ 500, capacity: 5KN, Ogawa Seiki C. Ltd., Japan (Fig. 3.5) at a cross head speed of 10 mm/min, (cross head speed was maintained constant for testing all the samples). Control panel attached to the universal tensile testing machine, where load and the respective strains were displayed is shown in Fig. 3.6. Effective length between the supports was 60 mm. Tensile tests were conducted following ASTM D 638-01 [86] and each test was preformed until tensile failure occurred except 100% polypropylene. Dumbbell-shaped injection moulded composites were used as test specimen without having any kind of machining. Dimension of tensile test specimen is shown in Fig. 3.7, 3.8 and its length, width, thickness were 148.5 mm, 10 mm and 4 mm respectively. To predict the tensile behavior of short jute fibre reinforced polypropylene, the relationship of tensile strength, modulus and failure strain with the reinforcing fibre length, volume fraction and diameter is very important.

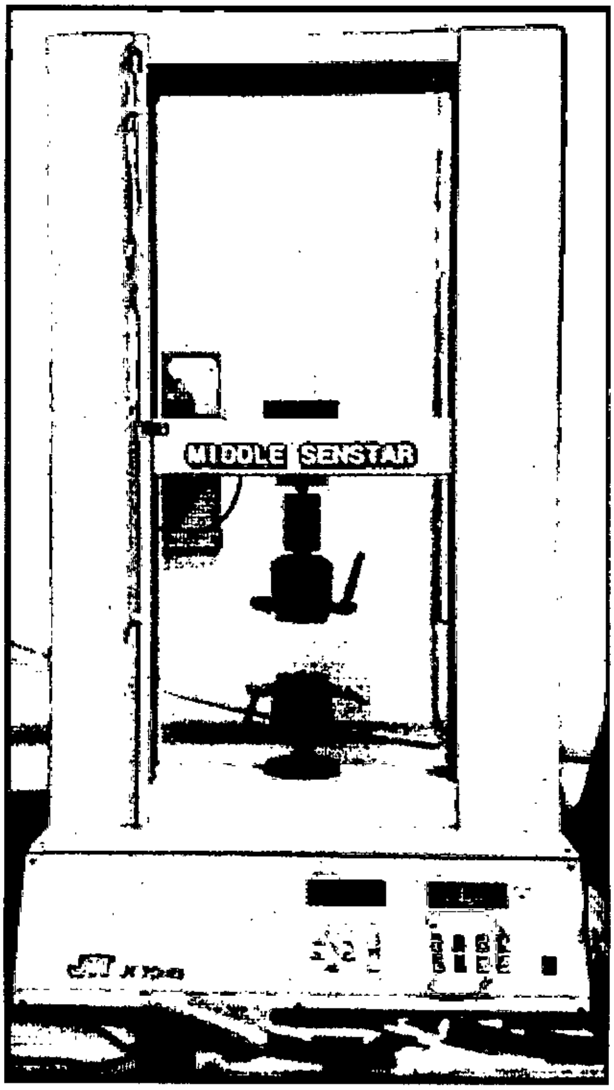


Figure 3.5: Photograph of Universal Tensile Testing Machine

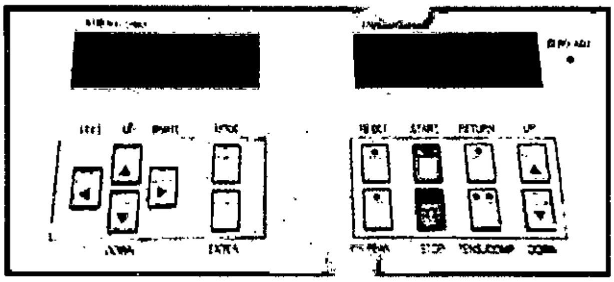


Figure 3.6: Control panel attached to the universal tensile testing machine

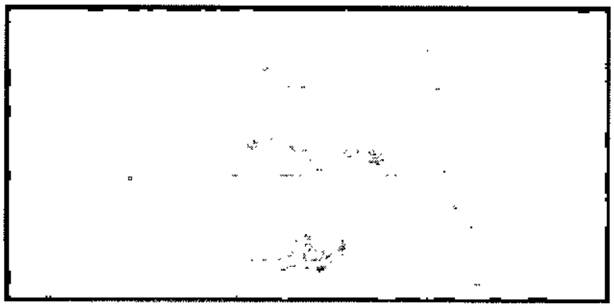


Figure 3.7: Photograph of tensile test specimen

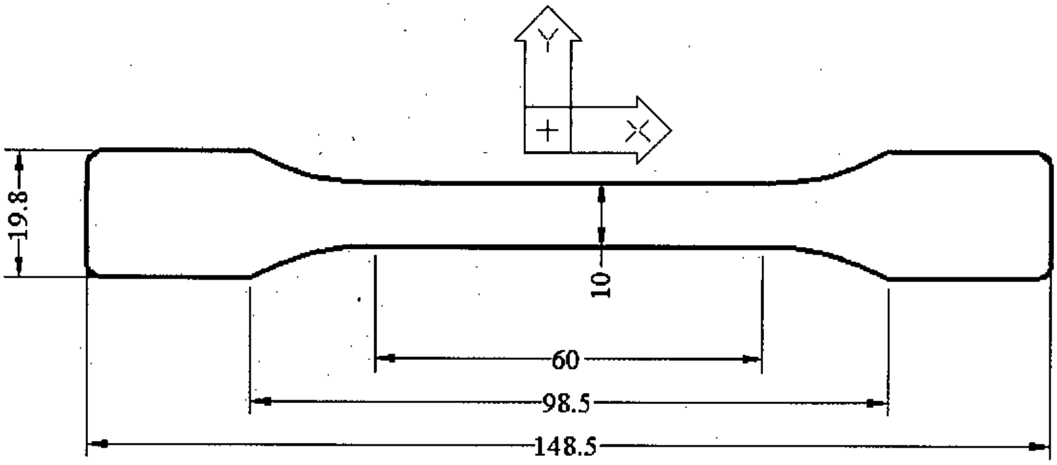


Figure 3.8: Schematic view of tensile test specimen

Eight to ten specimens of each composition were tested and average values were reported. The load vs. elongation curves were obtained by the electronic chart recorder of the instrument. The maximum (peak) load values were also recorded by the instrument, which can be recalled after the completion of the tests. The highest load in the tensile test gives the tensile, or ultimate strength. The tensile strength (σ_{UT}) is calculated from the following equation [86]:

$$\text{Tensile Strength, } \sigma_{UT} = \frac{W}{A_T} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

Where, W is the maximum load and A_T is the original cross sectional area.

Tensile stress, strain and modulus values were calculated from the load vs elongation curves. Then the tensile stress vs. strain curves were drawn and tensile modules were determined from the initial slope of the stress-strain curve.

3.7.2 Charpy impact test

The dynamic charpy impact tests of the composites were done according to ASTM D 6110-97 [87]. Figure 3.9 shows the photograph of Universal impact testing machine, Type: TIT-30, Tokyo Testing machine MFG. Co. Ltd., Japan. This machine was used to perform charpy Impact tests of all the samples. The weight of the hammer of the machine was 3.72 kg and the length of the arm was 0.815 m. The span between the supports was 40 mm. The striking energy of the hammer was too large for thermoplastics or composites based on thermoplastic matrix. Therefore, modification was done on the hammer for the current research work. The modification is described in detail in Appendix.

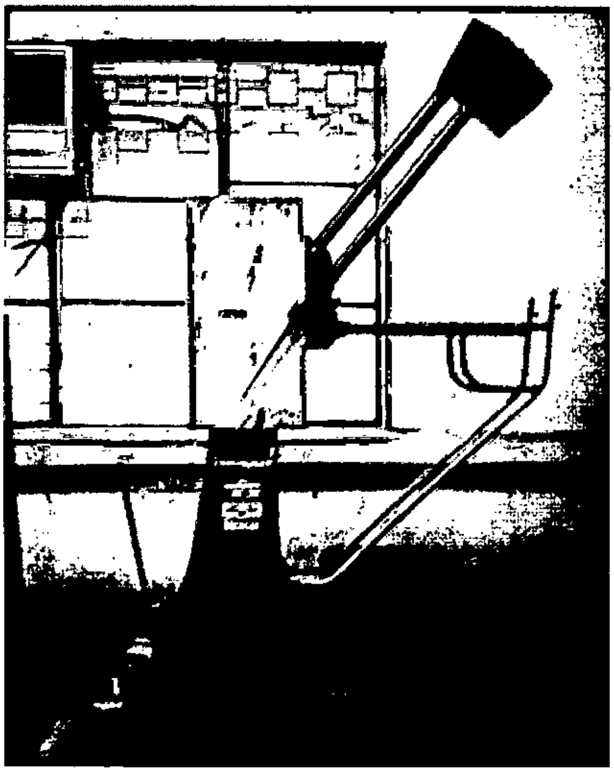


Figure 3.9: photograph of the universal impact testing machine

The charpy impact test specimens were injection-moulded. The width, thickness and length of the specimens are 10 mm, 4 mm and 80 mm respectively. Test method of ASTM D 6110-97 was followed to conduct this experiment. Notched specimens were used. The dimension of the test specimen and the design of the notch on it is shown below :(Figures 3.10, 3.11)

Figure 3.10: Photograph of the impact test specimen

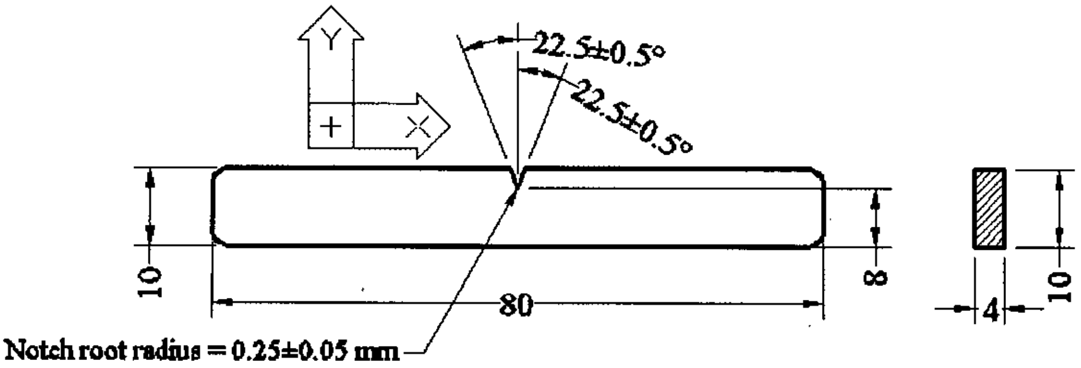


Figure 3.11: Schematic view of the impact test specimen

Notching of the test specimens was done on a milling machine and the contour and depth of notch are shown in Figure 3.11. In the current work, as the width and thickness are 10 mm and 4 mm so notch were cut on the 4 mm shorter side. ASTM D 6110-97 test methods specified the notch depth should be 2.54 mm on the 12.7 mm depth test specimen. So, we made 2 mm depth notch cut on the 10 mm depth specimen and the radius of curvature at the apex of notch cut was 0.25 ± 0.05 mm. The impact tests were performed approximately after 30 hours of notching. To conduct this experiment, according to test method, the specimen was supported on a horizontal simple beam and was broken by a single swing of the pendulum with the impact line midway between the supports and directly opposite to the notch. Free rotational angle of the hammer was 135° and the radius of the pendulum movement was 0.822 m. The effective length of striking was 0.672 m. Calculation of the effective length (position of centre of gravity of the hammer) is given in Appendix. The results were calculated in terms of energy absorbed per unit of specimen width using the following procedure.

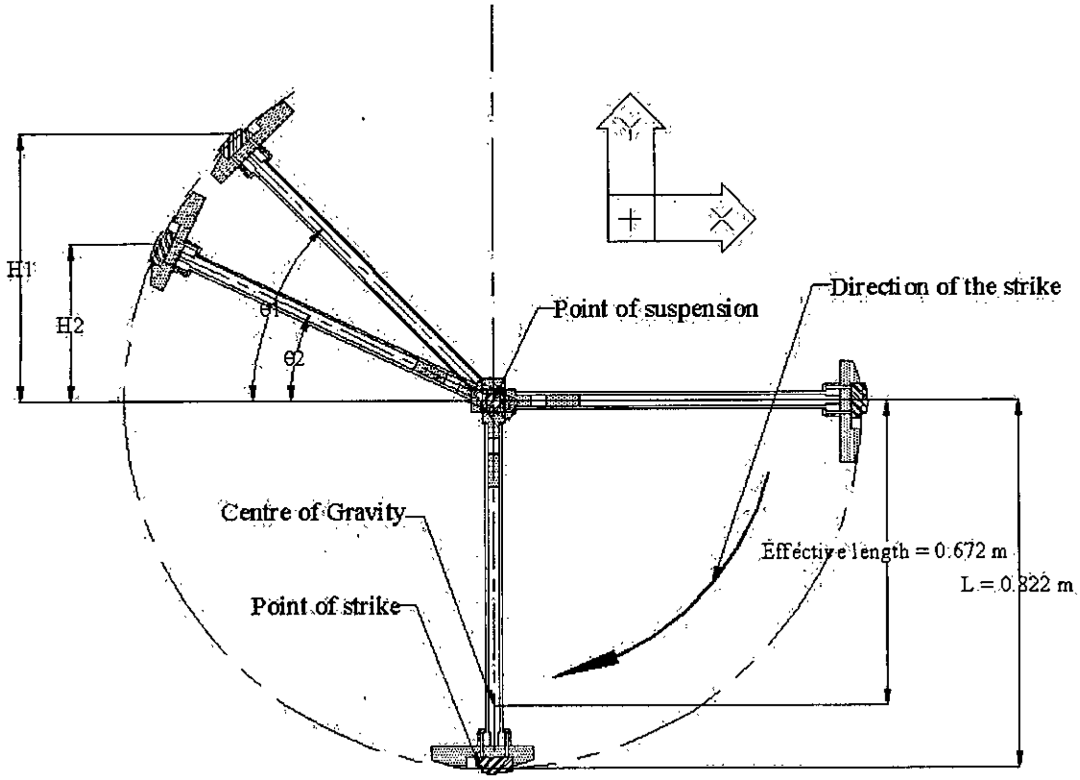


Figure 3.12: Schematic diagram of the impact tester to facilitate the impact energy calculation.

$$\text{Impact Energy} = \frac{\{(W \times H_1) - (W \times H_2)\}}{t} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

Where, W = Weight of the hammer = 2.5816 kg

t = Small thickness width of the notch = 0.004 m

(H_1-H_2) = Height difference before and after striking

And from the Figure 3.12,

$$\sin\theta_1 = \frac{H_1}{L} \quad \text{and} \quad \sin\theta_2 = \frac{H_2}{L}$$

$$\Rightarrow H_1 = L \times \sin\theta_1 \quad \text{and} \quad \Rightarrow H_2 = L \times \sin\theta_2$$

Where, θ_1 = angle created by the free swing of the hammer

θ_2 = angle created by the swing of the hammer after striking the specimen.

L = effective length of the hammer, distance of CG from the suspension point of the hammer = 0.672 m.

$$\text{So, Impact Energy} = \frac{[W \times L \times \{\sin(\theta_1) - \sin(\theta_2)\}]}{t}$$

$$\text{or, Impact Energy} = \frac{W \times L}{t} \times \{\sin(\theta_1) - \sin(\theta_2)\} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (4)$$

3.7.3 Calculation of critical reinforcing fibre length

An effective use of fibre strength is dependent on both the interfacial adhesion and the critical fibre length. The mean interfacial shear strength from single fibre pull-out test was collected from literature [100]. It is well known that fibre length plays an important role in the mechanical performance of fibre reinforced composites.The critical fibre length in case of composite structures, meaning that the failure mode of fibres longer than this value is breakage and the fibres shorter than this value slide out during failure, hence they do not exert their theoretically maximal reinforcing impact. Using the Kelly-Tyson theory, the critical fibre length, defined as the minimum fibre length where the maximum allowable fibre tensile stress can be achieved, is roughly calculated as:

$$l_c = \frac{\sigma_{fu} \times r_f}{\hat{\tau}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

Where,

σ_{fu} = The tensile strength of the fibre

$\hat{\tau}$ = Mean interfacial shear strength

r_f = The mean radius of the fibre

l_c = The critical fibre length

3.8 Comparison of single fibre properties

Fibre characteristics such as strength, length, diameter and chemistry vary from species to species [16]. One of the aim of this work was to compare these single fibre properties. Properties and physical parameters for jute in this work (collected from BJRI) [96] were compared with those of other fibres found in the literature [16, 39].

3.8.1 Microscopic evaluation of fibre morphology

Scanning Electron Microscope (SEM) (Philips, Model: XL – 30, Made in Netherlands), run at 10 kV was used. Samples were sputter coated with gold to make them conductive prior to SEM observation. Individual fibres were also viewed under a calibrated eyepiece at 250x and 800x magnification using an Olympus BX 60 optical microscope for diameter and length measurement.

3.9 Comparison of Composite properties

Values of mechanical properties of Jute fibre reinforced polypropylene composites obtained in the current investigation were compared with other natural fibre (such as, hemp, Kenaf, slabwood, Luaan, thinning, etc.) reinforced polypropylene composites from literature [78, 80, 81, 83].

A comparative study of mechanical properties were also presented in the current research work between short jute fibre reinforced polypropylene composite, short glass fibre reinforced polypropylene composite and short carbon fibre reinforced polypropylene composites. Data for the glass and carbon fibre reinforced PP composites were collected from literature [88, 89, 90].

3.10 Difficulties faced:

During the fabrication of the jute fibre reinforced polypropylene composite the problems faced and the works of overcoming those are:

The extruder used in the current research became overheated when worked continuously, though there is a microcontroller based heating system. A temperature of 180 °C was to be maintained at the extruder. But when in continuous operation it temperature rose to 190 °C or even higher. Which may cause the natural fibre to burn. The work had to be interrupted for cooling the extruder using a fan.

As the injection moulding machine was a manual operated, i.e., pressure had to be applied manually, sometimes the material flow from the heated injection moulding machine barrel to the tensile or impact specimen mould was restricted due to solidification. As the pressure was not much high, as it is applied manually, materials take more time to fill the die. So specimen preparation especially the tensile specimen became problematic. To overcome this problem the moulds (dies) were heated up to 70 – 80 °C, which delayed the solidification of the composite material.

The difficulties faced after fabrication:

The matrix (polypropylene) of the fabricated samples is to be dissolved to find out the amount of breakage of the reinforcing fibres occurred during fabrication. As the matrix is a thermoplastic which is nonpolar in nature, different polar solvents like Xylem, Carbon tetrachloride, Chloroform, Di-methayl sufoxaide, Di-methyle formamide are tried to dissolve the polypropylene. These solvents are applied to polypropylene for 48 to 72 hours at the atmospheric temperature and even at elevated temperature of 100 °C to dissolve polypropylene but all the work is in vein.

Chapter Four

RESULTS AND DISCUSSION

4.1 Introduction

Mechanical properties like tensile strength, Young's modulus, failure strain, notched charpy impact energy for jute fibre reinforced polypropylene composite are carried out considering the length and volume fraction of the reinforcing fibre as variables. Comparison of tensile strength, Young's modulus, failure strain, notched charpy impact energy, mean interfacial shear stress for jute, carbon and glass fibre reinforced polypropylene composites were carried out. Comparison of properties like tensile strength, young's modulus, composite density for jute fiber reinforced polypropylene composite with other natural fiber (slabwood, thinnings, luaan, hemp and eucalyptus) reinforced polypropylene composites were also performed. Calculation of composite density with different fibre volume percentages and fiber lengths were performed. Calculation of specific tensile strength and specific Young's modulus were also performed. Theoretical calculations of composite tensile strength values for different volume fractions of fibre were carried out to compare with experimentally obtained values. Fibre efficiency factor for the composite strength, fibre efficiency factor for composite modulus and theoretically composite's strength prediction are calculated using the modified rule of mixtures.

4.2 Properties of Polypropylene (PP):

Properties of isotactic polypropylene, that was used as matrix in the current research were tested. And the results are shown in Table 4.1.

Table 4.1 Mechanical properties of Pure PP

Material	Tensile strength (σ_{UT}) (MPa)	Standard deviation of σ_{UT}	Tensile Young's modulus (E) (GPa)	Standard deviation of E	Total strain before failure, ε_f
Polypropylene (PP)	30.36	± 0.35	1.216	± 0.4	More than 100%

4.3 Properties of Jute reinforced PP composite:

Jute fibre reinforced polypropylene composite's tensile strength, young's modulus, failure strain and notched charpy impact strength are determined experimentally following the ASTM Standard. Variation of tensile properties (Tensile Strength, Young's Modulus and Total Strain before Failure) of jute fibre reinforced polypropylene composite with reinforcing fibre length and volume fraction is summarised in Table 4.2. Standard deviation of the experimentally obtained data is also displayed. Variation of Notched Charpy Impact Energy of jute fibre reinforced polypropylene composite with reinforcing fibre length and volume fraction is summarised in Table 4.3.

Table 4.2 Results of Tensile test of jute fibre reinforced polypropylene composite.

Fibre length (mm)	Fibre loading (volume fraction) (%)	Tensile strength, (σ_{UT}) (MPa)	Standard deviation of σ_{UT} (MPa)	Young's modulus, E (GPa)	Standard deviation of E (GPa)	Failure Strain ε_f (%)	Standard deviation of ε_f (%)
1	0	30.366	± 0.35	1.216	± 0.40	more than 100	-
	8	31.949	± 0.60	1.725	± 0.15	9.1667	± 0.55
	16	32.453	± 0.45	2.001	± 0.14	8.3333	± 0.76
	25	32.983	± 0.55	2.613	± 0.09	7.3333	± 0.90
	32	31.264	± 0.50	3.091	± 0.24	5.3333	± 0.24
	40	29.842	± 0.90	3.206	± 0.10	4.0000	± 0.10
2	0	30.366	± 0.35	1.216	± 0.40	more than 100	-
	8	31.432	± 0.45	1.605	± 0.10	8.8333	± 0.66
	16	31.955	± 0.40	1.745	± 0.15	8.0000	± 0.92
	25	33.733	± 0.75	2.596	± 0.25	7.1667	± 0.78
	32	31.250	± 0.55	2.778	± 0.17	5.0000	± 0.35
	40	30.227	± 0.90	3.095	± 0.30	3.8333	± 0.22
3	0	30.366	± 0.35	1.216	± 0.40	more than 100	-
	8	31.496	± 0.50	1.554	± 0.08	8.5000	± 0.89
	16	31.832	± 0.45	1.760	± 0.15	7.5000	± 1.15
	25	32.317	± 0.25	2.020	± 0.10	7.0000	± 0.82
	32	30.769	± 1.05	2.272	± 0.26	5.3333	± 0.46
	40	28.822	± 1.20	2.564	± 0.35	4.3333	± 0.24

Table 4.3 Results of Charpy Impact test of jute fibre reinforced polypropylene composite.

