Experimental Analyses and Characterization of Natural Fiber Reinforced Polymer Composites Produced by Injection Molding Method

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APPROVAL

The thesis titled “Experimental Analyses and Characterization of Natural Fiber Reinforced Polymer Composites Produced by Injection Molding Method”, submitted by Murtaja Hasan, Student ID: 16MME025P, Session: 2017-2018, has been accepted as satisfactory in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering on May 2025.

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ABSTRACT

Natural fibers have been used as reinforcement in composite development over synthetic fiber in the recent years due to the biodegradability, sustainability, availability, recyclability and clean environment. This study examines the prospect of jute fiber using as reinforcement in High-Density Polyethylene (HDPE) composites. Three different fiber weight fractions of 5%, 10% and 20% have been considered and termed as HDPEDJ-5, HDPEDJ-10, and HDPEDJ-20, correspondingly. Jute fiber was chemically treated as a part of the surface modification using 5% NaOH to adhere the bonding between reinforcement and matrix. Injection molding technique has been employed to prepare the samples as per the ASTM standards. The effect of the amount of fiber on composite performance was investigated through tensile strength, impact strength and hardness. In mechanical characterization, the HDPEDJ-10 sample provided better results by showing 25.5 MPa of tensile strength and 3.15 kJ/m^2 of impact strength, whereas HDPEDJ-5 sample exhibited maximum Rockwell hardness of 90.9 RHB. It was observed from the data that the mechanical properties of the material improved as the content of jute fiber increased, which posits this eco-friendly composite as a potential candidate for industrial usage.

সার-সংক্ষেপ

স্থায়িত্ব, প্রাপ্যতা, ও পুনর্ব্যবহারযোগ্যতার কারণে সাম্প্রতিক বছরগুলিতে কম্পোজিট ম্যাটেরিয়ালস প্রস্তুতকরনে কৃত্রিম তন্তুর তুলনায় প্রাকৃতিক তন্তু অধিক পরিমানে ব্যবহৃত হচ্ছে। এই গবেষণায় উচ্চ-ঘনত্ব পলিইথিলিন (HDPE) যৌগের শক্তিবৃদ্ধিকরণের উপাদান হিসেবে পাট তন্তু ব্যবহারের সম্ভাবনা পরীক্ষা করা হয়েছে । তিনটি ভিন্ন ফাইবার ওজন ভগ্নাংশ, যেমন 5%, 10% এবং 20% বিবেচনা করা হয়েছে এবং যথাক্রমে HDPEDJ-5, HDPEDJ-10, এবং HDPEDJ-20 হিসাবে অভিহিত করা হয়েছে। শক্তিবৃদ্ধি এবং ম্যাট্রিক্সের মধ্যে বন্ধন সুদৃঢ়করণের জন্য 5% NaOH ব্যবহার করে পৃষ্ঠ পরিবর্তনের অংশ হিসাবে পাট তন্তুকে রাসায়নিকভাবে ট্রিটমেন্ট করা হয়েছিল । নমুনা প্রস্তুত করার জন্য ইনজেকশন ছাঁচনির্মাণ কৌশল ব্যবহার করা হয়েছে এবং নমুনাগুলি ASTM মান অনুযায়ী প্রস্তুত করা হয়েছে। প্রসার্য শক্তি, প্রভাব শক্তি এবং কঠোরতার মাধ্যমে যৌগিক কর্মক্ষমতার উপর তন্তুর পরিমাণের প্রভাব পরীক্ষা করা হয়েছিল। যান্ত্রিক বৈশিষ্ট্যায়নে, HDPEDJ-10 নমুনাটি 25.5 MPa প্রসার্য শক্তি এবং 3.15 kJ/m^2 প্রভাব শক্তি দেখিয়ে ভালো ফলাফল প্রদান করেছে, যেখানে HDPEDJ-5 নমুনাটি সর্বাধিক 90.9 রকওয়েল কঠোরতা প্রদর্শন করেছে। তথ্য থেকে দেখা গেছে যে, পাটের আঁশের পরিমাণ বৃদ্ধির সাথে সাথে উপাদানের যান্ত্রিক বৈশিষ্ট্যগুলি উন্নত হয়েছে, যা এই পরিবেশ-বান্ধব যৌগিকটিকে শিল্প ব্যবহারের জন্য একটি সম্ভাব্য প্রার্থী হিসাবে তুলে ধরে।

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Chapter-1
Introduction

1.1 INTRODUCTON

A composite is an item created by blending together multiple distinct materials, resulting in something distinct from its individual components. In recent years, composite materials have become widely utilized due to their favorable attributes, such as being low in weight, durable, and environmentally sustainable in specific applications. Composites strengthened with fibers are especially used in intricate and load-sensitive structures. The mechanical behavior of polymer-based composites is strongly affected by the amount, type, size, and orientation of the reinforcing fibers. In fiber-reinforced plastics, a polymer matrix forms the base, which is enhanced with various fiber materials. These advanced materials provide multiple advantages, including exceptional mechanical strength and rigidity relative to their weight, excellent physical characteristics, flexible design potential, and a relatively simple manufacturing process.

1.2 BACKGROUND OF THE STUDY

The base structure secures and supports the fiber-based reinforcements, resists crack propagation and degradation, and enhances inter-laminar shear strength in composite materials. Various matrix materials could be used to manufacture composites, which are categorized primarily as thermosets or thermoplastics.

Thermoset polymers such as epoxy, phenolic, polyurethane, polyester, and silicone, with a chemical reaction on heating or curing, create hard, interconnected networks which are permanently set and cannot be reshaped when reheated. Unlike thermoplastics such as polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polyethylene terephthalate (PET) and polyamide (PA) which can be remelted or reshaped, enabling them to be recycled (due to their properties remaining largely intact), and can be adjusted to meet a number of applications.

Polyethylene comprises low-density polyethylene (LDPE) and high-density polyethylene (HDPE) where HDPE is typically found in the construction of plastic bottles, pipelines,

and geo-membranes, while LDPE accounts for a large proportion of materials used in packaging.

Fibers in composites are classified as natural or synthetic. Natural fibers derive from botanical, zoological, or geological origins, whereas synthetic fibers are produced through chemical processes.

Cellulose, protein fibers, and mineral fibers are natural fibers: plant fibers such as cotton, jute, sisal, and hemp; animal fibers, for example, wool, and silk; and mineral fibers such as asbestos and fiberglass. Petrochemical-derived synthetic fibers include polyester, nylon and acrylic.

Natural fibers often require chemical or physical surface treatment to improve bonding with the matrix material. This involves treating fiber surfaces to remove contaminants or adjust surface properties through chemical processes like acid or alkali treatment, as well as physical techniques like plasma or corona treatment.

The ultimate characteristics of fiber-reinforced composites (FRCs) are significantly affected by the chosen manufacturing techniques. Methods like injection molding, pultrusion, extrusion, compression molding, resin transfer molding (RTM), hand lay-up, and filament winding each have their own unique benefits and limitations. Depending on the desired component geometry, production volume, cost and mechanical properties required, each processing technique has a different level of preference.

Following this upsets the mechanical process that won't affect the composite's performance, thus they have to be given paramount importance to obtain results with consistency and the composite will be of high quality. While the choice of polymer matrix, fibers, surface treatments, and processing techniques all contribute to customizing fiber-reinforced composites, the matrix material choice is dependent on its bonding ability, stress transfer, chemical resistance, environmental acceptability, and thermal stability needed for end-use applications.

Driven by environmental considerations, numerous researchers have turned their attention to advancing composite reinforcements using natural fibers, which offer several benefits compared to traditional glass and carbon fibers. Recently, sustainable, reusable, and eco-degradable fibers like flax, hemp, jute, sisal, kenaf, coir, and banana have found uses in various industries due to their potential to lower carbon dioxide emissions.

Natural fibers are also nonirritating to skin and lung, safer to handle and less abrasive to machinery. Composites made from natural fibers are more light in weight and offer greater stiffness compared to those reinforced with glass fibers, making them not only more favorable for certain applications although being easier on the environment.

Numerous studies have focused on improving the mechanical performance of natural fiber-reinforced composites and exploring their practical uses. To promote better bonding among the fibers, substances such as starch, phenol, and natural resins like latex have been incorporated, but scientists continue to re-engineer them into stronger and more durable composites that can work with lesser-known thermoplastic polymers (commonly polyolefins like polypropylene and polyethylene) into the end-plastic use the same as glass-fiber reinforced plastics.

The strategies include a search for ideal combinations of natural fibers, polymers, and methods of processing that contribute to composites with improved mechanical properties.

The literature review makes it evident that HDPE composites incorporated with jute fibers, prepared by using the injection molding technique has a lot of scope for research.

1.3 OBJECTIVES

Overall objective of this study is to characterize the mechanical properties of the Jute fiber reinforced HDPE composite.

The specific objectives are listed as follows:

- To fabricate the jute fiber reinforced HDPE composite using injection molding technique.
- To investigate the mechanical properties, i.e., tensile strength, impact strength, and hardness of the fabricated samples.
- To conduct a comparative analysis of the mechanical properties of other samples with different matrix and fiber.

1.4 SCOPE AND LIMITATION OF THE STUDY

The global utilization of thermoplastic polymers is steadily rising. Polyethylene is among the most commonly used synthetic polymers in the plastics industry. This thesis focuses

on examining the characteristics of natural fiber composites with respect to their injection molded counterparts and to determine how these properties relate to those of traditional thermoplastics. Natural bio composite polymer materials, made by combining natural fibers with thermoplastic materials, have more favorable technical and mechanical properties than common thermoplastic materials and are environmentally friendly.

There is a huge opportunity for these composites in automotive and construction industry. Among the various advantages, natural fibers also have some limitations as composite materials. These include low compatibility of the hydrophobic polymer matrix with hydrophilic fibers, leading to poor interfaces and the returned effect on the composite's mechanical performance.

Natural fibers already have some disadvantages, such as being hydrophilic and poor thermal stabilities. Because of the phenomenon of swelling, dimensional instability, and degradation of fiber along with the weakening of the fiber-matrix interface, water absorption in the composites is one of the major areas of concern.

Issues such as expansion, structural inconsistency, fiber deterioration, and weakening of the bond between fiber and matrix contribute to concerns in composite materials. To address these challenges, surface treatments of natural fibers—such as alkali treatment, silane treatment, isocyanate treatment, latex coating, permanganate treatment, acetylation, and UV-induced monomer grafting—have been applied, showing different degrees of effectiveness in enhancing fiber durability and the bonding quality between fiber and matrix in natural fiber composites.

1.5 METHODOLOGY OF THE RESEARCH/STUDY

The outline of this study is presented in below Figure 1.1 as a flowchart:

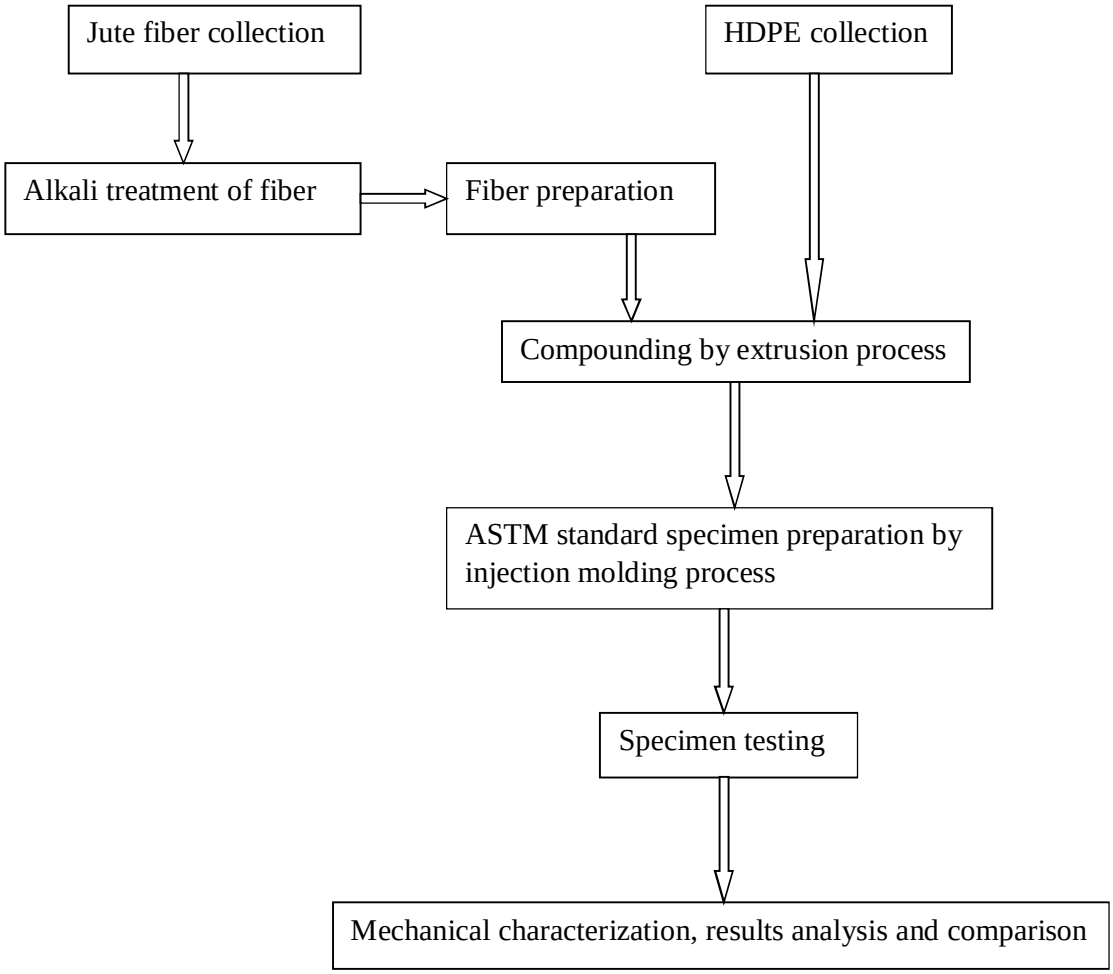


Figure 1.1: Methodology of research work in a flow chart

1.6 ORGANIZATION OF THE THESIS/THESIS OUTLINE

This report is structured in a way that follows a specific workflow, which is outlined as follows:

Chapter 2 gives descriptions of multiple varieties of matrix materials, fibers, and composites. It also describes the process of treating natural fiber surfaces. Moreover, it offers a summary of earlier research on natural fiber polymer composites. And finally, it compares the mechanical behaviour of natural fiber composite materials that are found in earlier studies.

Chapter 3 explains the resources and methodologies applied in this thesis. It describes how jute fiber & HDPE were collected. It also explains the processes which were used

for fiber treatment and compounding the jute fiber with HDPE. This chapter ends by describing the production of composite by injection molding method.

Chapter 4 explicates the data collection process from the physical experiments conducted in this study. The physical experiments include tests of mechanical properties such as tensile test, hardness test, and impact test. The chapter also expands on the equations and explanations associated with these tests.

Chapter 5 illustrates all of the experimental results, which are a crucial part of the thesis. The findings from the mechanical characterization tests are thoroughly discussed in this chapter. The chapter also presents an analysis comparing the behavior of composites containing different fiber loadings to the properties of HDPE.

In the final chapter (Chapter 6), the research conclusions are drawn including a summary of the experiments measures and recommendations for future work in this domain.

Chapter 2

Literature Review

2.1 GENERAL

This section offers an elaborate insight into the present scenario from research publications and recent findings in so far as research in natural fiber composites.

It also provides insights into the mechanical characteristics of natural fiber composites. By adjusting their composition, structure, and processing parameters, the features of these composites can be tailored as needed. In contrast, the presence of these materials remains a hopeful research direction that can be used to replace materials that are not renewable and not biodegradable.

2.2 MATRIX MATERIAL

In a composite, the matrix is the substance that when mixed with a reinforcing material, generally fibers, creates a composite. Its fundamental purpose is to precisely align the reinforcement fibers in order to evenly distribute any desired loads across the fibers.

It can also prevent the cracks to propagate and multidirectional damages. Further, it improves the inter laminar shear strength of the composite. Selection of the matrix material is based not only on bonding to the reinforcing material and transferring stresses from the matrix to the reinforcing materials, but also on chemical resistance, environmental-friendly properties, thermal properties, etc.

Different applications may have different performance requirements, so different matrix materials can be selected for different applications.

2.2.1 Polymers & Their Classifications

Composite materials vary greatly matrix materials. They are categorized into thermosets and thermoplastics based on the polymer matrix. This particular polymer is chosen for the performance aspects of the composite material. For example, if the fiber-reinforced material is needed to resist chemicals and higher temperature levels, then thermoset matrices will better serve the purpose than thermoplastics. On the other hand, If a

composite with excellent damage resistance and ease of recycling is needed, thermoplastic matrix may be desired [1].

2.2.2 Thermoset Polymers

Thermoset polymers are type of polymers that, as they cure they undergo a chemical reaction to form a hard, rigid, and permanently cross-linked structure when they are heated or cured. Once cured, they cannot be melted or remold by heating. These cross-links create a three-dimensional network of strong covalent bonds, imparting thermoset (TS) polymers with their distinctive characteristics of high strength, and rigidity, heat resistance, its chemical stability, dimensional stability and long lasting durability.

Some common types of thermosets include:

1) Epoxy

Epoxy is a thermosetting polymer, consisting of a resin and a hardener, which is created through a chemical reaction. Epoxy resins, as a class, are usually created by reaction of epichlorohydrin with bisphenol A or comparable compound.

The resulting cured polymer is a highly cross-linked structure featuring strong adhesion, chemical resistance, and mechanical properties.

It is used as coatings, adhesives, and composites, which are part of epoxy. There are known for its great bonding strength, which makes it widely used for bonding metals, plastics, and other materials. Epoxy coatings are utilized as well to offer a line of defense to corrosion, abrasion and chemical attacks.

Moreover, epoxy composites differ from other types of plastics as they are used in many industries that require high strength and stiffness, such as aerospace and automotive. Epoxy is likewise employed in the development industry like a binder for concrete and being a coating for flooring and partitions.

Epoxy is a type of resin that can be designed for a specific performance criteria. A variety of epoxy formulations can be used in accordance with the application requirement e.g. high-temperature resistant, low viscosity, electrically conductive epoxies.

2) Phenolic

The phenolic polymer results from the chemical reaction of phenol with formaldehyde. They are, perhaps most well-known today, as their applications range widely from a binder in a treatment for human body implants to use as a fire retardant.

Molded parts, laminates, and coatings are some of the most common applications of phenolic polymers. Its applications include adhesives, insulation materials, and carbon-fiber-reinforced polymer (CFRP) production.

Nevertheless, phenolic polymers have a tendency to become brittle and are not particularly resistant to impact, which can limit their use in certain applications.

3) Polyurethane

Polyurethanes are thermoset polymers produced from the reaction network between isocyanates and polyols. These polymers are widely used, ranging from foams, coatings and adhesives to elastomers. Another application of polyol is in the manufacturing of polyurethane foam, widely used in the furniture and bedding industry for its excellent resilience and cushioning properties. These polymers are utilized in their coatings to protect against corrosion, abrasion, and chemical attack, while polyurethane adhesives are used for bonding plastics, metals, and other materials. Many applications require elastomers made from these polymers to provide excellent abrasion resistance and long-lasting performance; as a result, such elastomers are extensively utilized in hundreds of automotive and industrial applications. They are also common for use in building wheels, rollers, and other industrial parts. Yet these polymers are susceptible to moisture and UV light, which can undermine their performance over time.

Also, isocyanates, a component used to make polyurethane polymers, can be toxic if not prudentlly handled.

4) Polyester

Polyester polymers, the most common of which is polyethylene terephthalate (PET), are used to manufacture fibers, films, and packaging materials. Polyester polymers exhibit excellent physical performance, offering superior toughness, rigidity, and dimensional stability. They are known for their outstanding resistance to chemicals, moisture and UV light, and as such are used in a diverse array of applications.

Polyester is one such example, commonly employed in the textile sector for manufacturing carpets, upholstery and clothing, packaging, electrical insulation, and magnetic tapes all utilize polyester films, for example. Polyester resins can also be found in coatings, adhesives and composites.

5) Silicone

Elastomers based on silicone polymers are being used to manufacture gaskets, seals and other products requiring high flexibility and durability.

Polymers can also serve as the base material in everything from adhesives to coatings to mold-making materials. One of most significant properties of silicone polymers is high-temperature resistance. In addition, silicone polymers have excellent electrical insulation capabilities, which renders them ideal for application within the electrical and electronics sectors. They are also biocompatible, which enables their utilization in biomedical applications (hydrogels, implants, prostheses, etc.).

These polymers can be more expensive than other kinds of polymers and, consequently, prohibit their use in some fields.

They have lower tensile strength and tear resistance than most of the other elastomers, which limits their use at higher mechanical strength applications.

2.2.3 Thermoplastic Polymers

Thermoplastics, in contrast, can be repeatedly heated and reshaped into new products without experiencing a substantial loss in their properties. This property makes them very reusable and recyclable materials.

Thermoplastic polymers consist of long polymer chains connected by comparatively mild intermolecular attractions such as Van der Waals forces. Weak intermolecular forces allow the chains to slide past one another when heated, which allows them to be molded and reshaped.

As the thermoplastic material cools down, intermolecular forces reform which leads to the rigid framework. Thermoplastics exhibit a wide range of physical and mechanical characteristics, which can be tailored to suit particular uses.

Depending on factors like polymer molecular weight, chain branching, and the inclusion of specific additives, their characteristics can range from soft and flexible to hard and

rigid. As a result, thermoplastic polymers are adapted for diverse uses across industries such as automotive, aerospace, electronics, packaging, construction, and consumer goods.

They may be utilized in everything from simple household items to complex engineering components. Thermoplastics have a lot of benefits, but they do have some drawbacks. Unlike thermosetting polymers, their heat resistance might be lower, preventing them from being used at high temperatures.

Furthermore, some thermoplastics may be susceptible to creep (deformation under constant loading) or have limited resistance to certain solvents or UV light. That said, these drawbacks can often be mitigated using additives or simply by choosing the right thermoplastic for the job at hand.

