Study of Mechanical and Hydrophilic Characteristics of Hybrid Composites Manufactured by Vacuum Infusion Process

A thesis submitted in partial fulfillment of the requirements for the degree of **Master of Science in Mechanical Engineering**

By

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APPROVAL

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ABSTRACT

The increasing demand for lightweight, durable, and multifunctional materials in various engineering sectors have encouraged extensive research into hybrid composite materials. Hybrid composites, which combine different fiber and matrix constituents, offer enhanced mechanical properties and tailored functionalities, making them a promising alternative to traditional composites. This study involves fabricating hybrid composites comprising synthetic glass fibers and natural jute fibers in a polymeric matrix. The vacuum infusion process setup was developed to optimize resin distribution and minimized void content, crucial for achieving consistent mechanical performance. Comprehensive mechanical testing like tensile, flexural, hardness and impact tests were conducted to evaluate the mechanical behavior of the fabricated hybrid composites. In the study, only jute fiber composite has shown lower tensile stress, flexural stress, Impact strength and hardness. On the other hand, blending of jute with glass fiber hybrid composites have shown higher Tensile Stress(237%), Flexural Stress (800%), Impact Strength (1800%) and Hardness (22%). The stacking sequence of jute and glass fiber in the composite lamina has significant influence on the mechanical properties of the hybrid composite. The mechanical properties like tensile stress increases 11.62%, flexural modulus increases 61%, impact strength increases 60% and hardness value remained unchanged while changing the stacking sequence of jute and glass fiber in the composite laminate. The water absorption behavior of the hybrid composites were also analyzed both in fresh and salt water. The glass fibers at the outer layers of the hybrid composite lamina reduces water absorption. The jute fibers at the outer layers of the composite lamina increases fresh water absorption (1.35%, 0.86%, 3.72% and 1.26%) and comparatively reduced salt water absorption (0.47%, 0.46%. 1.60% and 0.80%). The experimental result indicates that the jute glass fibers hybrid composite has exhibited a synergistic improvement in the mechanical performances by leveraging the high strength of synthetic fibers and the eco-friendliness of the natural fibers. However, surface treatments of fibers were found to significantly improves mechanical properties by enhancing fiber-matrix adhesion and reducing moisture ingress. The findings contribute to the development of next-generation composite materials for applications in automotive, aerospace, and marine industries, where mechanical robustness and environmental sustainability are paramount.