Fibre length (mm)	Fibre loading (volume fraction) (%)	Notched charpy impact energy (NCIE) (J/m)	Standard deviation of NCIE (J/m)
1	0	25.01	± 0.35
	8	49.94	± 0.60
	16	46.82	± 0.45
	25	43.71	± 0.55
	32	44.75	± 0.50
	40	45.78	± 0.90
2	0	25.01	± 0.35
	8	46.3	± 0.45
	16	43.71	± 0.40
	25	41.13	± 0.75
	32	38.54	± 0.55
	40	39.06	± 0.90
3	0	25.01	± 0.35
	8	51.49	± 0.50
	16	48.89	± 0.45
	25	46.3	± 0.25
	32	39.05	± 1.05
	40	35.16	± 1.20

Figure 4.1 shows combined effect of reinforcing fibre length and volume fraction on the Tensile Strength of the jute fibre reinforced polypropylene composite. The surface plot shows tensile strength variation from 26 to 34 MPa. Peak of the surface represents the highest tensile strength found at a combination of 2 mm reinforcing fibre length and 25% fibre loading.

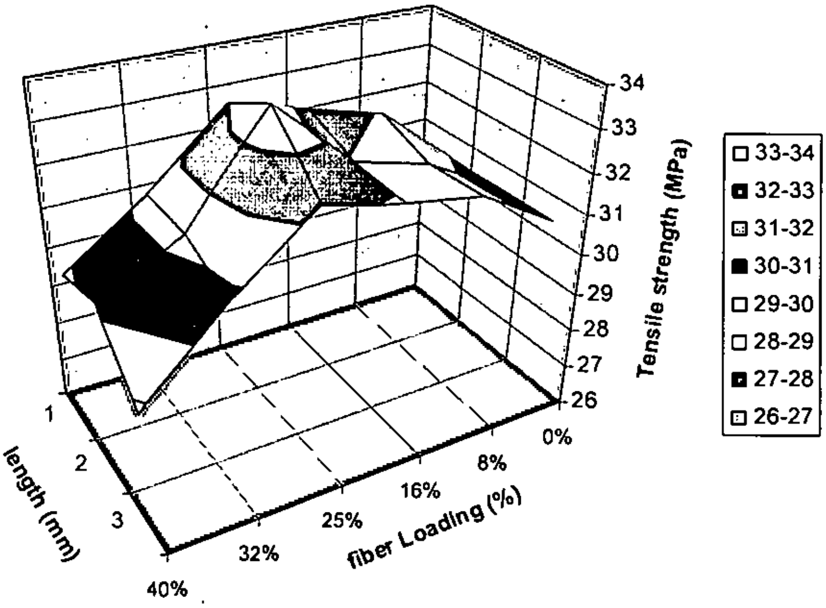


Figure 4.1: Tensile strength variation of jute fibre reinforced polypropylene composite with the variation of fibre length (mm) and Fibre volume fraction (%).

4.3.1 Stress-strain diagrams:

Stress-strain diagrams (Figures 4.2 – 4.5) shows that young's modulus is the highest when the reinforcing fibre length is less than the critical length (failure mode of fibres longer than critical length is breakage and the fibres shorter than this value slide out during failure). And as the jute fibre length is increased tensile modulus of the respective composite decreases gradually. There is strong influence of fibre volume fraction on the tensile modulus of the composite. Young's modulus of the composite increases as the fibre loading increases. Elongation at break can easily be observed for different fibre loading and fibre length.

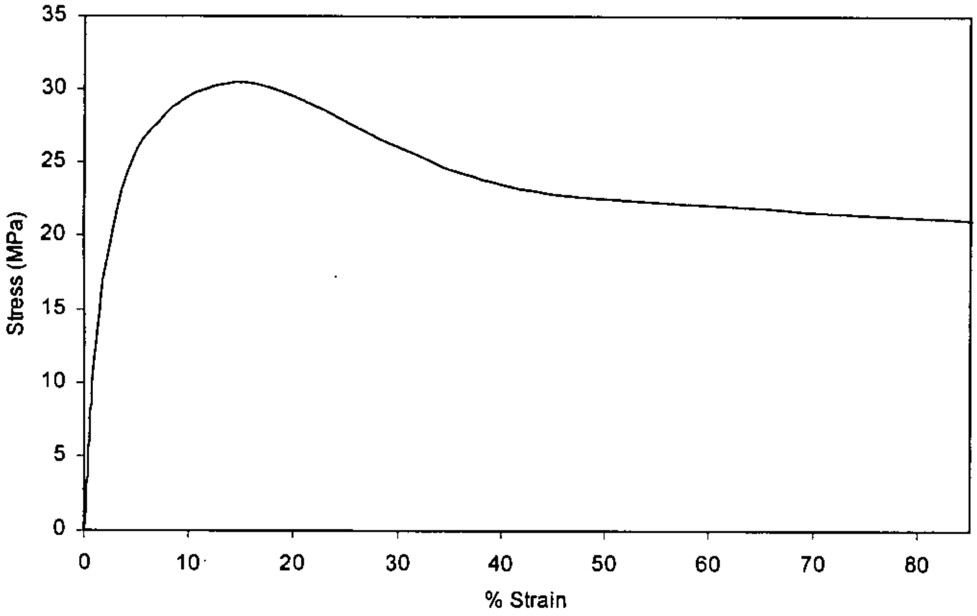


Figure 4.2: Typical tensile stress-strain curve for the pure polypropylene matrix material.

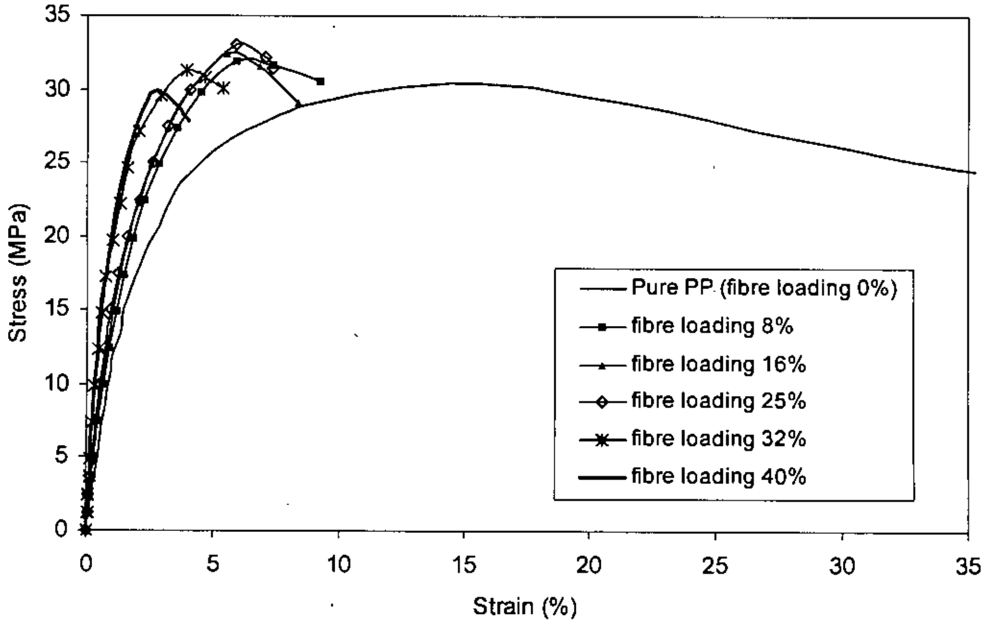


Figure 4.3: Stress-strain curve for the raw jute fibre reinforced polypropylene composites of different fibre volume fraction (%), (Reinforcing fibre length 1 mm).

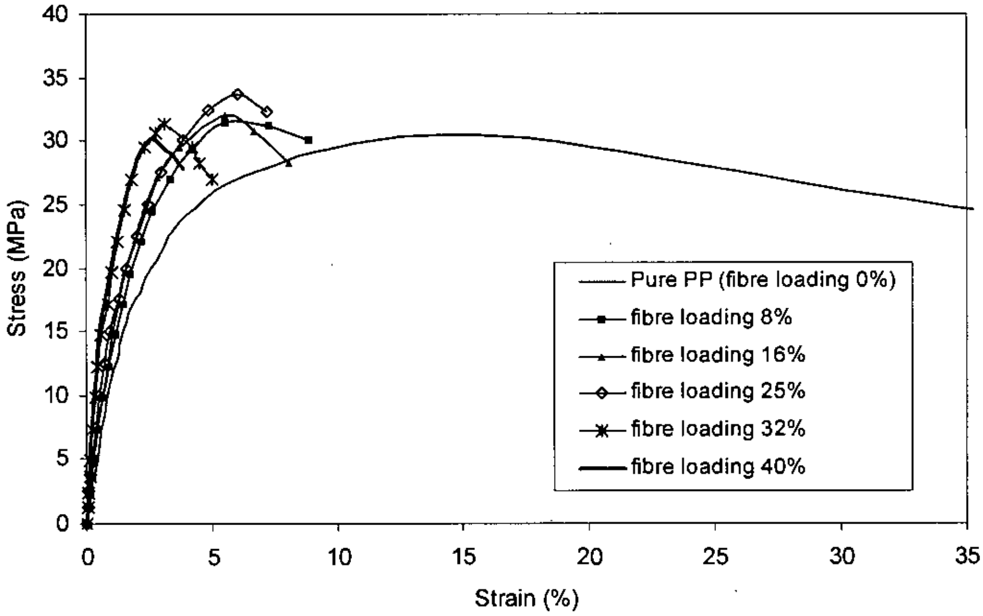


Figure 4.4: Stress-strain curve for the raw jute fibre reinforced polypropylene composites of different fibre volume fraction (%), (Reinforcing fibre length 2 mm).

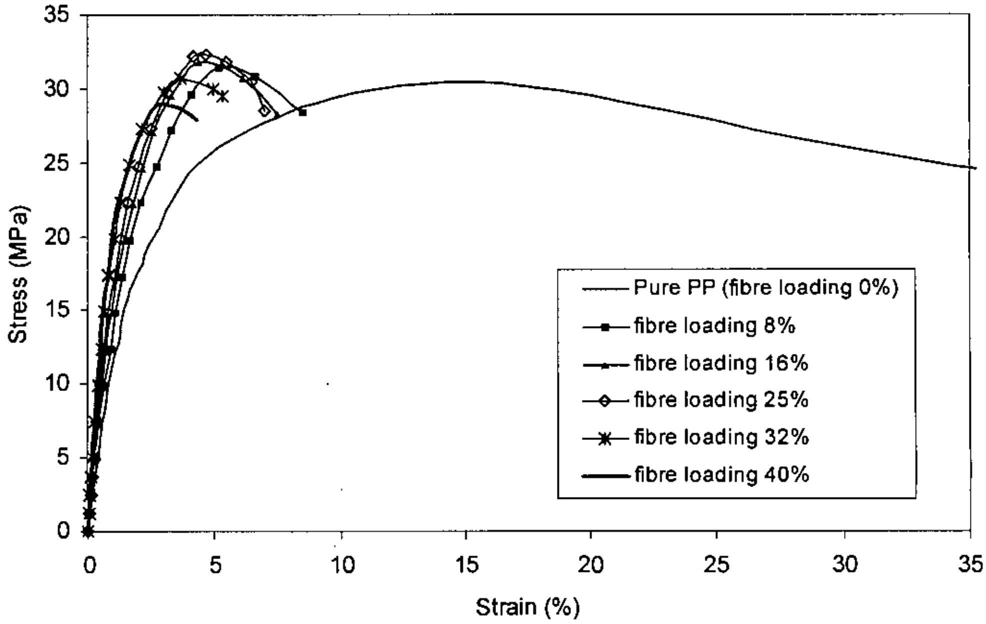


Figure 4.5: Stress-strain curve for the raw jute fibre reinforced polypropylene composites of different fibre volume fraction (%), (Reinforcing fibre length 3 mm).

4.4 Mechanical Properties of jute fibre reinforced polypropylene composites (as a function of fibre volume fraction):

4.4.1 Tensile strength variation with fibre volume fraction:

Figure 4.6 shows the variation of the ultimate tensile strength as a function of fibre volume fraction for JF/PP composites. For different fibre volume fraction, all samples tested were plotted on a tensile strength versus fibre volume fraction plot (Figure 4.6). Fibres are oriented along the longitudinal direction of the loading in the composite. The addition of jute fibres effectively enhances the ultimate tensile strength. The tensile strength of the composites increases with the increase of fibre loading up to the fibre volume fraction 25% as can be seen from the positive slope of the initial portion of the curve. Apparently, the higher the reinforcing fibre content the higher the tensile strength of the composite. After the volume fraction crosses the value 25 the strength starts decreasing gradually. This may be the combined effect of fibre breakage during processing and the lack of stress transfer from the polypropylene matrix to jute fibres. The breakage of fibres during processing leads to the reduction in mean fibre length. It is observed that as the fibre volume fraction increases, the composite strength increases slightly only and decreases if loading is continued after 25-30%. This observation exhibits that the effect of mean fibre length on composite strength is significantly large, so that the combined effect of fibre volume fraction and mean fibre length leads to only a slight increase in composite strength, as the fibre volume fraction increases. The decrease in the composite strength caused by the reduction in mean fibre length almost offsets the increase in the composite strength caused by the increase in fibre volume fraction. When the reinforcing fibre loading is increased beyond 25-30% amount of fibre breakage also increases and become prominent to influence the ultimate tensile strength of the composite.

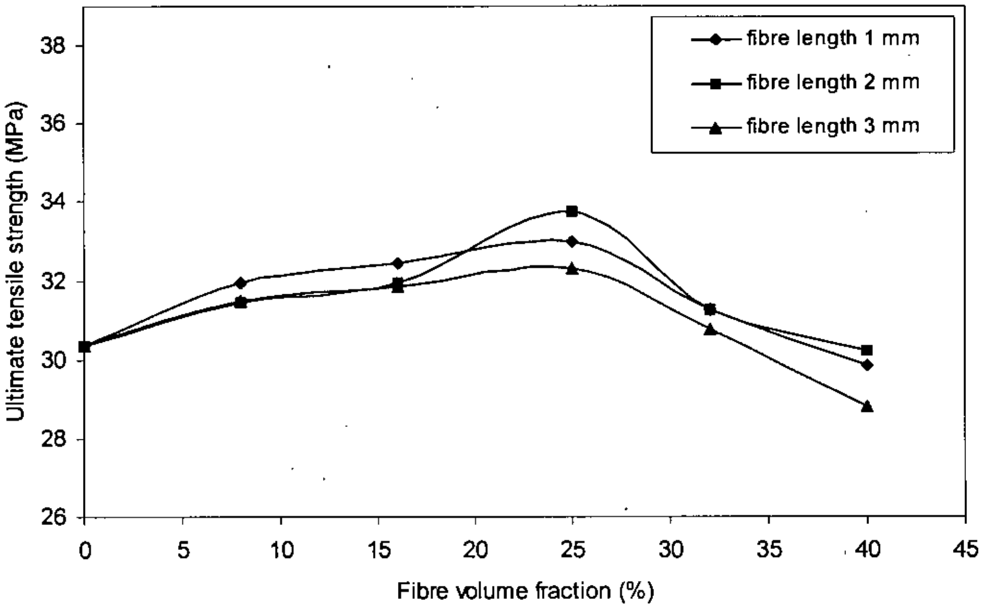


Figure 4.6 Ultimate tensile strength versus fibre volume fraction for jute reinforced PP composites at different fibre length.

4.4.2 Young's modulus variation with fibre volume fraction:

Figure 4.7 shows the variation of young's modulus of jute fibre reinforced polypropylene composites as a function of the fibre volume fraction.

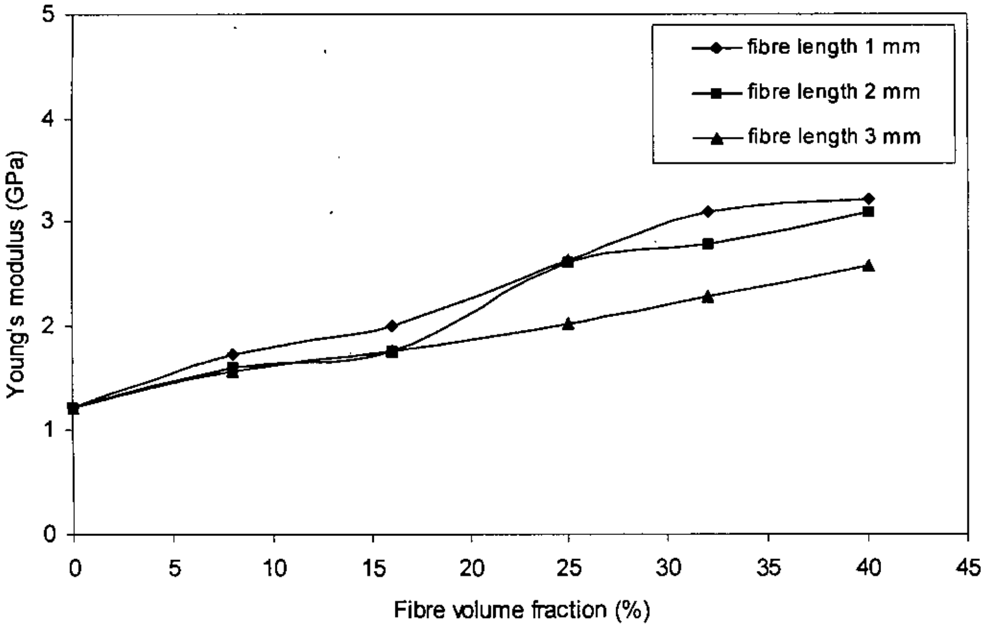


Figure 4.7: Young's modulus versus fibre volume fraction for jute reinforced PP composites at different fibre length.

The introduction of the reinforcing fibre to the PP matrix enhances the tensile modulus significantly. The tensile modulus enhancement continues with further fibre reinforcement. Figure 4.7 indicates that the composite modulus is more dependent on fibre volume fraction and less dependent on fibre length than the composite strength does. In other words, the effect of mean fibre length on the young's modulus must be much smaller than that of fibre volume fraction. Otherwise, the combined effect of fibre volume fraction and mean fibre length would not lead to a significant increase in the composite tensile modulus.

4.4.3 Fracture surface observation of the tensile test specimens:

The (SEM) scanning electron micrographs of the fracture surfaces of jute fibre reinforced polypropylene composites with different fibre volume fraction and length are presented in the Figures 4.8 – 4.14.

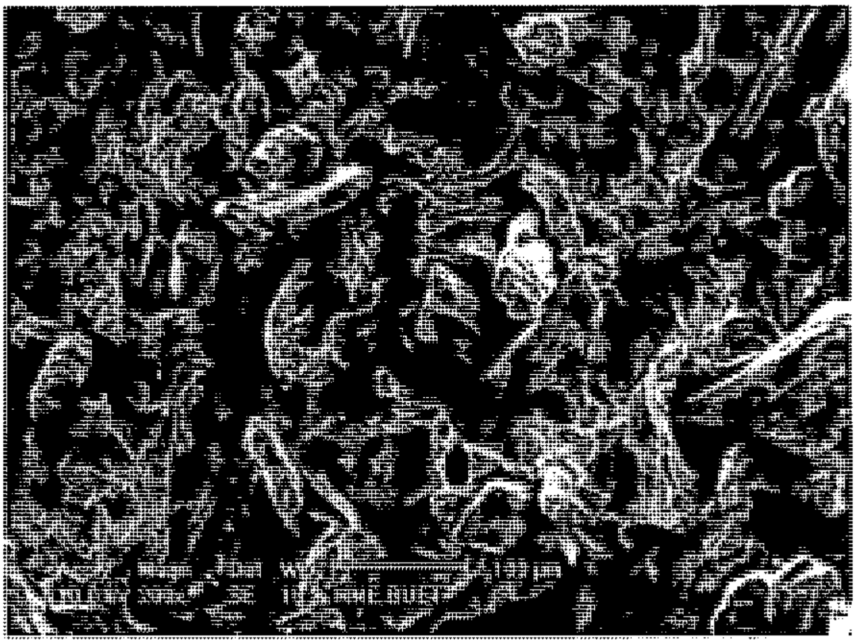


Figure 4.8: Scanning Electron Micrographs of jute fibre reinforced Polypropylene composite fracture surface with fibre length 3 mm and fibre volume fraction 40%.

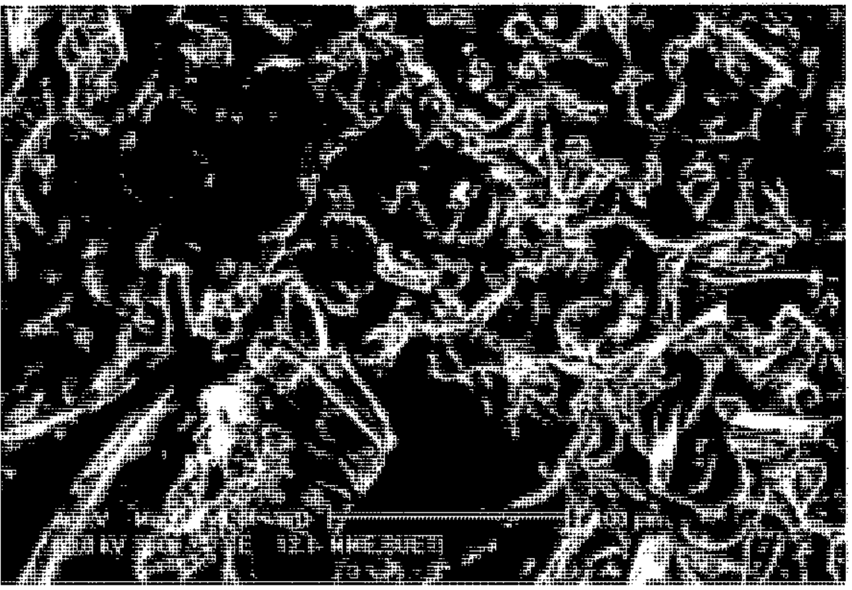


Figure 4.9: Scanning Electron Micrographs of jute fibre reinforced Polypropylene composite fracture surface with fibre length 3 mm and fibre volume fraction 32%.