Some of the common thermoplastics are polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polyethylene terephthalate (PET), and polyamide (PA) etc.

1) Polyethylene (PE)

Polyethylene is made up of extended ethylene chains; it may be high-density polyethylene (HDPE), low-density polyethylene (LDPE), or ultra-high-molecular-weight polyethylene (UHMWPE).

LDPE plastics are widely utilized for items like packaging material, whereas HDPE plastics are typically used for products including geometric membranes, plastic bottles, and pipes. Applications for UHMWPE include bulletproof vests, orthopedic implants, and mechanical applications owing to its superior strength and resilience.

Polyethylene can be fabricated easily with many methods including extrusion, injection molding, and blow molding. It is a commonly used material across industries including packaging, construction, automotive, healthcare, and more.

2) Polypropylene (PP)

Polypropylene (PP) is a polymer thermoplastic formed from long chain monomer propylene, available in several grades including homo polymer and copolymer grades.

The full form of the plastic is claimed to be used on a large way there are chips, packaging, automotive industry in construction and textiles. It is extensively employed in the packaging sector for items such as food containers, bottles, and films. In the automotive industry, it can be found in items such as fuel tanks, bumpers and interior trim.

In construction, it's used in pipes, roofing and insulation. It is a natural fiber used in the textile industry for fibers, fabrics and carpets. It can be shaped by various processes, such as injection molding, extrusion, blow molding, thermoforming, etc.

It's also widely praised for being exceptionally recyclable, so it's an environmentally friendly material option.

3) Polyvinyl Chloride (PVC)

PVC ranks among the most commonly used plastic materials and is produced through the polymerization of vinyl chloride monomers. As a thermoplastic, it can be repeatedly melted and reshaped without significant loss of quality. It is also resistant to many chemicals and can be made flame-retardant with the use of certain additives.

As a widely used polymer, it can be made as either (fully) rigid or flexible, enabling numerous applications. Rigid PVC is used in pipes, siding, window frames and many other building materials. Conversely, flexible PVC is widely used in applications including electrical cable insulation, inflatable products, and medical devices.

On the other hand, PVC has drawn flak over its potential effects on environment and human health. PVC can leak dangerous chemicals during its production and disposal, and some studies have associated PVC exposure with health problems like cancer, asthma and reproductive problems. This has led to initiatives to limit or prohibit the use of PVC in specific products and industries.

4) Polystyrene (PS)

Styrene monomer polymerizes to create the synthetic polymer polystyrene. It is a stiff, see-through, and low-weight plastic used widely in various common items, from food wrappers to one-use cups and plates, insulation materials as well as toys.

Polystyrene is made by suspension polymerization or bulk polymerization process. This material can be formed into different geometric forms using injection molding, extrusion, or thermoforming.

Although polystyrene is widely used in many practical applications, it is also non-biodegradable and can stay in natural surroundings for a very long time. It has been controversial because of its environmental effects and potential health hazards from styrene exposure.

2.3 FIBERS AND THEIR CLASSIFICATIONS

Fibers can be broadly categorized into two groups: natural and synthetic. Natural fibers are derived from sources such as plants, animals, or geological processes, whereas synthetic fibers are manufactured using chemical compounds and polymers.

Natural fibers are classified into three categories: plant-based fibers, animal-based fibers, and mineral-based fibers. Well known examples of plant fibers would be cotton, jute, sisal, and hemp. Such fibers are wool, silk, and mohair, to name a few. Mineral fibers are fibers derived from geological processes, and include asbestos and fiberglass.

Synthetic fibers are categorized into two types: regenerated fibers and fibers made from synthetic polymers. The raw material of these fibers is the cellulose of natural materials, but they have been processed in such a way so that they consequently become a new fiber. Regenerated fiber examples are rayon, modal and lyocell.

Unlike regenerated fibers, synthetic polymers are produced from petrochemical sources and include materials such as polyester, nylon, and acrylic.

Fibers are further classified based on physical characteristics like length, fineness, strength, and elasticity. These attributes determine their suitability for a range of uses, such as clothing, household textiles, and industrial fabrics.

2.3.1 Natural Fibers

Natural fibers are sourced from plants, animals, or geological processes and can be spun, woven or knitted into textile fabrics. Fiber from these can be used as clothing, furniture, and construction.

Cotton, wool, silk, linen, jute, sisal, hemp, and bamboo are some examples of natural fibers. Note: Each fiber has different quality and properties, based on which it is used. Cotton is soft and breathable, and hence is commonly used for clothing, whereas wool is warm and sturdy and therefore suitable for use in carpets and blankets.

Being renewable and biodegradable, natural fibers are a more sustainable substitute to synthetic fibers produced from petrochemicals. But just because their production process is eco-friendly doesn't mean that their production doesn't have environmental impacts.

Natural fibers are increasingly being utilized in replacement of synthetic fibers in an attempt to combat the fashion and textile industry's detrimental environmental impact.

2.3.2 Synthetic Fibers

Synthetic fibers, in contrast, are manufactured by man from petrochemicals, or other chemical compounds.

Polymers are formed during the process of polymerization, where small molecules click into long polymer chains. Having various shapes and sizes, synthetic fibers can be made and supplied for various applications.

Synthetic fibers include polyester, nylon, acrylic, and spandex. These fibers are known for being durable, strong, and resistant to wrinkles and shrinking. They are used in clothing, home textiles and industrial applications including tire cords, ropes and upholstery.

Synthetic fibers also have drawbacks, despite their many advantages. They are frequently non-biodegradable, unable to decompose easily in the ecosystem which may leads to pollution and waste. Some synthetics also can feel uncomfortable against the skin because they are not breathable and can retain moisture next to the skin.

While synthetic fibers have traditionally dominated the market, there has been a growing shift toward sustainable, natural, and environmentally friendly alternatives in recent years.

2.4 COMPOSITE MATERIALS

Composite materials are formed by combining two or more distinct substances with significantly different physical or chemical properties.

These constituent materials, when merged, create a new material with characteristics that differ from those of the individual components.

Composite materials are broadly classified according to their matrix type which can be polymeric, metallic, ceramic, etc.

A reinforcing material is used that can be fibers, particles, or flakes.

Composites are widely used across various industries, including aerospace, automotive, construction, sports gear, and medical devices. By definition, composite materials consist of multiple unique components, each with its own physical or chemical traits, resulting in a final product that exhibits enhanced performance compared to its separate elements. Figure 2.1 showed the classification of composite materials.

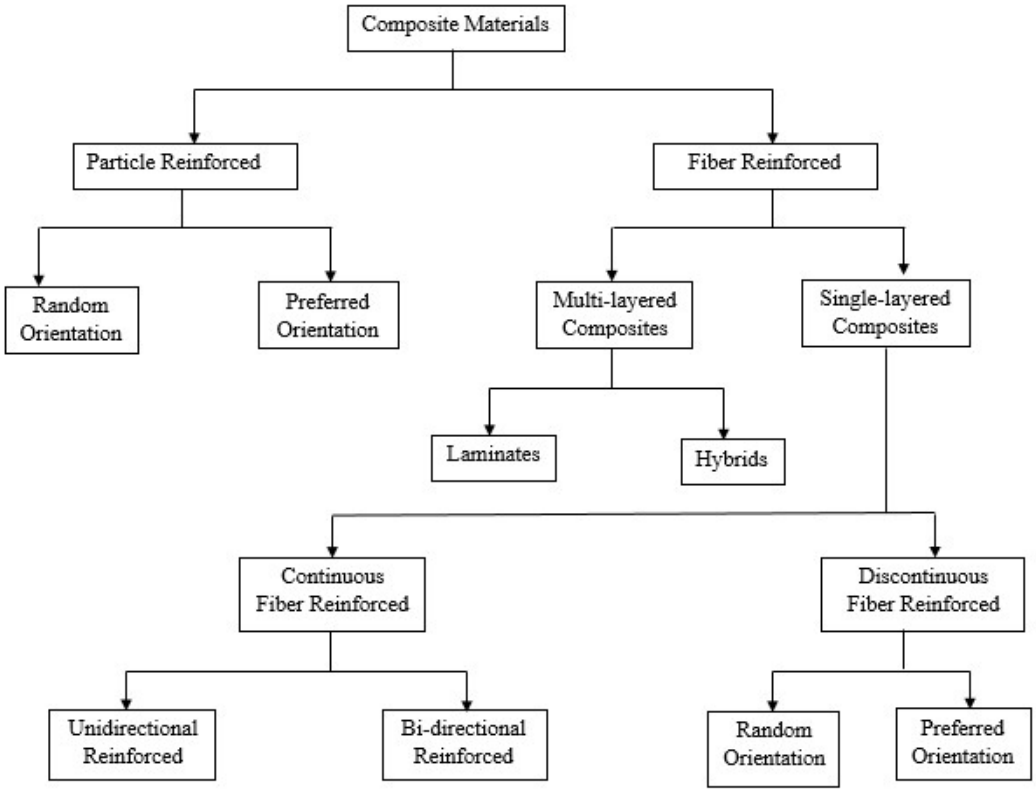


Figure 2.1: Classification of composite materials [2]

Composites are categorized based on the type of matrix material, the reinforcement used, and the overall composite structure. Here are some typical types:

2.4.1 Polymer Matrix Composites

Polymer Matrix Composites (PMCs) consist of a polymer base such as epoxy or polyester resin, reinforced with high-strength fibers or particles. The combination of the polymer matrix and the reinforcing phase results in a material with improved strength, stiffness, and overall performance compared to the unreinforced polymer.

A wide variety of fiber can be utilized for reinforcing PMC, including carbon fibers, glass fibers, and aramid fibers. It is strung along one or more directions (or orientations) in the direction of the fibers to maximize their strength and stiffness. Fibers are used in a polymer matrix material that is used to impregnate or injection into the fibers.

PMCs are widely used across various industries including aerospace, automotive, marine, and sporting goods. These composites are made by embedding reinforcing fibers like carbon, aramid, or glass into a polymer matrix such as epoxy resin.

PMC can however be brittle and sensitive to impact damage, and may undergo changes in physical properties under varying temperature and humidity. As such, PMC components must be crafted with careful attention to detail in their design and manufacturing processes to ensure reliability in the real world.

2.4.2 Metal Matrix Composites

Metal Matrix Composites (MMCs) feature a metal base typically aluminum, magnesium, or titanium reinforced with strong fibers, particles, or whiskers to enhance mechanical properties. The reinforcing material is generally crystalline materials like silicon carbide or alumina, or carbon-based materials (like graphite fibers).

MMC materials provide very good properties like high strength, stiffness, and also high thermal conductivity. They also exhibit good wear resistance and thermal stability. MMCs find uses in numerous sectors, from electronic parts to aerospace and automotive.

This can be achieved through various methods of MMC manufacturing processes, wherein the desired shape of the reinforcement material is dispersed in the metallic form. This method is used by MMCs in their fabrications to ensure their final metal integrities.

Variations in type and concentration of reinforcing materials, as well as the metal matrix material itself allow MMC materials to be tailored and customized for specific

applications. Nevertheless, MMCs can be costly to produce and also notoriously difficult to machine because of their hardness and wear resistance.

2.4.3 Ceramic Matrix Composites

Ceramic Matrix Composites (CMCs) are composed of a ceramic base such as silicon carbide, aluminum oxide, or zirconia, strengthened with high-performance fibers or particles. The reinforcement is composed either of ceramic fibers, carbon fibers or metallic fibers.

CMCs offer excellent characteristics including high strength, rigidity, and thermal stability. They also demonstrate strong wear and heat resistance, making them suitable for demanding environments. These materials are employed in automotive, aerospace, and energy sector applications.

The specific components are dispersed, allowing the material to be processed, creating the desired shape. Chemical vapor infiltration (CVI) is currently the most commonly employed manufacturing technique for CMCs, whereby the reinforcing material is infiltrated with a gaseous ceramic material to form the substantial material.

Different types and amounts of reinforcing material and various kinds of ceramic matrix material can be used in CMC materials, allowing for design and optimization for specific applications. CMCs can be costly to turn out, though, and they also can be brittle and susceptible to impact damage. Thus, CMC components need to be carefully designed and made to assure reliability and representativeness during real-world service conditions.

2.4.4 Carbon/Carbon Composites

A carbon/carbon composites is composites consisting of carbon fibers or carbon fabrics reinforced with carbon matrixes.

Carbon fibers or the carbon fabric make up the structure, and the carbon matrix material fastens the fibers and reinforces them. C/C composites possess many attractive features, including high specific strength, dimensional stability, good thermal and oxidation resistance, low thermal expansion, and high wear resistance.

C/C composites are commonly processed by several cycles of carbonization and densification. During carbonization, the carbon fibers or fabric are heated to elevated

temperatures (2000°C — 3000°C) in a non-reactive environment to eliminate elements other than carbon and raise the carbon proportion in the material.

This process uses a carbon matrix material, woven in a fabric, and the entire material is subjected to an elevated temperature within a regulated environment to increase the density and strength of the material.

Carbon–carbon (C/C) composites are typically utilized in critical applications such as aircraft braking systems, rocket nozzles, and thermal protection structures, as well as in high-performance sporting equipment including golf club heads and bicycle frames. These materials are widely employed in the aerospace, defense, and advanced sports sectors due to their exceptional mechanical properties and structural versatility. The inherent adaptability of C/C composites enables the attainment of superior strength and durability, rendering them highly suitable for use in environments demanding high-performance materials.

However, C/C composites are relatively expensive to manufacture compared to other materials, and their mechanical properties can also be influenced by the fiber orientation, as well as the manufacturing technique. Thus, the reliability and performance of C/C composite components depend largely on how they were designed and manufactured.

2.4.5 Natural Fiber Composites

Natural cellulose fibers (fibers obtained from plants) are used in a variety of bio-composites and NFC (natural fiber composites) can be reinforced with a polymer matrix (thermoplastic or thermosetting) such as flax, hemp, jute, sisal, kenaf, and bamboo.

It has to be built on sustainable products, with NFC, which is a whole new form of composite material that's made from renewable resources and biodegradable at the end of it. They also exhibit favorable mechanical properties including high strength, stiffness, and impact resistance, and can be produced with economical processing methods.

NFC has a complex manufacturing process, where first, the natural fibers are prepared, then combined with the matrix material to produce a composite material. Fibers can be woven, knitted or pressed into specific shapes and structures.

This matrix material is added to the fibers through impregnation or injection to create a strong and homogenous material.

There are various NFC materials available for diverse plans from various industries. They may be used for internal parts of cars, furniture, and packaging materials. NFCs, however, are sensitive to moisture and temperature changes, and environmental factors can have an impact on the mechanical performance of NFCs.

2.4.6 Metal-Polymer Composites

Metal polymer composite (MPC) is a type of composite material made of a metal matrix, such as aluminum or magnesium, reinforced with polymer particles or fibers. The polymer may be introduced to the metal matrix in any form (powder, granules, or fibers).

MPCs represent a distinct category of biocomposite materials that integrate the properties of a high-strength stiffness, low-density, good damping properties, and wear-resistant. Common uses of silver include automotive and aerospace components, bearings, and electrical contacts.

MPC manufacturing process includes mixing polymer particles or fibers and metal matrix material and processing the mixture into designed shape.

Processing the most common manufacturing method for MPCs in powder metallurgy by adding the reinforcing material to disperse metal powders and then compacting and sintering it to obtain the final material.

They can be tailored and optimized for specific applications by adjustment of the type and volume fraction of the reinforcing material and the metal matrix material.

MPCs are expensive to manufacture, however, and can also be susceptible to thermal and mechanical stresses. As such, designing and manufacturing the components of an MPC needs to be done in a way that they remain reliable and durable in real-world environments.

2.4.7 Sandwitch Composites

The sandwich composite structure consists of a pair of thin external layers (face sheets) surrounding a thicker piece of core material. The core material can be a low-density material like foam, honeycomb, or balsa wood, while the face sheets are usually high-strength composites like carbon fiber or fiberglass. Sandwich composites are manufactured by bonding the core material between two face sheets with the use of

adhesive bonding, mechanical fastening, or vacuum infusion. Commonly, the core material is shaped as per requirement and the face sheets are pre-formed as per alignment and fit. The sandwich structure has a distinct combination of high stiffness, strength and lightweight which is applied extensively.

By manipulating the kinds of face sheets and core material, sandwich composites can be adapted and optimized for certain applications. Sandwich composites are widely used in the aerospace, automotive, marine, and construction sectors.

It should be noted that not all these properties can be varied independently, so the design process can be complex.

2.5 METHODS FOR SURFACE MODIFICATION OF NATURAL FIBERS

Natural fibers are optimized for coherence with the composite material matrix through the process of surface modification. Natural fibers have a complex surface structure that can include waxes, oils, and lignin, making it challenging to bond them effectively with the very fiber matrix material which they will be embedded with.

Surface modification refers to the treatment of natural fiber surfaces to eliminate or alter surface impurities, thereby improving their interfacial bonding with the matrix material.

Common techniques include chemical treatments (such as acid or alkali processing) and physical methods (e.g., plasma or corona discharge treatments).

These modifications enhance the mechanical properties of fiber-reinforced composites, such as tensile, flexural, and impact strength.

Additionally, they improve the material's resistance to moisture, heat, and various environmental conditions.

The surface modification of natural fibers is an option that can be tailored to particular applications, and matrix materials, and can also be helpful in improving characteristics such as performance and durability of the composite material made. As such, surface modification is considered a critical initial step in the fabrication of natural fiber-reinforced composite materials.

2.5.1 Physical Methods

Physical methods are physical treatments, which adjust the surface of fibers; no chemical agents are used.

Some of the most common physical methods are as follows:

Plasma treatment: This method implicates uncovering the natural fibers to a low-temperature plasma, resulting in surface reactions that can modify the surface chemistry and create functional groups. Plasma treatment can progress the wettability and bonding of the fibers to the matrix material.

Ultraviolet (UV) treatment: UV treatment is a method that exposes the natural fibers to ultraviolet radiation; this method has the ability to break down surface contaminants and create reactive sites on the fiber surface. This UV treatment enhances the bonding of the fibers with the matrix material.

Corona Treatment: In this approach, the natural fibers are subjected to a high-voltage electrical discharge that results in the production of reactive species that alter the surface chemistry of the fibers. Corona treatment enhances fiber wettability and adhesion to the matrix material.

Mechanical treatment: This technique can be implemented using physical processes such as grinding or sanding, which aid in eliminating surface impurities from the fibers and producing a rougher texture that improves bonding with the matrix material.

While physical treatments are generally milder compared to chemical methods for modifying the surface of natural fibers, their impact may sometimes be inadequate in terms of enhancing the mechanical and physical properties of the composite.

Still, they are not as efficient as chemical reactions for generating functional groups on fiber surface.

2.5.2 Chemical Methods

Several chemical techniques have been documented for modifying the surface of natural fibers.

Here are some examples:

Acetylation: The natural fibers are treated with acetic anhydride or acetyl chloride to obtain acetyl functional groups attached to the outer layer of the fibers. This enhances the fiber's suitability with some polymers and enhances its hydrophobicity.

Silane treatment: The natural fibers are treated with the organosilane compounds to introduce some silane groups at the fiber surface. It improves the adhesion of the fiber to the polymer and hydrophobicity.

Alkali treatment: This treatment usually involves an alkaline solution, such as sodium hydroxide (NaOH) or potassium hydroxide (KOH), being applied to the fibers to change their surface characteristics. The process consists of immersing the fibers in an alkaline solution for a specific duration, which may range from several minutes to a few hours.

The hemicellulose and lignin components of the fibers are disentangled and cancelled via the alkaline solution, which purifies with fibers and increases their area of surface. This helps to improve adhesion as there is a greater surface area for the fibers to bond with surrounding material.

Alkali treatment might also create hydroxyl functional groups at the surface of fiber components, thus making the fiber more polar and able to interact with polar material (ex: polar polymers, water and many others). This gives rise to the higher surface polarity, leads to increased wettability of the fiber and sufficient absorption of any liquid can thus be achieved.

Natural fibers such as cotton, flax, hemp, jute, and sisal can have their surface properties modified through an alkali treatment. For a particular application, surface properties may be tailored specifically for a range of treatment conditions, including alkaline solution concentration, treatment time, and pH.

Benzoylation: Here the natural fibers are reacted with benzoyl chloride to introduce benzoyl groups on the fiber surface. This makes the fiber more compatible with some polymers and enhances its hydrophobicity.

Grafting: The technique entails the attachment of polymer chains onto the surface of natural fibers. Several polymerization strategies, such as free radical polymerization, ATRP, and RAFT, are applicable for this purpose. Grafting polymers onto fibers enhances fiber–matrix compatibility, leading to improved mechanical performance of the composite material.

2.6 PROCESSING METHODS FOR FIBER REINFORCED COMPOSITES

Manufacturing techniques have a major influence on the final properties and performance capabilities of fiber-reinforced composites (FRCs). The production of fiber-reinforced composites makes utilization of a broad range of processing methods, each of which comes with its own individual set of advantages and disadvantages. The intended component geometry, production volume, cost limits, and required mechanical qualities all have a role in the decision of which processing method to use. In order to make composites with consistent and desirable qualities, it is vital to pay strict attention to the process parameters as well as quality control during the manufacturing process, regardless of the method that is used.

2.6.1 Injection Molding

Injection molding involves forcing molten rubber or plastic into a mold to form specific shapes. This is achieved by heating the material above its melting temperature, the solid polymer is more easily transformed into a molten fluid that has a viscosity that is more manageable. To determine the shape of the item to be created, material is pushed into a closed mold. The material is heated, ultimately deforming into the desired shape, and then allowed to cool. The last piece of plastic is then removed. Schematic of the injection molding machine is depicted in Fig. 2.2.