সার-সংক্ষেপ

প্রকৌশল খাতে হালকা, টেকসই এবং বহুমুখী উপকরণের ক্রমবর্ধমান চাহিদা হাইব্রিড কম্পোজিট উপকরণের উপর ব্যাপক গবেষণাকে উৎসাহিত করেছে। হাইব্রিড কম্পোজিট বিভিন্ন ফাইবার এবং ম্যাট্রিক্স উপাদানগুলিকে একত্রিত করে উন্নত যান্ত্রিক বৈশিষ্ট্য এবং উপযুক্ত কার্যকারিতা প্রদান করে, যা এগুলিকে ঐতিহ্যবাহী কম্পোজিটগুলির একটি আশাব্যঞ্জক বিকল্প করে তোলে। এই গবেষণায় সিন্থেটিক কাচের তন্তু এবং প্রাকৃতিক পাট তন্তু সমন্বিত হাইব্রিড কম্পোজিট তৈরি করা হেয়েছ। ভ্যাকুয়াম ইনফিউশন প্রক্রিয়ায় রেজিন এর ব্যবহার সীমিত করে, হাইব্রিড কম্পোজিট লেয়ারের মধ্যে শূন্যতা কমিয়ে উন্নত যান্ত্রিক গুনাগুণ অর্জন করা সম্ভব। নিমিত হাইব্রিড কম্পোজিটের যান্ত্রিক গুনাগুণ মূল্যায়নের জন্য টেনসাইল, ফ্লেক্সসারাল, হাইব্রিড কম্পোজিটের কঠোরতা এবং ঘাত সহনশীলতার অবস্থা পযবেক্ষণ করা হয়। গবেষণায়, পাট তন্তু দ্বারা নিমিত কম্পোজিটে টেনসাইল, ফ্লেক্সসারাল, কম্পোজিটের কঠোরতা এবং ঘাত সহনশীলতার অবস্থা পযবেক্ষণ করা হয়েছে। অন্যদিকে, কাচের তন্তু এবং প্রাকৃতিক পাট তন্তু সমন্বিত হাইব্রিড কম্পোজিট উচ্চতর টেনসাইল স্ট্রেস (২৩৭%), ফ্লেক্সসারাল স্ট্রেস (৮০০%), ঘাত সহনশীলতার (১৮০০%) এবং কম্পোজিটের কঠোরতা (২২%) পওয়া গেছে। কম্পোজিট ল্যামিনায় কাচ তন্তু এবং পাট তন্তুর সজ্জার ক্রমধারা হাইব্রিড কম্পোজিটগুলির যান্ত্রিক বৈশিষ্ট্যের উপরও উল্লেখযোগ্য প্রভাব রাখে। কম্পোজিট ল্যামিনেটে পাট এবং কাচের তন্তুর সজ্জার ক্রমধারা পরিবর্তনের মাধ্যমে যান্ত্রিক বৈশিষ্ট্য যেমন টেনসাইল স্ট্রেস ১১.৬২% বৃদ্ধি পায়, ফ্লেক্সসারাল মডুলাস ৬১% বৃদ্ধি পায়, ঘাত সহনশীলতা ৬০% বৃদ্ধি পায় এবং কঠোরতার মান অপরিবর্তিত থাকে। হাইব্রিড কম্পোজিটগুলির পানি শোষণ আচরণ মিঠা এবং লবণাক্ত পানি উভয় ক্ষেত্রেই বিশ্লেষণ করা হয়েছে। হাইব্রিড কম্পোজিট ল্যামিনার বাইরের স্তরে কাচের তন্তু পানি শোষণ হ্রাস করে। কম্পোজিট ল্যামিনার বাইরের স্তরে পাটের তন্তুগুলি মিঠা পানি শোষণ বৃদ্ধি করে (১.৩৫%, ০.৮৬%, ৩.৭২% এবং ১.২৬%) এবং তুলনামূলকভাবে লবণাক্ত পানি শোষণ হ্রাস করে (০.৪৭%, ০.৪৬%, ১.৬০% এবং ০.৮০%)। পরীক্ষালব্দ ফলাফল হতে দেখা যায়, সিন্থেটিক ফাইবারের উচ্চ শক্তি এবং প্রাকৃতিক ফাইবারের পরিবেশ-বান্ধবতাকে কাজে লাগিয়ে হাইব্রিড কম্পোজিটের যান্ত্রিক বৈশিষ্ট্য উন্নতি করা হয়েছে । সিন্থেটিক ফাইবারের বহিঃআবরন হাইব্রিড কম্পোজিটে আর্দ্রতা প্রবেশ নিয়ন্ত্রণ করে আর্দ্রতার প্রভাব উল্লেখযোগ্যভাবে হ্রাস করতে সহায়তা করে। এই গবেষণায় প্রাপ্ত হাইব্রিড কম্পোজিটের ফলাফল গুলি যানবাহন, মহাকাশযান এবং সামুদ্রিক জাহাজে পরবর্তী প্রজন্মের যৌগিক উপকরণের বিকাশে অবদান রাখবে, যেখানে কম্পোজিটগুলির যান্ত্রিক দৃঢ়তা এবং পরিবেশগত স্থায়িত্ব অগ্রগন্য হবে।

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Chapter 1

INTRODUCTION

1.1. **Preface**

Hybrid composites made of natural fibers and synthetic fibers have grown considerable interest in the field of traditional composites [1]. This growing attention is primarily motivated by the desire to use environment-friendly materials in various industries [2]. Natural fiber offers a promising future to reduce the environmental impact of composite materials, preserving important mechanical properties [3]. Traditional glass and carbon reinforced polymer composites, while offering excellent mechanical properties, are derived from non-renewable resources and often require energy-intensive manufacturing processes [4-8]. Natural fiber hybrid composite is known for it's lower carbon footprint. While natural fibers may not match the mechanical properties of synthetic fibers, they still offer a respectable balance between strength and weight. The mechanical performance of natural fiber hybrid composites can be improved through various processes, such as hybridization of natural fibers with synthetic fibers and optimization of the manufacturing process [9]. The production of glass and carbon fibers involves energy-intensive processes and the release of greenhouse gases. Natural fibers, on the other hand, require less energy for processing and have a smaller environmental impact throughout their lifecycle. This makes them an environmentally responsible choice for reducing carbon emissions.