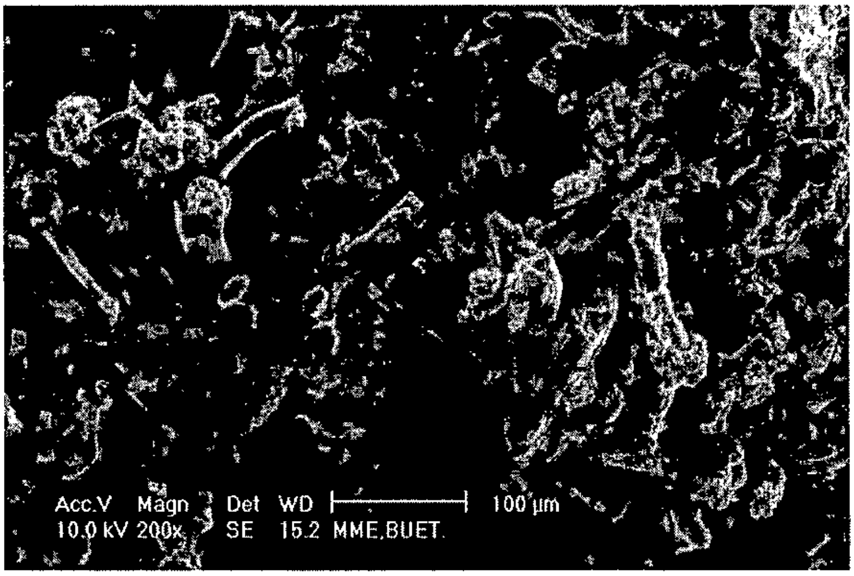


Figure 4.10: Scanning Electron Micrographs of jute fibre reinforced Polypropylene composite fracture surface with fibre length 3 mm and fibre volume fraction 25%.

Figure 4.11: Scanning Electron Micrographs of jute fibre reinforced Polypropylene composite fracture surface with fibre length 3 mm and fibre volume fraction 16%.

Figure 4.12: Scanning Electron Micrographs of jute fibre reinforced Polypropylene composite fracture surface with fibre length 3 mm and fibre volume fraction 8%.

Figures 4.8 - 4.12 shows the fracture surfaces of jute reinforced polypropylene composite of reinforcing fibre length 3 mm. From the figures an idea of the orientation of the reinforcing fibres in the matrix is obtained. Good dispersion of fibres are found in the 8%, 16% and 25% fibre loading showed in figures 4.10, 4.11 and 4.12 respectively.

Fibre orientation and dispersion is observed better at the fracture surface of jute reinforced polypropylene composite with 2 mm reinforcing fibre length and 40% fibre loading, which is shown in Fig. 4.13.

Fibre pull out is observed at fig. 4.14. Here fracture surface of jute reinforced polypropylene with 40% reinforcing fibre (length 1 mm) loading is shown. As the length is lower than the critical fibre length, during failure fibre slide out of the matrix.

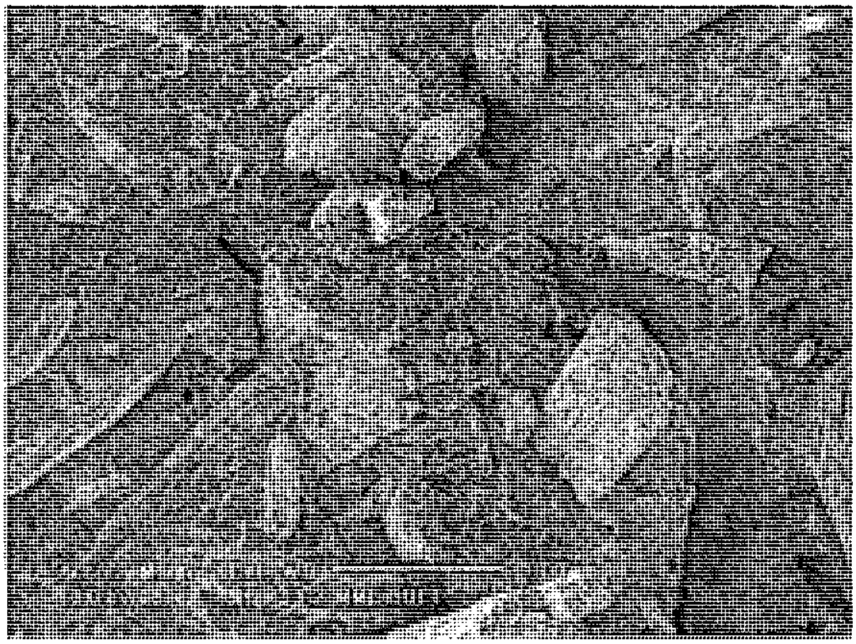


Figure 4.13: Scanning Electron Micrographs of jute fibre reinforced Polypropylene composite fracture surface with fibre length 2 mm and fibre volume fraction 40%.

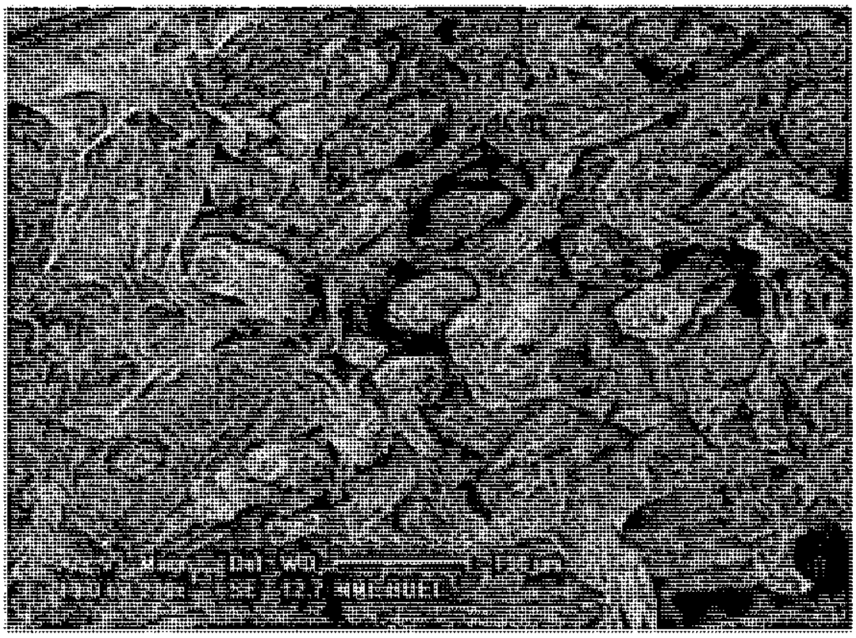


Figure 4.14: Scanning Electron Micrographs of jute fibre reinforced Polypropylene composite fracture surface with fibre length 1 mm and fibre volume fraction 40%.

4.4.4 Failure strain variation with fibre volume fraction:

The failure strains of short jute fibre reinforced polypropylene (SJF/PP) composites are exhibited in Figure 4.15. Figure shows that as the fibre volume fraction increases, the composite failure strain decreases. The reduction in the elongation at break is caused by an embrittlement effect as the stiffness of the composites is improved (see Figure 4.7) when the fibre volume fraction is increased. The cause of this effect has been identified as matrix crack formation at the ends of the reinforcing fibres. Subsequently, as the strain is increased more cracks form progressively at the ends of shorter fibres. Initially this cracking can be accommodated by load transfer to adjacent fibres which "bridge" the cracked region. Final failure occurs when the extent of cracking across the weakest section of a specimen reaches a critical level when the surrounding fibres and matrix can no longer support the increasing load [94, 93,].

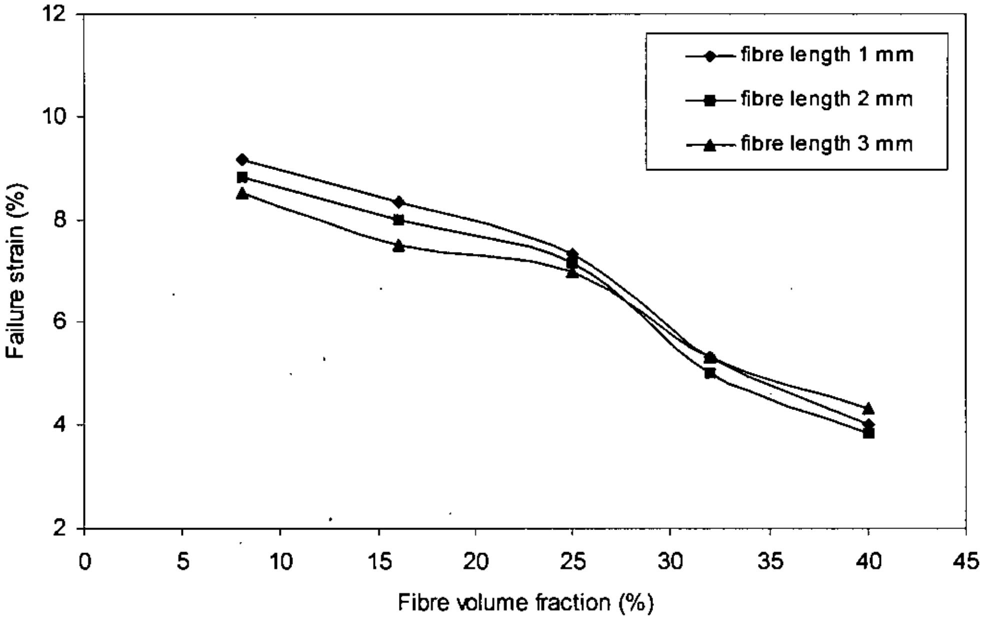


Figure 4.15: Failure strain versus fibre volume fraction for jute reinforced PP composites at different fibre length.

4.4.5 Notched charpy impact energy variation with fibre volume fraction:

Fracture resistance is one of the important properties of engineering materials, a measure of fracture resistance being given by the specific work of fracture (WOF) or fracture toughness. For short fiber composites, the fracture is caused by any of the following failure mechanisms [91, 92]: (1) fiber-matrix interfacial debonding, (2) post-debonding friction, (3) matrix plastic deformation, (4) fiber plastic deformation, (5) fiber fracture, (6) matrix fracture, (7) fiber pull-out. The above failure mechanisms is closely related to the fiber volume fraction and fiber length.

Figure 4.16 shows the notched charpy impact energy of short jute fibre reinforced polypropylene (SJF/PP) composites as a function of fibre volume fraction. Figure indicates that the notched charpy impact energy is considerably enhanced by the introduction of jute fibres to polypropylene. This indicates that the fibres play a dominant role in terms of fracture energy. Moreover in the investigated jute fibre volume fraction range, no noticeable influence of increase in the fibre volume fraction on the fracture energy is observed. As the volume fraction increases fibre breakage during processing also increases. So with the increase of the fibre loading, mean reinforcing fibre length decreases, which offset the effect of increase of fibre volume fraction.

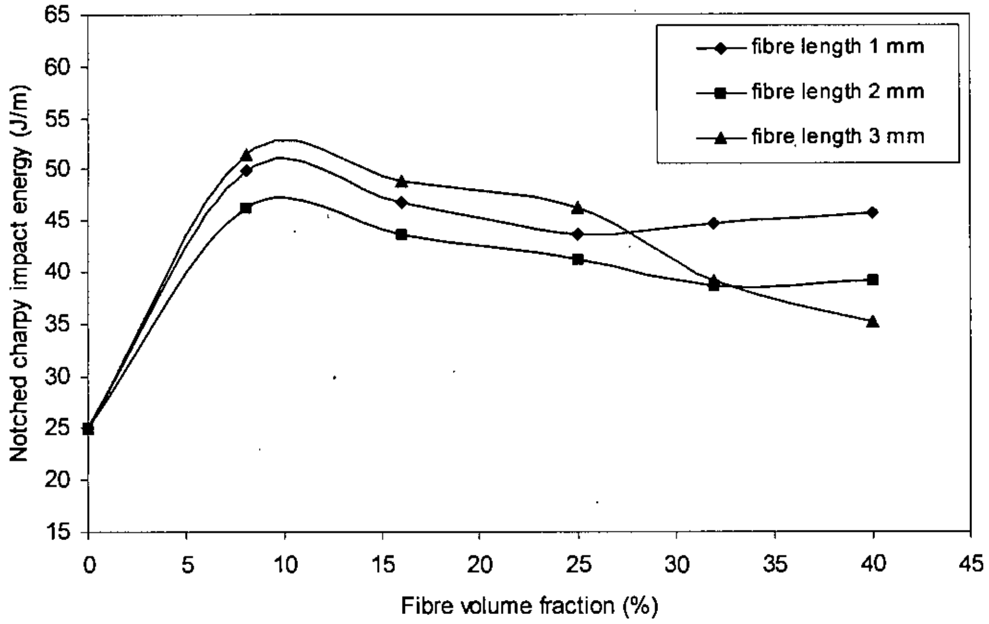


Figure 4.16: Notched charpy impact energy versus fibre volume fraction for jute reinforced PP composites at different fibre length.

4.5 Mechanical Properties of jute fibre reinforced polypropylene composites (as a function of reinforcing fibre length):

4.5.1 Tensile strength variation with fibre length:

Figure 4.17 shows the variation of ultimate tensile strength as a function of reinforcing fibre length. Three different length of jute fibre is used for the reinforcement in the polypropylene matrix. The critical fibre length for the fibre-matrix (jute/polypropylene) combination is 1.012 ± 0.240 mm. Figure indicates that the composite with the fibre length 1 mm at different loading show better performance, except for 25% and 40% fibre loading, where, with the increase of fibre length strength increases. Tensile strength shows an increasing tendency with longer length. Strength should be higher for longer fibre reinforced PP composites but here in most of the cases strength decreases when longer fibre is reinforced, this is because the fibre breakage rate is higher for the longer fibres. As a result, the mean reinforcing fibre length becomes less. No of fibre ends also increases, which enhance an early failure.

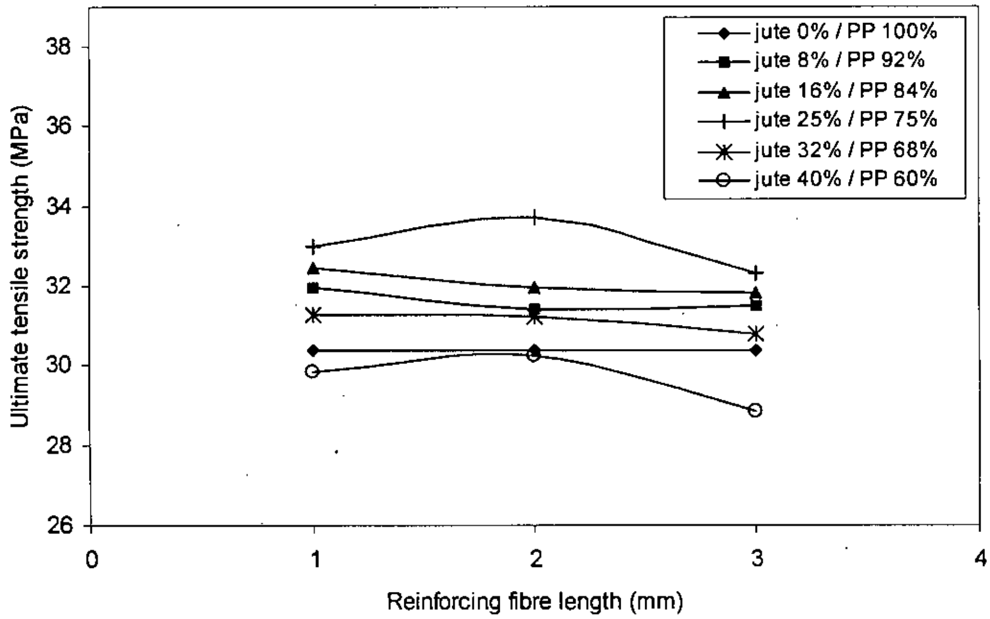


Figure 4.17: Ultimate tensile strength versus mean fibre length for jute reinforced PP composites at different fibre volume fraction.

4.5.2 Young's modulus variation with fibre length:

Decreasing trend of composite Young's Modulus was found when the reinforcing fibre length was increased. Results shown in the figure 4.18. Longer fibres are more susceptible to breaking during fibre-fibre interaction, fibre-matrix interaction and fibre interaction with the surfaces of the processing equipment. This obviously cause a decrease in the modulus. But with the increasing number of ends as a result of the enhanced fibre breakage composites toughness was increased little bit. This ultimately results in a slight decrease in tensile modulus with the increasing reinforcing fibre length. Tensile modulus decreases from 3.206 GPa to 3.095 GPa, as the reinforcing fibre length increases from 1mm to 2 mm respectively for composite of jute volume % 40 and polypropylene volume % 60.

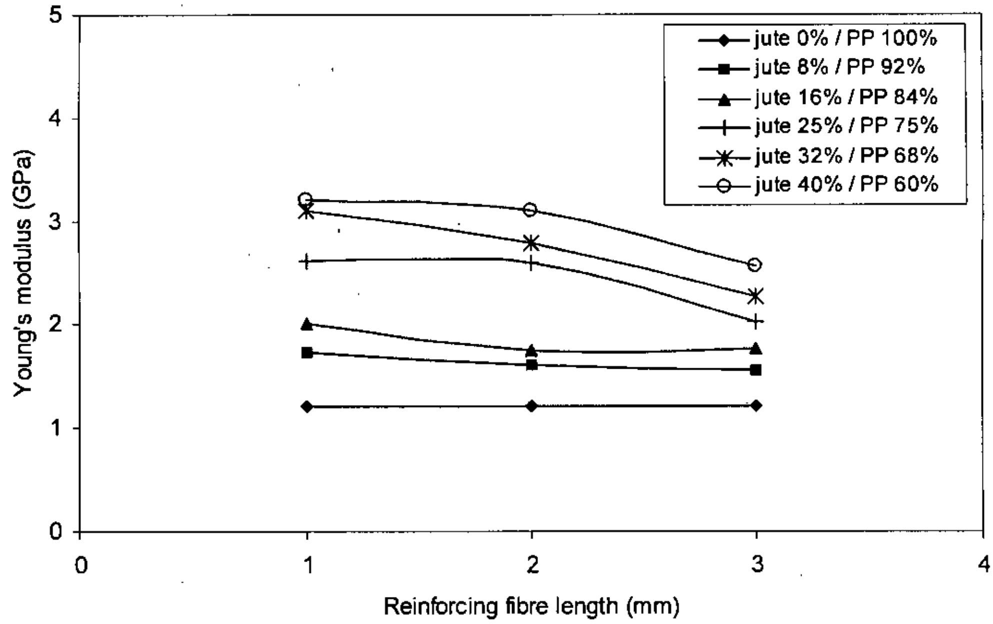


Figure 4.18: Young's modulus versus mean fibre length for jute reinforced PP composites at different fibre volume fraction.

4.5.3 Failure strain variation with fibre length:

Variation of total strain before failure (elongation at break) with the reinforcing fibre length is found to be insignificant. Fig. 4.19 shows a slight decrease in failure strain with the increase of reinforcing fibre length.

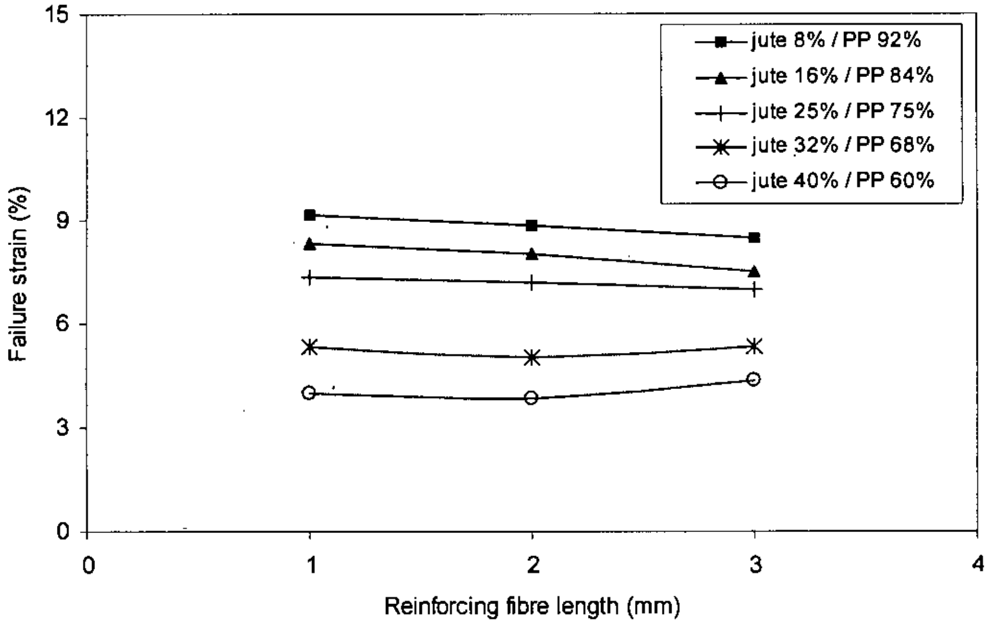


Figure 4.19: Failure strain versus mean fibre length for jute reinforced PP composites at different fibre volume fraction.

4.5.4 Notched Charpy Impact Energy variation with fibre length:

Tensile modulus shows a decreasing tendency with the increasing reinforcing fibre length (Fig. 4.18). But Figure 4.20 shows that with the increase of reinforcing fibre length the notched charpy impact energy increases (slightly). With the increase of the reinforcing fibre length fibre breakage during processing increases. Longer fibres break easily during processing. Dispersion is not good with longer reinforcing fibre. This obviously cause a decrease in the impact strength but as with the increasing breakage number of fibre ends increases which actually enhance the toughness of the resulting composite. From Figure 4.20, Composite of 8 volume % jute and 92 volume % polypropylene with fibre length 1 mm, 2 mm, 3 mm have impact strength 49.94 J/m, 46.3 J/m and 51.49 J/m respectively.