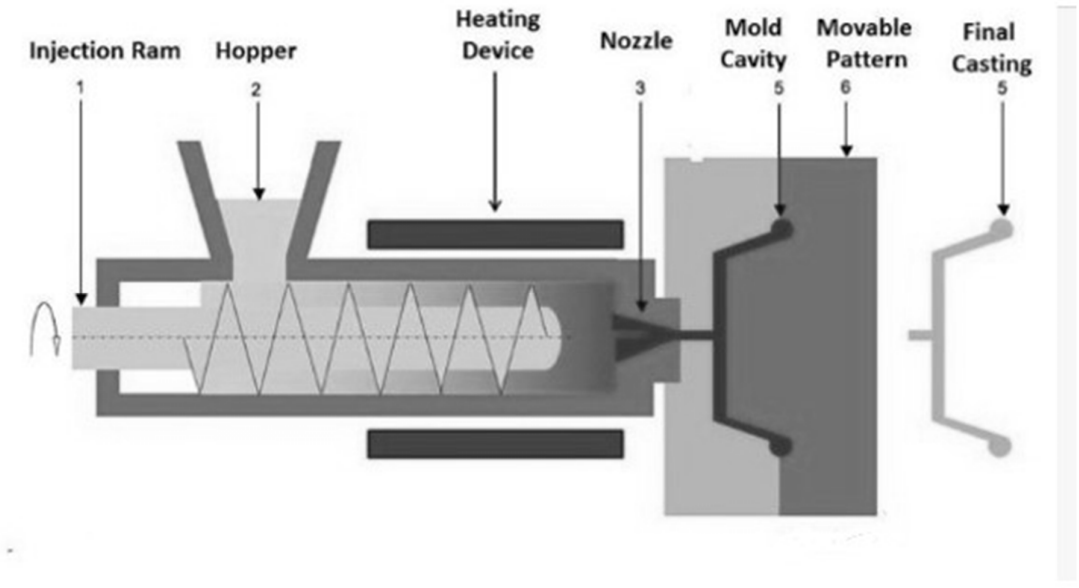


Figure 2.2: Schematic of injection molding process [3]

The injection molding can be used to make wire spools, items such as toys, combs (including pocket combs), musical instruments, small furniture like tables and chairs, storage boxes, automotive parts, and many other things. The most significant drawbacks of this manufacturing method include its restriction to basic geometries, the difficulty of attaining uniform fiber dispersion, and the possibility that fibers may be damaged during the processing stage.

2.6.2 Pultrusion

Pultrusion is a fully automated and efficient manufacturing technique used to produce Polymer Matrix Composites as continuous, long-length products with uniform cross-sectional shapes.

The creels are used to extract reinforcing fibers. The pulling mechanism controls the pulling motion. The fibers are bundled by the guide plates and directed to the resin solution by the guide plates. Fibers are wetted and impregnated with liquid resin as they enter the resin reservoir. Liquid resin consists of a mixture of polymer, pigment, filler, catalyst, and various additives. Once the fibers exit the resin bath, they enter the preforming stage, where any excess resin is removed and the material begins to take shape. The shaped fibers are then pulled through a heated die, which sets the final cross-sectional profile and initiates the curing of the resin. Finally, a cut-off saw is used to trim the cured composite to the required length. Figure 2.3 showed the schematic diagram of the pultrusion process.

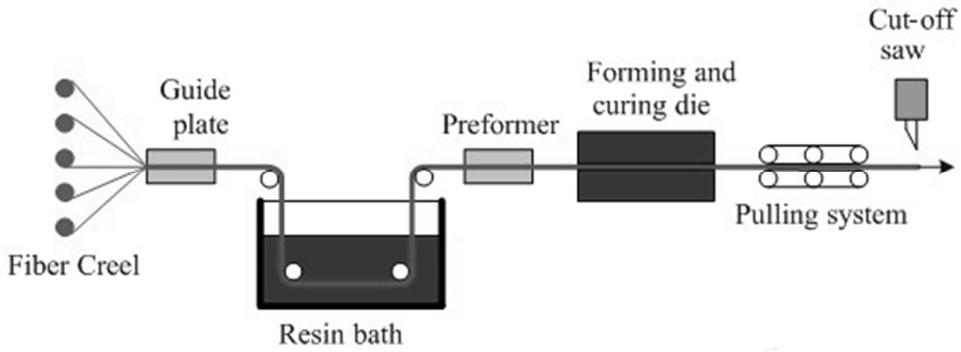


Figure 2.3: Schematic of pultrusion process [4]

The main characteristics of the pultrusion process are its extraordinary productivity, readily controllable process parameters, minimal manual labour section, exact dimensional control of cross-sections and excellent surface quality, among others.

2.6.3 Extrusion

Extrusion is a manufacturing process used to create products with a specific cross-sectional shape by pushing material through a die that matches the desired profile. Compared to other methods, it offers two main advantages: it can effectively process brittle materials since the material undergoes only compressive and shear stresses, and it allows for the formation of highly complex cross-sectional geometries. In addition, it produces an outstanding surface finish and provides a great deal of design flexibility.

Polymer material, typically in pellet form, is loaded into the extruder via a hopper (Fig. 2.4). A rotating screw then conveys the material forward, applying pressure as it moves it toward the die, where it is shaped into a continuous polymer product. Along the length of the barrel, heating elements melt and soften the polymer to facilitate the extrusion process. The material's temperature is regulated using thermocouples. After exiting the die, the product is cooled using either a water bath or forced air. In contrast to metal extrusion, polymer extrusion is a continuous process that lasts as long as feedstock pellets are provided. Extrudates are the generic term for extrusion products.

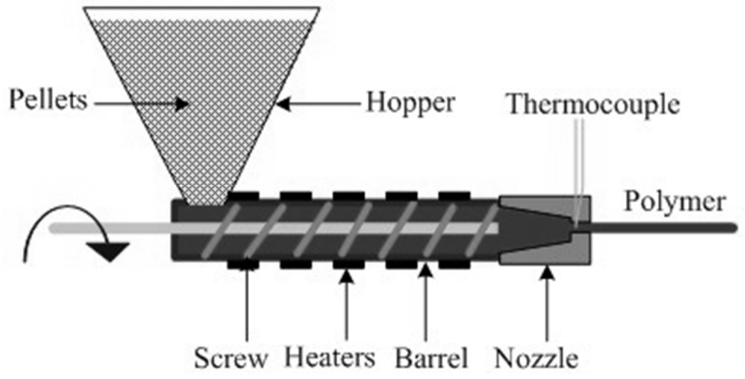


Figure 2.4: Schematic of extrusion process [5]

Extrusion is mostly used for thermoplastics, although it may also be utilised for elastomers and thermosets. This manufacturing technique is limited to linear forms, difficult to achieve complicated geometries, and fiber breakage.

2.6.4 Compression Molding

Compression molding is a molding technique in which the preheated molding material is initially put in an open, heated mold cavity (Fig. 2.5). This technique, referred to as compression molding or 'vulcanization' when dealing with rubber involves closing the mold using a top plate or plug, then applying pressure to ensure the material fills the entire mold cavity. Heat and pressure are sustained until the material fully cures.

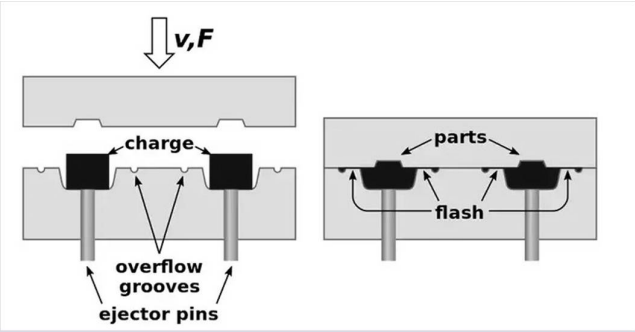


Figure 2.5: Schematic of compression molding [6]

2.6.5 Resin Transfer Molding (RTM)

The RTM method is a type of closed-mold manufacturing in which a fiber-based preform is positioned inside of a mold cavity before a pressurised resin injection takes place (Fig. 2.6). In this process, the fibers are saturated with resin, and the composite is cured into its final shape. Various forms of resin transfer molding exist, each differing in the method used to deliver the resin to the reinforcing material within the mold cavity.

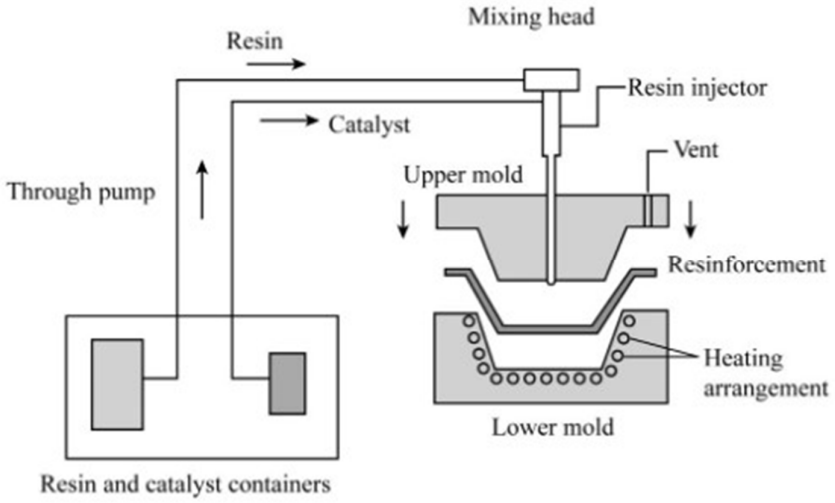


Figure 2.6: Schematic of Resin Transfer Molding (RTM) [7]

2.6.6 Filament Winding

Filament winding is a manufacturing process primarily used to produce cylindrical (open-ended) or closed structures such as pressure vessels and storage tanks. In this method, fibers are wound under tension around a rotating mandrel. A fiber delivery eye moves horizontally along the mandrel's axis, placing the fibers at specific angles or patterns relative to the rotation. Commonly used fibers include glass and carbon that are saturated with resin during the winding process. After the mandrel is coated to the desired thickness, the resin is cured—either in an autoclave, an oven, or by rotating under radiant heat. Once curing is complete, the mandrel is removed to reveal the hollow composite structure. However, for certain products like gas cylinders, the mandrel remains as a permanent internal component, and serving as a liner to prevent leakage or to shield the composite from stored fluids. Key parameters controlled during winding include fiber type, resin content, winding angle, tow or band width, and the thickness of the fiber bundle.

Key parameters controlled during the winding process include the type of fiber, the amount of resin, and the winding angle, the width of the tow or band, and the thickness of the fiber bundle. The characteristics of the finished product can be altered by adjusting the angle at which the fiber is wrapped throughout the manufacturing process. Circumferential strength comes from a "hoop" with a high angle, while longitudinal or axial strength comes from shapes with a lower angle, such as polar or spiral ones.

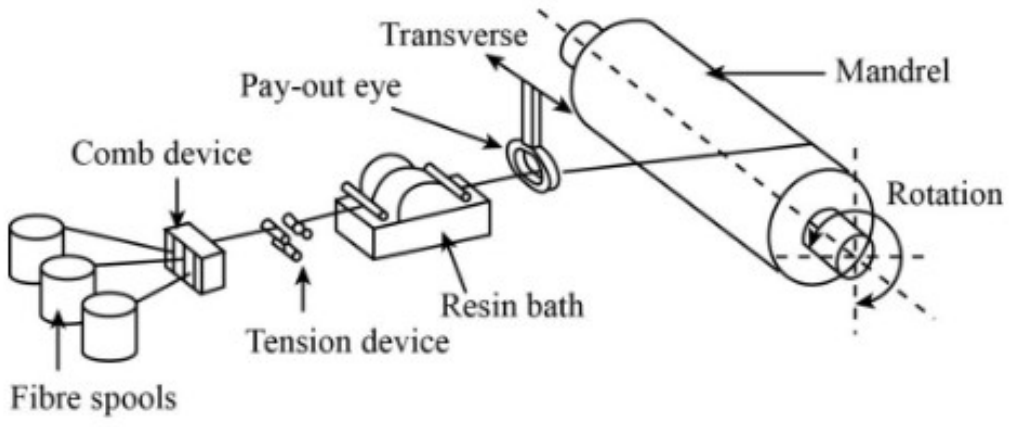


Figure 2.7: Schematic of Filament Winding [8]

2.6.7 Hand Lay-Up

To make a laminated composite structure, the hand layup method uses an open mold to shape successive layers of resin and support (Fig. 2.8). These layers are then applied by hand to the open mold. It is a process that requires physical labour, takes a lot of time, and requires a lot of effort.

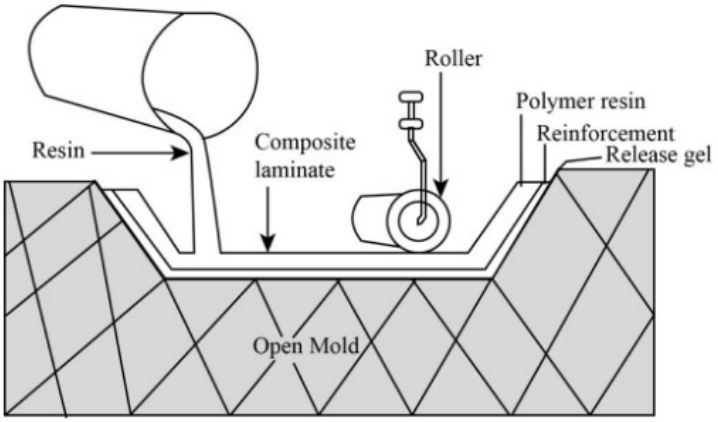


Figure 2.8: Schematic of Hand Lay-Up [9]

2.7 SOME PREVIOUS STUDIES IN THIS FIELD

The study conducted by Gupta, Srivastava, and Bisaria [2] was centered on the mechanical characterization of composites made from jute fiber reinforced polymers (JFRPC). This study investigated the mechanical properties of JFRPC, including tensile, flexural, and impact properties. The mechanical properties of JFRPC were discussed in relation to various elements, such as fiber loading, fiber size, fiber orientation, and chemical treatment.

N. Jahan [10] conducted research on fiber orientation, prediction, and strength assessment of composite spur gears reinforced with discontinuous fibers. Key properties of polymer composites such as elastic modulus, strength, thermal expansion, thermal and electrical conductivity were significantly affected by the amount, type, dimensions, and alignment of the reinforcing fibers. The fiber orientation was altered during processing, driven by the flow behavior of the polymer matrix. Various injection molding parameters played a crucial role in determining fiber alignment and, consequently, the structural performance of the molded materials.

Barkoula, Garkhail, and Peijs [11] conducted experiments to investigate how compounding and injection molding influence the mechanical properties of flax fiber-reinforced polypropylene composites. Using four different techniques, including the kneading process, the henschel kinetic mixer, extrusion compounding, and the creation of long fiber thermoplastic (LFT) granules through pultrusion, flax is blended with two different grades of PP (with and without maleic anhydride MA-PP grafting). Due to enhanced fiber alignment in the direction of polymer flow and improved fiber efficiency resulting from dimensional changes caused by fiber opening, the decrease in fiber length during injection molding had minimal impact on the tensile properties of the systems studied. The tensile strength of injection-molded composites increased as a result of the inclusion of MA-PP. When compared to other compounding techniques, composites that were made using a kneader demonstrated the highest tensile strength and stiffness.

Mohamed, El-Gamsy, and El-Wahab [12] focused on improving the mechanical properties of flax fiber-reinforced HDPE composites during the injection molding process through numerical optimization techniques. The higher order interactions of the injection temperature, injection speed, and screw speed also revealed their pronounced effects on the ultimate tensile strength (UTS) as well as toughness. Using non-linear optimization, the UTS and toughness were maximized.

Mishra and Biswas [13] investigated the physical and mechanical properties of an epoxy-based composite reinforced with bidirectional jute fibers. The composites were fabricated using the hand lay-up technique with varying fiber loadings of 0, 12, 24, 36, and 48 wt.%. The highest values for tensile strength, tensile modulus, flexural strength, flexural modulus, and impact energy were observed in the composite containing 48 wt.% fiber.

Research conducted by Hossain et al. [14] on the tensile behavior of epoxy-laminated composites reinforced with jute fibers also highlighted the influence of fiber orientation. By using a vacuum assisted resin infiltration approach and maintaining a consistent fiber content of 25%, the composite was created. Jute fiber was stacked in the following patterns: (0/0/0/0), (0/+45°/-45°/0), and (0/90°/90°/0). The study revealed that lamina composites with stacking sequences of 0/0/0/0 and 0/+45°/-45°/0 exhibited greater longitudinal tensile strength compared to their transverse strength. In contrast, the

0/90/90/0 configuration showed nearly identical tensile strength in both longitudinal and transverse directions.

Gowda, Naidu, and Chhaya [15] investigated the mechanical properties of polyester-based composites reinforced with jute cloth. The composites were fabricated using the hand lay-up technique with a fixed fiber volume fraction of 45%. The study focused on tensile, flexural, and impact properties. Results showed that the longitudinal tensile strength of the composites was approximately five times higher than that of the neat polyester resin, while the transverse tensile strength was about twice as high. Flexural performance improved by nearly twofold, and the addition of jute cloth significantly enhanced the impact resistance of the polyester resin.

The mechanical characteristics of vinylester resin composites reinforced with jute fiber were investigated by Ray et al. [16] . The composites were produced using the pultrusion method and various fiber volumes (8%, 15%, 23%, 30%, and 35%). They came to the conclusion that adding more jute fiber to composite materials increased their mechanical qualities. The composite with a 35 vol% fiber loading has the greatest mechanical characteristics.

Rashed, Islam, and Rizvi [17] studied how fiber length affects the tensile strength of jute/polypropylene composites. The composites were fabricated using hot compression with varying jute fiber weight percentages (5%, 10%, and 15%) and lengths (1, 2, and 4 mm). The tensile strength increased with fiber length and fiber content up to a certain point, after which further increases led to a decline in strength.

Khan, Hassan, and Drzal [18] also witnessed a parallel research experiment on jute fiber reinforced polycarbonate composite materials. The composite was made using the compression molding process, and various amounts of jute fiber were added at various stages of preparation (13%, 23%, 26%, 32%, 35%, and 42%). The composite with 32% jute fiber exhibited the greatest tensile and flexural strength values.

Y. Seki [19] studied investigated the effects of oligomeric siloxane treatment on the mechanical properties of jute fiber-reinforced epoxy and polyester composites. These composites were produced by compression molding, using jute fibers as reinforcement and unsaturated polyester and epoxy resins as matrices. The study found that oligomeric siloxane treatment improved the tensile and flexural properties of alkali-treated jute composites.

Liu and Dai [20] worked on the impact of sodium hydroxide (NaOH) and Maleic anhydride-grafted polypropylene (MPP) emulsion on the efficiency of jute/polypropylene (PP) composites manufactured by the film stacking method. It was observed that the treatment of jute fiber improved the composite's fibre-matrix adhesion.

S. Sharma [21] examined the influence of alkali treatment on jute fiber composites. Jute fibers were treated with a 5% NaOH solution for varying durations 0, 2, 4, 6, and 8 hours at 30°C. The composites made with fibers treated for 4 hours showed the most significant improvement. Crystallinity increased with longer treatment times, leading to corresponding increases in tenacity by 12%, 68%, and 79% after 4, 6, and 8 hours, respectively. When the slopes representing improvements in flexural strength and tenacity were plotted against treatment time, two distinct failure mechanisms emerged: fiber pull-out dominated between 0 and 4 hours, while transverse fracture with minimal fiber pull-out was observed from 6 to 8 hours. SEM analysis of the fracture surfaces supported these findings.

K. M. Siddiquee [22] carried out a study on how jute fiber influences the biodegradation process of polymer composites. The research explored the potential use of jute fiber in developing environmentally friendly, biodegradable polymer composites. Fiber was used to strengthen polyethylene and polypropylene at 5%, 10%, and 15%. The degradation behavior of the composites was examined under compost, soil, and natural weather conditions by measuring the percentage of weight loss and the reduction in mechanical properties. The results showed that composites exhibited greater biodegradability in compost compared to soil and natural weather. Among the three environments, composting led to the highest degradation rates. Additionally, an increased fiber reinforcement ratio was found to accelerate the degradation process, while fiber length had little to no impact on the rate of deterioration.

E. A. O. Al-Bahadly [23] worked on on the mechanical behavior of natural fiber composites, focusing primarily on the bonding interaction between kenaf fabric and unsaturated polyester resin. The research revealed that the styrene content significantly influenced both the mechanical properties and the curing behavior of the resin. The composite models were utilized to cross-reference the experimental data. The findings indicated a strong association with Hirsch's theoretical framework. The diffusion coefficients were observed to be within the range of 10-12 m2/sec. Furthermore, the

power-law creep strain model was successfully applied to predict the long-term creep performance of composites made from natural fibers and thermosetting polymers.

M. Billah [24] examined the mechanical and thermal properties of polypropylene composites reinforced with rattan fiber. Incorporating 30% rattan fiber led to a 24% enhancement in the tensile strength of the discontinuous fiber composite. When the fiber was used in a continuous arrangement, the improvement was 59%. In all cases, the flexural strengths displayed values that were greater than the corresponding tensile strength values. Among the various mechanical properties evaluated, notched impact strength showed the most significant improvement due to the presence of rattan fiber.

Ray D et al. [25] investigated how alkali-treated jute fibers affect the properties of composites. The jute fibers were treated with a 5% sodium hydroxide (NaOH) solution at 30°C for durations of 0, 2, 4, 6, and 8 hours. The treatment enhanced the fibers' modulus by 12%, 68%, and 79% after 4, 6, and 8 hours respectively, due to increased crystallinity. Tenacity improved by 46% after 6 and 8 hours, while the percentage of breaking strain dropped by 23%. For composites containing 35% of 4-hour treated fibers, flexural strength rose from 199.1 MPa to 238.9 MPa (a 20% increase), the modulus improved from 11.89 GPa to 14.69 GPa (a 23% rise), and the laminar shear strength increased from 0.238 MPa to 0.2834 MPa (a 19% gain). When the slope values derived from the rate of change in flexural strength and modulus were plotted against NaOH treatment time, two distinct failure patterns emerged: between 0 and 4 hours, fiber pull-out was the dominant failure mode, whereas between 6 and 8 hours, transverse fracture with minimal fiber pull-out occurred. Scanning Electron Microscopy (SEM) analyses of fracture surfaces confirmed these findings.