1.2. **Background**

Hybrid composite material is being manufactured through the combination of two or more fibers in a manner that imparts superior properties to the resulting material [10-11]. These composite materials consist of two main components: different types of fibers and a matrix. The fibers are the load-bearing members of the composites. The matrix distributes load evenly throughout the composite structure [12-13].

Different reinforcements are available for hybrid composites, with glass fibers/carbon fibers/aramid fibers are being the most commonly employed [14-16]. Similarly, diverse types of thermosetting polymer resins serve as matrices to bond with the reinforcement material. In the realm of composite manufacturing, glass fibers have garnered favor due to their widespread availability and cost-effectiveness, making them a preferred choice over carbon or aramid fibers [17]. Glass fibers are strong and durable and are not affected by the environmental factors like temperature, humidity. Glass fibers are cheaper than other synthetic fibers like carbon fibers. Glass fibers have low fracture toughness, good strength-

to weight ratio while compared to other synthetic fibers [18-19]. Hybrid composites are used in various applications in aircraft, automobiles, marine vessels, etc [20-21].

Hybridization reduces the adverse effects of single fiber matrix composites. Blending of two or more fibers supplements one's advantage with another's. According to Okafor et al. [22], actual hybridization is required for retaining the strength; cost reduction, weight reduction, and other environmental factors.

In recent years, there has been an increased attention in research works regarding the utilization of plant-derived fibers as fillers or reinforcements in polymer composites [23-24]. This innovative approach aims to produce sustainable and cost-effective engineering materials, aligning with the increasing environmental awareness, evolving norms and regulations, and consumer demand for bio-based materials [25]. These NFC materials, including fibers like jute, sisal, hemp, banana, and coir, offer a renewable, non-abrasive, and eco-friendly alternative [26-28]. Consequently, they are widely embraced as filler materials for bio-composites. Notably, natural fiber-based composites exhibit upgraded properties, including low weight and high mechanical properties [29].

Nonetheless, natural fiber composites do exhibit some limitations. They are prone to water absorption and thickness swelling, which can be mitigated through the incorporation of synthetic fibers [30-31]. Despite these limitations, natural fiber-based composites possess several advantages, including lower weight, cost-effectiveness, recyclability, and eco-friendliness. However, they do exhibit a lower modulus and a hydrophilic nature that results in moisture absorption, ultimately leading to reduced mechanical properties when compared to synthetic fibers. To overcome these challenges and enhance their overall performance, researchers have shifted their focus towards hybridizing natural fibers with synthetic counterparts [32-33].

From early days, composite materials have been used in many engineering applications. Ancient people used bamboo to construct mud walls by Egyptians in 1500 BCE. The swords were laminated with a composite coating in 1800 AD. The use of composite materials is increasing day by day from design to manufacturing [34]. This interest is related to the inherent advantages of natural fibers (NFs). The NFs are cost-effective, lightweight, and eco-friendly. Natural fibers selection for developing sustainable composites will improve hybrid composites performance [35].

To achieve desired mechanical properties polymer based hybridization is the ultimate choice. Here, we have to consider availability of polymer based raw materials with their prevailing high cost. In these circumstances, we may analyze feasibility of polymer based hybridization

i.e. carbon fiber and glass fiber blend for hybridization. Both have their unique combination of properties with their own set of strength and weaknesses. Following are the strength and weaknesses of polymer based hybridization:

Table 1.1: Strength and weaknesses of polymer-based hybridization

	Strength	**Weakness**
1.	High strength-to-weight ratio in Hybrid Composite.	Complex manufacturing than that of single-fiber composites.
2.	Relatively lightweight and used where efficiency and performance are essential.	Composites' properties are highly variable depending on the fiber ratio and orientation.
3.	Better load-bearing capacity due to high Stiffness.	Unexpected failures may occur under certain conditions due to high brittleness.
4.	Highly resistant to environmental factors	Difficult to recycle or dispose of
5.	Exhibit excellent fatigue resistance against cyclic loading	Different polymer has dissimilar coefficients of thermal expansion
6.	Enhance toughness and impact resistance	May not perform well in high-temperature environment
7.	Hybrid composites can be cost-effective compared to pure carbon fiber composites	Expensive material and limit their use in selected applications