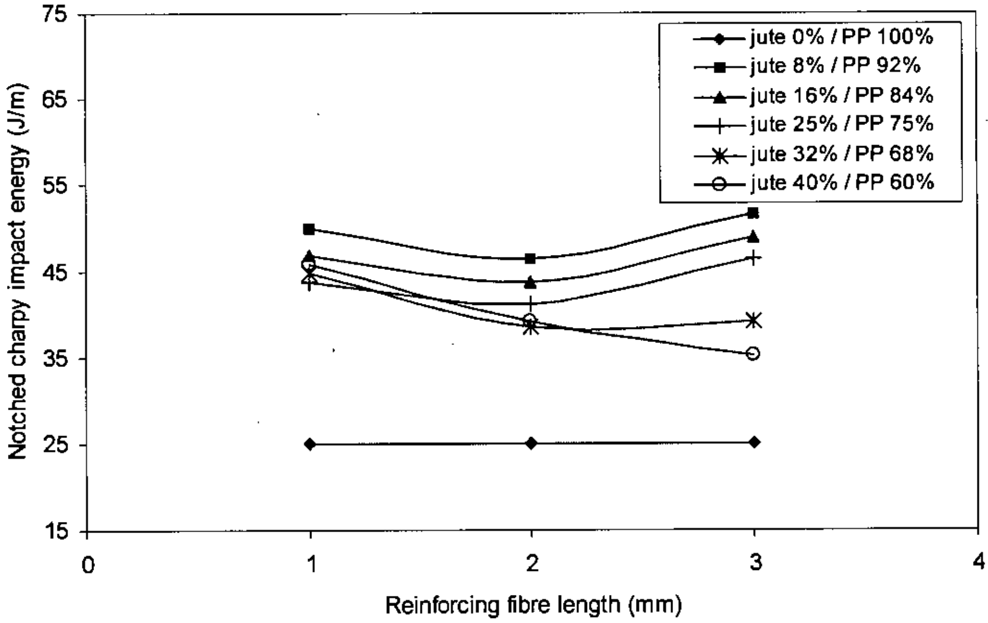


Figure 4.20: Notched charpy impact energy versus mean fibre length for jute reinforced PP composites at different fibre volume fraction.

4.6 Other composite properties:

4.6.1 Composite density and specific properties:

The densities of jute fibre reinforced composites were determined to make a comparison of specific properties (property/density). Density and specific tensile strength and specific Young's modulus of composites of different fibre loading are included in Table 4.4. The obtained values compared well with the literature (see Table 2.7 of section 2.4.4 of chapter 2). Highest specific tensile strength among all the fibres reinforced composites was 34.35 Pam^3/g, and obtained from composite with 8% jute fibre volume fraction with a mean reinforcing fibre length 1 mm and highest specific Young's modulus was 2.952 KPam^3/g and obtained from composite with 40% (volume fraction) jute fibre and mean reinforcing fibre length 1 mm.

Table 4.4: Comparison of densities and specific properties of jute fibre reinforced composites with different reinforcing fibre length.

Composite fibre content (volume %)	Composite density (g/cm^3)	Specific tensile strength (Pa.m^3/g)	Specific Young's modulus (KPa.m^3/g)
Reinforcing fibre length 1 mm			
0	0.903	32.65	1.347
8	0.930	34.35	1.855
16	0.965	33.63	2.074
25	1.010	32.66	2.587
32	1.041	30.03	2.969
40	1.086	27.48	2.952
Reinforcing fibre length 2 mm			
0	0.903	32.65	1.347
8	0.937	33.55	1.713
16	0.960	33.29	1.818
25	0.995	33.90	2.609
32	1.050	29.76	2.646
40	1.096	27.58	2.824
Reinforcing fibre length 3 mm			
0	0.903	32.65	1.347
8	0.930	33.87	1.671
16	0.970	32.82	1.814
25	1.000	32.32	2.020
32	1.057	29.11	2.149
40	1.099	26.23	2.333

4.6.2 Variation of Composite density:

As the density of the reinforcing fibre is higher than that of the matrix material, with the increase of reinforcing fibre volume fraction composite density increases. This is observed in Fig. 4.21, which shows the variation of composite density with the reinforcing fibre volume fraction. Fig. 4.22 shows the variation of composite density with the reinforcing fibre mean length. Insignificant variation of density is observed with varying reinforcing fibre length.

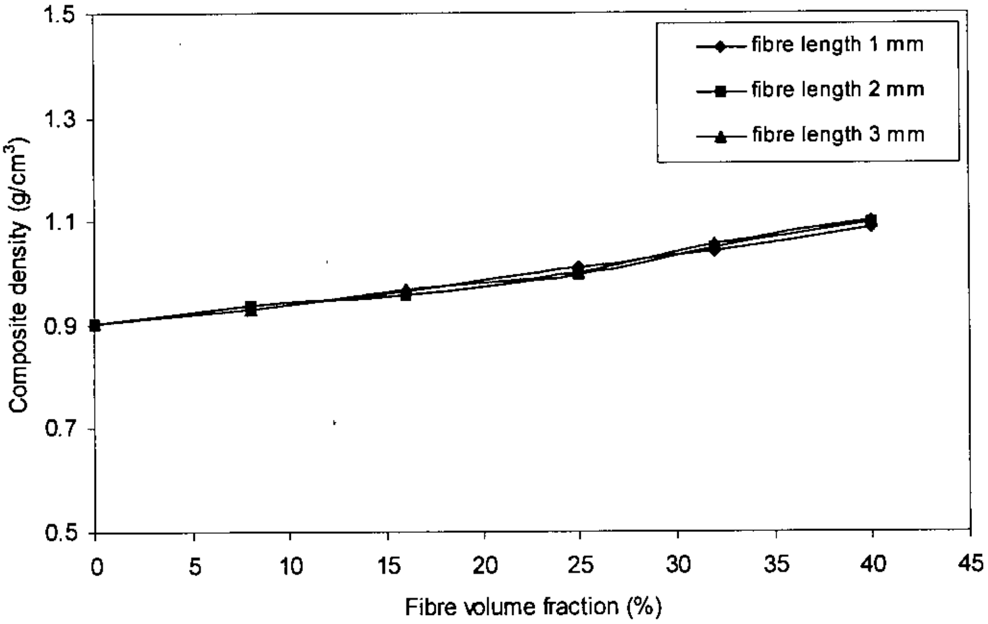


Figure 4.21: Composite density versus fibre loading for jute reinforced PP composites at different mean reinforcing fibre length.

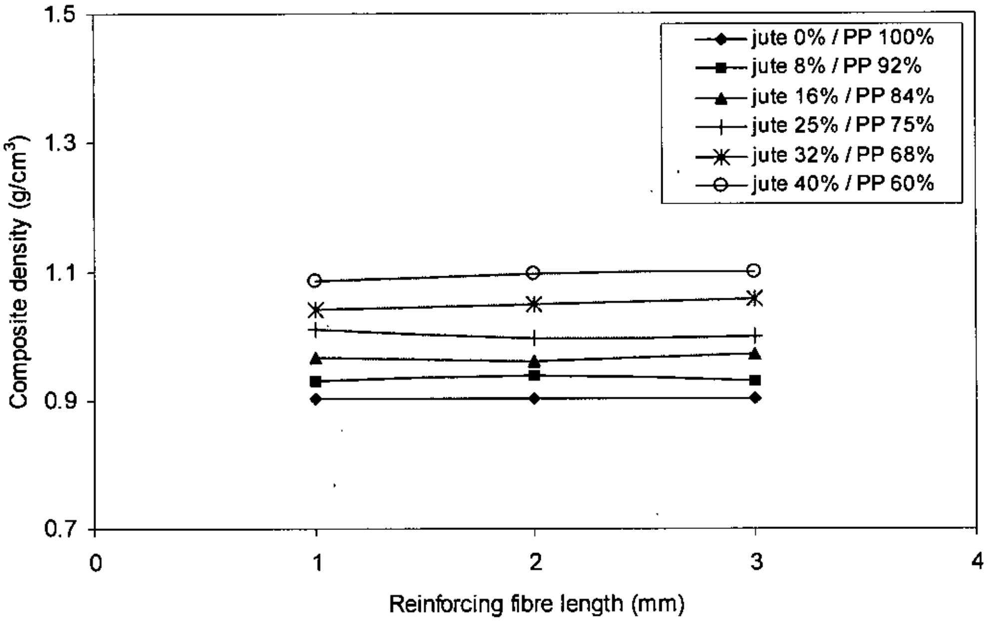


Figure 4.22: Composite density versus mean reinforcing fibre length for jute reinforced PP composites at different reinforcing fibre volume fraction.

Variation of dispersion is observed clearly while comparing fig. 4.23 and fig. 4.24. Surface wetting of the reinforcing fibres are poor in fig. 4.24, which shows the SEM micrographs of the fracture surface of jute reinforced polypropylene composite with reinforcing fibre length 2 mm and fibre loading 40%. With 25% reinforcing fibre (2 mm) loading, fibre are separated, i.e., surface wetting is good.

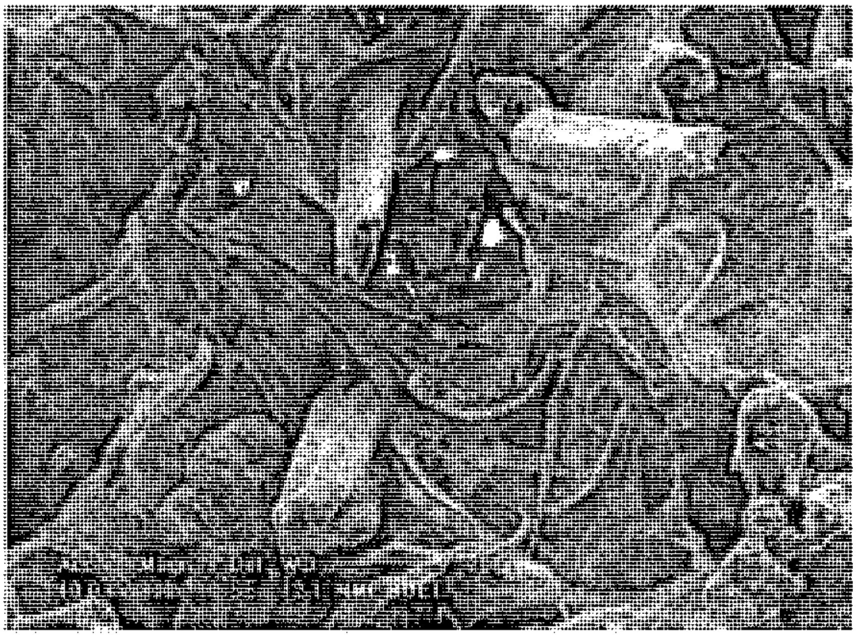


Figure 4.23: Scanning Electron Micrographs of jute fibre reinforced Polypropylene composite fracture surface with fibre length 2 mm and fibre volume fraction 25%.

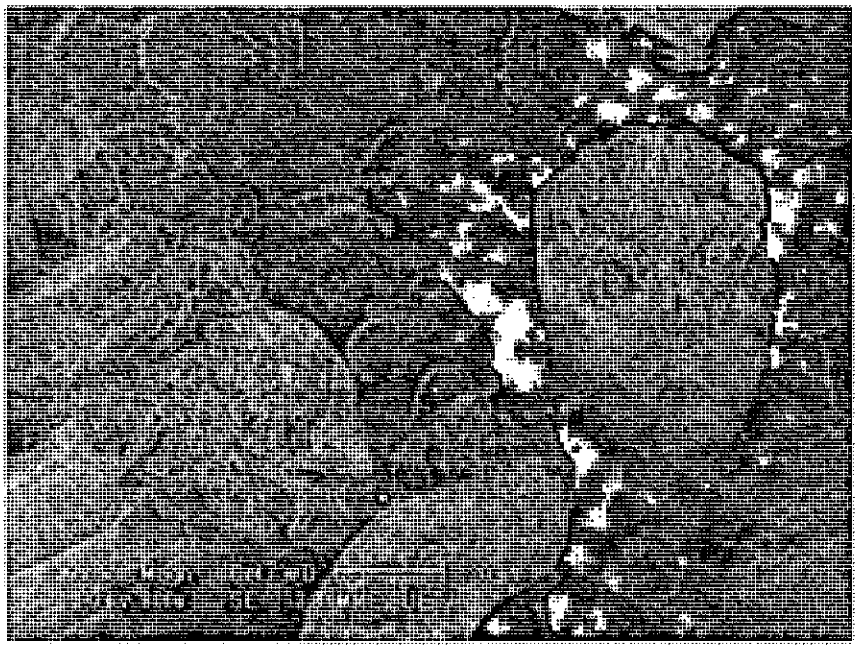


Figure 4.24: Scanning Electron Micrographs of jute fibre reinforced Polypropylene composite fracture surface with fibre length 2 mm and fibre volume fraction 40%.

4.6.3 Variation of Composite specific properties:

This study was performed because specific properties give a better indication of the benefits that are achievable with a material. With the increase of the reinforcing fibre volume fraction the specific tensile strength increases slightly. Increase of specific tensile strength is insignificant up to 25% fibre loading. Further addition of reinforcement, i.e., if the fibre volume fraction is increased further specific tensile strength decreases. Figure 4.25 shows the variation of specific tensile strength with fibre loading. And Fig. 4.26 shows that composites specific tensile strength has an increasing tendency with the increasing reinforcing fibre length.

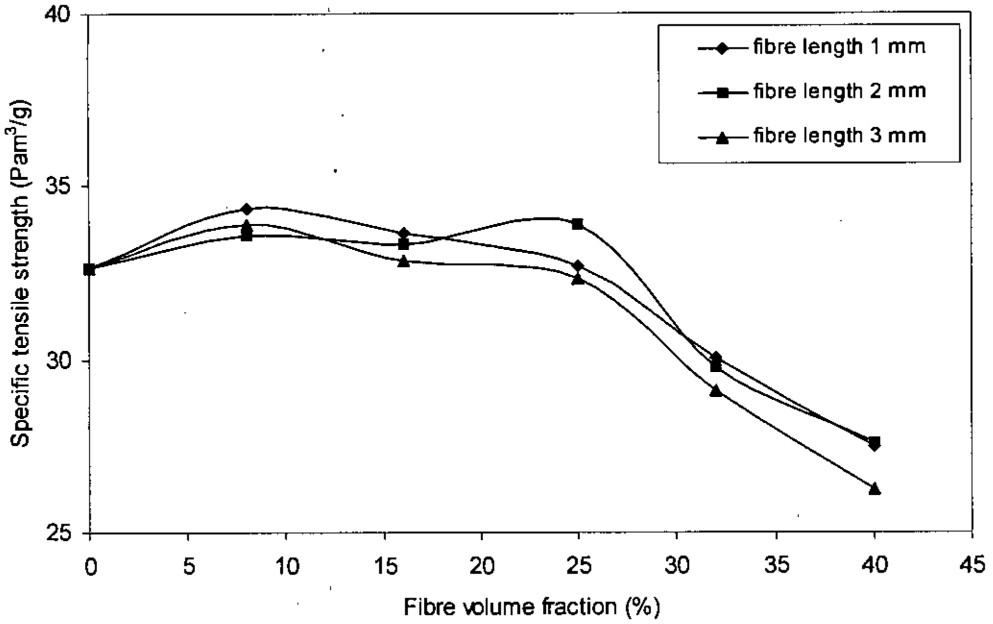


Figure 4.25: Composite specific tensile strength versus fibre loading for jute reinforced PP composites at different mean reinforcing fibre length.

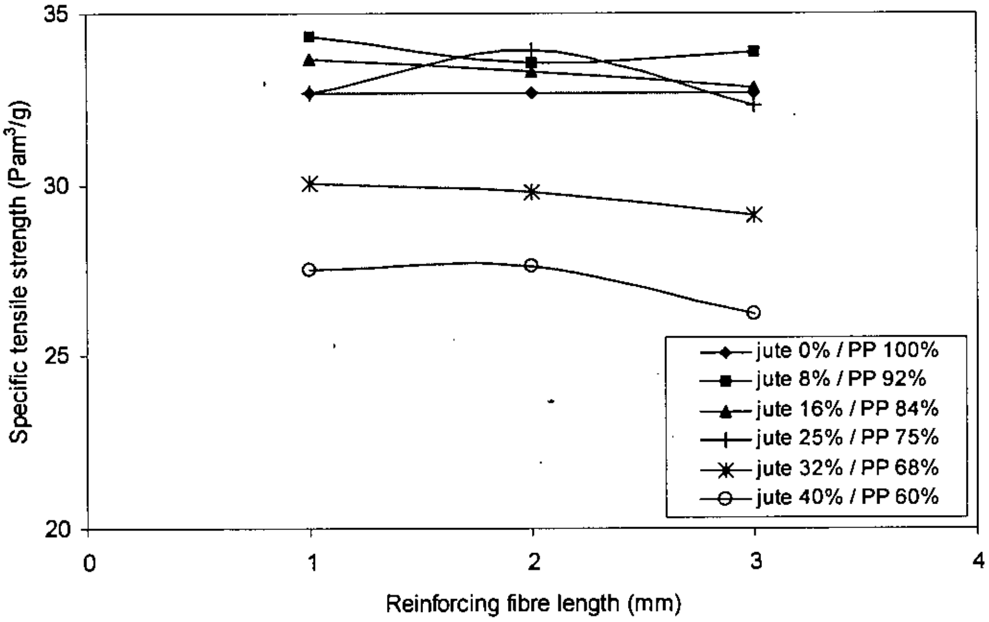


Figure 4.26: Composite specific tensile strength versus mean reinforcing fibre length for jute reinforced PP composites at different reinforcing fibre volume fraction.

Figures 4.27 and 4.28 shows the variation of composite specific tensile modulus with reinforcing fibre volume fraction and mean length respectively. Like the Young's modulus specific Young's modulus increases with the increasing reinforcement and with the longer reinforcing fibre length specific Young's modulus shows a decreasing trend.

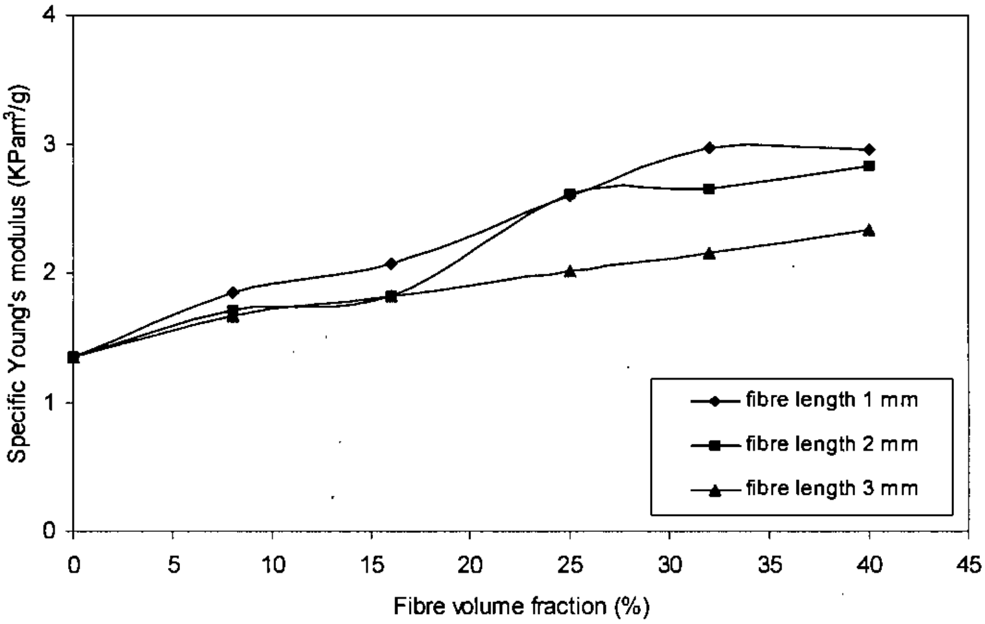


Figure 4.27: Composite Specific young's modulus versus fibre loading for jute reinforced PP composites at different mean reinforcing fibre length.

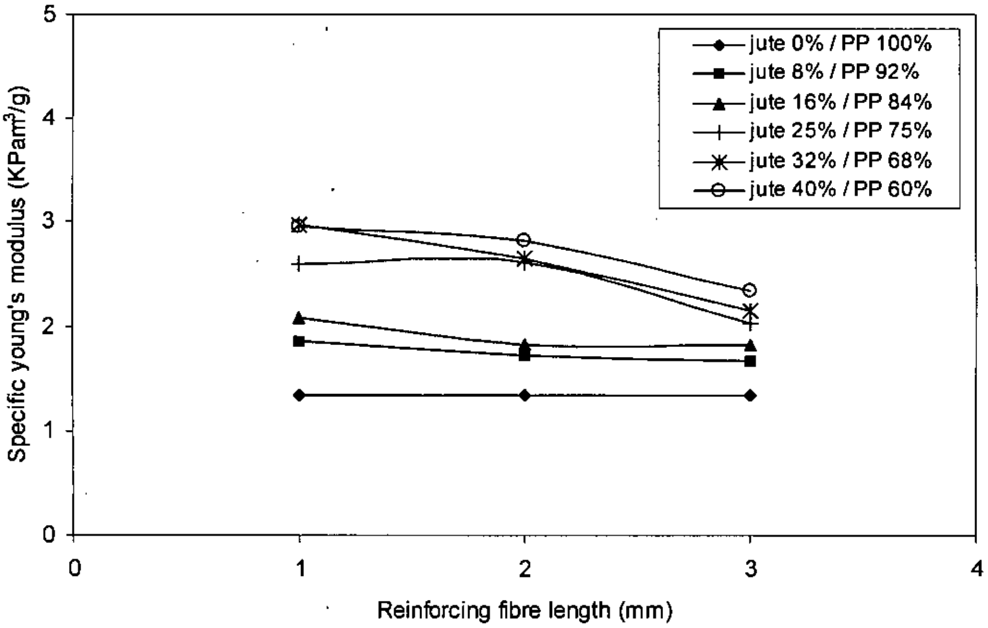


Figure 4.28: Composite specific young's modulus versus mean reinforcing fibre length for jute reinforced PP composites at different reinforcing fibre volume fraction.