M. Souvenir [26] conducted a study to explore how fiber length and volume fraction influence the mechanical performance of jute fiber-reinforced polypropylene composites. The research focused on how the average length and proportion of reinforcing jute fibers affect key mechanical properties. The composites were fabricated using injection molding and extrusion methods, with moisture removed at various stages. This investigation evaluated properties such as fracture resistance, tensile strength, tensile modulus, strain at failure, critical fiber length, and interfacial shear strength, based on fiber content and length. Tensile tests were conducted on sets of 10 samples, following ASTM standards (excluding pure polypropylene), and continued until failure. The results

showed that incorporating jute fibers improved both tensile strength and modulus. Tensile strength increased with fiber volume up to 25%, beyond which little or no further improvement was observed. The highest tensile strength recorded was 33.733 MPa at 25% fiber content with 2 mm long fibers. Fiber length was positively correlated with tensile strength. However, tensile modulus showed a tendency to decline as fiber length increased. Fracture resistance was evaluated through notched Charpy impact tests, which indicated that adding jute fibers significantly improved impact strength, although increasing the fiber amount beyond a certain point had minimal additional effect. The study also analyzed the properties of both the polypropylene matrix and individual jute fibers.

Yu, Li, and Ren [27] worked on the development and performance of short natural fiber-reinforced poly(lactic acid) (PLA) composites. Ramie and jute short fibers were used as reinforcements within a PLA matrix to fabricate the composites. Their mechanical and thermal properties were thoroughly analyzed. Findings showed that these fiber-reinforced composites exhibited enhanced properties compared to pure PLA. The best mechanical performance was observed at a fiber content of 30%. Dynamic mechanical analysis indicated increased storage modulus for both PLA/ramie and PLA/jute composites relative to neat PLA. Additionally, the composites displayed a significantly higher Vicat softening temperature. Thermo gravimetric analysis further revealed that the inclusion of fibers in the PLA matrix raised the thermal degradation temperature of the PLA.

Islam, Azmy, and Almamun [28] studied on the mechanical properties of epoxy composites reinforced with banana and rattan fibers. The research involved extracting both types of fibers and fabricating unidirectional fiber composites using the hand lay-up method. To assess mechanical performance, tensile and flexural strengths of the composites were compared. Results showed that the banana fiber-reinforced composite had a tensile strength 2.57 times higher than that of the rattan fiber-reinforced composite. However, both types of composites demonstrated comparable flexural strength.

Rachchh, Ujeniya, and Misra, [29] carried out experiments on the mechanical characterization of rattan fiber-reinforced polyester composites. The study evaluated properties such as tensile strength, flexural strength, density, and hardness of composite plates made using rattan fiber and unsaturated polyester resin (GP-7150). The objective

was to develop lightweight, cost-effective laminates using renewable natural fibers through the hand lamination process. Six types of laminates were prepared with varying rattan fiber content. Results indicated that mechanical properties improved with increasing fiber content up to 12.5%. Beyond this point, the properties declined due to insufficient resin to effectively transfer loads between the fibers.

Sun, Han, and Dai [30] examined how formulation choices and compounding routes influence the mechanical behavior of injection-molded natural-fiber/PP composites. Using thermo gravimetric analysis, they showed sisal fibers possess higher thermal stability than jute. They further evaluated the roles of fiber loading, coupling agent, fiber geometry, and dispersion, finding that adding a coupling agent, using longer fibers, and achieving uniform distribution all enhanced composite performance. For sisal/PP composites with MAPP, the critical fiber length was 2.27 mm and the interfacial shear strength was 22.03 MPa. The Kelly–Tyson model was employed to theoretically predict the composites' tensile strength.

Nahar et al. [31] conducted a comparative study on the mechanical and interfacial properties of jute and bamboo fiber-reinforced polypropylene composites. Composites containing 50 wt% of either jute or bamboo fibers were fabricated using compression molding. The jute/PP composite exhibited tensile strength of 48 MPa, bending strength of 56 MPa, tensile modulus of 900 MPa, and bending modulus of 1500 MPa. In contrast, the bamboo/PP composite demonstrated significantly higher mechanical properties, with a tensile strength of 60 MPa, bending strength of 76 MPa, tensile modulus of 4210 MPa, and bending modulus of 6210 MPa. Soil degradation tests conducted over 24 weeks revealed that bamboo fiber composites retained their mechanical performance more effectively than jute fiber composites. Interfacial shear strength, measured via single-fiber fragmentation tests, was found to be 2.14 MPa for jute and 4.91 MPa for bamboo fibers. SEM analysis of fracture surfaces confirmed stronger fiber-matrix bonding in bamboo-reinforced composites compared to those reinforced with jute.

2.8 MECHANICAL PROPERTIES OF NATURAL FIBER COMPOSITES

Overall, these investigations demonstrate that the mechanical performance of natural fiber composites (NFCs) can be significantly enhanced by refining fiber–matrix interactions, fiber orientation, processing techniques, and environmental conditions.

Researchers are therefore better equipped to develop and tailor novel composite materials based on NFCs for successful deployment across various fields of use.

Table 2.1 listed the details of the mechanical properties of Polypropylene-based NFCs compiled from prior literature.

Table 2.1: Mechanical properties of Polypropylene based NFCs

Fiber	Matrix	Fiber percentage (%)	Tensile Strength (MPa)	Flexural Strength (MPa)	Young's modulus (GPa)	Flexural modulus (GPa)	Process	Reference
Hemp	PP	40	52	86	4	4	Injection molding	[32]
Kraft	PP	40	52	90	3	4	Injection molding	[32]
Flax	PP	30	52	60	5	5	Injection molding	[33]
Jute	PP	60	74	112	11	12	Injection molding	[34]
Cordenka	PP	42	90	-	4	-	Injection molding	[35]
Kenaf	PP	30	46	58	5	4	Compression molding	[36]
Hemp	PP	46	-	127	-	11	Compression molding	[37]
Flax	PP	50	40	-	7	-	Compression molding	[38]
Flax yarn	PP	30	89	-	7	-	Pultrusion	[39]
Flax yarn	PP	72	321	-	29	-	Filament wounding	[40]
Rattan	PP	30	40.74	48.83	1.79	1.62	Injection molding	[24]

Table 2.2 summarizes the mechanical properties of LDPE-based NFCs compiled from previous researches:

Table 2.2: Mechanical properties of LDPE based NFCs

Fiber	Matrix	Fiber percentage (%)	Tensile Strength (MPa)	Flexural Strength (MPa)	Young's modulus (GPa)	Flexural modulus (GPa)	Process	Reference
Coconut	LDPE	20	2.2	11	0.065	0.19	Compression molding	[41]

Jute	LDPE	44	50	23	1.3	-	Compression molding	[42]
Glass	LDPE	44	45	13	2.4	-	Compression molding	[42]

Mechanical properties of PLA based NFCs which are gathered from previous studies are described in the Table 2.3.

Table 2.3: Mechanical properties of PLA based NFCs

Fiber	Matrix	Fiber percentage (%)	Tensile Strength (MPa)	Flexural Strength (MPa)	Young's modulus (GPa)	Flexural modulus (GPa)	Process	Reference
Cordenka	PLA	25	108	-	4	-	Injection molding	[35]
Hemp	PLA	30	83	143	11	7	Compression molding	[43]
Kenaf	PLA	40	82	126	8	7	Compression molding	[44]
Harakeke	PLA	30	102	-	8	-	Compression molding	[45]

Mechanical properties of Epoxy based NFCs which are found from previous researches are described in the Table 2.4.

Table 2.4: Mechanical properties of Epoxy based NFCs

Fiber	Matrix	Fiber percentage (%)	Tensile Strength (MPa)	Flexural Strength (MPa)	Young's modulus (GPa)	Flexural modulus (GPa)	Process	Reference
Hemp	Epoxy	50	105	126	9	8	Compression molding	[45]
Bamboo	Epoxy	40	23	58	-	-	Compression molding	[46]
Flax	Epoxy	46	280	-	35	-	Resin transfer molding	[47]
Sisal	Epoxy	37	183	-	15	-	Resin transfer molding	[48]
Jute	Epoxy	36	102	53	3.8	4	Hand lay-up	[13]

Banana	Epoxy	40	108	72	-	-	Hand lay-up	[49]
Coir	Epoxy	40	21	14	1	-	Hand lay-up	[50]
Flax	Epoxy	31	160	190	15	15	Hand lay-up	[51]
Flax	Epoxy	52	191	-	28	-	Filament wounding	[52]

Mechanical properties of Polyester, VE, UP & Polyurethane based NFCs which are compiled from previous literature are described in Table 2.5.

Table 2.5: Mechanical properties of Polyester, VE, UP & Polyurethane based NFCs

Fiber	Matrix	Fiber percentage (%)	Tensile Strength (MPa)	Flexural Strength (MPa)	Young's modulus (GPa)	Flexural modulus (GPa)	Process	Reference
Jute	Polyester	30	41	71	-	-	Hand lay-up	[53]
Rattan	Polyester	18	12	31	-	-	Hand lay-up	[54]
Flax yarn	VE	35	111	128	10	10	Resin transfer molding	[55]
Bamboo	UP	15	22	-	4	-	Hand lay-up	[56]
Hemp	Polyurethane	30	122	145	18	12	Pultrusion	[57]

2.9 RESEARCH GAP / MOTIVATION OF THE STUDY

It is discovered that very few studies involving HDPE polymer and jute fiber have been conducted. Therefore, with the superiority of jute fiber as well as HDPE composites, a lot of potential works could be done in the future to develop jute fiber HDPE composites as bio-safe alternatives in various engineering fields.

Despite of having fantastic characteristics of HDPE in engineering application, it is needed to strengthen the polymer for diversifying use in various fields. Natural fiber could be an option to strengthen the polymer. Though various composition techniques are available in literature for composite fabrication, challenges arrived due to the poor adhesion, uneven fiber dispersion and so on. Therefore it is needed to introduce injection molding technique to fabricate samples comprises with jute fiber and HDPE polymer, and conduct the mechanical characterization accordingly.

2.10 CONCLUSION

Natural fiber composites (NFCs) have received recent attention as an answer to a highly demanded environmentally friendly and sustainable substitute for synthetic fiber reinforced polymer composites. Mechanical characterization of NFCs is important for developing an understanding of structural behavior, optimizing performance and extending the application.

Different polymer matrices such as epoxy, polypropylene (PP), polyethylene (PE), poly lactic acid (PLA) and polyethylene (PE) have been used for NF caring. Polymer matrix selection is a key factor in determining the mechanical behavior of composites.

On the other hand, natural fiber composites (NFCs) have been produced using various manufacturing techniques, including compression molding, injection molding, and extrusion. These methods affect the composite's ultimate properties, as well as the fiber-matrix bonding and fiber distribution.

This literature review provides an outline with respect to the fibers, matrix, composite material categories as well as fiber surface treatment techniques. It further summarizes the key findings from previous studies in this field. The review further compares the mechanism between various NFCs previously studied.

Chapter 3

Materials and Methodology

3.1 INTRODUCTION

This chapter outlines a comprehensive insight into all the elements and techniques used to investigate and study the properties of the composite constructing material. This chapter also provides a strong foundation for the subsequent chapters by emphasizing the selection of materials and the process of using these materials. It informs the readers adequately about the experimental setup and techniques used – which are critical components that assure validity and reliability of the research findings.

3.2 MATERIALS

In this section, properties of the selected materials for the research study are discussed. Jute fiber and HDPE are selected as fiber and matrix respectively. In addition to this, jute fiber & HDPE collection process and then how jute fiber was prepared for the manufacturing process has also been described.

3.2.1 Jute Fiber

The jute plant (Corchorus Olitorius and Corchorus Capsularis) provides a low-cost, renewable, natural, long, soft, and shiny vegetable bast fiber known as jute. Jute fiber is extracted from two primary species within the Corchorus genus, namely Corchorus olitorius and Corchorus capsularis.

It is the principal and most extensively utilized fiber in the world and is extensively valued for its versatility, low cost, and green properties. Jute is commonly referred to as the "golden fiber" due to its golden-brown colour and its historical significance and high demand across various industries.

Jute has been cultivated for centuries, in the Indian subcontinent and elsewhere with suitable climates. Jute is also cultivated in countries such as India, Myanmar, Nepal, China, Taiwan, Thailand, Vietnam, Cambodia, Brazil, and several others. As a broadleaf plant, it thrives in a warm, humid climate with ample rainfall and well-drained soil. The majority of global jute production comes from Bangladesh and India.

Jute fiber comes from the stem of the jute plant, which is the outer layer of the stem. Once the plants have reached maturity, generally 120 to 150 days post-seeding, the harvest process begins. After the stalks are chopped down to ground level, a technique called "retting" is used to remove the fibrous components from the rest. Stems that have been collected are retted by submerging them in water or letting them soak for several days in natural water sources like rivers or ponds. This process also aids in separating the fibers from the plant's woody centre.

Jute is utilized to produce a wide range of fabrics and materials, such as sacks, bags, carpets, rugs, and clothing. Due to their durability and breathability, jute sacks are widely used for packaging agricultural goods like grains, coffee, and cocoa beans.

In interior design, jute is used to craft tablecloths, curtains, wall art, and decorative objects. Jute fiber is used by the crafts people for making jute based art and craft, jewellery and other creations. Jute geotextiles are an organic alternative to synthetic geotextiles utilized for slope stabilization and erosion control.

Due to its biodegradability, renewable fiber source, and comparatively low energy consumption in production relative to synthetic fibers, jute is regarded as an environmentally sustainable fiber. Jute farming also benefits soil fertility because jute plants nourish the soil by contributing organic materials. Chemical composition of various types of natural fiber and the mechanical properties of jute fiber are listed in Table 3.1, 3.2, and 3.3.

Table 3.1: Chemical contents (%) of some plant fibers [58]

Fiber type	**Cellulose**	**Hemicellulose**	**Lignin**	**Pectin**
Abaca	61-64	21	12	0.8
Bagasse	32-48	21	19.9-24	10
Banana	60-65	6-19	5-10	3-5
Bamboo	26-43	15-26	21-31	-
Coir	46	0.3	45	4
Cotton	82-96	2-6	0.5-1	5-7
Flax	60-81	14-19	2-3	0.9
Hemp	70-92	18-22	3-5	0.9
Jute	51-84	12-20	5-13	0.2
Kapok	13-16	-	-	-

Kenaf	44-57	21	15-19	2
Phormium	67	30	11	-
Pineapple	80-81	16-19	4.6-12	2-3
Ramie	68-76	13-15	0.6-1	1.9-2
Sisal	43-78	10-13	4-12	0.8-2
Wood	45-50	23-30	27	2.2-5

Moreover, it is worth noting that jute plants has the ability to incorporate a substantial quantity of carbon dioxide during their life cycle, so contributing to the mitigation of greenhouse gas emissions. Roughly 15 tonnes of carbon dioxide (CO_2) and 11 tonnes of oxygen (O_2) are taken up by jute plants throughout their 120-day life cycle. The demonstrated potential of jute highlights its status as the preeminent environmentally sustainable natural fiber.

Table 3.2: Chemical contents of jute fiber [59][60]

Contents	**Value**
Cellulose (wt%)	67-71.5
Hemicellulose (wt%)	13.6-20.4
Lignin (wt%)	12-13
Pectin (wt%)	0.2
Wax (wt%)	0.5
Moisture (wt%)	12.6
Micro-fibril/spiral angle	8.0

Table 3.3: Mechanical properties of Jute fibers [21]

Parameter (unit)	**Value**
Density (g/cm^3)	1.3
Elongation (%)	7.0-8.0
Tensile strength (MPa)	393-773
Young's modulus (GPa)	26.5

3.2.2 Jute fiber collection

Jute fiber was sourced from Reazuddin Market, Chattogram. In this study, a mixed grade of Tossa variety (Corchorus olitorius) jute fiber was used (Fig. 3.1).

3.2.3 Fiber preparation

To improve adhesion with the matrix material and remove or modify surface impurities, the jute fibers first underwent surface modification.



Figure 3.1: Jute fiber collected from local market

This was achieved through an alkali treatment process, which was selected from a range of available options. Solution of sodium hydroxide (NaOH) was utilised in this alkaline treatment procedure.

An experiment by Ray D et al. [25] demonstrated that treating jute fibers with a 5% alkaline (NaOH) solution at 30°C for 4 hours enhances their mechanical properties. In this process, the fibers were soaked in the 5% NaOH solution for 4 hours (Fig. 3.2), followed by thorough rinsing with clean water to remove any residual NaOH. Finally, the fibers were washed with distilled water to ensure complete purification.

Using scissors, the jute fibers were cut to get shorter fibers. The fibers were then exposed to sunlight for 48 hours to dry (Fig. 3.3). Lastly, the length of the dried fiber was kept short (~ 10 mm) due to the proper mixing with matrix and expected to be extruded through the heating chamber of the molding machine.



Figure 3.2: Jute fibers immersed in 5% alkaline (NaOH) solution



Figure 3.3: Jute fibers kept for drying under open atmosphere

3.2.4 HDPE

High-Density Polyethylene (HDPE) is a type of polyethylene polymer characterized by a relatively simple chemical structure. It is composed of repeating units of the ethylene monomer. Chemically, HDPE is denoted by the formula $(C_2H_4)_n$ and is categorized as a linear polymer, consisting predominantly of straight polymer chains with few or no side branches. In addition to its great density and strength, its linear structure also adds to its other physical characteristics. Since the polymer chains don't spread out much, they can pack together tightly, making a thick and strong material. General structure of HDPE chain in showed in Fig. 3.4.

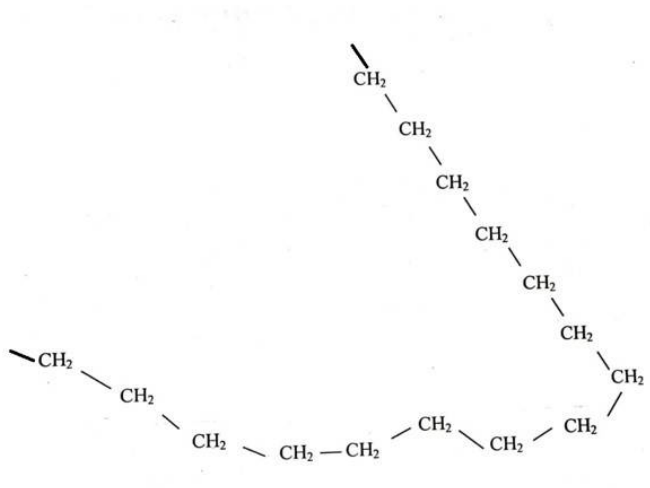


Figure 3.4: General structure of HDPE

HDPE is high-density polyethylene that comes in different types, each made to meet different needs and uses. When it comes to molecular shapes, qualities, and processes, these grades can be different. Properties of HDPE are listed in Table 3.4:

Table 3.4: Properties of HDPE [66]

Parameter (unit)	Value
Density (g/cm^3)	0.954
Elongation (%)	7.5
Tensile strength (MPa)	26
Young's modulus (GPa)	1

3.2.5 HDPE collection

High-density Polyethylene (HDPE) is regularly imported in Bangladesh from various plastics and chemical manufacturers, suppliers, and distributors (Fig. 3.5). These may involve acquiring sources domestically or abroad. The HDPE utilized in this investigation was obtained locally from Reazuddin Market, Chattogram.



Figure 3.5: HDPE collected from local market

3.3 INSTRUMENTS USED

The following instruments were utilised in this study:

- Scissor
- Weight machine
- Single-screw extruder
- Plastic grinding machine
- Injection-molding machine
- Universal Tensile Tester
- Rockwell Hardness Tester
- Universal Impact Tester

3.4 COMPOSITE PREPARATION

HDPE and jute fibers were compounded in varied weight fractions in a single screw extrusion machine.

Composites were produced by passing compositions of Jute and HDPE (with specific weight fractions) through a single screw extruder (Figure 3.6). Extrusion processing temperature was regulated at 140 degrees Celsius. The jute-HDPE mixers were fed into the extruder in a continuous stream. A consistent rate of delivery was maintained for the composites as they passed through a die. Table 3.5 contains the fiber loading weight percentage and the specimen name.

Table 3.5: Relative amounts of Jute fiber and HDPE by weight fraction

Notation	**Specimen name**	**Reinforcing Discontinuous Jute fiber weight fraction (%)**	**HDPE matrix weight fraction (%)**
	HDPE	00	100
1	HDPEDJ-5	05	95
2	HDPEDJ-10	10	90
3	HDPEDJ-20	20	80

The extruder used in this study was manufactured in a local workshop. The photograph of the extruder is shown below:

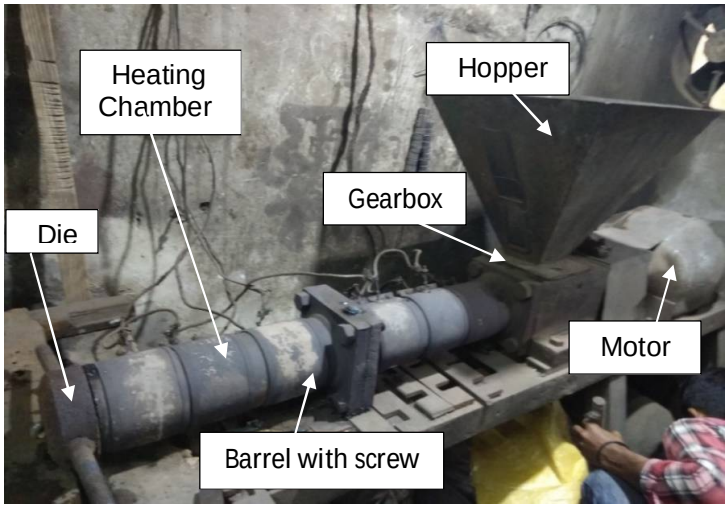


Figure 3.6: Single screw extruder

Screw diameter of this single screw extruder was 45 mm. The barrel length & overall length was 1.8 meter & 2.5 meter respectively. After getting small pieces of composites from extruder machine, they were fed into a plastic grinding machine to make them pallets for injection molding process. For getting consistent particle size, which helps in smooth feeding into the hopper of injection molding machine ensuring a stable melt & quality parts, grinding was done in the plastic grinding machine. This plastic grinder (Fig. 3.7) was also manufactured by the same local workshop.