Polymer composite materials have emerged as an adaptable material for wide range of industries applications, owing to their exceptional properties. For our study of hybridization, we will have to choose a polymer composite which will be available and cost effective. In that case, GFRP demonstrates the remarkable interaction of polymers and cost-effective glass fibers in different industrial applications. GFRP composites are strong compared to natural fiber composites. Glass fibers, primarily sourced from silica-rich materials like sand, are widely available, making them a cost-effective choice for reinforcement. When embedded in a polymer matrix, such as epoxy or polyester, these fibers impart remarkable tensile and flexural strength to the composite, offering a lightweight yet durable alternative to traditional construction materials like steel or concrete. This has significant cost savings, not only in

terms of material expenses but also in labor and transportation, as GFRP components are lighter and easier to handle and transport [36].

In natural fiber based hybridization i.e blend of polymer based glass fiber and natural base fiber, both have their unique combination of properties with their own set of strengths and weakness. Following are the strengths and weaknesses of natural fiber based hybridization:

Table 1.2: Strengths and weaknesses of natural fiber based hybridization

	Strength	**Weakness**
1.	Natural fibers are environmental friendly	Natural fibers are leading to long-term degradation
2.	Generally lightweight and making them suitable for various applications	Natural fibers have lower tensile strength compared to synthetic fibers
3.	Natural fibers are biodegradable	Susceptible to biological degradation, such as mold and insect infestations
4.	Natural fibers offer excellent thermal insulation properties	May not perform well in high-temperature applications
5.	Natural fibers can reduce abrasive wear on processing equipment, extending their lifespan	Mechanical properties reduce due to moisture absorption
6.	Low density and good stiffness	Low resistant to chemical exposure
7.	Manufacturing involves lower energy consumption compared to synthetic fibers	Adds complexity to the engineering design and process
8.	Engineers can tailor the composite properties	May not perform well in high-performance, high-stress applications.

Natural fiber hybrid composites have gained advantages in recent years as sustainable and cost-effective alternatives to synthetic composites. Among many natural fibers, jute fiber is abundantly available in Bangladesh. The jute fibers can significantly reduce the material expenses involved in composite manufacturing [37]. This, in turn, benefits industries looking for economical solutions. The moisture-absorbent nature of natural fibers can lead to dimensional changes in the composite, potentially affecting its mechanical properties over

time. Therefore, to maintain the properties of the natural fiber-based hybrid composite, proper moisture protection measures are essential. Furthermore, the mechanical strength of natural fiber composites may not match the high level of performance from synthetic fiber like glass fiber, limiting their use in applications requiring extreme strength and stiffness [38].

Manufacturing processes for hybrid composites influence the strength and stability of hybrid composites. There are number of process to manufacture hybrid composite considering their needs and productivity with cost effectiveness. The known process of manufacturing are Hand Layup, Automated tape making, Injection molding, Vacuum Infusion process etc. All of the manufacturing process offers range of options, each with its own advantages for ideal applications. Hand layup compression molding provides flexibility and is cost-effective for small-scale production and prototypes. Hand layup is one of the oldest and most traditional methods for fabricating composite structures [39]. It involves manually layering reinforcing fibers like carbon, glass, or aramid fibers onto a mold and wetting them with a resin matrix. The process offers great flexibility, making it ideal for small-scale application.

Automated tape making is more modern and semi-automated process for high-volume production. It involves the creation of pre-impregnated composite tapes, where fibers are pre-woven, pre-impregnated with resin, and then wound onto spool. These tapes can be made with different fiber types, allowing for hybridization. During the manufacturing process, the tapes are laid down onto a mold or substrate, layer by layer, with precision. The key advantages of this method are repeatability, reduced labor requirements, and minimal waste. Automated tape making is particularly well-suited for high-volume production in industries.

Injection molding is a process adopted in the plastic manufacturing industries, and it has also found applications in hybrid composite manufacturing. In this process, chopped fiber reinforcements are combined with a polymer matrix and injected into a mold. The injection molding has a key advantage in producing complex products. It is a particularly useful method for creating hybrid composites with short-fiber reinforcements. The injection molding for industries is essential where high production rates and part complexity are essential.