4.6.4 Mean interfacial shear strength, critical length and theoretical prediction of strength:

An effective use of fibre strength is dependent on both the interfacial adhesion and the critical fibre length. The mean interfacial shear strength from single fibre pull-out test was collected from literature [100].

Table 4.5: Interfacial property and the critical fibre length for jute/PP composite.

Sample	Mean interfacial shear strength ± standard deviation (MPa) $\hat{\tau} \pm s.d.$	Fibre tensile strength (MPa) σ_{fu}	Mean fibre radius (mm) r_f	Fibre critical length (mm) l_c
Raw jute fibre reinforced Polypropylene composite	9.7 ± 1.5	610 ± 198	0.013 ± 0.006	1.012 ± 0.140

Composite strength prediction:

By using the modified rule of mixtures, it is possible to calculate the theoretical tensile strengths of composites, and then to compare them to the actual strengths obtained during tensile testing. The modified rule of mixtures strength prediction method is as follows [95]:

From chapter 2, considering equation (1)

$$\sigma_c = (V_m \times \sigma_m^*) + (V_f \times \sigma_f \times K_1 \times K_2)$$

Where,

σ_c = the tensile strength of the composite

σ_f = the tensile strength of the fibre

V_m = the matrix volume fraction

V_f = the fibre volume fraction

K_1 = orientation factor

K_2 = a factor dependent on the stress transfer between the matrix and the fibres

$\sigma_m{}^*$ = the tensile contribution of the polymer matrix at the failure strain of the composite

As the volume fraction was considered in preparing the composite, the first two variables the volume fraction of the matrix (V_m) and the reinforcing fibre (V_f) are readily available. The density of jute fibre is 1.48 g/cm^3 (collected from BJRI) and the density of polypropylene is 0.903 g/cm^3 [51].

Table 4.6: Theoretical composite tensile strengths

Jute fibre volume fraction (%)	V_f	V_m	Theoretical tensile strength (MPa)		
			Fibre orientation		
			3 – D random	Planar random	Aligned
0	0.00	1.00	30.36	30.36	30.36
8	0.08	0.92	37.6912	46.2312	76.7312
16	0.16	0.84	45.0224	62.1024	123.1024
25	0.25	0.75	53.27	79.9575	175.27
32	0.32	0.68	59.6848	93.8448	215.8448
40	0.40	0.60	67.016	109.716	262.216

The next two variables, namely the orientation factor (K_1) and the factor dependent on the stress transfer between the matrix and the fibre (K_2) can only be determined experimentally. To calculate the maximum theoretical tensile strength, however, it is possible to make certain assumptions on these variables [95]:

K_1 = 1/5 for a 3-dimensional random orientation

K_1 = 3/8 for a planner random orientation
K_1 = 1 for aligned fibres
K_2 = 1 assuming perfect adhesion between the fibres and matrix

The tensile strength (σ_f) of jute fibre is 610 MPa and the tensile strength of the polypropylene matrix (σ_m*) is 30.366 MPa. The theoretical tensile strengths for each composite were then calculated using equation (1), and the results are summarised in Table 4.6.

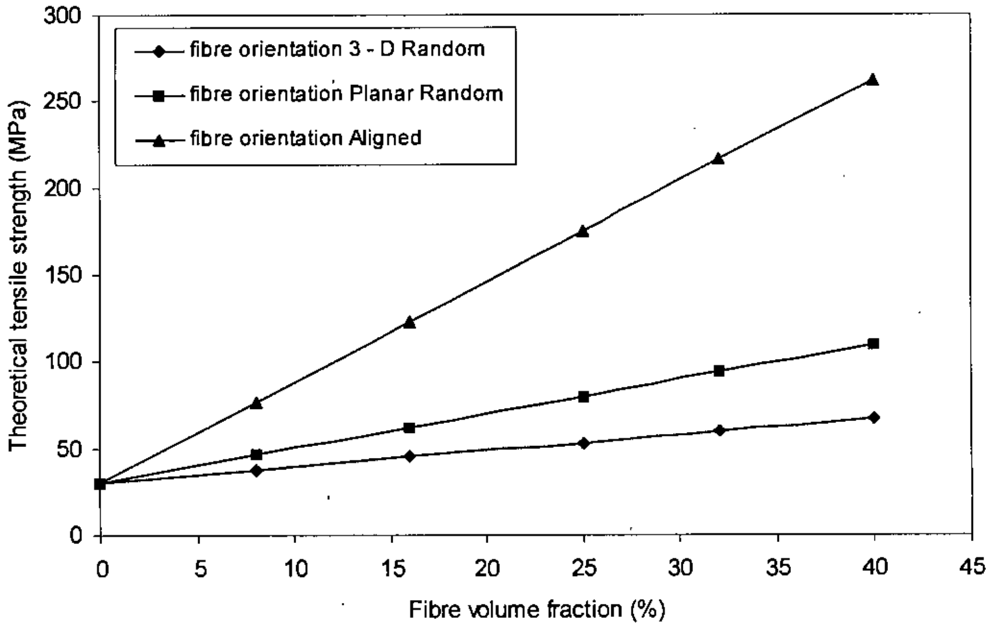


Figure 4.29: Theoretical tensile strength versus fibre loading for jute reinforced PP composites at different fibre orientation.

It can be seen from these results that, improving the fibres alignment, as well as increasing the fibre volume fraction in the composite could lead to great improvements in tensile strength. When comparing the theoretical tensile strength values in Table 4.6 to the actual composite tensile strength values in Table 4.2, it can be seen that there are large differences between the theoretical and actual strengths. The injection-moulded composites were thought to have had an approximately planar random fibre configuration, caused by the linear flow of the molten composite into the mould. The composites would never actually be as strong as the theoretical values due to fibre damage incurred during composite processing and variations in interfacial bonding, but the theoretical values do provide a benchmark from which to judge the performance of the composites. The main reasons why the composites appeared to be so much weaker than the theoretical values especially in case of jute fibre reinforced polypropylene composites presumably due to their poor interfacial bonding.

It can therefore be concluded that, to improve the strength of jute fibre reinforced polypropylene composites apparently a strong treatment is needed. For further improvement of the tensile properties for jute fibre reinforced composites, fibres need to be aligned in the direction of the applied tensile loads.

4.6.5 Fibre efficiency factor for composite strength (λ_σ) and fibre efficiency factor for composite modulus (λ_E):

The tensile strength (σ_c) of SFRP composites can be predicted using the modified rule of mixtures equation [41]:

$$\sigma_c = \lambda_\sigma \sigma_{fu} V_f + \sigma_m (1 - V_f) \quad \text{(6)}$$

$$E_c = \lambda_E E_f V_f + E_m (1 - V_f) \quad \text{(7)}$$

Where,

λ_σ = The fibre efficiency factor for the composite strength

λ_E = The fibre efficiency factor for the composite modulus

σ_c = Composite tensile strength

E_c = Composite young's modulus

σ_{fu} = Reinforcing fibre tensile strength = 610 ± 198 MPa

E_f = Reinforcing fibre young's modulus = 48.1 GPa

σ_m = The tensile strength contribution of the polymer matrix = 30.366 MPa

E_m = The young's modulus contribution of the polymer matrix = 1.216 GPa

V_f = Reinforcing fibre volume fraction

At Table 4.1 the Efficiency factors are summarised with different reinforcing fibre length and volume fraction. Fibre efficiency factors describes the effectiveness of utilization of fibre stiffness and strength.

Fig. 4.30 shows the variation fibre efficiency factor for composite strength with different fibre loading. Results showed that the fibre efficiency factor for composite strength decreases with the increasing fibre volume fraction. And Fig. 4.31 shows that the fibre efficiency factor for composite modulus decreases slightly with increasing fibre loading. It can be seen that the fibre efficiency factor for composite strength (λ_σ) was much lower than the fibre efficiency factor for composite modulus (λ_E).

Table 4.7: Prediction of fibre efficiency factor for strength and modulus for jute fibre reinforced polypropylene composites.

Fibre length (mm)	Fibre loading (volume fraction) (%)	σ_c Composite Tensile strength (MPa)	E_c composite Young's modulus (GPa)	Fibre efficiency factor for composite strength, λ_σ	Fibre efficiency factor for composite modulus, λ_E
1	0	30.366	1.216	-	-
	8	31.949	1.725	0.066	0.158
	16	32.453	2.001	0.058	0.127
	25	32.983	2.613	0.054	0.141
	32	31.264	3.091	0.044	0.147
	40	29.842	3.206	0.038	0.129
2	0	30.366	1.216	-	-
	8	31.432	1.605	0.058	0.126
	16	31.955	1.745	0.053	0.094
	25	33.733	2.596	0.058	0.140
	32	31.250	2.778	0.044	0.127
	40	30.227	3.095	0.040	0.123
3	0	30.366	1.216	-	-
	8	31.496	1.554	0.059	0.113
	16	31.832	1.760	0.052	0.096
	25	32.317	2.020	0.051	0.092
	32	30.769	2.272	0.042	0.094
	40	28.822	2.564	0.035	0.095

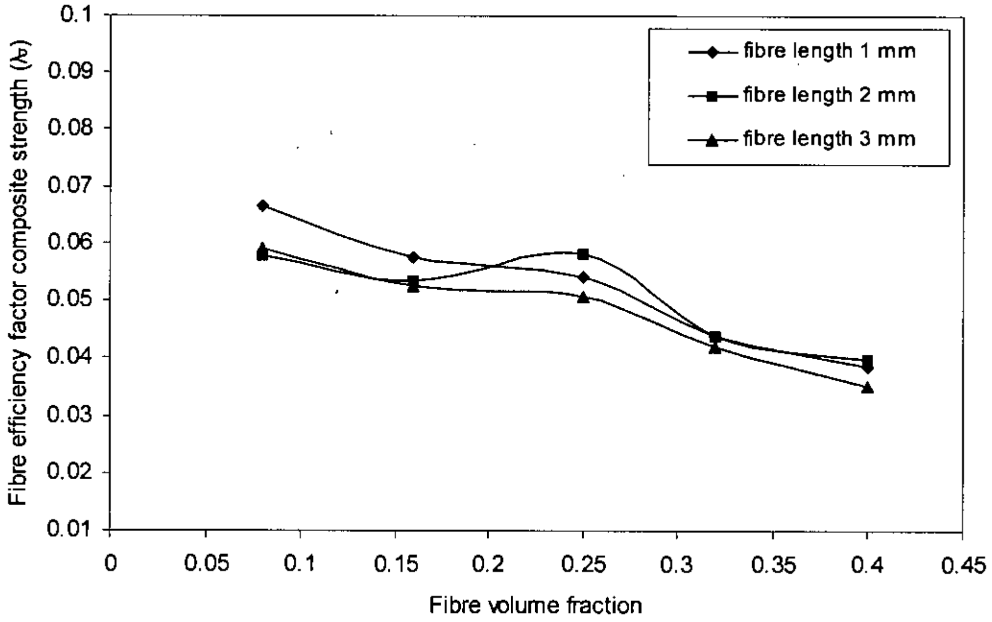


Figure 4.30: Fibre efficiency factor for composite strength versus fibre loading for jute reinforced PP composites at different reinforcing fibre length.

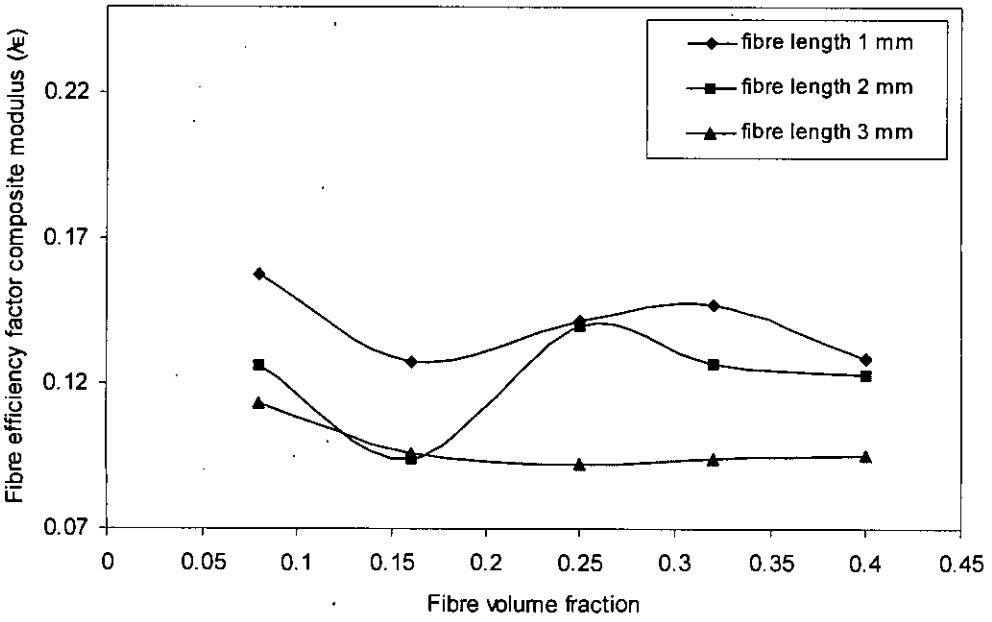


Figure 4.31: Fibre efficiency factor for composite modulus versus fibre loading for jute reinforced PP composites at different reinforcing fibre length.

4.7 Comparison of single fibre properties:

Several physical, chemical and mechanical properties are important in selecting a suitable natural fibre for use in composites. Following are the single fibre properties that were studied: wall thickness, fibre shape, peripheral length, diameter, fibre length, cross-sectional area, fibre surface, lignin content, fibre separation, tensile strength, Young's modulus, specific tensile strength and specific Young's modulus.

4.7.1 Physical parameters:

Dimensional properties of single fibre are listed in Table 4.8. Physical parameters of jute fibre are calculated from SEM and the properties of other fibres are taken from the literature [16, 96].

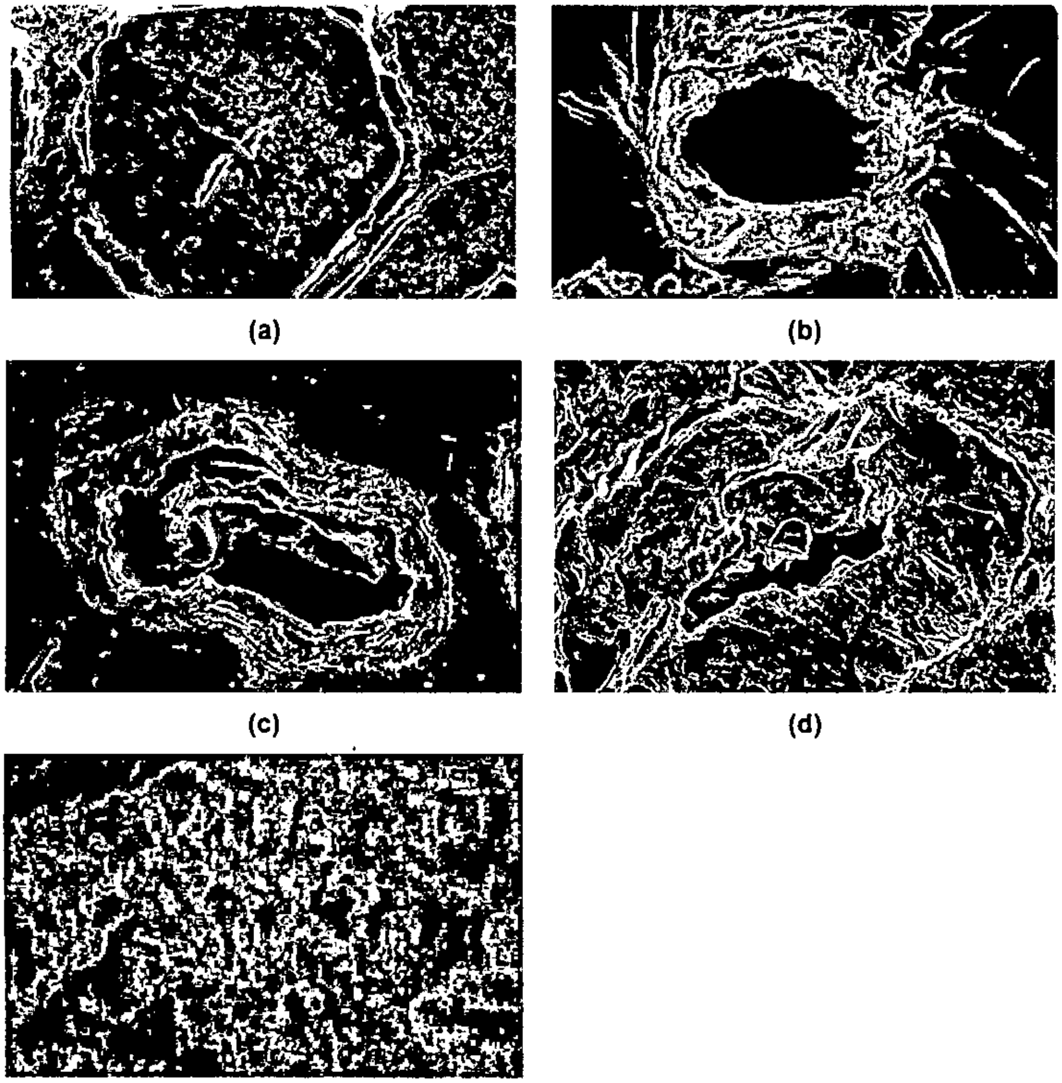
Table 4.8: Single fibre physical characteristics (hemp and jute fibres are almost solid with very narrow lumen).

Type of Fibre	Average wall Thickness (μm)	Average peripheral length (μm)	Average cross-sectional area taking lumen into consideration (μm^2)	Average diameter (mm)	Average fibre length (mm)	Aspect ratio (length/ diameter)
Jute	-	-	540	0.0250	3 ± 0.7	130 ± 20
Hemp	-	-	618	0.0270	25	926
Slabwood	5.92	84.6	506	0.0354	3.6	101.69
Thinnings	5.4	73.11	412	0.0347	3.4	97.8
Luaan	5.03	63.85	349	0.0343	2	58.20
Eucalyptus	-	-	-	0.0200	1	50

The dimensional values obtained for jute, shown in Table 4.8, compared well with the literature values [16, 39] (see Table 2.4 of section 2.2.5 of chapter 2). Though the highest aspect ratio was found for hemp, aspect ratio of jute is higher than any other natural fibre.

4.7.2 Cross-sectional parameter:

Scanning electron micrographs of cross-section of jute, hemp and wood fibres showed that the fibres posses non-uniform geometrical characteristics (Figure 4.32). The jute fibres exhibited a shape fairly circular and outer surface uneven, looks like a bundle of several thin fibres. The hemp fibre exhibited a polygonal shape with five to seven sides, and had a lumen smaller than that of wood fibres. Hemp, slabwood, thinnings, luaan fibre cross sections are collected from literature [16, 78]. The wood fibres were found to have bigger lumens than hemp and jute fibres. The highest average cross-sectional area was found for jute and hemp fibres.

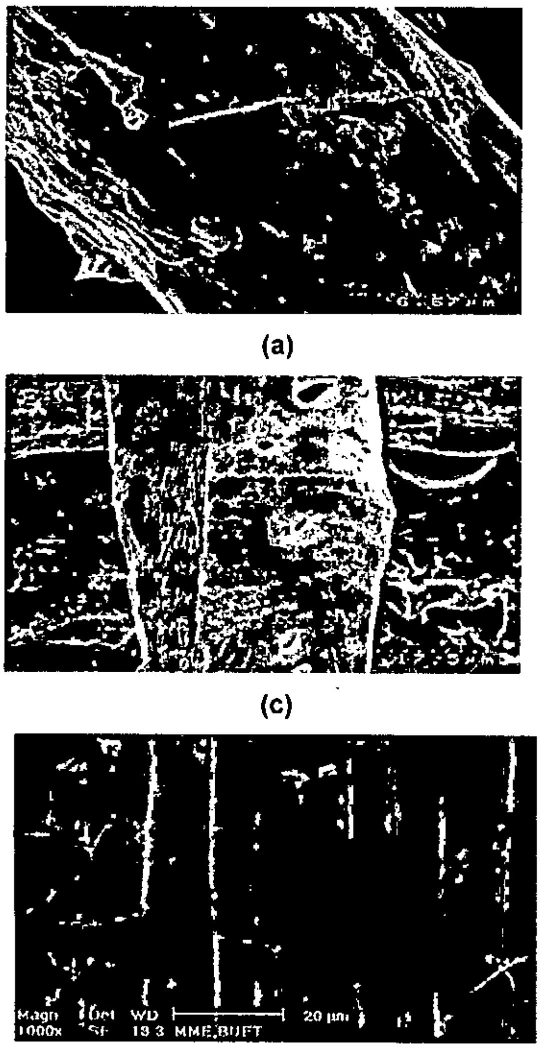


(a) (b) (c) (d) (e)

Figure 4.32: Scanning electron micrograph (SEM) of cross-sections of single fibre (a) hemp (b), slabwood, (c) thinnings, (d) luaan [16, 78] and (e) Jute

4.7.3 Shape and fibre surface:

The jute and hemp fibres contain less defects and imperfections compared to wood fibres (see Figure 4.33) (Magnification: 1000x). A surface with less defects results in minimum stress concentration and stronger fibre [30]. Wood fibres have numerous structural imperfections, and defects such as pits, nodes along the length of the fibre (see Figure 4.33 b, c, d), which although result in weaker single fibres, but at the same time approximately will make more reactive hydroxyl groups available on the fibre surface [36]. In addition, wood fibres are also more suitable for mechanical interlocking inside the composites [36].