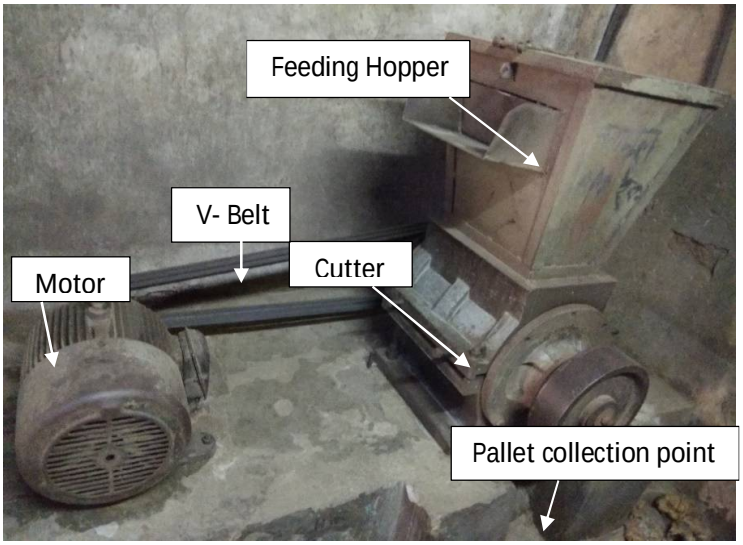


Figure 3.7: Plastic grinding machine

3.5 SPECIMEN PREPARATAION

To accurately characterize composite materials, various mechanical tests are typically required, such as tensile, flexural, impact, and hardness testing. However, in this study, only tensile testing, Charpy impact testing (V-notched), and Rockwell hardness testing were performed. This research only conducted tensile testing, Charpy impact testing (V-notched), and hardness testing (Rockwell). The specimens required for these tests were manufactured using an injection molding machine.

Initially, a mild steel mold was created to manufacture composite test samples. Prior to mold manufacturing, test sample dimensions were set in compliance with ASTM standards as shown in Table 3.6. The mold was specifically made to enable the extraction of all specimens required for evaluating the tensile strength, impact strength, and hardness of composite materials from a single mold. After that, the injection molding machine was paired with this mold so that the desired specimens could be manufactured.

Table 3.6: Test Standards

SI No.	Tests Name	Specimen Standards
01	Tensile Test	ASTM D638 type IV
02	Charpy Impact Test (V-Notched)	ASTM E23
03	Hardness (Rockwell) Test	ASTM D785

The pellets prepared by the plastic grinding machine were introduced into the injection molding unit. The injection molding unit utilized in this research was developed and constructed as part of a previous project by the Mechanical Engineering Department at Chittagong University of Engineering and Technology (CUET). This machine was vertically oriented and manually controlled (Fig.3.8). The pellets were warmed until melted in the heating chamber, then forced into the enclosed mold cavity using a plunger or ram within the heated cylinder. The melting temperature of HDPE is 130°C. Based on the melting temperature of the HDPE, the temperature was regulated at a constant value of 140°C by a heating system and sufficient force has been exerted manually for sample preparation. The heating chamber of the machine had 15 cm height and 4 cm diameter. The extruding diameter was 5 mm. The pressure, temperature, and heating duration of the samples were consistently regulated to ensure uniformity in the preparation of all composite test samples. Upon completion of the injection molding procedure, the

products were afterwards removed and allowed to undergo adequate cooling. The samples for the specified testing are then extracted from the products. Figure 3.9, 3.10, and 3.11 depicted the drawing of the specimen and the prepared samples accordingly as per the ASTM standards.

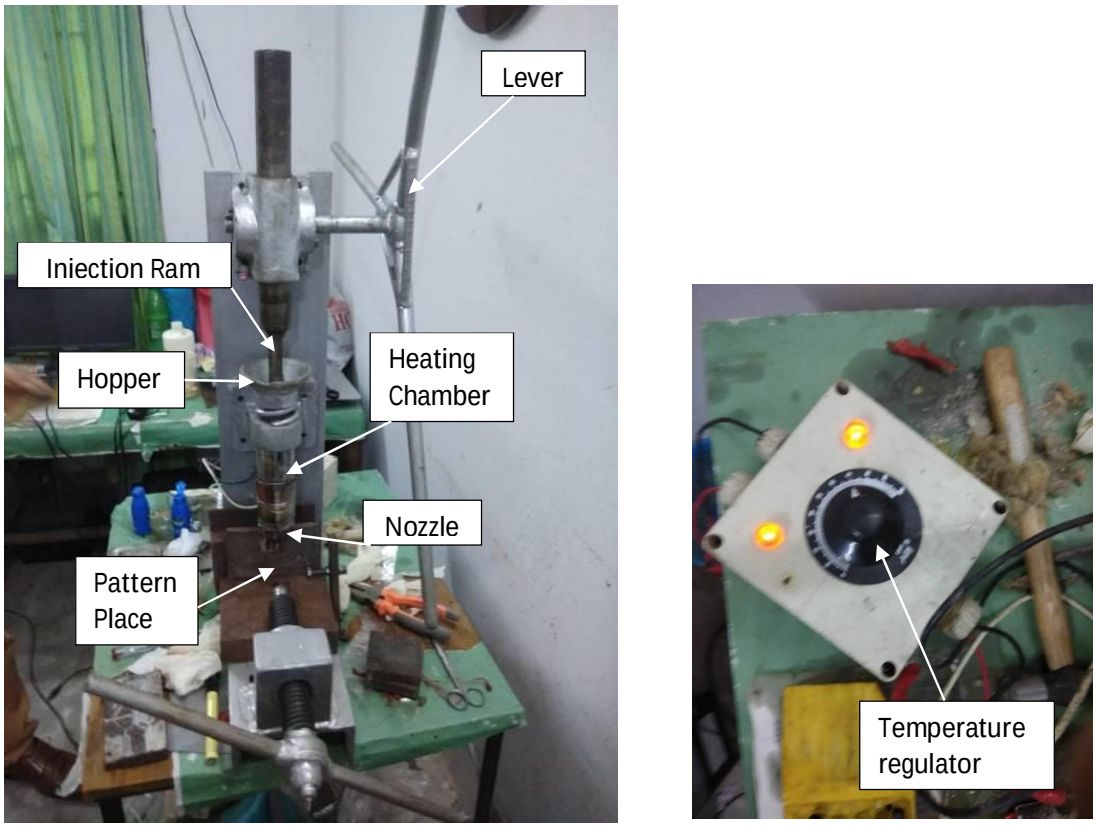
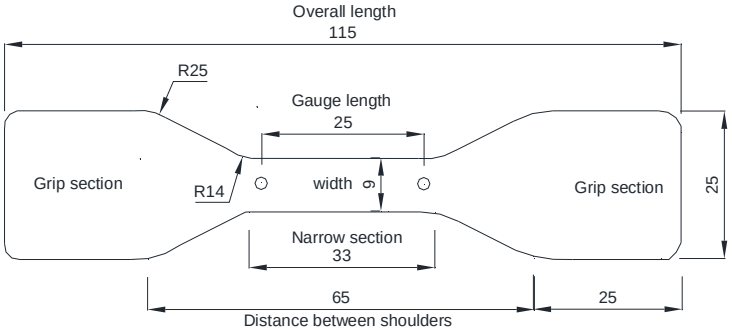
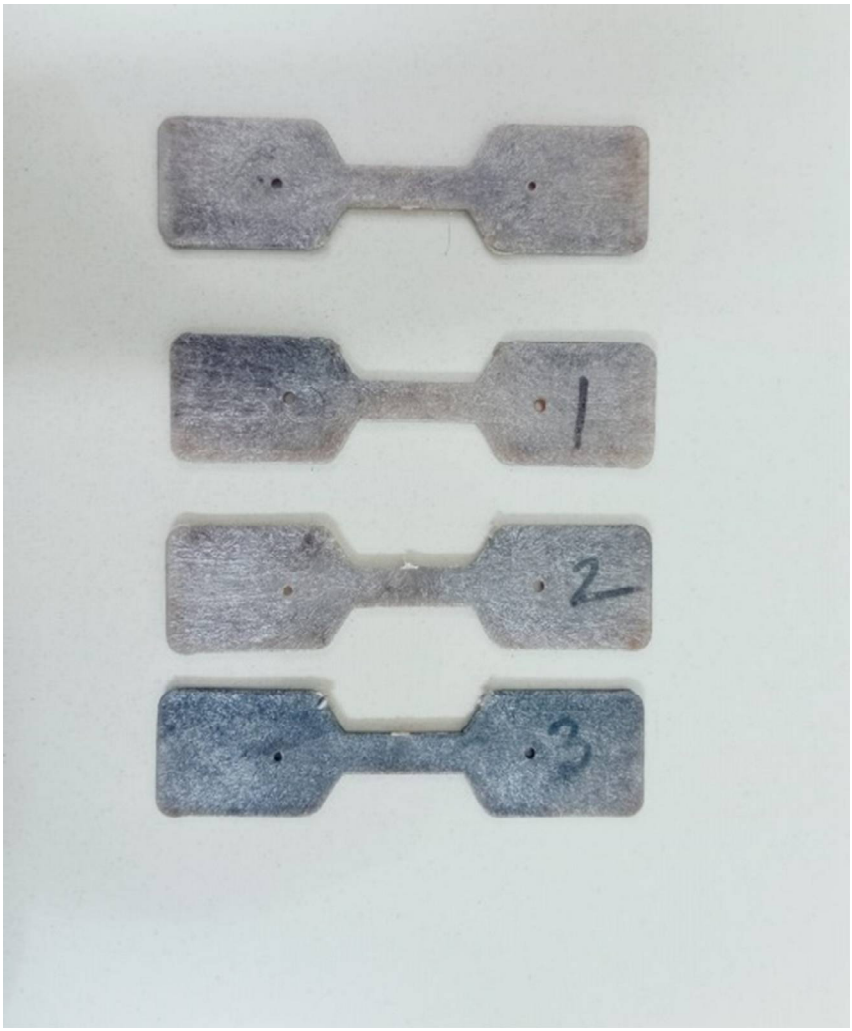


Figure 3.8: Injection molding machine



Thickness of the specimen is 3 mm
All dimensions are in mm

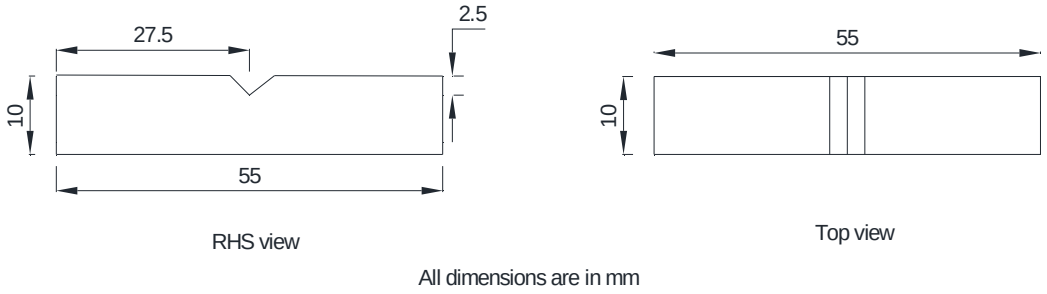
(a)



(b)

Figure 3.9: (a) Dimensions of tensile test specimen

(b) Prepared specimen for tensile test

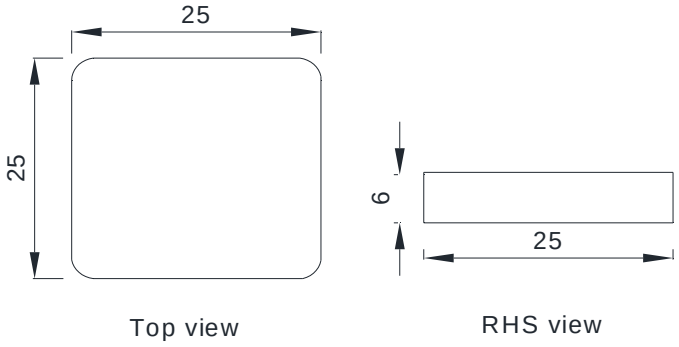


(a)



(b)

Figure 3.10: (a) Dimensions of impact test specimen
(b) Prepared specimen for impact test



All dimensions are in mm

(a)



(b)

Figure 3.11: (a) Dimensions of hardness test specimen
(b) Prepared specimen for hardness test

3.6 CONCLUSION

This chapter builds a strong basis for the succeeding chapters by providing an in-depth description of the materials selection, manufacturing methodologies, outlining techniques, and testing procedures. This approach ensures reliability, credibility, and a meaningful contribution to the progress of understanding in the area of composite materials. Building on this basis, the next chapters will show the experimental results, data analysis, and interpretation, thereby producing insightful comments and conclusions.

Chapter 4

Data Collection

4.1 INTRODUCTION

This section of the thesis is devoted on a comprehensive evaluation of the physical characteristics displayed by the composites made of jute fiber and high-density polyethylene (HDPE). The evaluation is done using a methodical approach combining theoretical knowledge with the actual data collecting under accepted theoretical equations.

4.2 TENSILE PROPERTIES TEST

Tensile properties are mechanical characteristics of a material that define its behavior under tensile or stretching stresses. These characteristics give important details on the capacity of a material to resist axial stresses, extend without breaking, and revert to its original form upon the removal of the forces. Tensile testing is a common method used to determine these properties. In this experiment, the tensile testing of the composites was performed using a universal testing machine (Figure 4.1).



Figure 4.1: Arrangement of tensile test in a universal tester (Model: Autograph AGS-X Series (10KN), Manufacturer: Shimadzu Corporation, Japan)

Three samples from each formulation were examined, and the mean results were computed. The force versus displacement graphs were recorded electronically by the testing device. The peak load applied was also captured by the system. Stress and strain were determined using the measured load and displacement data. Finally, the ultimate tensile strength, break elongation, and elastic modulus of the samples were calculated using the following formulas:

Stress:

One of the most important factor in materials testing, and the study of material behavior is stress. It denotes the internal resistance or force that a material encounters when subjected to an external load or force. Stress is a crucial notion for comprehending material responses to mechanical forces and is essential in the design and study of structures, components, and materials in diverse engineering applications. It is conventionally represented by the symbol σ (sigma). The equation for stress is,

$$\sigma = \frac{F}{A} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.1)$$

Here, σ = Stress, F= Applied force, and A= Cross section area

Strain:

Strain is still a crucial consideration for material research. It describes the deformation or change in form a material undergoes under an external force or stress. It evaluates the extent of material compression or stretching brought on by stress, that is, force. Since it explains the resultant change in the shape or dimensions of the material, strain is a basic idea in knowledge of how materials react to mechanical forces and is closely associated with stress.

Strain is typically denoted by the symbol ε (epsilon). The equation for strain is,

$$\varepsilon = \frac{\Delta L}{L} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.2)$$

Here, ε = Strain, ΔL = Change in length, and L= Original length

Tensile Strength:

The tensile strength (TS) of a material is calculated using the following equation:

$$\text{Tensile Strength (TS)} = \frac{Maximum\ Tensile\ Force\ (F)}{Cross\text{-}sectional\ Area\ (A)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.3)$$

Where,

- Tensile Strength (TS) is measured in units of pressure, typically Pascals (Pa) or Megapascals (MPa).
- Maximum Tensile Force (F) is the maximum force applied to the material during the tensile test, usually measured in Newtons (N).
- Cross-Sectional Area (A) is the original cross-sectional area of the material before the test, typically measured in square meters (m^2) or square millimeters (mm^2).

The outcome of the aforementioned equation will yield the tensile strength of a material, indicating the maximum stress it can endure when exposed to a tensile force prior to failure.

Young's Modulus:

Young's Modulus (E), referred to as the elastic modulus or modulus of elasticity, computes a material's stiffness or its capacity to withstand elastic deformation under an applied force.

The equation for Young's Modulus (E) is as follows:

$$E = \frac{Stress\ (\sigma)}{Strain\ (\varepsilon)} \quad \text{..... (4.4)}$$

Where,

- It is measured in units of pressure, typically Pascals (Pa) or Megapascals (MPa) or Gigapascals (GPa).
- Stress (σ) represents the applied force (in Newtons, N) per unit area (in square meters, m^2).
- Strain (ε) is the ratio of the change in length (ΔL) to the original length (L) of the material.

Elongation at break:

In a tensile test, the elongation at break also known as the strain at break or ultimate elongation, measures the extent of stretching a material can experience before it breaks.

It is expressed as a percentage and is calculated using the following equation:

$$\text{Elongation at break} = \frac{\text{Change in Length } (\Delta L)}{Original\ Length\ (\text{L})} \text{ x } 100\% \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4.5)$$

Where,

- Elongation at break (%) is the percentage increase in length of the material at the point of fracture.
- Change in length (ΔL) is the difference between the final length of the material after it breaks during the tensile test and its original length.
- Original length (L) is the initial length of the material sample before the test.

When materials are required to withstand tensile stresses or stretching, as in the design of flexible materials, textiles, and other products where elongation and ductility are essential factors, this property is critical to consider.

From stress-strain diagram, proportional limit, elastic limit, yield limit, ultimate strength and rupture strength etc. can also be found. The limit up to which stress is proportional to strain is called proportional limit. On the other hand, the ordinate of a point almost coincident with proportional limit is known as the elastic limit, up to which a material maintains its elastic property. In addition to this, the ordinate at which there is an increase in strain with no increase in stress is known as the yield point of the material.

The maximum ordinate of the stress-strain curve is known as the ultimate strength and the stress at failure is called the rupture strength.

4.3 IMPACT TEST

An impact test is a type of material test, it measures a material's ability to deform or break under a quickly applied load or impact. This test is important for assessing the strength, stability and durability of metals and polymers, which may encounter sudden impact in a broad use case.

When a force acts on a material over a very brief duration, it is termed an "impact." Impact is a type of dynamic loading in which load is imposed abruptly, for as through the impact of a moving mass. As per ASTM, "an impact test is a dynamic test in which a selected specimen, machined or surface ground and usually notched, is struck and broken

by a single blow in a specially designed testing machine and the energy absorbed in breaking the specimen is measured".

To conduct the test, a material sample with specified dimensions and shape is subjected to a prompt load. Having a notch, defect, or crack makes the material more likely to break under abrupt loads or impacts.

Charpy specimens are typically positioned horizontally and Izod specimens are positioned vertically (Fig. 4.2, and Fig. 4.3). Charpy impact test was used in this study, and V-notch samples of the composites were used.

This test involves releasing a heavy pendulum from a location at a height h_1 and an angle α. When the test specimen is broken, the angle of rise reaches a peak at h_2 with an angle β. The potential energy difference can be estimated using h_1, h_2, α, and β values. This difference in energy reflects the impact energy necessary to fracture the test sample. The ability of a substance to survive an impact blow is commonly known as its toughness.

Impact toughness/strength can be calculated from the following equations:

$$\text{Energy absorbed, } E = mg(h_1 - h_2) = mgR(\cos\beta - \cos\alpha) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4.6)$$

and,
$$\text{Impact strength, } U = \frac{E}{A} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.7)$$

Here,

E = Energy absorbed

m = Mass of the pendulum

g = Gravitational acceleration

$h_1 - h_2$ = Height difference

R = Arm radius

α= Angle of fall

β= Angle of rise

U = Impact strength

A = Cross section area at notch

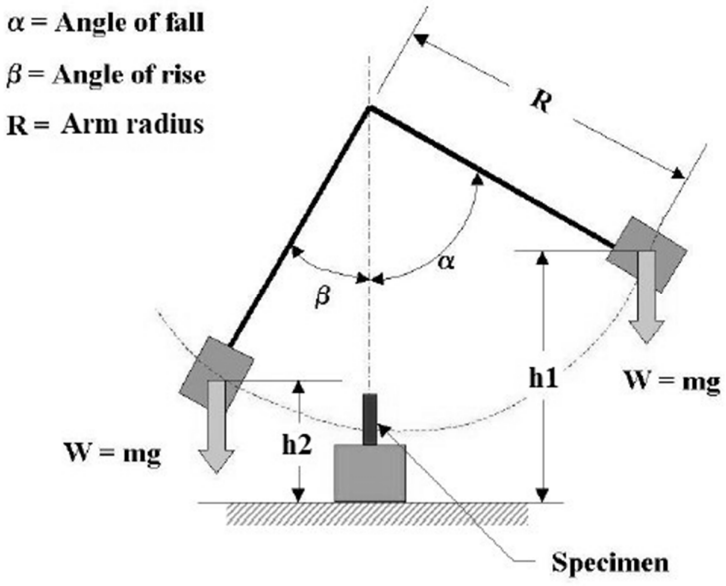


Figure 4.2: Schematic of a typical Charpy Impact test [61]

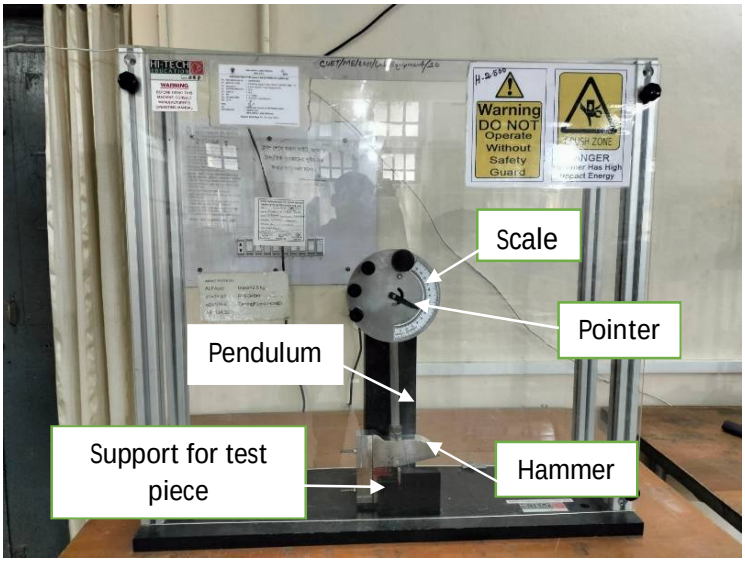


Figure 4.3: Pendulum Impact Tester used in this study
(Model: HSM41, Manufacturer: PA Hilton, England)

4.4 HARDNESS TEST

To find out how resistant a material is to being scratched or indented, a mechanical test is employed, known as a hardness test. This kind of testing is frequently used in R&D, quality control, and production. Strength, wear resistance, and ductility are just a few of the material attributes that may be learned from the tests.

Hardness may be tested in numerous ways for different materials and purposes. Hardness testing is assessed using multiple scales that vary depending on the precise hardness testing method employed. For all conventional scales, a substance's hardness is related to its hardness value; a harder material has a greater hardness. A hardness value is not a unit, but rather a number on a scale connected with a certain test. However, hardness values are provided together with the scale and test used to create them. HR denotes Rockwell hardness, HB represents Brinell hardness, HV represents Vickers hardness, and so on. In this study, the Rockwell method was applied to evaluate the surface resistance of the sample specimens.

Rockwell hardness test quantifies the extent to which an indenter is able to penetrate a surface when subjected to a significant force (major load) followed by a lesser force (minor load). Table 4.1 showed the details of the hardness test.

Table 4.1: Rockwell hardness test method and corresponding load

Method	**Load range**	**Standard**
Rockwell	15 kgf–150 kgf	ASTM D785

The Rockwell hardness test measures how deeply an indenter penetrates a material when subjected to a specified load, which is often a combination of a major load (to generate the indentation) and a minor load (to establish a reference point). Figure 4.4 depicted the schematic of the hardness test.

Below is a step-by-step process for doing a Rockwell hardness test:

Specimen Preparation: Grinding or polishing the specimen's surface is necessary to guarantee its flatness, smoothness, and absence of surface irregularities or contaminants that may have an impact on the test outcomes. It is necessary for the surface to be perpendicular to the loading orientation.

Choosing the appropriate indenter and scale: It is necessary to determine the proper indenter and scale in accordance with the material undergoing testing and the anticipated range of hardness. Steel balls, diamond, and tungsten carbide indenters are commonly used. The A, B, and C Rockwell scales are the most commonly used.

Implementation of the minor load, or the preliminary load: The load is first applied on the indenter is known as a minor load, the purpose of this minor load is to place the indenter and provide a reference point.

Implementation of the Major Load: Then a significant load which is known as major load is given to the indenter. The major load is usually bigger than the minor load and is placed on it for a set amount of time to generate a depression in the specimen's surface.

Release of the Major Load: Once the major load has been placed for the appropriate period of time, the load is released while maintaining the minor load. This enables the indenter to withdraw partly, leading to a detectable depth of indentation.

Determining the Depth of Indentation: The depth of the indentation is determined by utilising either a depth-measuring microscope or a dial gauge. The Rockwell hardness value is obtained by measuring the difference in depth between the indentation caused by the major applied load and the residual depth remaining after the load is removed.

Measuring the Hardness Value: The Rockwell hardness value is subsequently documented in accordance with the specific scale and the measured depth of indentation.

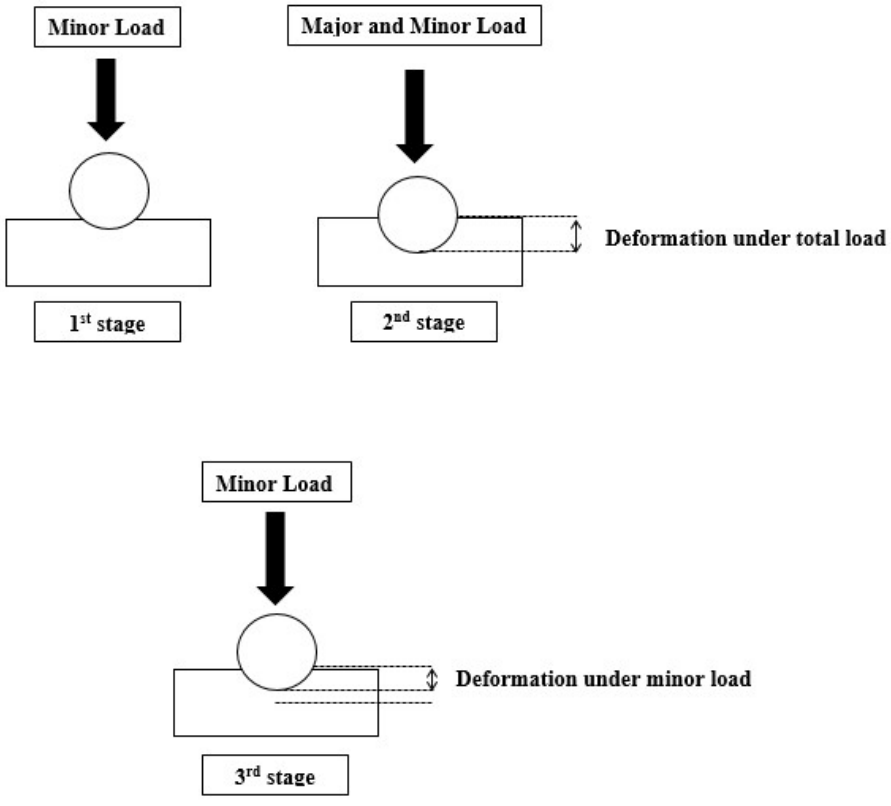


Figure 4.4: Schematic of a Rockwell hardness test

A PA Hilton hardness tester with an indenter diameter of 0.25 inches was utilized for the purpose of conducting the Rockwell hardness test in this study. Using the indenter, a minor load of 10 kg-f was exerted on the material's surface until a stable condition was achieved. Following that, the indenter delivered a major load of 60 kg-f in addition to a minor load on the surface of the material until the steady-state condition was detected. Then, the major load was removed from the surface and the minor load remained in its place. The hardness tester reading was obtained under these conditions. This chapter has elucidated about data collection procedures for this experiment. The instrument has been used to measure the hardness shown in Fig. 4.5.

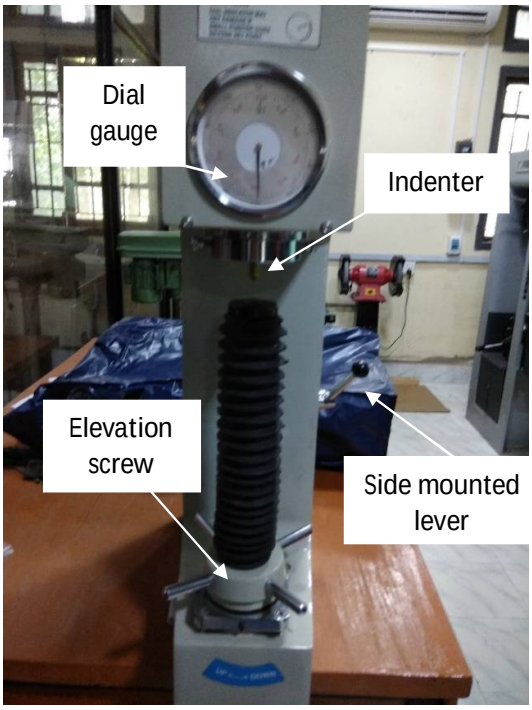


Figure 4.5: Hardness Tester used in this study
(Model: HSM51, Manufacturer: PA Hilton, England)

4.5 CONCLUSION

The current chapter provides a short description regarding the data collection processes involving this experiment. The equations that achieve the required outcomes have also been provided here. The results obtained from these methods and equations are consolidated in the next chapter.

Chapter 5

Results and Discussions

5.1 OVERVIEW

This chapter presents a comprehensive discussion of all experimental results from the mechanical characterization tests, including tensile, impact, and hardness tests. Furthermore, the obtained results are analyzed and compared with findings from previous studies conducted on various types of fiber-reinforced polymer composites.

5.2 PROPERTIES OF COMPOSITES OF HDPE WITH DISCONTINUOUS JUTE FIBER

5.2.1 Tensile Properties

To evaluate the tensile properties of composites with varying fiber content, tensile tests were conducted using a Shimadzu universal testing machine at a jaw speed of 50 mm/min. Stress-strain curves (Figure 5.1) for pure HDPE and discontinuous jute fiber-reinforced HDPE composites were generated based on the test data. The curves reveal that pure HDPE and the composite containing 20% fiber by weight exhibit lower ductility compared to the other two composites. The tensile strength, modulus of elasticity, and percentage elongation at break derived from these stress-strain curves are summarized in Table 5.1 and Fig. 5.2, 5.3, and 5.4 illustrated the corresponding plots.

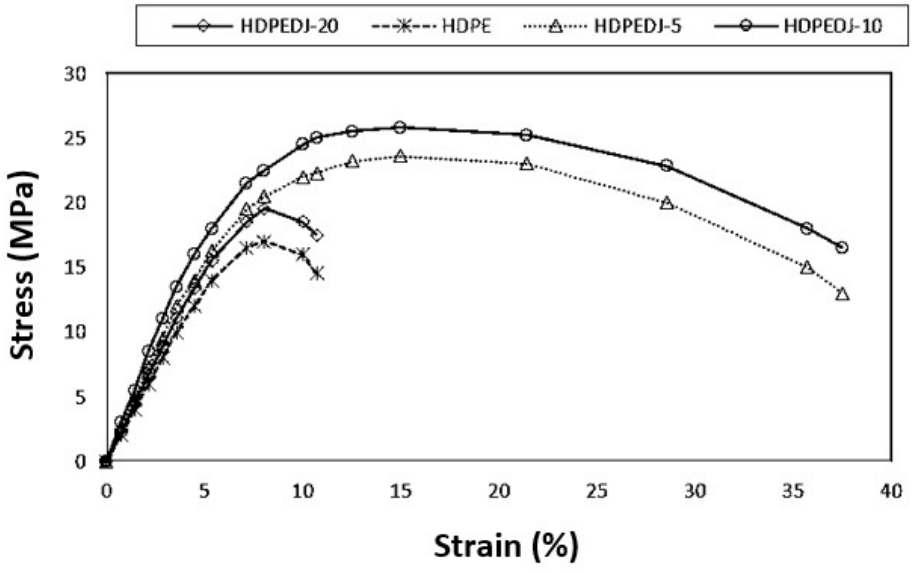


Figure 5.1: Stress versus Strain (%) curves of HDPE, HDPEDJ-5, HDPEDJ-10 and HDPEDJ-20

It was found that the tensile strength and young's modulus increase with the increase of fiber loading up to 10% weight percentage of fiber. This might be due to adding reinforcement improve the load-bearing capability, restricting the deformation of the matrix and enabling better stress transfer [67].

But, they decrease in the case of 20% weight percentage of fiber content. The reason might be due to the poor fiber-matrix interfacial bonding, fiber agglomeration at high loading and reduced continuity of the load bearing matrix [68].
The outcomes show that the rise in fiber content may not have significant impact on the tensile properties after a certain percentage (10%) of fiber content.

Table 5.1: Tensile properties of HDPE, HDPEDJ-5, HDPEDJ-10 and HDPEDJ-20

Composite samples	**Tensile Strength (MPa)**	**Young's Modulus (MPa)**	**Elongation at Break (%)**
HDPE	17	272	24.5
HDPEDJ-5	23.6 ± 0.8	305 ± 12	5.36 ± 0.6
HDPEDJ-10	25.5 ± 0.9	341 ± 15	12.5 ± 0.5
HDPEDJ-20	19.5 ± 0.6	293 ± 11	3.93 ± 0.7

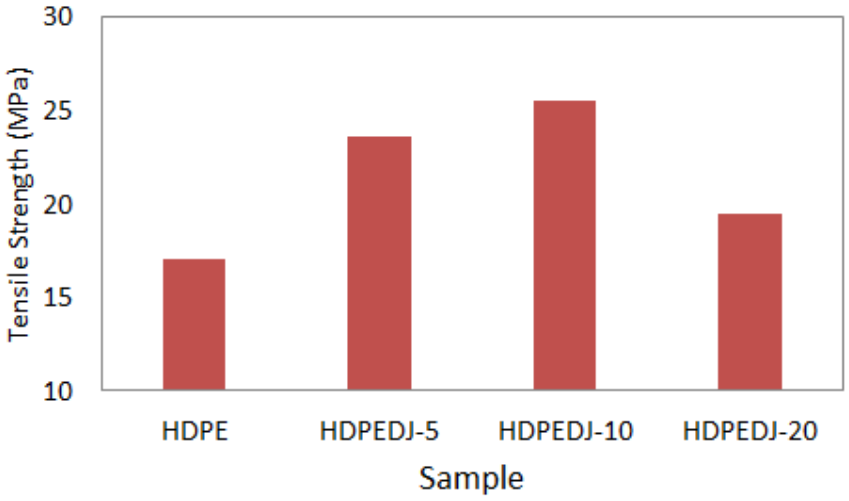


Figure 5.2: Tensile strength versus composite samples of jute fiber reinforced HDPE

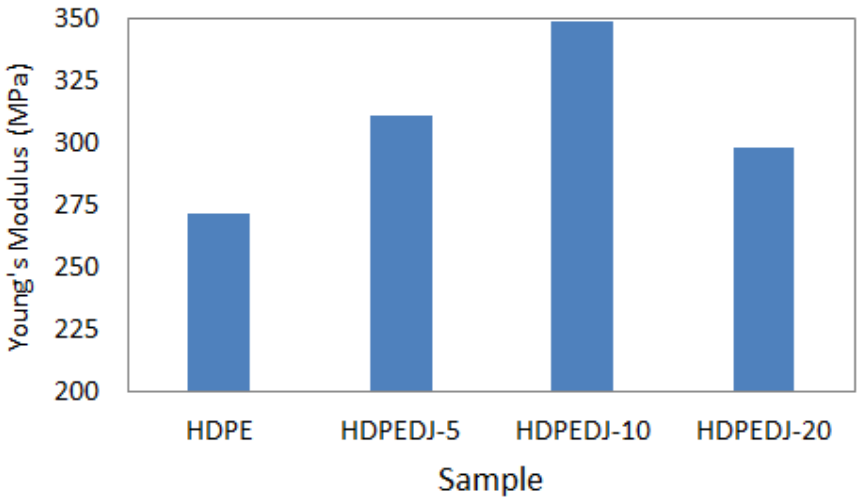


Figure 5.3: Young's modulus versus composite samples of jute fiber reinforced HDPE

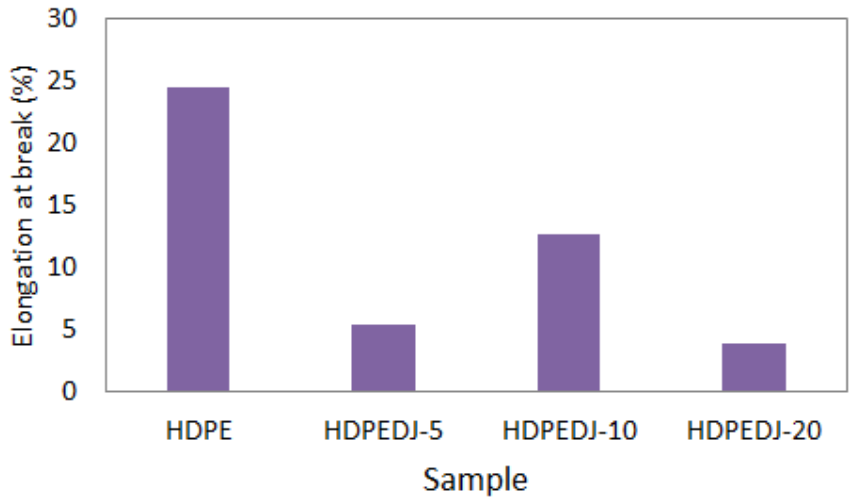


Figure 5.4: Elongation at break (%) versus composite samples of jute fiber reinforced HDPE

From the tensile tests, it is observed that elongation at break for pure HDPE is 24.5%. It reaches to 5.36 when fiber content is 5% and increases to 12.5 with increase of fiber loading which amounts 10%. But, after that it reaches to 3.93 at 20% of fiber content. The results indicate that elongation at break decreases as the fiber content rises.

5.2.2 Impact Strength

The Charpy impact test was performed using a basic pendulum hammer impact tester where V-notch specimens of the composites were used. The impact load was 2.5 kg for this test. The experimental results obtained from the mentioned Charpy impact test of the specimens are listed in Table 5.2 and illustrated in Figure 5.5.

Table 5.2: Impact Strength of HDPE and HDPEDJ-5, HDPEDJ-10 and HDPEDJ-20

Composite samples	Impact Strength (kJ/m^2)
HDPE	6.32
HDPEDJ-5	2.85 ± 0.15
HDPEDJ-10	3.15 ± 0.18
HDPEDJ-20	2.64 ± 0.12

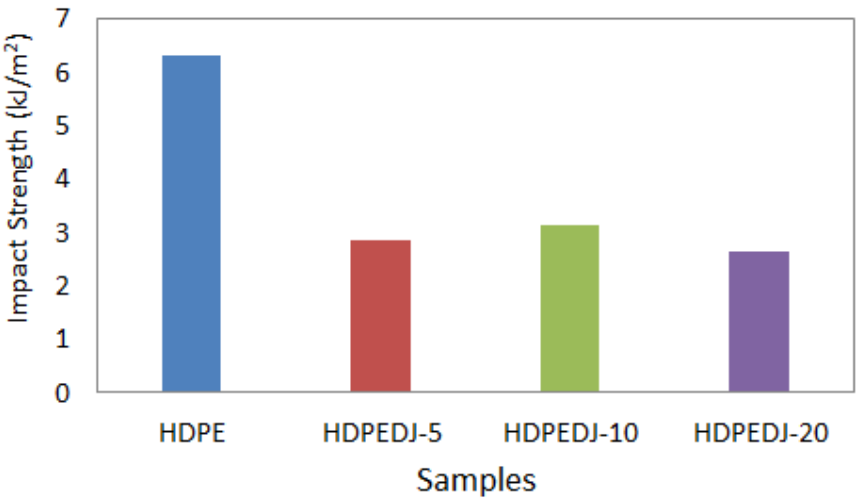


Figure 5.5: Impact Strength versus composite samples of jute fiber reinforced HDPE

From the test, it is observed that impact strength is 6.32 kJ/m^2 for pure HDPE. But, it decreases to 2.85 kJ/m^2 when 5% jute fiber content is loaded. As HDPE is ductile material, adding stiff fibers reduces ductility, making the composite brittle, thus the impact property can be reduced [69].

It is observed that the strength slightly rises to 3.15 kJ/m^2 with the rise of fiber percentage which amounts to 10%. Adding more fibers could stop or deflect cracks, making it harder for the crack to propagate, thus could absorb more energy during impact test. On the contrary, it falls and reaches to 2.64 kJ/m^2 when fiber content rises to 20%. This can be due to the higher percentage could deteriorate the interfacial bonding, causes the poor strength. The results show that the impact strength of the composites gradually declines as the fiber content increases.

5.2.3 Hardness Number

The Rockwell hardness test was conducted using a Hardness Tester on the L scale, applying a major load of 60 kg-f. The test results of the specimens are listed in Table 5.3 and illustrated in Figure 5.6.

Table 5.3: Rockwell hardness number of HDPE, HDPEDJ-5, HDPEDJ-10 and HDPEDJ-20

Composite samples	Rockwell Hardness Number (L)
HDPE	62
HDPEDJ-5	90.9 ± 1.5
HDPEDJ-10	74.8 ± 1.2
HDPEDJ-20	78.5 ± 1.3

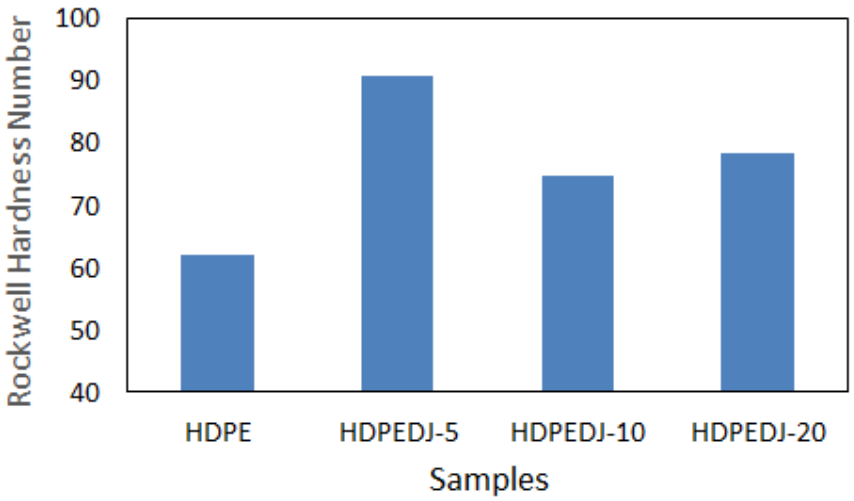


Figure 5.6: Rockwell hardness number versus composite samples of jute fiber reinforced HDPE

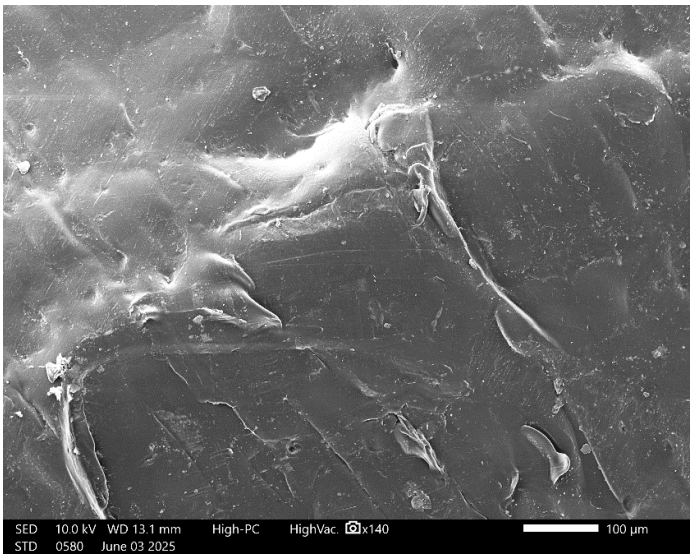
From the test, it was found that Rockwell hardness number increases significantly from 62 to 90.9 when the fiber content is 5%. As it is known that the fiber is stiffer and harder than matrix, so the polymer chain movement is restricted. It is capable of bear more load and improve resistance to indentation [70].