(a) (b)

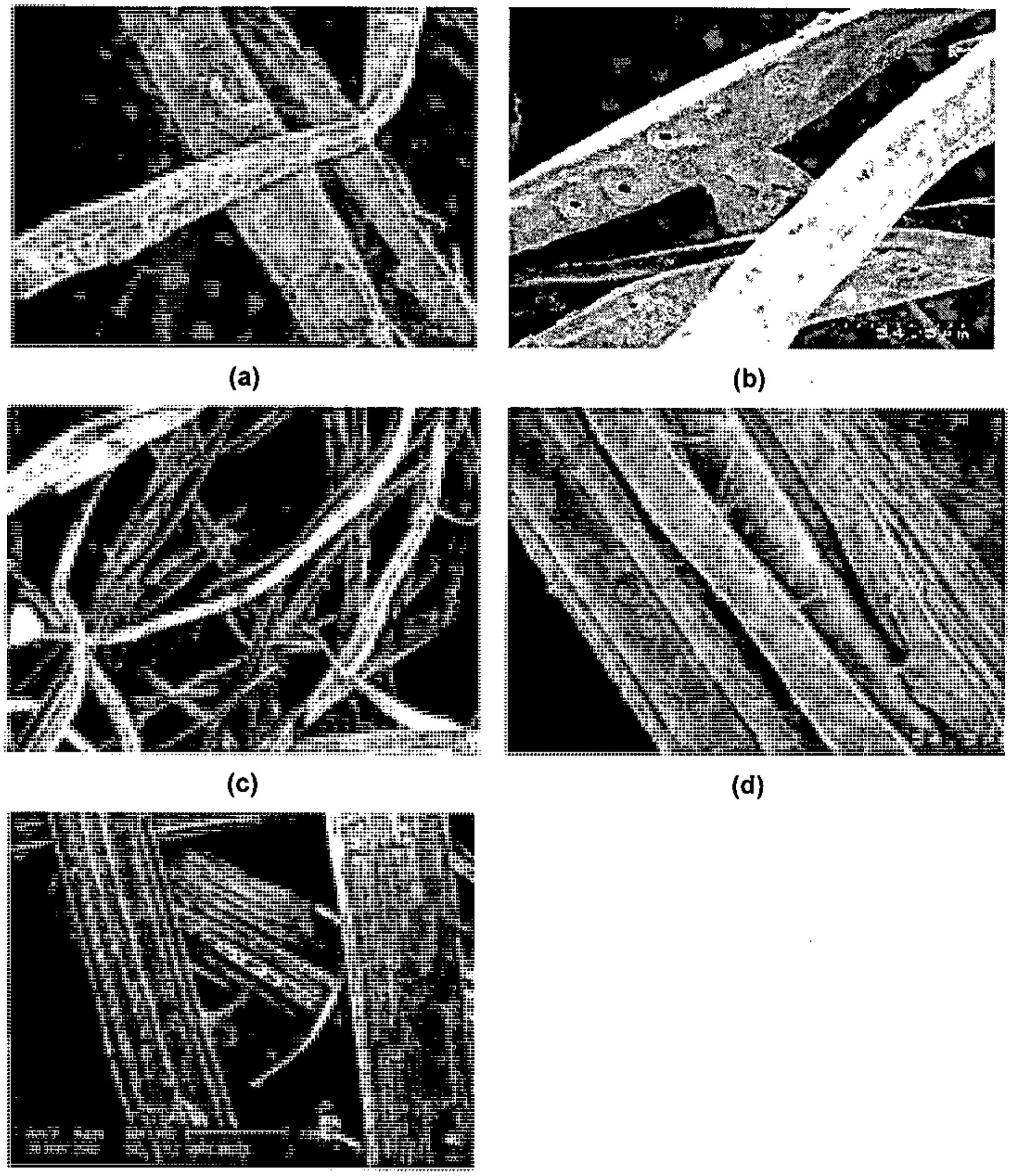
(c) (d)

(e)

Figure 4.33: Scanning electron micrographs (SEM) of single fibre surface; (a) hemp, (b) slabwood, (c) thinnings, (d) luaan [16, 78] and (e) jute.

4.7.4 The extent of fibre separation:

Fig. 4.34 shows that the extent of separation of jute fibre is better than hemp fibre. This is important for good reinforcement. Magnification of the photographs supplied is 250x. Hemp, slabwood, thinnings, luaan fibre separation observations are collected from literature [16, 78].



(a) (b)

(c) (d)

(e)

Figure 4.34: Scanning electron micrograph (SEM) of fibre separation; (a) slabwood, (b) thinnings, (c) luaan, (d) hemp [16, 78] and (e) Jute

4.7.5 Lignin content:

The removal of lignin from natural fibres is important for producing strong and stiff natural fibre reinforced thermoplastic composites. It is found elsewhere that the jute fibres with the lowest surface lignin contents show the largest increases in tensile properties when used in composites. Referring to Table 2.3 lignin content is lowest for the hemp fibre. But the jute fibres have lower lignin than any wood fibre.

4.7.6 Comparison of single fibre tensile strength and young's modulus:

The average strength obtained for all the individual fibres that were collected are shown in Figure 4.35. Hemp fibres are the strongest among the natural fibres. The jute fibres are slightly weaker than hemp fibres but stronger than wood fibres, even when it's lumen taken into account, apparently the surfaces have less defects as compared to wood fibres (as can be seen from Figure 4.33). Hemp, slabwood, thinnings, luaan fibre strengths are collected from literature [16]. And carbon and glass fibre strengths are collected from literature [88, 89].

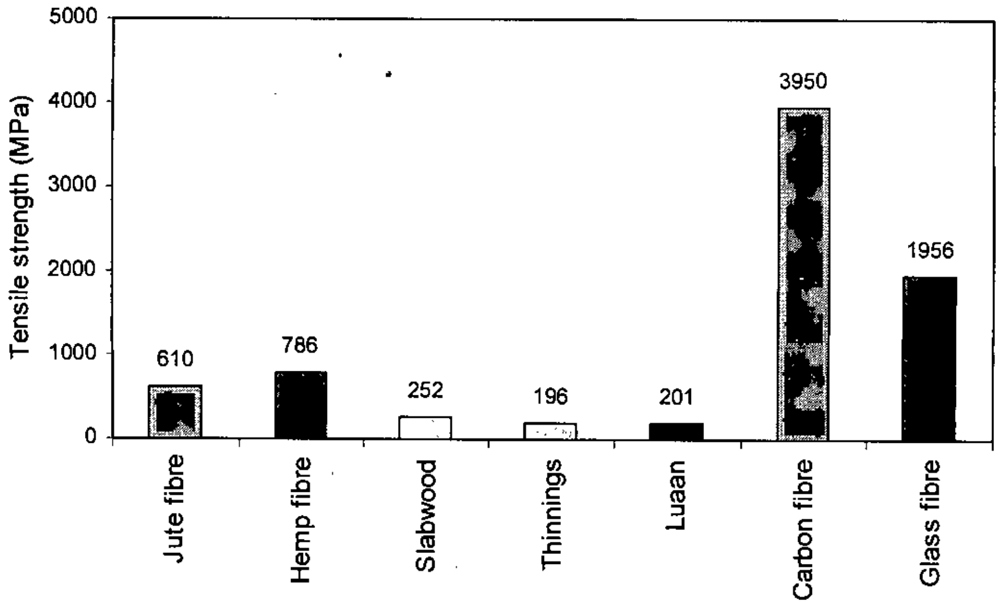


Figure 4.35: Comparison of tensile strength for different types of fibre.

The tensile strength of carbon fibre (manmade mineral fibre) is highest (3950 MPa) among all the fibres observed here. Manmade mineral fibre, glass fibre shows a lower value (1956 MPa). As they are much more compact in construction and have comparatively smoother surface their contribution to the tensile strength is much higher than those of the natural fibres. The tensile strength (786 MPa) of hemp fibre is higher than that of jute fibre (610 ± 198 MPa). Softening of the inter-fibrillar matrix (lignin, hemicellulose and pectin) adversely affects the stress transfer between the fibrils and, thereby the overall stress development in the fibre under tensile deformation outweighs the increase of tensile strength by the removal of weaker material (lignin, hemicellulose and pectin) [16, 39, 96] (See section 2.2.6 of chapter 2). A gradual decrease in both strength and Young's modulus of the fibres with lignin removal was also reported elsewhere [36].

It was found that the strength of slabwood, thinnings and luaan fibres are lower than the strength of jute and hemp fibres. Tensile strengths were calculated assuming that jute fibres were solid and cylindrical. Tensile strength is calculated by dividing the tensile load by the fibre cross-sectional area. Diameter of the fibre was used to calculate the fibre cross-section ($\pi d^2/4$, where d = diameter). As a result, fibre diameter has more influence on strength calculation in case of slabwood fibre than jute and hemp fibre as wood fibre has bigger lumen and jute and hemp fibres are almost solid.

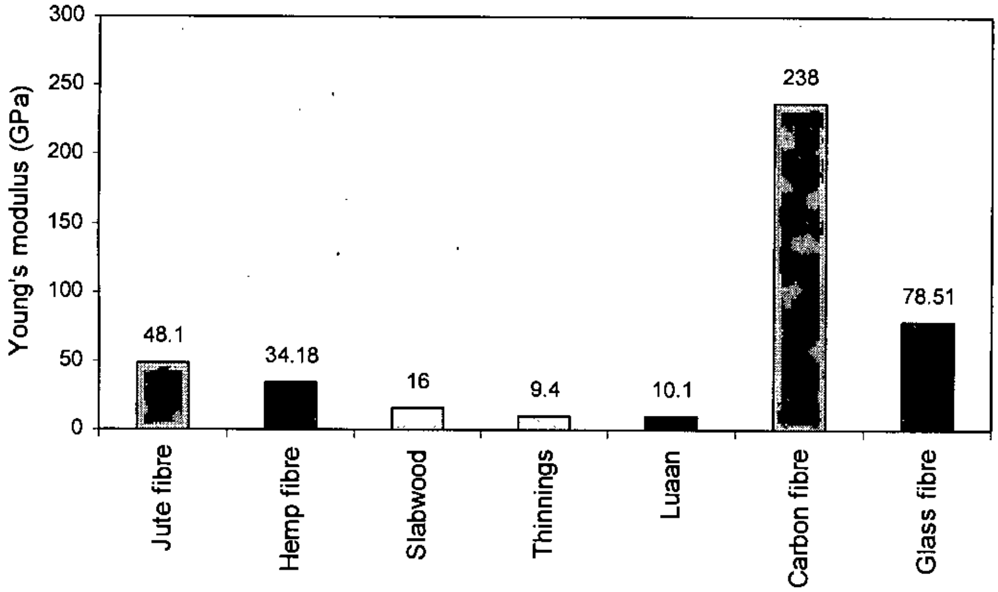


Figure 4.36: Comparison of Young's modulus for different types of fibre.

Young's modulus values for the different fibres studied can be seen in figure 4.36. The value for the carbon fibre is very high compared to the others. Here the jute fibres show the highest value of young's modulus among all the natural fibres studied.

4.7.7 Comparison of specific strength and specific Young's modulus:

This study was performed because specific properties give a better indication of the benefits that are achievable with a material. The density of hemp fibre is 1.48 gcm^{-3} and wood (both soft and hard) is 1.4 gcm^{-3} [16] (See Table 2.5 of section 2.2.6 of chapter 2). The density of jute fibre is 1.48 gcm^{-3}, The densities of carbon and glass fibres are 1.77 gcm^{-3} and 2.55 gcm^{-3} respectively. These values were used to calculate specific properties by dividing the tensile strength and Young's modulus by density. From the Figure 4.37, it can be seen that the specific properties for natural fibre compared well with the literature values (See Table 2.5 of section 2.2.6 of chapter 2 of present study). Hemp fibres in general have better specific properties than wood fibres as expected (see figure 4.37). Slabwood fibres have better specific properties than other wood fibres (see figure 4.37).

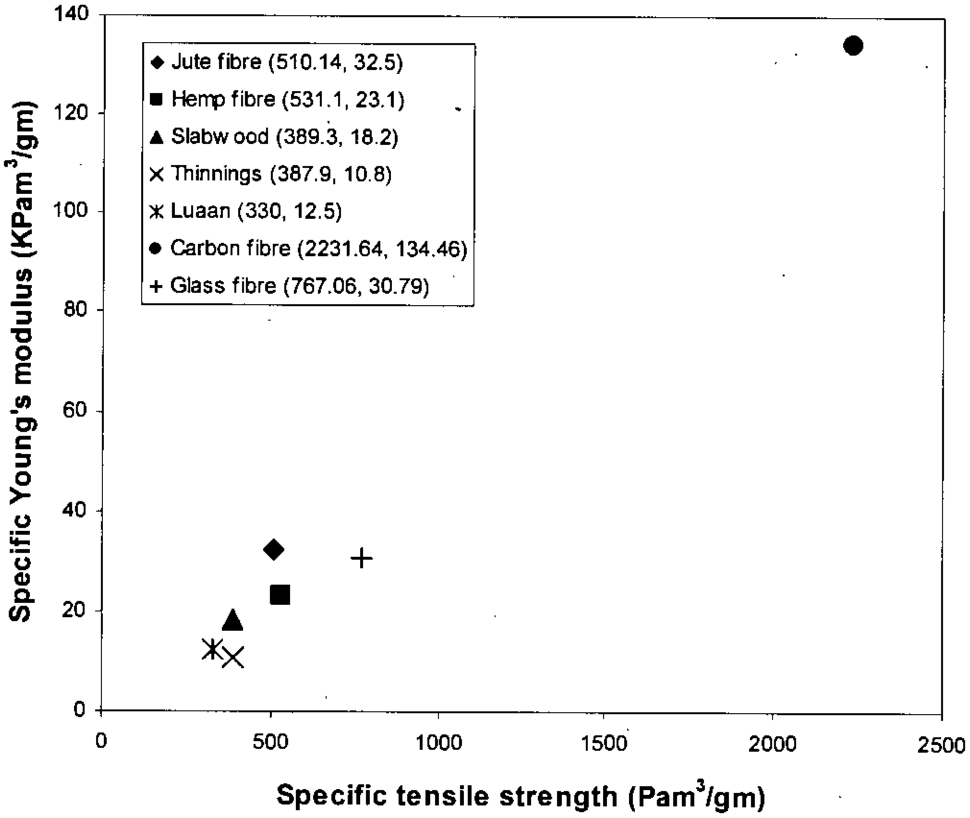


Figure 4.37: A comparison of natural fibres specific properties for composite production.

4.8 Comparison of composite properties:

4.8.1 Process optimisation for composite production:

This study was carried out to maximise composite mechanical properties by process optimization. Polypropylene (PP) supplied was in pellet form. Average sizes of the pellets were approximately 5 - 7 mm in diameter. It was also assumed that double pass through the extruder would mix the composite better than the single pass and would result in better composite mechanical properties.

4.8.2 Comparison of natural fibre reinforced Composites tensile strength and young's modulus:

Figure 4.38 shows the tensile strengths of natural fibre reinforced polypropylene composites with 25% and 32% (volume fraction) fibre reinforcement. Here, jute fibre reinforced PP composites exhibit highest strength of 33.733 MPa at 25% fibre volume fraction. At 32% fibre loaded composites again jute reinforced polypropylene composite shows the best value (31.25 MPa). Jute and slabwood reinforced PP composites exhibit the similar trend when reinforcing fibre loading is increased. They shows a decrease in composite strength as the fibre loading increased from 25% to 32%. But the hemp fibre reinforced PP composite shows an increase of tensile strength with the increase of fibre volume fraction.

Figure 4.39 shows that the superiority goes to hemp fibre reinforced PP composites when young's modulus of natural fibre reinforced polypropylene composites with 25% and 32% (volume fraction) fibre reinforcement is considered. Here, hemp fibre reinforced PP composites exhibit highest modulus of 3.32 GPa at 25% fibre volume fraction. At 32% fibre loaded composites slabwood/PP composite shows the best value (4.42 GPa). Jute fibre reinforced PP composites shows a value (2.596 GPa at 25% fiber volume fraction and 2.778 GPa at 32% fibre volume fraction) lower than the hemp and slabwood fibre reinforced PP composites. Here all the fibres reinforced

PP composites exhibit the similar increasing trend when reinforcing fibre loading is increased.

Figure 4.40 shows scanning electron micrographs of the tensile fracture surfaces of different natural fibre reinforced polypropylene composites with a fibre volume fraction of 32%. The fracture surfaces indicates the proper mixing of fibres in the polymer matrix. Fibre pullout, and very few fibre breakages were observed, which leading to lower tensile strengths and Young's modulus values.

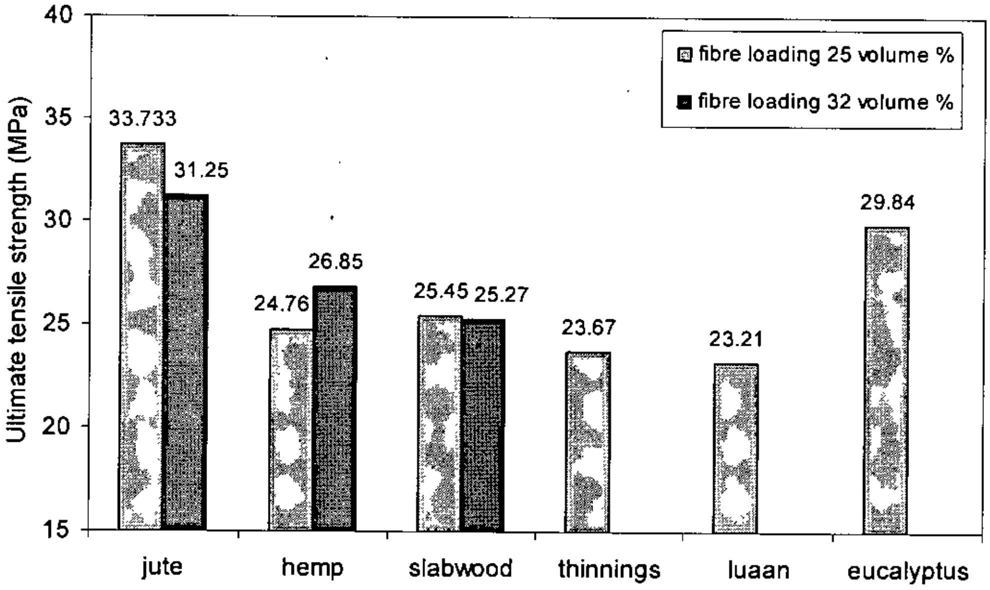


Figure 4.38: Comparison of tensile strength of different natural fibre reinforced PP composites.

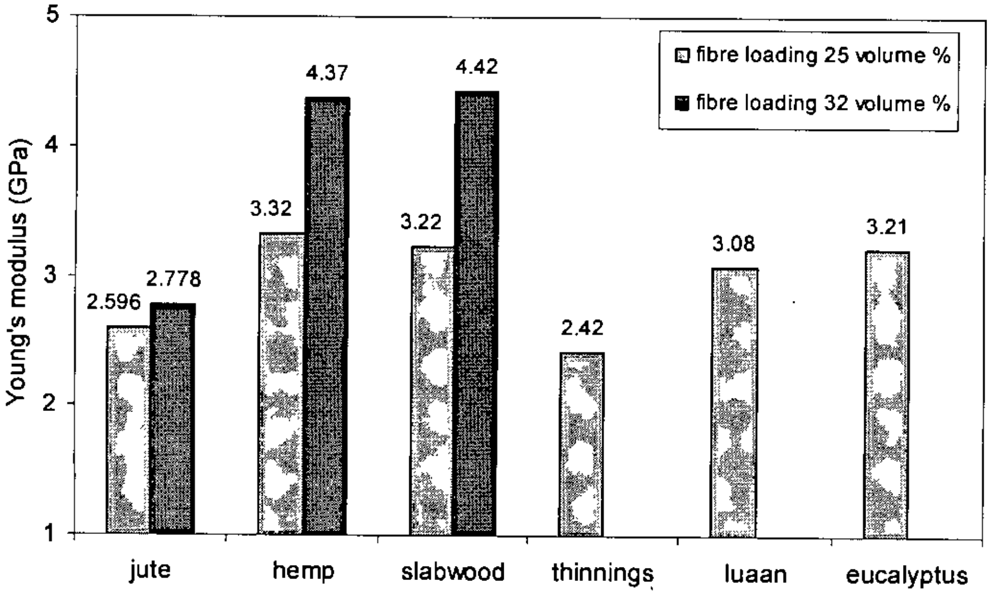
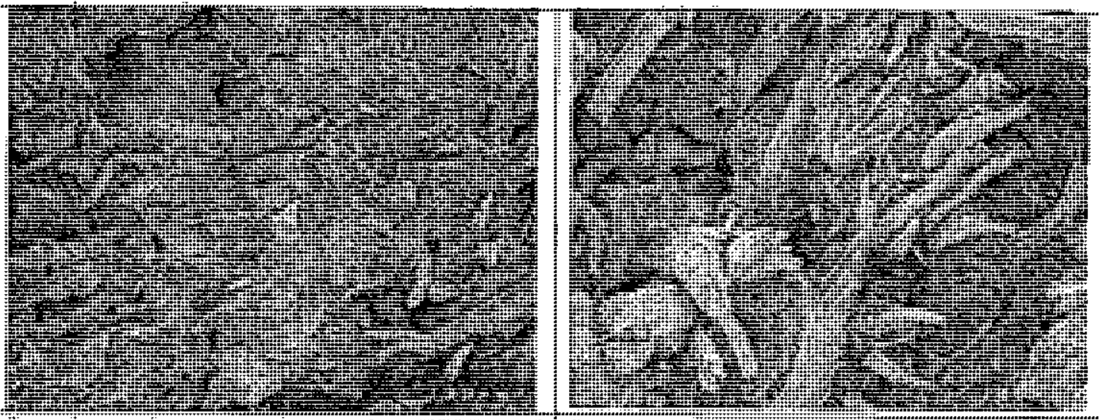
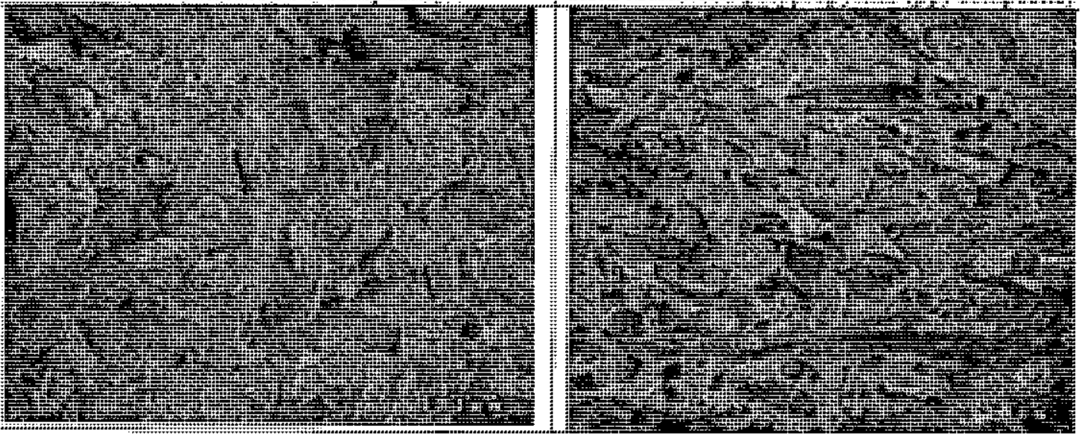


Figure 4.39: Comparison of young's modulus of different natural fibre reinforced PP composites.