Thus, up to an optimal point, hardness is improving. However, the number reaches to 74.8 by falling slightly when the fiber loading increases to 10%. This might be due to poor dispersion or agglomeration and subsequent weak interfacial bonding. High percentage of fiber often leads to fiber clumping and can be act as defects instead of

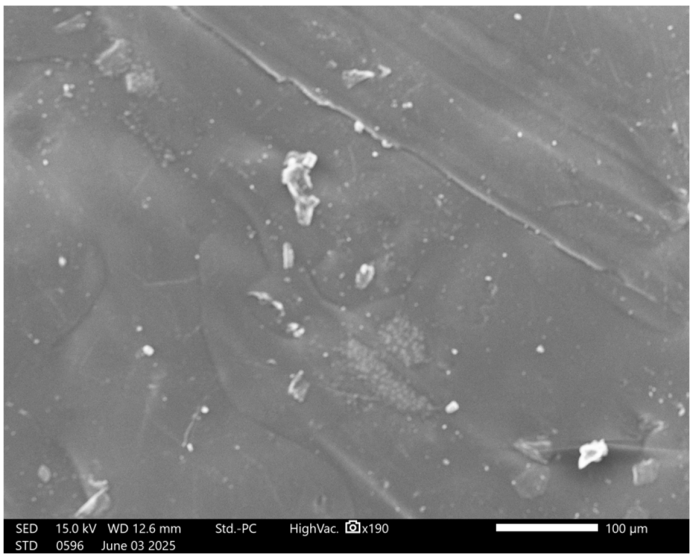
reinforcing agents. Furthermore, more fibers mean more surface area to bond with the matrix, could lead poor interfacial bonding. And, it rises again and reaches to 78.5 with further increase of fiber percentage which amounts to 20%. To wrap up, it can be said that hardness number is enhanced with the increase of fiber weight fraction.

5.2.4 Scanning Electron Microscopy (SEM)

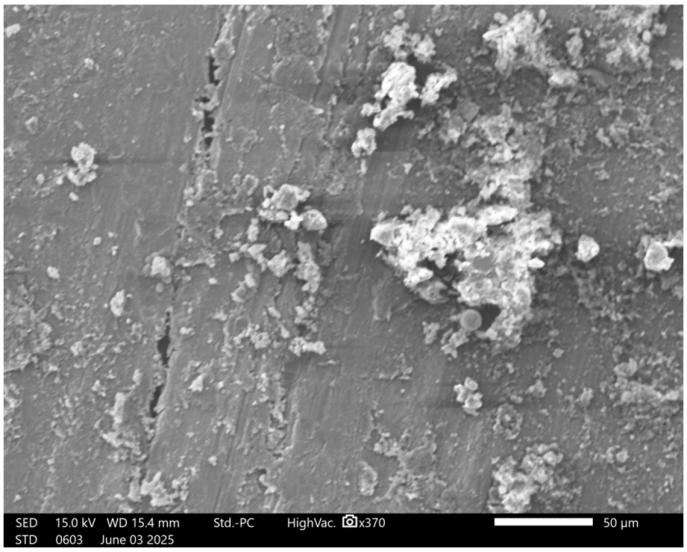
To find out the materials integrity, SEM analysis was conducted. The samples were investigated under uniform environment. As the samples were fabricated using injection molding machine, it was not possible to prepare sample with multiple layer. Due to this reason, delamination couldn't be appeared, thus only surface has been examined to check the bonding. Such uniformity has been considered to get the proper explanation about the experimental results of the fabricated composites. Figure 5.7 showed the SEM results. In case of the mechanical properties, it was observed that with the increasing of the fiber contents up to 10%, mechanical properties have been improved. For the sample containing 20% fiber loading, the strength reduced. This incident can be explained form the Figure 5.7 (c). It can be seen that, cracks has been formed into the samples after removing from the injection molding machine. Enough time has not been allowed to solidify the product, causes the crack generation. And subsequently, strength of the samples has been reduced.



(a)



(b)



(c)

Fig. 5.7: SEM images of fabricated composite samples (a) HDPEDJ-5, (b) HDPEDJ-10, and (c) HDPEDJ-20

5.3 COMPARISON WITH PREVIOUS WORKS

The results obtained from some similar previous studies and present study are compared in this segment. The tensile strength of composite materials, including other natural fiber-reinforced HDPE and jute fiber-reinforced thermoplastics, is compared with the findings of the current study.

5.3.1 Comparison with textile fiber reinforced HDPE composite

Souza et al. [62] conducted a study on the mechanical properties of high-density polyethylene (HDPE) composites reinforced with textile fibers. The textile fibers were pretreated with sulfuric acid before preparing composites containing 5% and 10% fiber by weight using the injection molding process. The research focused on evaluating the tensile strength, elastic modulus, and moisture absorption capacity of the composites. The results revealed that incorporating textile fibers into the HDPE matrix enhanced tensile strength, elastic modulus, and moisture absorption. Analysis of the fracture area indicated excellent fiber dispersion within the matrix and strong fiber-matrix interfacial bonding, which contributed to the improved mechanical properties of the composites.

The tensile strengths of the composites of 5% and 10% weight fiber obtained from this study are compared and illustrated in the Figure 5.7. From the comparative study, we can find that tensile strength increases with the increase of fiber percentage in both the cases. Tensile strength enhances 8.5% in the case of HDPE/textile fiber composite and 11.2% in the case of HDPE/jute fiber composite when fiber loading increases from 5% to 10%.

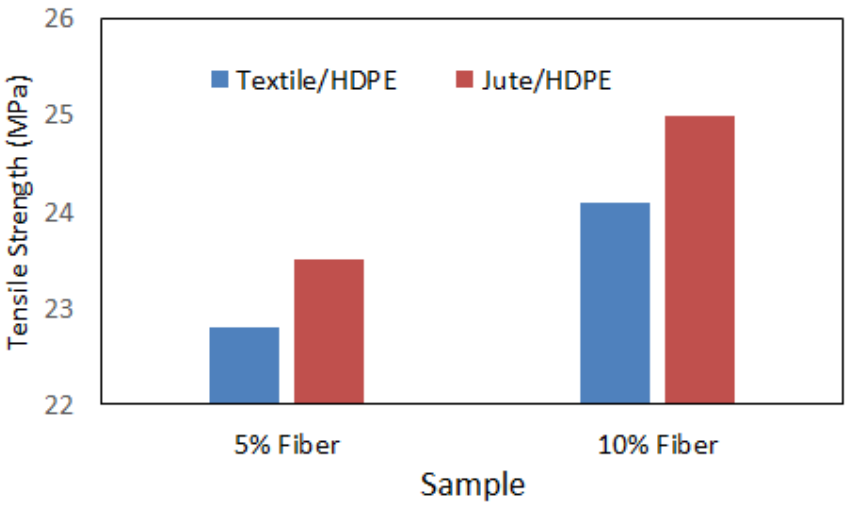


Figure 5.8: Tensile strengths comparison of Textile and Jute Fiber [62]

5.3.2 Comparison with flax fiber reinforced HDPE composite

Li et al. [63] investigated experiment on flax fiber-reinforced composites, using flax fiber as the reinforcement and high-density polyethylene (HDPE) as the matrix. The flax fibers were blended with HDPE and processed via injection molding. The fiber content

in the composites ranged from 5% to 30% by weight. Mechanical properties of the composites, including tensile and flexural strength, were evaluated. The study found that increasing the fiber content led to improvements in both tensile and flexural strength.

The Fig. 5.8 compares the tensile strength of HDPE composites reinforced with flax and jute fibers at 5%, 10%, and 20% fiber content. At 5%, both composites show similar tensile strength, with jute-HDPE performing slightly better. At 10% fiber, tensile strength increases for both, with jute-HDPE reaching its peak and significantly outperforming flax-HDPE. However, at 20% fiber, tensile strength decreases for both composites, and flax-HDPE performs better than jute-HDPE. This indicates that 10% fiber content provides the best tensile strength for jute-HDPE, while flax-HDPE shows more consistent performance.

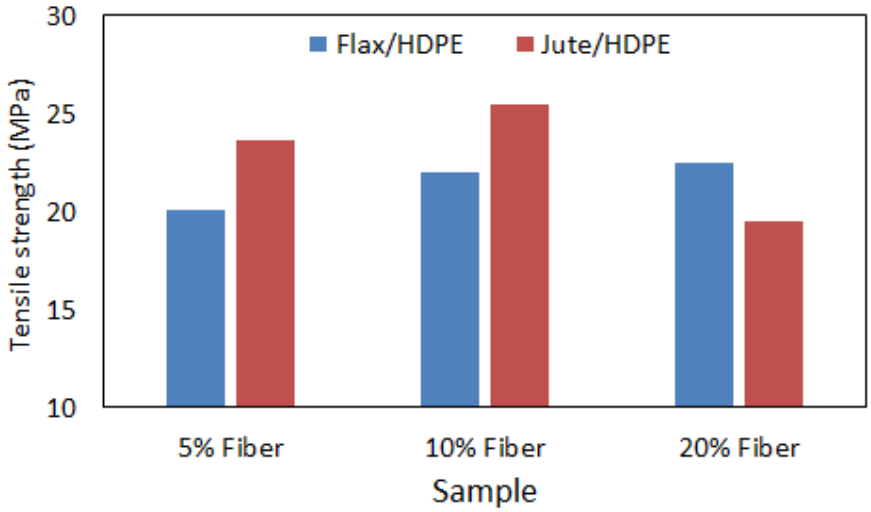


Figure 5.9: Tensile strengths comparison of Flax and Jute Fiber [63]

5.3.3 Comparison with jute fiber reinforced Polypropylene composite

Rashed, Islam, and Rizvi [17] investigated the impact of processing parameters on the tensile strength of jute fiber-reinforced thermoplastic composites. Using hot compression molding, jute fiber-reinforced polypropylene composites were produced to study the effects of fiber condition, size, and content. Both treated and untreated jute fibers of different lengths (1 mm, 2 mm, and 4 mm) and weight percentages (5%, 10%, and 15%) were used. Tensile testing and scanning electron microscopy (SEM) were performed to characterize the composites. The results showed that tensile strength improved with increasing fiber length and weight percentage, reaching an optimum at 2 mm length and

10% fiber content, after which it decreased. Additionally, treated fibers did not show a significant tensile strength improvement over untreated fibers, indicating limited effectiveness of the treatment. This research underscores the potential of natural jute fibers as environmentally friendly reinforcements but also highlights the necessity for better fiber treatments and optimized processing to enhance composite performance.

The Figure 5.9 compares the tensile strengths of Jute/Polypropylene composite and Jute/HDPE composite at 5% and 10% fiber content of 4 mm jute fiber. At 5% fiber, Jute/Polypropylene composite shows significantly higher tensile strength than Jute/HDPE composite. However, Jute/Polypropylene composite demonstrates a decrease in tensile strength at 10% Fiber Content where Jute/HDPE composite has a slight increase in tensile strength. In this case, Jute/Polypropylene composite still outperforms Jute/HDPE composite, though the gap is narrower compared to the 5% fiber content.

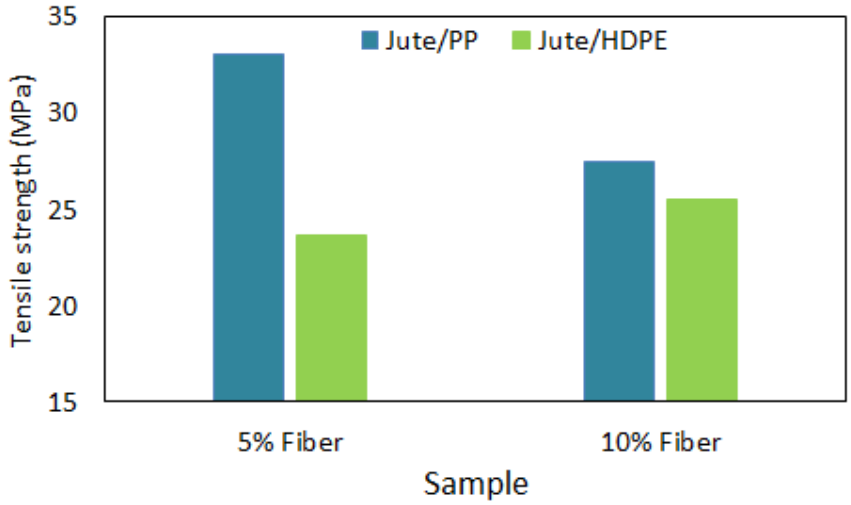


Figure 5.10: Tensile strengths comparison of Jute/PP composite and Jute/HDPE composite [17]

5.3.4 Comparison with jute fiber reinforced LDPE composite

M. J. Miah, M. A. Khan, and R. A. Khan, [64] carried out experiment on the fabrication and characterization of jute fiber-reinforced low-density polyethylene (LDPE) composites. The composites, containing 10–30% fiber by weight, were manufactured using the compression molding technique. Results showed that the jute-reinforced composites exhibited greater tensile strength (TS), bending strength (BS), and bending elongation (BE) compared to pure LDPE.

To enhance performance, jute fibers were chemically treated in a methanol solution containing a monomer 2-hydroxyethyl methacrylate (HEMA) combined with two different initiators. The fibers were soaked in two formulations: 10% HEMA + 2% Irgacure-184 (F1) and 3% HEMA + 2% benzoyl peroxide (F2), then dried for two hours at 80°C before compression molding. The chemically treated fibers significantly improved the mechanical properties of the composites by 56% in TS, 30% in BS, and 35% in BE compared to untreated LDPE. Among the two, the F2 formulation (3% HEMA + 2% benzoyl peroxide) yielded better mechanical performance than F1.

Additionally, the dielectric constant and loss tangent of the composites increased with temperature up to a transition point, after which both properties declined. Fracture surface analysis through scanning electron microscopy (SEM) confirmed that chemical treatment enhanced the adhesion between the fibers and the matrix.

Figure 5.10 presents a comparison of the tensile strengths of Jute/LDPE and Jute/HDPE composites at fiber loadings of 10% and 20% by weight. The tensile performance of jute-reinforced composites shows notable differences depending on whether the matrix is low-density polyethylene (LDPE) or high-density polyethylene (HDPE). In the case of Jute/LDPE composites, tensile strength improves as the fiber content increases from 10% to 20%, indicating enhanced fiber-matrix bonding and more efficient load distribution. Beyond 20%, a decline in tensile strength may occur due to factors such as poor adhesion or fiber agglomeration. On the other hand, as the fiber content increases from 10% to 20%, the tensile strength of jute/HDPE composites tends to drop likely because the stiffer nature of HDPE makes it harder for the fibers to bond well and share stress effectively with the matrix. Interestingly, at the 10% fiber level, jute/LDPE composites don't perform as strongly in tension compared to the jute/HDPE ones, potentially due to the superior inherent mechanical properties of HDPE. However, at 20% fiber content, jute/LDPE composites outperform jute/HDPE composites, benefiting from LDPE’s flexibility and enhanced fiber-matrix bonding.

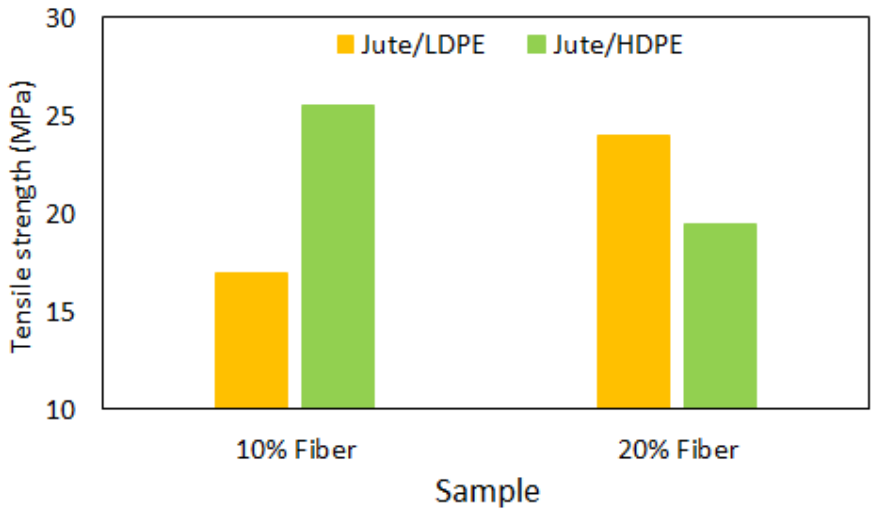


Figure 5.11: Tensile strengths comparison of Jute/LDPE composite and Jute/HDPE composite [64]

5.3.5 Comparison with jute fiber reinforced PET composite

Huq et al. [65] explored how adding linear low-density polyethylene (LLDPE) affects the properties of jute fiber-reinforced PET composites with a 50% fiber content by weight. Their research centered on understanding the mechanical performance of these composites when blended with different amounts of LLDPE, ranging from 20% to 80%. The materials were processed into thin films using compression molding. They also looked into how much water the composites absorbed to assess their hydrophilic nature. To evaluate environmental sustainability, they examined how the materials broke down in soil. Overall, the study provided a well-rounded view of how LLDPE influences the strength, water resistance, and biodegradability of jute/PET composites.

Figure 5.11 shows a comparison between the tensile strengths of jute PET/LLDPE and jute HDPE composites, each containing 20% fiber. The results reveal a clear advantage for the jute PET/LLDPE composites, which achieve a tensile strength of 27 MPa which is noticeably higher than the 19.5 MPa recorded for the jute HDPE composites, demonstrating the critical role of matrix material in determining mechanical performance. The PET/LLDPE blend benefits from PET's rigidity and crystallinity combined with LLDPE's flexibility and enhanced fiber-matrix adhesion, resulting in superior stress transfer and load-bearing capacity. In contrast, the HDPE matrix, while providing rigidity, exhibits weaker interfacial bonding with the hydrophilic jute fibers due to its non-polar nature, leading to lower tensile strength. These differences highlight

the suitability of jute PET/LLDPE composites for structural and high-strength applications, whereas jute HDPE composites are better suited for moderate-strength uses like outdoor furniture or construction materials.

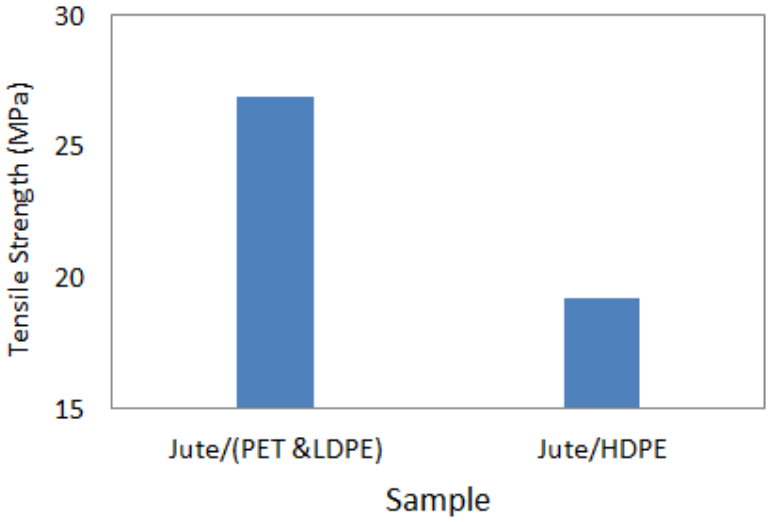


Figure 5.12: Tensile strengths comparison of Jute/PET composite and Jute/HDPE composite [65]

5.4 SUMMARY

This chapter explores the mechanical behavior of HDPE composites reinforced with short jute fibers, using tensile, impact, and hardness tests. The results clearly demonstrate that the amount of fiber added plays a key role in shaping the composite's overall strength and durability. To put the findings into perspective, the tensile performance of these jute-reinforced HDPE composites is also compared with that of other natural fiber-reinforced HDPEs, as well as jute composites using different thermoplastic materials. The next chapter will conclude the research with the examination of main findings and potential implications for this field.

Chapter 6

Conclusions and Future Works

6.1 CONCLUSIONS

Polyethylene is a highly versatile material that can be shaped using several processing methods, such as extrusion, injection molding, and blow molding. Meanwhile, natural fibers like jute are gaining attention as eco-friendly alternatives to synthetic fibers because they are biodegradable and renewable. This study aims to develop jute fiber-reinforced HDPE composites using the injection molding technique and to assess their mechanical properties through comparative analysis for better understanding and characterization.

In this study, jute fiber was used to reinforce a polymer matrix made of HDPE. The experiments involved varying the fiber content by weight to observe how different levels of reinforcement affected the composite's performance.

From the investigations of this study, it can be summarized that inclusion of the natural fiber as reinforcement resulting improvement in mechanical characteristics, such as HDPEDJ-10 sample exhibits better tensile and impact properties whereas HDPEDJ-5 showed better performance in hardness test. Segregated conclusions can be made as the followings:

1) The tensile strength of HDPE reinforced with jute fiber improved by around 39% when the fiber content reached 5%. This increase continued up to 50% as the fiber loading was raised to 10%. However, beyond this point, the tensile strength began to decline with further increases in fiber percentage. Similarly, the composite's elastic modulus steadily grew as more fiber was added. It was found maximum at 10% weight fraction of fiber which amounts to 341 MPa. It revealed that elastic modulus of the composite increased 25.36% by increase of fiber content of 10%. But, they decrease in the case of 20% weight percentage of fiber content.