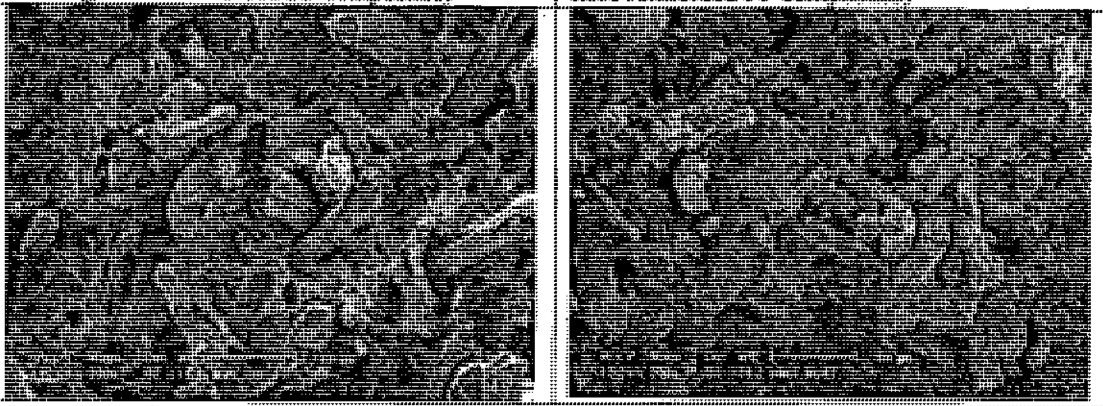
Scanning electron micrograph (SEM) of composite fracture surface (30 volume % [illegible] fibre reinforced PP composite)

Scanning electron micrographs (SEM) of composite fracture surface (30 volume % hemp fibre reinforced polypropylene (pp) composite)



Scanning electron micrograph (SEM) of composite fracture surface (30 volume % thinnings fibre reinforced PP composites)

Scanning electron micrograph (SEM) of composite fracture surface (30 volume % kenaf fibre reinforced PP composites)



Scanning electron micrograph (SEM) of composite fracture surface (32 volume % jute fibre reinforced PP composites)

Scanning electron micrograph (SEM) of composite fracture surface (25 volume % jute fibre reinforced PP composites)

Figure 4.40: Comparison of Scanning Electron Micrographs of fracture surface of different natural fibre reinforced composites [78, 80, 81].

4.8.3 Comparison of jute fibre reinforced Composites with other manmade mineral fibre reinforced composites:

A comparative study of natural fibre reinforced polypropylene composites and some manmade mineral fibre reinforced polypropylene composites is exhibited in this section. Figure 4.41 shows the variation of tensile strength of jute, glass and carbon fibre reinforced PP composites. In addition, the effect of reinforcing fibre volume fraction on tensile strength of each category is published. All the fibre reinforced PP composites show a similar increasing trend in tensile strength with the increased fibre reinforcement. The strength of short carbon fibre reinforced polypropylene (SCF/PP) (highest) and short glass fibre reinforced polypropylene (SGF/PP) composites are higher than those of short jute fibre reinforced polypropylene (SJF/PP) composites. This is because carbon and glass fibres have a much higher strength than jute fibres. As far as the nature of data is concerned, SCF/PP and SGF/PP composites have more scattered data than SJF/PP composites. This is because carbon and glass fibres are more brittle than jute fibres. Carbon and glass fibre reinforced polypropylene composite strengths are collected from literature [88, 89].

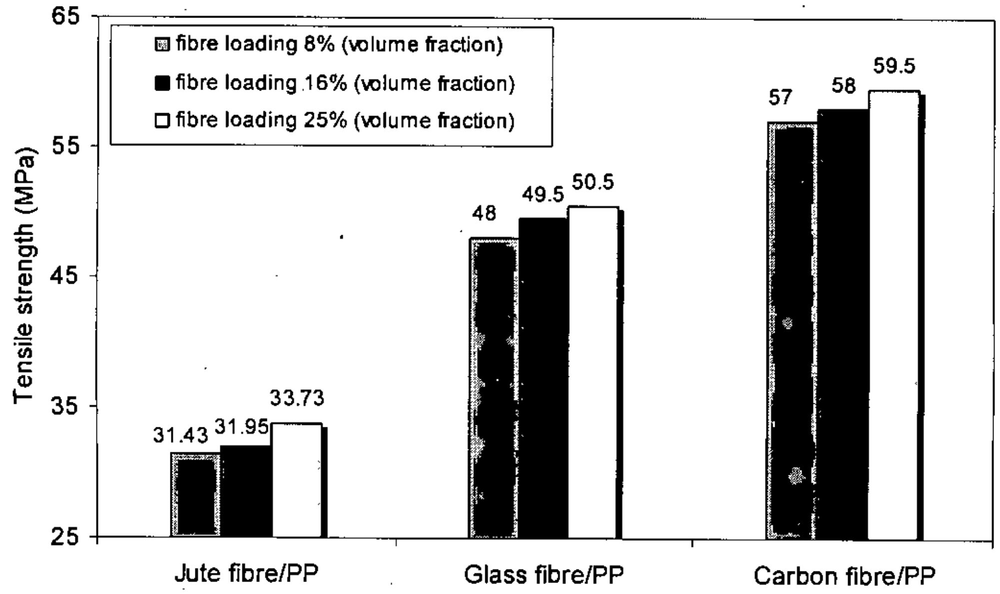


Figure 4.41: Comparison of tensile strength of jute, glass and carbon fibre reinforced PP composites at three different fibre loading [88, 89].

The variation of the tensile modulus of SCF/PP, SGF/PP and SJF/PP composites as a function of fibre volume fraction are shown in Figure 4.42. It can be seen that the young's modulus for all types of composites increases dramatically with the increase of fibre volume fraction. Figure indicates that the composite tensile modulus is more dependent on fibre volume fraction and less dependent on fibre length than the composite strength does. The young's modulus of carbon and glass fibres are higher than the jute fibres. Similarly, carbon and glass fibre reinforced PP composites show better tensile modulus than the jute fibre reinforced PP composites.

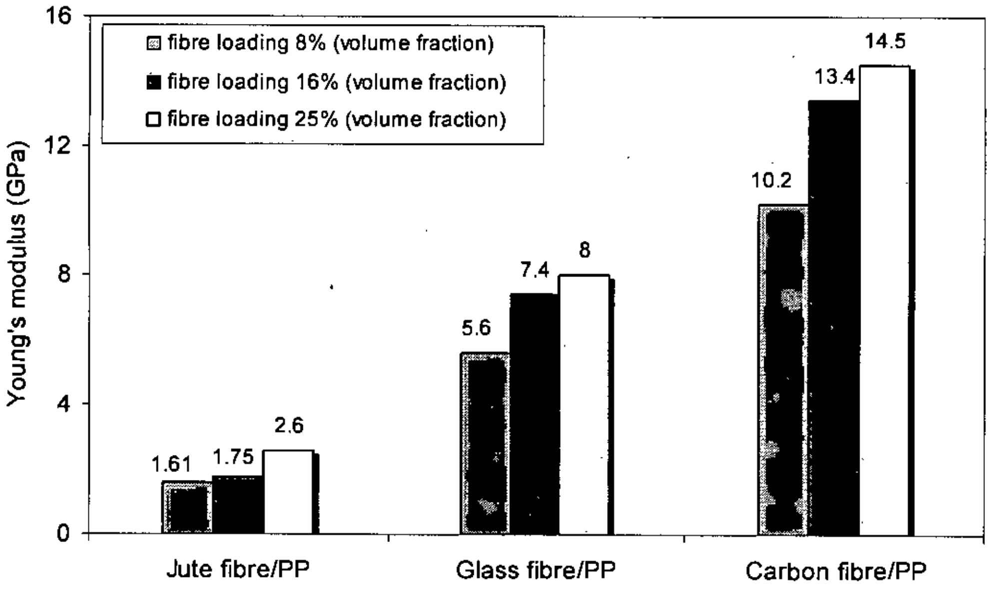


Figure 4.42: Comparison of young's modulus of jute, glass and carbon fibre reinforced PP composites at three different fibre loading [88, 89].

The variation of the failure strain of SCF/PP, SGF/PP and SJF/PP composites as a function of fibre volume fraction are shown in Figure 4.43. It can be seen that the elongation at break for all types of composites decreases with the increase of fibre volume fraction. The effect of elasticity of reinforcing fibre enhances the elongation at break during tensile testing. As jute fibre is comparatively more elastic than the carbon and glass fibres, the failure strain measured for jute fibre reinforced PP composites is much higher than those of carbon and glass fibre reinforced PP composites. Figure 4.44 shows the fracture resistance of SCF/PP, SGF/PP and SJF/PP composites. Variation of notched charpy impact energy of jute, glass and carbon fibre reinforced PP composites is exhibited. In addition, the effect of reinforcing fibre volume fraction on the impact energy of each category is shown. Energy absorbed during impact is highest for the glass fibre reinforced PP composites. With the increasing fibre reinforcement all fibre reinforced composites show a decreasing trend in impact energy. It is true for all the fibre reinforced PP composites that the introduction of reinforcement of these fibres obviously dramatically enhances the impact energy. But after that if the fibre loading is increased though very little but impact energy decreases gradually.

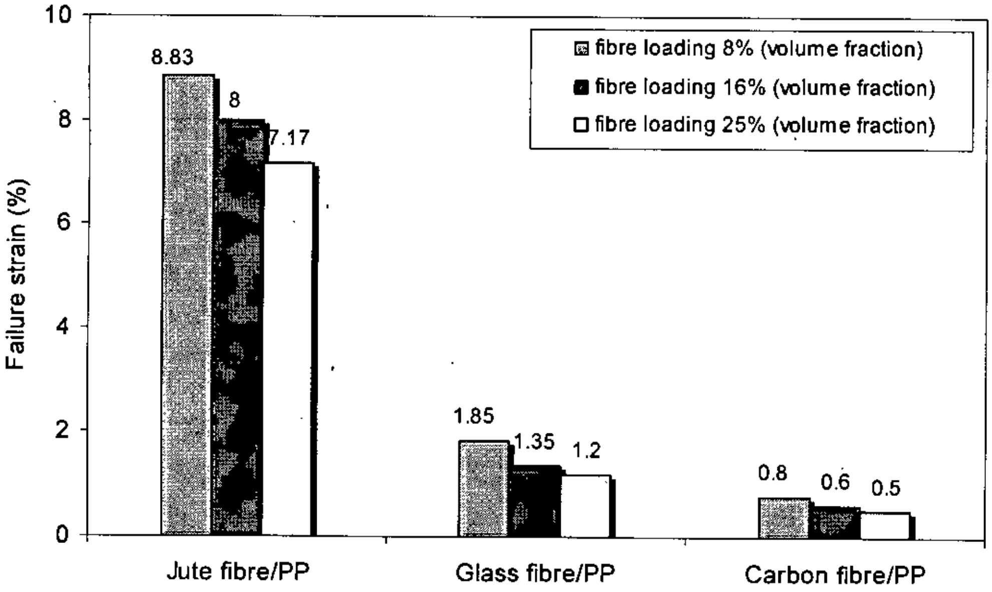


Figure 4.43: Comparison of failure strain of jute, glass and carbon fibre reinforced PP composites at three different fibre loading [88, 89].

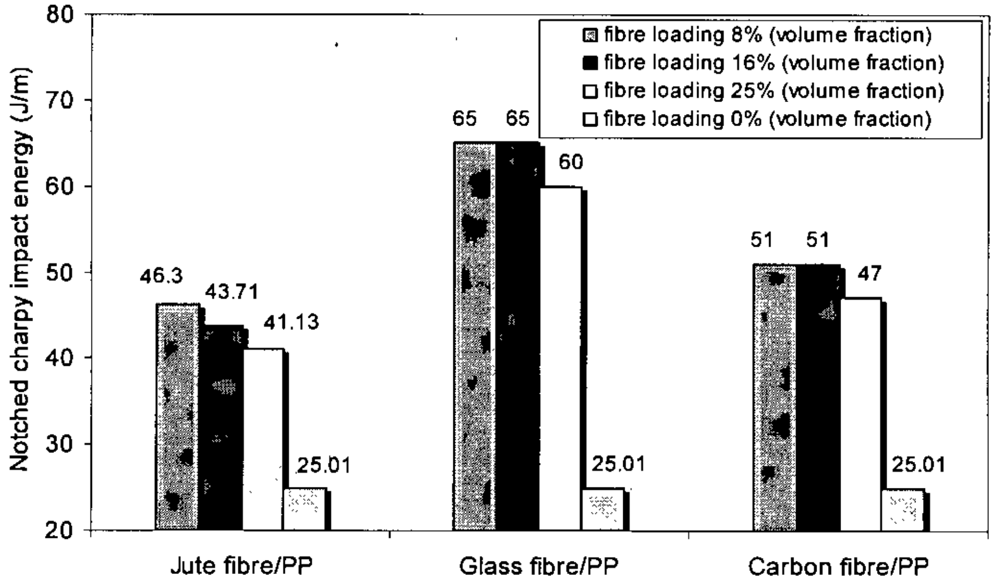


Figure 4.44: Comparison of Notched Charpy Impact Energy of jute, glass and carbon fibre reinforced PP composites at three different fibre loading [88, 89].

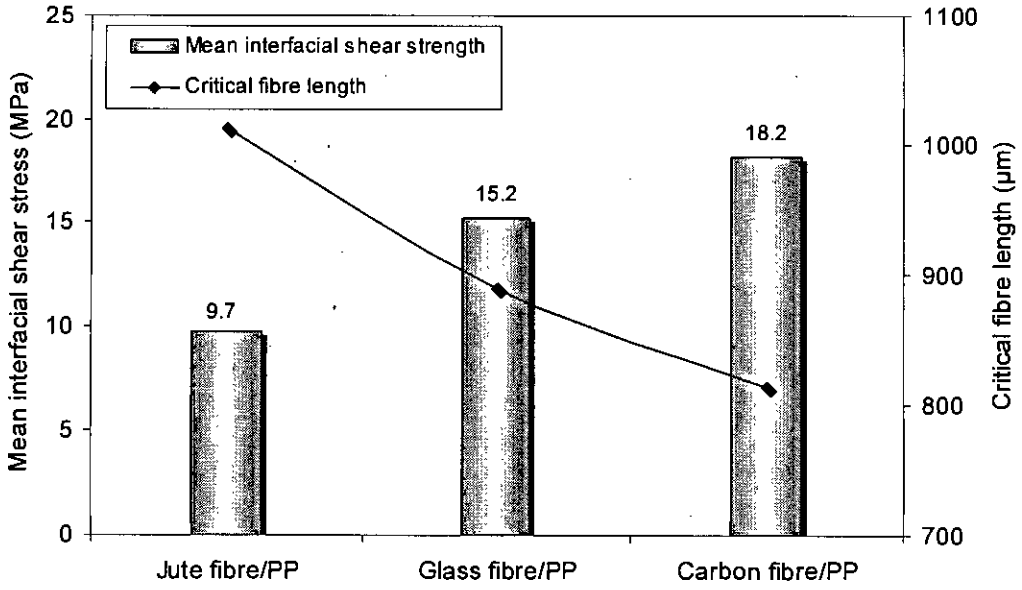


Figure 4.45: Comparison of mean interfacial shear strength and the critical fibre length for the different fibre matrix combination.

The variation of the mean interfacial shear strength and the critical fibre length of different fibre matrix combination (SCF/PP, SGF/PP and SJF/PP) are shown in Figure 4.45. But the critical fibre length, defined as the minimum fibre length where the maximum allowable fibre tensile stress can be achieved, is highest (more than 1 mm) for jute in polypropylene matrix.

Chapter Five

CONCLUSIONS AND RECOMMENDATIONS

This research work comprises of experimental determination and theoretical prediction of the effect of reinforcing fibre volume fraction and the mean reinforcing fibre length on the mechanical properties of short jute fibre reinforced polypropylene composite.

Composites of polypropylene reinforced with short jute fibre are prepared with extrusion compounding and injection moulding techniques. The mechanical properties like tensile strength, Young's modulus, failure strain, notched charpy impact energy for jute fibre reinforced polypropylene composite are carried out considering the length and volume fraction of the reinforcing fibre as variables.

The results have shown that fibres are oriented approximately along the longitudinal direction in the composite. The addition of jute fibres effectively enhances the ultimate tensile strength. The tensile strength of the composites increases with the increase of fibre loading up to the fibre volume fraction 25%. Apparently, the higher the reinforcing fibre content the higher the tensile strength of the composite. Study showed a maximum of 11% increase in strength with 25% jute fibre (2 mm reinforcing fibre length) loading. After the volume fraction exceeds 25%, the strength starts decreasing gradually. This may be the combined effect of fibre breakage during processing and the lack of stress transfer from the polypropylene matrix to jute fibres. The breakage of fibres during processing leads to the reduction in mean fibre length. It was observed that as the fibre volume fraction increases, the composite strength increases slightly only and decreases if loading was continued after 25-30%. This observation exhibits that the effect of mean fibre length on composite strength was significantly large, so that the combined effect of fibre volume fraction and mean fibre length leads to only a slight increase in composite strength, as the fibre volume fraction increases. The decrease in the composite strength caused by the reduction in mean fibre length almost offsets the increase in the composite strength caused by the increase in fibre volume fraction. When the reinforcing fibre loading was increased beyond 25-30%, amount of fibre breakage also increases and become prominent to influence the ultimate tensile strength of the composite. The critical fibre length for the fibre-matrix (jute/PP) combination was found to be 1.012 ± 0.140 mm. The composite with the fibre length 1 mm at different loading show better performance, except for 25% and 40% fibre loading, where, with the increase of fibre length strength increases. Tensile strength shows an increasing tendency with longer length. Strength should be higher for longer fibre reinforced PP composites but here in most of the cases strength decreases when longer fibre was reinforced, this was because the fibre breakage rate was higher for the longer fibres. As a result, the mean reinforcing fibre length becomes less. No of fibre ends also increases, which enhance an early failure.

Reduction in strength at higher fibre loading (40%) is mainly because of the poor surface wetting and poor dispersion of fibres in the matrix. Highest strength is achieved at 2 mm reinforcing fibre length And strength decreases if the reinforcing fibre length is decreased or increased. At 3 mm fibre length and 40% fibre loading strength is lowest, cause of this is poor dispersion and surface wetting and the length is too large from the critical length.

The highest tensile strength (33.733 MPa) was obtained from 25% jute fibre loaded polypropylene composite and the reinforcing fibre length was 2 mm. For reinforcing fibre length 1 mm, 25% fibre loaded PP composites have strength 32.983 MPa and 32.317 MPa for 25% jute fibre loaded PP composite with reinforcing fibre length 3 mm.

The introduction of the reinforcing fibre to the PP matrix enhances the tensile modulus significantly. The highest tensile modulus (3.206 GPa) was obtained with 40% jute fibre reinforced PP composite. A maximum of 163% increase of tensile modulus was observed. The tensile modulus enhancement continues with fibre reinforcement. Results indicate that the composite modulus was more dependent on fibre volume fraction and less dependent on fibre length than the composite strength does. In other words, the effect of mean fibre length on the young's modulus must be much smaller than that of fibre volume fraction. Otherwise, the combined effect of fibre volume fraction and mean fibre length would not lead to a dramatic increase in the composite tensile modulus. Decreasing trend of composite Young's Modulus was found when the reinforcing fibre length was increased. Longer fibres are more susceptible to breaking during fibre-fibre interaction, fibre-matrix interaction and fibre interaction with the surfaces of the processing equipment. This obviously causes a decrease in the modulus. But with the increasing number of ends as a result of the enhanced fibre breakage composites toughness was increased little bit. This ultimately results in a slight decrease in tensile modulus with the increasing reinforcing fibre length. Tensile modulus decreases from 3.206 GPa to 3.095 GPa, as the reinforcing fibre length increases from 1mm to 2 mm respectively for composite of jute (40 volume %) and polypropylene (60 volume %).

With the increase of fibre volume fraction, the composite failure strain decreases. The reduction in the elongation at break was caused by an embrittlement effect as the stiffness of the composites was improved when the fibre volume fraction was increased. The cause of this effect has been identified as matrix crack formation at the ends of the reinforcing fibres. Subsequently, as the strain was increased more cracks form progressively at the ends of shorter fibres. Initially this cracking can be accommodated by load transfer to adjacent fibres which "bridge" the cracked region. Final failure occurs when the extent of cracking across the weakest section of a specimen reaches a critical level when the surrounding fibres and matrix can no longer support the increasing load. The notched charpy impact energy was considerably enhanced by the addition of jute fibres to polypropylene. This indicates that the fibres play a dominant role in enhancing fracture energy. With the addition of further fibre i.e., with the increase of fibre volume fraction, impact strength start decreasing. However, the highest impact strength (51.49 J/m) was found for 8% jute fibre loaded PP composite of reinforcing fibre length 3 mm, among the three different reinforcing fibre length better impact strengths are exhibited by the composites comprised of reinforcing fibre length 1 mm. All the tensile properties showed a decreasing tendency with the increasing reinforcing fibre length. But results showed that with the increase of reinforcing fibre length the notched charpy impact energy increases (slightly). With the increase of the reinforcing fibre length fibre breakage during processing increases. Reduction in mean fibre length obviously cause a decrease in the impact strength but as with the increasing breakage number of fibre ends increases which actually enhance the toughness of the resulting composite. Composite of 8 volume % jute and 92 volume % polypropylene with fibre length 1 mm, 2 mm, 3 mm have impact strength 49.94 J/m, 46.3 J/m and 51.49 J/m respectively.

Highest specific tensile strength among all the fibres reinforced composites was 34.35 Pam^3/g, and obtained from composite with 8% jute fibre volume fraction with a mean reinforcing fibre length 1 mm and highest specific Young's modulus was 2.952 $KPam^3/g$ and obtained from composite with 40% (volume fraction) jute fibre and mean reinforcing fibre length 1 mm. Jute fibre reinforced PP composite density was found to be in the range 0.930 – 1.099 gm/cm^3.

An effective use of fibre strength is dependent on both the interfacial adhesion and the critical fibre length. Mean interfacial shear strength obtained for the investigating fibre-matrix combination was 9.7 ± 1.5 MPa. Using the Kelly-Tyson theory, the critical fibre length, defined as the minimum fibre length where the maximum allowable fibre tensile stress can be achieved, was roughly calculated as 1.012 ± 0.140 mm.

Theoretical tensile strength predicted using the modified rule of mixtures shows that, improving the fibres alignment, as well as increasing the fibre volume fraction in the composite could lead to great improvements in tensile strength. When comparing the theoretical tensile strength values to the actual composite tensile strength values, it can be seen that there are large differences between the theoretical and actual strengths. The injection-moulded composites were thought to have had an approximately planar random fibre configuration, caused by the linear flow of the molten composite into the mould. The composites would never actually be as strong as the theoretical values due to fibre damage incurred during composite processing and variations in interfacial bonding, but the theoretical values do provide a benchmark from which to judge the performance of the composites. The main reasons why the composites appeared to be so much weaker than the theoretical values especially in case of jute fibre reinforced polypropylene composites presumably due to their poor interfacial bonding.

The fibre efficiency factors, respectively, for composite strength (λ_σ) and composite modulus (λ_E) have been studied for short jute fibre reinforced polypropylene composite. Results showed that the fibre efficiency factors decrease with increasing fibre volume fraction and the factors for carbon and glass fibre reinforced polypropylene composites are higher than those for jute fibre reinforced PP composites. This was because the fibre efficiency factors decrease with decreasing mean fibre length or mean fibre aspect ratio. Mean fibre aspect ratio found for jute fibre is lower than that of carbon and glass fibre. Moreover, it can be seen that the fibre efficiency factor (λ_σ) for the strength was much lower than the fibre efficiency factor (λ_E) for the composite modulus. This was because the fibre efficiency factor (λ_σ) for the strength was dependent on both mean fibre length and critical fibre length while the mean fibre length decreases with the increasing fibre volume fraction. As the mean fibre length go below the critical fibre length, this will lead to a relatively low fibre efficiency factor (λ_σ) for the strength. On the other hand, the modulus is a property of material at low strain and is not very sensitive to the fibre-matrix interface or critical fibre length, so the fibre efficiency factor (λ_E) for the composite modulus was relatively high.

A comparison of the mechanical properties of other natural and manmade fibres (collected from literature) with jute fibre was presented in this work. The tensile strength of carbon fibre (manmade mineral fibre) was highest (3950 MPa) among all the fibres observed here. As the manmade fibres are much more compact in construction and have comparatively smoother surface their contribution to the tensile strength was much higher than those of the natural fibres. The tensile strength (786 MPa) of hemp fibre was higher than that of jute fibre (610 ± 198 MPa). The tensile modulus value for the carbon fibre was very high compared to the others. Here the jute fibres show the highest value of young's modulus among all the natural fibres studied.

Among the natural fibre reinforced composites, as long as the strength was considered the superiority goes to jute fibre reinforced PP composite. Though while comparing the tensile modulus jute reinforced PP shows a weaker performance than hemp fibre reinforced PP composite, it is better than other natural fibre reinforced PP composites. Though the manmade fibres reinforced PP composite shows superior mechanical properties, other factors such as cost, availability and environmental issues widen the prospect of jute fibre reinforced PP composites.

Form the above discussion it can be concluded that the opportunities for Bangladesh grown jute fibre reinforced composites is immense. Characterisation of the fibre and composite properties will encourage increased use in composites and hence capture an ever-growing market share, boost the agricultural based economy and help the world to make it more environmentally friendly.

It is concluded that, interfacial strength is apparently as important as the single fibre strength to improve overall composites strength. Ideally a strong interface with a strong single fibre is needed to optimise composites properties to its full potential. So further research is required for better interfacial fibre-matrix bonding and better surface treatment of fibres.

APPENDIX

MODIFICATION OF THE HAMMER OF THE UNIVERSAL IMPACT TESTING MACHINE:

The hammer of the available Universal Impact Testing Machine is shown in the figure.

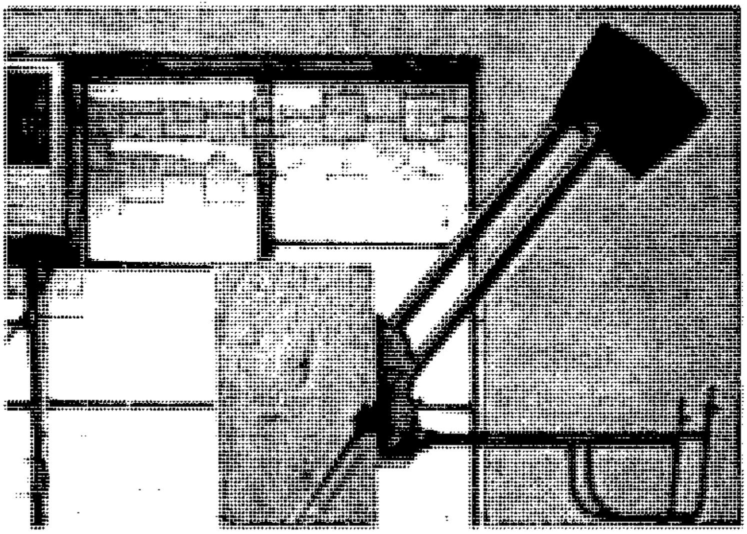


Figure A1: Original hammer of Universal Impact Testing Machine.

Specification:
Universal Impact Testing Machine
Type: TIT – 30
Pendulum type impact strength tester
Tokyo Testing Machine MFG. Co. Ltd.
Japan.

This machine was used to perform charpy impact test of tensile specimen of different metallic materials. The weight of the hammer of the machine was 3.72 kg and the length of the hammer was 0.815 m. The span between the supports was 40 mm. The striking energy of the hammer was too large for thermoplastics or composites based on thermoplastic matrix. So the modification is done on the hammer for the current research work. The hammer head was originally made of hard steel, with two large weights on both sides of the striking point. And there is long iron pipe which works as the handle of the hammer.

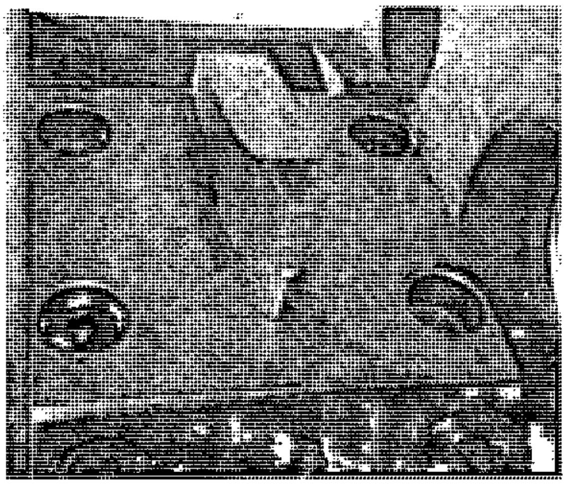


Figure A2: Striking tool of hammer head made of hard steel.

Modification:

- The heavy iron pipe handle is replaced by hollow pipe made of very light material, Aluminum.
- The portion of the hammer which contains the suspension point is replaced by wood.
- The weights of the hammer head were removed.
- The base of the hammer head made of hard steel was replaced by wood.
- The striking tool made of hard steel was remain unchanged and bolted to the wooden block which consist the base of the hammer head.

The modified hammer of the Universal Impact Testing Machine is shown in figure.

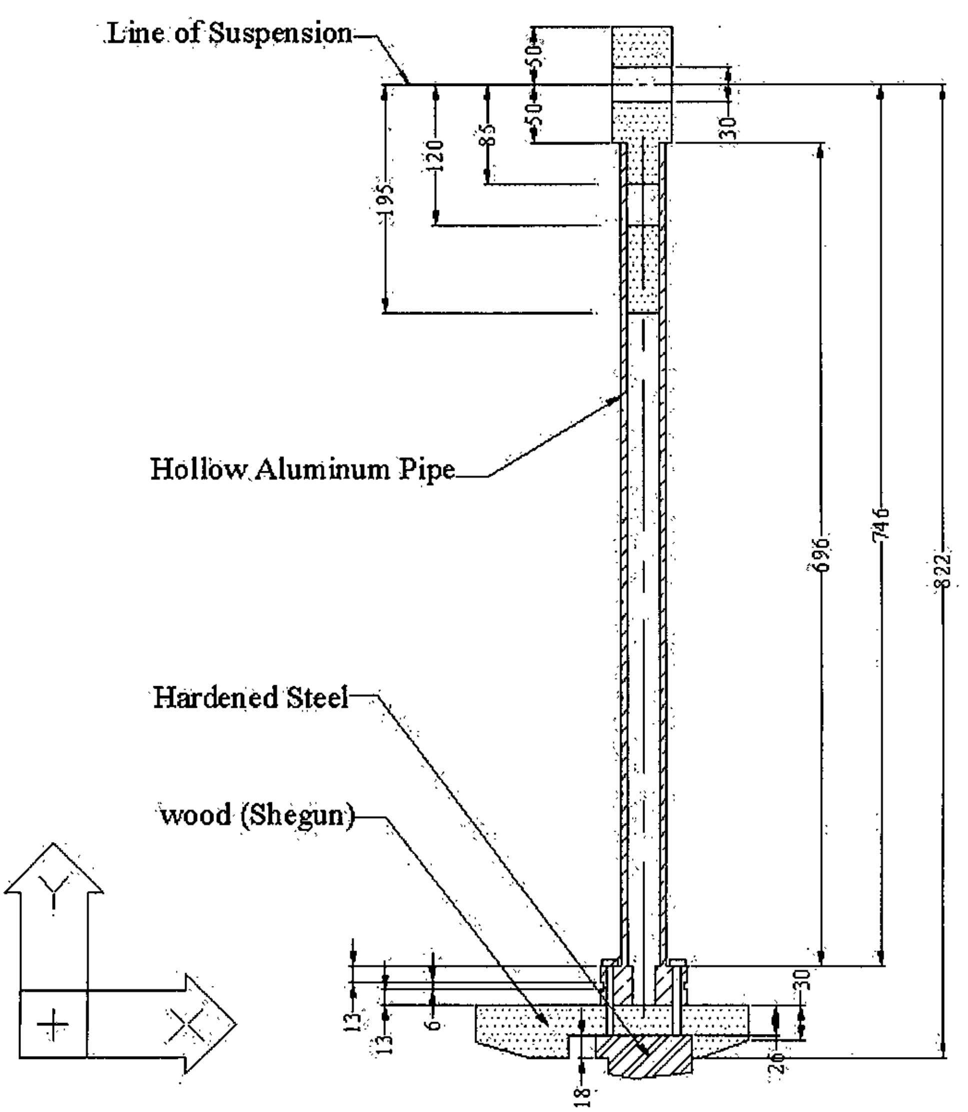


Figure A3: Sectional view of the modified hammer of the Universal Impact Testing Machine

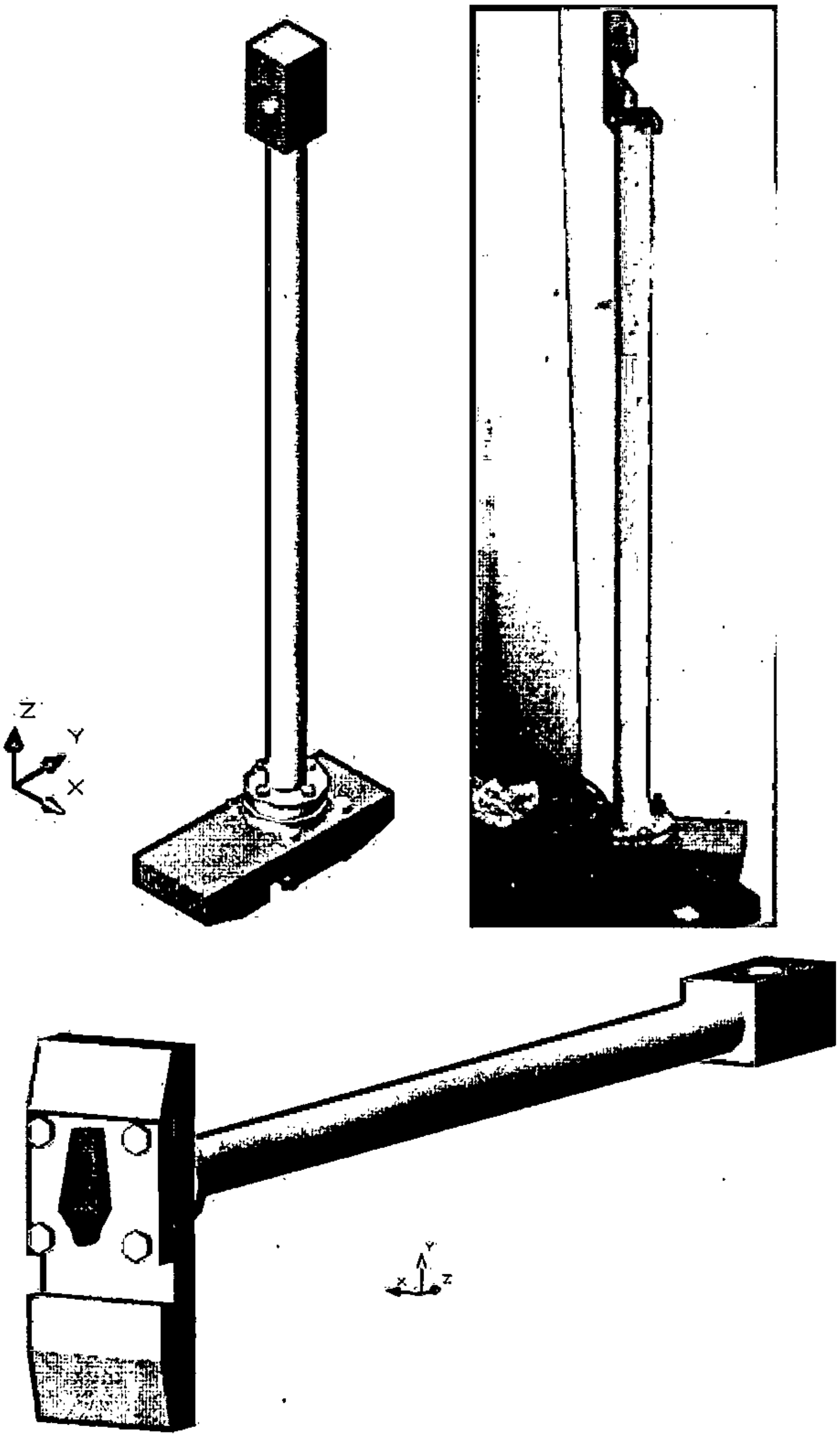
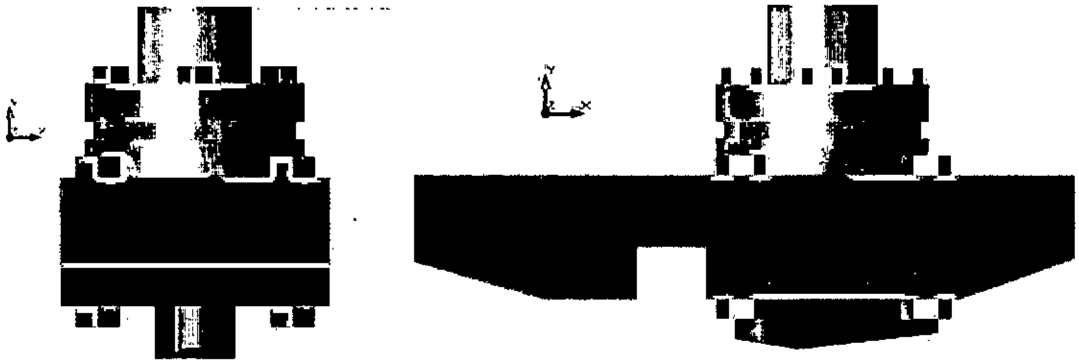


Figure A4: Pictorial view of the modified hammer.



(a) (b)

Figure A5: (a) front view of the modified hammer head, (b) side view of the modified hammer head.

Calculation for the measurement of the Centre of Gravity of the striker hammer:

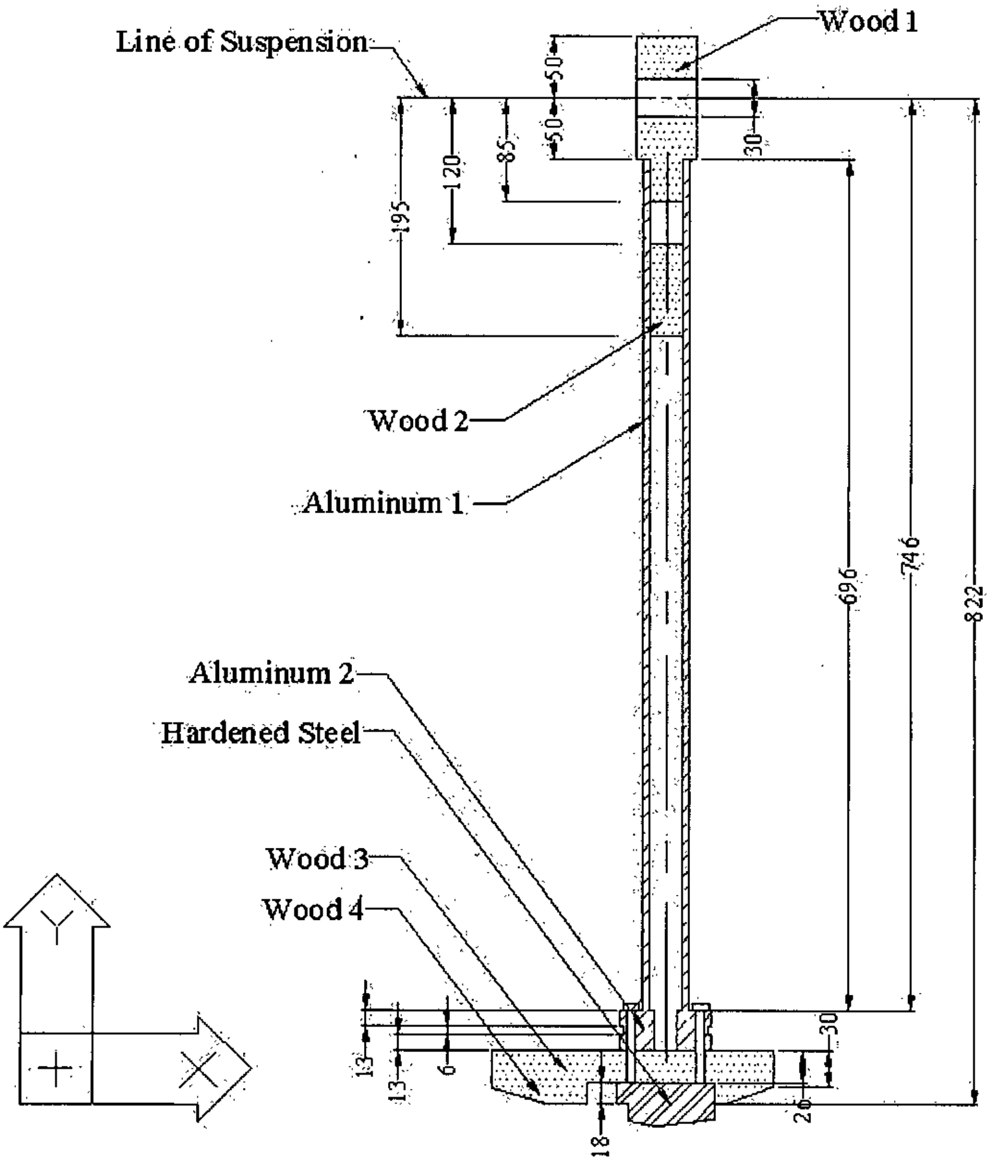


Figure A6: Sectional view of the hammer for the calculation of the centre of gravity.

Table A1: Calculation of centre of gravity of the striker hammer.

	Volume, V (m^3)	Density, ρ (kg/m^3)	Mass, m (kg)	$\bar{x}$ (m)	$\bar{x} \times m$
Wood 1	2.5300×10^{-4}	600	0.15180	0.0000	0.000000
Wood 2	6.8094×10^{-5}	600	0.04086	0.1500	0.006129
Aluminum 1	1.5653×10^{-4}	2600	0.40698	0.3891	0.158356
Aluminum 2	1.7158×10^{-4}	2600	0.44610	0.7665	0.341936
Wood 3	3.7917×10^{-4}	600	0.22570	0.7813	0.176339
Wood 4	1.7517×10^{-4}	600	0.10510	0.8021	0.084301
Hard Steel	1.5351×10^{-4}	7850	.1.20510	0.8036	0.968418
			$\sum(m) = 2.5816$		$\sum(\bar{x} \times m) =$ 1.735479

We know,

$$\bar{X} \times \sum(V) = \sum(\bar{x} \times V)$$

$$\bar{X} \times \sum(m) = \sum(\bar{x} \times m)$$

$$\Rightarrow \bar{X} = \frac{\sum(\bar{x} \times m)}{\sum(m)}$$

$$\Rightarrow \bar{X} = \frac{1.735479}{2.5816}$$

$$\Rightarrow \bar{X} = 0.672 \text{ m}$$

As center of gravity is 0.672m from the point of suspension. The effective hammer length, $L = 0.672$ m

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