   The results indicate that increasing the fiber content noticeably improved the tensile properties up to a point. The best performance was observed at 10% fiber loading. Beyond that, the benefits began to taper off. Adding more fiber likely led to greater

fiber breakage, which reduced the average fiber length and disrupted efficient stress transfer between the matrix and fibers. These factors together contributed to the decline in both tensile strength and elastic modulus.

2) From the tensile tests, we can also find that elongation at break for pure HDPE was 24.5%. It reached to 5.36 when fiber content was 5% and rose to 12.5 with increase of fiber loading which amounts 10%. But, it reached to 3.93 at 20% of fiber content. The findings indicate that elongation at break decreases with increase of fiber loading.

3) The impact strength of pure HDPE was 6.32 kJ/m2. But, it dropped by 55% to 2.85 kJ/m2 when 5% jute fiber content was loaded and slightly rose to 3.15 kJ/m2 with the rise of fiber percentage which amounts to 10%. On the contrary, it plummeted to 2.64 kJ/m2 when fiber content increased to 20%. The results demonstrate that impact strength of the composites decreases with the increase of fiber loading.

4) The Rockwell hardness number of the composite increased significantly by 46.6% when the fiber was added by 5% weight fraction. However, the number reached to 74.8 by falling slightly when the fiber loading increased to 10%. This could be due to poor dispersion of the fibers, leading to an uneven mixture with regions that are either too rich in resin or overloaded with fiber. Areas with excess resin tend to be weak, while fiber-heavy zones are more prone to developing micro-cracks. These micro-cracks can significantly reduce the overall mechanical performance of the composite [15]. The hardness number again escalated 26.6% from the pure HDPE and reached to 78.5 with further increase of fiber percentage at 20%. To wrap up, it can be said that hardness number is enhanced with the increase of fiber weight fraction.

HDPE is generally used in manufacturing of bottle caps, bottles and food storage containers. Now-a-days, it is gaining popularity to use HDPE as 3-D printing filaments. Likewise, toys can be manufactured by injection molded jute fiber reinforced HDPE composites. Because of their excellent strength-to-weight ratio, HDPE composites are well-suited for making products like boats, folding chairs and tables, and even fuel tanks in vehicles.

6.2 RECOMMENDATIONS

By analyzing the outcomes of this study, some recommendations can be given for future works which are described in the following:

- Inconsistent mixing of fibers and fiber-matrix adhesion are the leading causes of disappointing mechanical properties of the composites. This issue may be resolved through the application of appropriate surface treatments to the fiber or the use of optimal additives, such as coupling agents. In this investigation, the absence of a coupling agent is seen. Only alkali fiber treatment is utilized. To achieve improved mechanical characteristics, it is necessary to identify the appropriate coupling agent and optimal surface treatment method for the fiber.

- It's important to evaluate both the theoretical and actual tensile strength values to understand how closely real-world performance aligns with expectations. The modified rule of mixtures can be used to figure out the theoretical tensile strengths of composites and then be compared to the strengths that were actually found during tensile tests.

References

[1] N. . Azura, “Synthesis, characterization and properties of the new unsaturated polyester resins for composite application,” 2007.

[2] M. K. Gupta, R. K. Srivastava, and H. Bisaria, “Potential of Jute Fibre Reinforced Polymer Composites,” *Int. J. Fiber Text. Res.*, vol. 5, no. 3, pp. 30–38, 2015.

[3] “Injection Molding Machine : Construction, Working, Application, Advantages and Disadvantages.” https://mech4study.com/production-engineering/injection-molding-machine-construction-working-application-advantages-and-disadvantages.html/

[4] M. Mohammed *et al.*, “A Review on the Advancement of Renewable Natural Fiber Hybrid Composites: Prospects, Challenges, and Industrial Applications,” *J. Renew. Mater.*, vol. 12, no. 7, pp. 1237–1290, 2024, doi: 10.32604/jrm.2024.051201.

[5] “What is Plastic Extrusion? Understanding the Process and Its Applicationsle.” https://jfextruder.com/what-is-plastic-extrusion/

[6] S. Mirzaei and R. Siaumau, “Computational study of rapid direct metal laser sintering for compression mold manufacturing,” *Int. J. Adv. Manuf. Technol.*, vol. 130, no. 11–12, pp. 6073–6082, 2024, doi: 10.1007/s00170-024-13014-y.

[7] R. Payal, “Green composites: Versatile uses and applications in life,” *Green Sustain. Process Chem. Environ. Eng. Sci. Green Compos. Prep. Prop. Allied Appl.*, no. February, pp. 165–193, 2022, doi: 10.1016/B978-0-323-99643-3.00002-4.

[8] A. D. Nugraha *et al.*, “Investigating the mechanical properties and crashworthiness of hybrid PLA/GFRP composites fabricated using FDM-filament winding,” *Heliyon*, vol. 10, no. 20, 2024, doi: 10.1016/j.heliyon.2024.e39062.

[9] P. V. Narashima Rao *et al.*, “Fabrication and Analysis of the HLM Method of Layered Polymer Bumper with the Fracture Surface Micrographs,” *Adv. Mater. Sci. Eng.*, vol. 2022, 2022, doi: 10.1155/2022/3002481.

[10] N. Jahan, “Fiber Orientation Prediction and Strength Evaluation of Composite Spur Gears Reinforced by Discontinuous Fiber,” South Dakota State University, 2016.

[11] N. M. Barkoula, S. K. Garkhail, and T. Peijs, “Effect of compounding and injection molding on the mechanical properties of flax fiber polypropylene

composites," *J. Reinf. Plast. Compos.*, vol. 29, no. 9, pp. 1366–1385, 2010, doi: 10.1177/0731684409104465.

[12] T. A. Mohamed, R. El-Gamsy, and A. A. Abd El-Wahab, "Enhancing the Mechanical Properties of HDPE Reinforced with Flax Fibers Composites during Injection Molding Process using Numerical Optimization," *J. Manag. Eng. Integr.*, vol. 11, no. 2, p. 56, 2018.

[13] V. Mishra and S. Biswas, "Physical and mechanical properties of bi-directional jute fiber epoxy composites," *Procedia Eng.*, vol. 51, no. NUiCONE 2012, pp. 561–566, 2013, doi: 10.1016/j.proeng.2013.01.079.

[14] R. M. Hossain, A. Islam, A. W. Van Vuure, and V. Ignaas, "Effect of Fiber Orientation on the Tensile Properties of Jute Epoxy Laminated Composite," *J. Sci. Res.*, vol. 5, no. 1, pp. 43–54, 2012, doi: 10.3329/jsr.v5i1.10519.

[15] T. Munikenche Gowda, A. C. B. Naidu, and R. Chhaya, "Some mechanical properties of untreated jute fabric-reinforced polyester composites," *Compos. Part A Appl. Sci. Manuf.*, vol. 30, no. 3, pp. 277–284, 1999, doi: 10.1016/S1359-835X(98)00157-2.

[16] D. Ray, B. K. Sarkar, A. K. Rana, and N. R. Bose, "Mechanical properties of vinylester resin matrix composites reinforced with alkali-treated jute fibres," *Compos. Part A Appl. Sci. Manuf.*, vol. 32, no. 1, pp. 119–127, 2001, doi: 10.1016/S1359-835X(00)00101-9.

[17] H. Rashed, M. Islam, and F. Rizvi, "Effects of Process Parameters on Tensile Strength of Jute Fiber Reinforced Thermoplastic Composites," *J. Nav. Archit. Mar. Eng.*, vol. 3, no. 1, pp. 1–6, 1970, doi: 10.3329/jname.v3i1.923.

[18] M. A. Khan, M. M. Hassan, and L. T. Drzal, "Effect of 2-hydroxyethyl methacrylate (HEMA) on the mechanical and thermal properties of jute-polycarbonate composite," *Sci. Direct*, vol. 36, no. 1, pp. 71–81, 2005.

[19] Y. Seki, "Innovative multifunctional siloxane treatment of jute fiber surface and its effect on the mechanical properties of jute/thermoset composites," *Mater. Sci. Eng. A*, vol. 508, no. 1–2, pp. 247–252, 2009, doi: 10.1016/j.msea.2009.01.043.

[20] X. Y. Liu and G. C. Dai, "Surface modification and micromechanical properties of jute fiber mat reinforced polypropylene composites," *Express Polym. Lett.*, vol. 1, no. 5, pp. 299–307, 2007, doi: 10.3144/expresspolymlett.2007.43.

[21] S. S. S. Pavan Kumar, "Effect of Alkali treatment on jute fibre Composites," National Institute of Technology, Rourkela, India., 2007.

[22] K. M. Siddiquee, “Effects of Jute Fiber on the Biodegradation of Polymer Composites,” BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY, 2012.

[23] E. A. O. Al-Bahadly, “The Mechanical Properties of Natural Fiber Composites,” Swinburne University of Technology, 2013.

[24] M. Billah, “Mechanical Properties Characterization of Injection Molded Rattan Fiber Reinforced Polypropylene Composite Materials,” Chittagong University of Engineering & Technology, 2021.

[25] D. Ray, B. K. Sarkar, A. K. Rana, and N. R. Bose, “Effect of alkali treated jute fibres on composite properties,” *Bull. Mater. Sci.*, vol. 24, no. 2, pp. 129–135, 2001, doi: 10.1007/BF02710089.

[26] S. Muhammad, “Effect of Fiber Length and Volume Fraction on the Mechanical Properties of Jute Fiber Reinforced Polypropylene,” BANGLADESH UNIVERSITY OF ENGINEERING & TECHNOLOGY, 2006.

[27] T. Yu, Y. Li, and J. Ren, “Preparation and properties of short natural fiber reinforced poly(lactic acid) composites,” *Trans. Nonferrous Met. Soc. China (English Ed.*, vol. 19, no. SUPPL. 3, 2009, doi: 10.1016/S1003-6326(10)60126-4.

[28] M. S. Islam, S. Azmy, and A. Almamun, “Comparative Study on Mechanical Properties of Banana and Rattan Fiber Reinforced Epoxy Composites,” *Am. J. Eng. Res.*, no. 2, pp. 1–6, 2019, [Online]. Available: www.ajer.org

[29] N. V. Rachchh, P. S. Ujeniya, and R. K. Misra, “Mechanical Characterisation of Rattan Fibre Polyester Composite,” *Procedia Mater. Sci.*, vol. 6, no. December, pp. 1396–1404, 2014, doi: 10.1016/j.mspro.2014.07.119.

[30] Z. Y. Sun, H. S. Han, and G. C. Dai, “Mechanical properties of injection-molded natural fiber-reinforced polypropylene composites: Formulation and compounding processes,” *J. Reinf. Plast. Compos.*, vol. 29, no. 5, pp. 637–650, 2010, doi: 10.1177/0731684408100264.

[31] S. Nahar, R. A. Khan, K. Dey, B. Sarker, A. K. Das, and S. Ghoshal, “Comparative studies of mechanical and interfacial properties between jute and bamboo fiber-reinforced polypropylene-based composites,” *J. Thermoplast. Compos. Mater.*, vol. 25, no. 1, pp. 15–32, 2012, doi: 10.1177/0892705711404725.

[32] J. P. Manaia and A. Manaia, “Interface modification, water absorption behaviour and mechanical properties of injection moulded short hemp fiber-reinforced

thermoplastic composites," *Polymers (Basel).*, vol. 13, no. 10, 2021, doi: 10.3390/polym13101638.

[33] A. K. Bledzki, A. A. Mamun, M. Lucka-Gabor, and V. S. Gutowski, "The effects of acetylation on properties of flax fibre and its polypropylene composites," *Express Polym. Lett.*, vol. 2, no. 6, pp. 413–422, 2008, doi: 10.3144/expresspolymlett.2008.50.

[34] A. K. Rana, A. Mandal, and S. Bandyopadhyay, "Short jute fiber reinforced polypropylene composites: Effect of compatibiliser, impact modifier and fiber loading," *Compos. Sci. Technol.*, vol. 63, no. 6, pp. 801–806, 2003, doi: 10.1016/S0266-3538(02)00267-1.

[35] H. Fink and J. Ganster, "Novel Thermoplastic Composites from Commodity Polymers and Man-Made Cellulose Fibers," *Macromol. Symp.*, vol. 244, no. 1, pp. 107–118, 2006.

[36] M. Zampaloni *et al.*, "Kenaf natural fiber reinforced polypropylene composites: A discussion on manufacturing problems and solutions," *Compos. Part A Appl. Sci. Manuf.*, vol. 38, no. 6, pp. 1569–1580, 2007, doi: 10.1016/j.compositesa.2007.01.001.

[37] L. Zhang and M. Miao, "Commingled natural fibre/polypropylene wrap spun yarns for structured thermoplastic composites," *Compos. Sci. Technol.*, vol. 70, no. 1, pp. 130–135, 2010, doi: 10.1016/j.compscitech.2009.09.016.

[38] K. Oksman, "Mechanical Properties of Natural Fibre Mat Reinforced Thermoplastic," *Appl. Compos. Mater.*, vol. 7, no. 5, pp. 403–414, 2000, doi: 10.1023/A:1026546426764.

[39] I. Angelov, S. Wiedmer, M. Evstatiev, K. Friedrich, and G. Mennig, "Pultrusion of a flax / polypropylene yarn," *Compos. Part A Appl. Sci. Manuf.*, vol. 38, no. 5, pp. 1431–1438, 2007.

[40] B. Madsen and H. Lilholt, "Physical and mechanical properties of unidirectional plant fibre composites-an evaluation of the influence of porosity," *Compos. Sci. Technol.*, vol. 63, no. 9, pp. 1265–1272, 2003, doi: 10.1016/S0266-3538(03)00097-6.

[41] A. Mohammed Bukar, A. Mohammed El-Jummah, and A. A. Hammajam, "Development and Evaluation of the Mechanical Properties of Coconut Fibre Reinforced Low Density Polyethylene Composite," *Open J. Compos. Mater.*, vol. 12, no. 03, pp. 83–97, 2022, doi: 10.4236/ojcm.2022.123007.

[42] A. Jahan *et al.*, "Comparative Study of Physical And Elastic Properties of Jute And Glass Fiber Reinforced LDPE Composites," *Int. J. Sci. Technol. Res.*, vol. 1, no. 10, pp. 68–72, 2012.

[43] M. S. Islam, K. L. Pickering, and N. J. Foreman, "Influence of alkali fiber treatment and fiber processing on the mechanical properties of hemp/epoxy composites," *J. Appl. Polym. Sci.*, vol. 119, no. 6, pp. 3696–3707, 2011, doi: 10.1002/app.31335.

[44] N. Graupner and J. Mussig, "A comparison of the mechanical characteristics of kenaf and lyocell fibre reinforced poly (lactic acid) (PLA) and poly (3-hydroxybutyrate) (PHB) composites," *Compos. Part A Appl. Sci. Manuf.*, vol. 42, no. 12, pp. 2010–2019, 2011.

[45] T. M. Le, "Harakeke Fibre as Reinforcement in Epoxy Matrix Composites and Its Hybridisation with Hemp Fibre," University of Waikato, 2016. [Online]. Available: https://researchcommons.waikato.ac.nz/handle/10289/10690

[46] S. Sathish, K. Kumaresan, L. Prabhu, and N. Vigneshkumar, "Experimental investigation on volume fraction of mechanical and physical properties of flax and bamboo fibers reinforced hybrid epoxy composites," *Polym. Polym. Compos.*, vol. 25, no. 3, pp. 229–236, 2017, doi: 10.1177/096739111702500309.

[47] K. Oksman, "High quality flax fibre composites manufactured by the resin transfer moulding process," *J. Reinf. Plast. Compos.*, vol. 20, no. 7, pp. 621–627, 2001, doi: 10.1106/CA5A-6FAX-VJRB-80P0.

[48] K. Oksman, L. Wallström, L. A. Berglund, and R. D. Toledo Filho, "Morphology and mechanical properties of unidirectional sisal-epoxy composites," *J. Appl. Polym. Sci.*, vol. 84, no. 13, pp. 2358–2365, 2002, doi: 10.1002/app.10475.

[49] M. Ramesh, T. Sri Ananda Atreya, U. S. Aswin, H. Eashwar, and C. Deepa, "Processing and mechanical property evaluation of banana fiber reinforced polymer composites," *Procedia Eng.*, vol. 97, pp. 563–572, 2014, doi: 10.1016/j.proeng.2014.12.284.

[50] C. Obele and E. Ishidi, "Mechanical Properties of coir fiber reinforced epoxy resin composites for helmet shell," *Ind. Eng. Lett.*, vol. 5, no. 7, pp. 67–75, 2017.

[51] S. Goutianos, T. Peijs, B. Nystrom, and M. Skrifvars, "Development of flax fibre based textile reinforcements for composite applications," *Appl. Compos. Mater.*, vol. 13, no. 4, pp. 199–215, 2006, doi: 10.1007/s10443-006-9010-2.

[52] P. Lehtiniemi, K. Dufva, T. Berg, M. Skrifvars, and P. Järvelä, "Natural fiber-

based reinforcements in epoxy composites processed by filament winding," *J. Reinf. Plast. Compos.*, vol. 30, no. 23, pp. 1947–1955, 2011, doi: 10.1177/0731684411431019.

[53] A. Bindal, S. Singh, N. K. Batra, and R. Khanna, "Development of Glass/Jute Fibers Reinforced Polyester Composite," *Indian J. Mater. Sci.*, vol. 2013, pp. 1–6, 2013, doi: 10.1155/2013/675264.

[54] N. V. Rachchh, P. S. Ujeniya, and R. K. Misra, "Mechanical Characterisation of Rattan Fibre Polyester Composite," *Procedia Mater. Sci.*, vol. 6, no. January 2015, pp. 1396–1404, 2014, doi: 10.1016/j.mspro.2014.07.119.

[55] F. Felline, S. Pappada, R. Gennaro, and A. Passaro, "Resin transfer moulding of composite panels with bio-based resins," *SAMPE J.*, vol. 49, no. 3, pp. 20–24, 2013.

[56] T. Hojo, Z. Xu, Y. Yang, and H. Hamada, "Tensile properties of bamboo, jute and kenaf mat-reinforced composite," *Energy Procedia*, vol. 56, pp. 72–79, 2014.

[57] X. Peng, M. Fan, J. Hartley, and M. Al-Zubaidy, "Properties of natural fiber composites made by pultrusion process," *J. Compos. Mater.*, vol. 46, no. 2, pp. 237–246, 2012, doi: 10.1177/0021998311410474.

[58] T. Yimer, "Development of Natural Fiber composites for Automotive Applications," no. July, 2013.

[59] MYVIZHIRAJESWARI, G. SARAVANAN, and K., "Manufacturing and application of jute fiber composite," 2011, [Online]. Available: http://www.indiantextilejournal.com/articles/FAdetails.asp?id%0A=3732

[60] M. M. Kabir, H. Wang, K. T. Lau, and F. Cardona, "Chemical treatments on plant-based natural fibre reinforced polymer composites: An overview," *Compos. Part B Eng.*, vol. 43, no. 7, pp. 2883–2892, 2012, doi: 10.1016/j.compositesb.2012.04.053.

[61] N. M. Timme *et al.*, "IMPACT TEST," vol. 7, pp. 2–3, 2019.

[62] P. S. Souza, E. F. Rodrigues, J. M. C. Prêta, S. A. S. Goulart, and D. R. Mulinari, "Mechanical properties of HDPE / textile fibers composites," *Procedia Eng.*, vol. 10, pp. 2040–2045, 2011, doi: 10.1016/j.proeng.2011.04.338.

[63] X. Li, L. G. Tabil, S. Panigrahi, and W. J. Crerar, "Processing Flax Fiber-reinforced Polymer Composites by Injection Molding," *Biol. Syst. Can. Soc. Eng. Agric. food*, no. 05, pp. 0–8, 2005.

[64] M. J. Miah, M. A. Khan, and R. A. Khan, “Fabrication and Characterization of Jute Fiber Reinforced Low Density Polyethylene Based Composites : Effects of Chemical Treatment Fabrication and Characterization of Jute Fiber Reinforced Low Density,” *J. Sci. Res.*, no. November, 2011, doi: 10.3329/jsr.v3i2.6763.

[65] T. Huq, A. Khan, N. Noor, M. Saha, and R. A. Khan, “Fabrication and Characterization of Jute Fiber-Reinforced PET Composite : Effect of LLDPE Incorporation Fabrication and Characterization of Jute Fiber-Reinforced PET Composite : Effect of LLDPE Incorporation,” *Polym. Technol. Eng. 49 407–413, 2010*, no. March, 2010, doi: 10.1080/03602550903532174.

[66] J. Wang and Q. Yang, “Experimental Study on Mechanical Properties of Concrete Confined with Plastic Pipe,” *ACI Mater. J.*, vol. 107(2), 13, doi: 10.1007/978-3-031-68952-9_6.

[67] A. K. Mohanty, M. A. Misra, and G. I. Hinrichsen, "Biofibres, biodegradable polymers and biocomposites: An overview," *Macromolecular Materials and Engineering*, vol. 276, no. 1, pp. 1–24, 2000, doi: 10.1002/(SICI)1439-2054(20000301)276:1

[68] P. V. Joseph, M. S. Rabello, L. H. C. Mattoso, K. Joseph, and S. Thomas, "Environmental effects on the degradation behaviour of sisal fibre reinforced polypropylene composites," *Composites Science and Technology*, vol. 62, no. 10–11, pp. 1357–1372, 2002.

[69] M. D. F. Rosa *et al.*, "Cellulose nanowhiskers from coconut husk fibers: Effect of preparation conditions on their thermal and morphological behavior," *Carbohydrate Polymers*, vol. 81, no. 1, pp. 83–92, 2010.

[70] A. K. Bledzki and J. Gassan, "Composites reinforced with cellulose based fibres," *Progress in Polymer Science*, vol. 24, no. 2, pp. 221–274, 1999.