The vacuum infusion process is a versatile method for manufacturing hybrid composites [40]. It involves placing dry fiber reinforcements, including various types for hybridization, into a mold. The mold is then sealed and connected to a vacuum pump, creating a pressure differential that draws resin through the fibers. The infused resin cures to form a solid composite. Vacuum infusion is capable of producing lightweight, strong components with minimal voids. It's a popular choice in industries where weight reduction and high performance are critical, such as marine and wind energy. The hybrid composite

manufacturing process depends on some important factors such as strength, cost effectiveness, volume of production, complexity of shape. Therefore, we will adopt vacuum infusion process as the manufacturing process of natural fiber based hybrid composite.

Synthetic fiber composites have become essential in modern technology and industries due to their exceptional strength-to-weight ratio, corrosion resistance, thermal stability, and design flexibility. Carbon or glass fiber composites are driving innovation by enabling lighter, stronger, and more efficient designs in diverse applications. Composite materials are indispensable in the pursuit of energy efficiency, performance, and sustainability in modern-day technology. Composites are widely used in aerospace and aviation field. Carbon fiber composites are used in fuselages, wings, tail sections, and internal components for commercial jets and military aircraft to reduce weight and improve fuel efficiency. For space exploration rockets, satellites, and space probes use carbon fiber to withstand extreme conditions and minimize payload weight. Present automotive industries are developing composite material for high performance car, electric vehicles and in safety devices. Supercars and racing cars use carbon fiber in chassis, body panels, and aerodynamic elements (e.g., spoilers, diffusers) for reduced weight and enhanced speed. Lightweight carbon fiber components increase battery range and efficiency, crucial for EV performance. Composites crash structures improve energy absorption during collisions, enhancing passenger safety of modern cars. Composites are widely used in the Renewable Energy field. Carbon fiber composites make wind turbine blades lighter and more durable, increasing energy efficiency and reducing maintenance. Carbon fiber is used for lightweight and corrosion-resistant solar pannel frames, especially in harsh environments [41]. Carbon fiber and glass fiber composites are also used in the marine environment. In the field of defence and security composites are used to construct hulls and structure of naval vessels. Composite reduces radar signatures and improves stealth in military applications. Composites enhance ballistic protection while remaining lightweight. Composites reduce radar signature thereby military vehicle, naval ship and aircrafts become undetectable to the enemy. The use of composite increases military fighting efficiency. The increased use of synthetic fiber composites upsurges environmental hazard. Now a days, researcher is focusing on recycling synthetic fiber composites to mitigate environmental concern. On the other hand, synthetic fiber composites are costly. Therefore, fiber mixed hybrid composites are gaining popularity due to its excellent combination of mechanical performance, cost-effectiveness, and environmental sustainability. These composites combine the advantages of natural fibers, such as biodegradability and low density, with the high strength and stiffness of synthetic fibers. Natural fiber based hybrid composites are presently used in automotive industry to produce door panels, dashboards, and

other interior components along with lightweight structural elements for fuel efficiency and emission reduction. In marine and aerospace technology, it has been gaining popularity in non-critical load-bearing applications as well as enhanced durability in structures where water absorption needs control. The advantage of using natural fiber composite is biodegradable and renewable. It reduces carbon footprint compared to pure synthetic composites. Blending natural fibers mitigates waste management issues associated with pure synthetic fibers and it promotes the use of bio-based materials. Natural fiber enhances toughness, reduces brittleness, and balances weight where synthetic fibers provide high strength and stiffness. Natural fibers are cheaper than synthetic fibers, reducing overall production costs and it reduces raw material requirements without compromising strength. In this study, hybrid composites will be developed to optimize the ratio of jute to glass fiber hybrid composite to offer a promising solution for industries seeking to balance performance, cost, and environmental impact.

1.3. **Objectives**

(i) To develop an experimental setup for the manufacturing of hybrid composite materials by Vacuum Infusion Process (VIP).

(ii) To fabricate jute-glass fiber based hybrid composites by using Vacuum Infusion Process.

(iii) To investigate the mechanical properties of the hybrid composites.

(iv) To examine the hydrophilic characterization of the hybrid composite.

1.4. **Outline of Methodology**

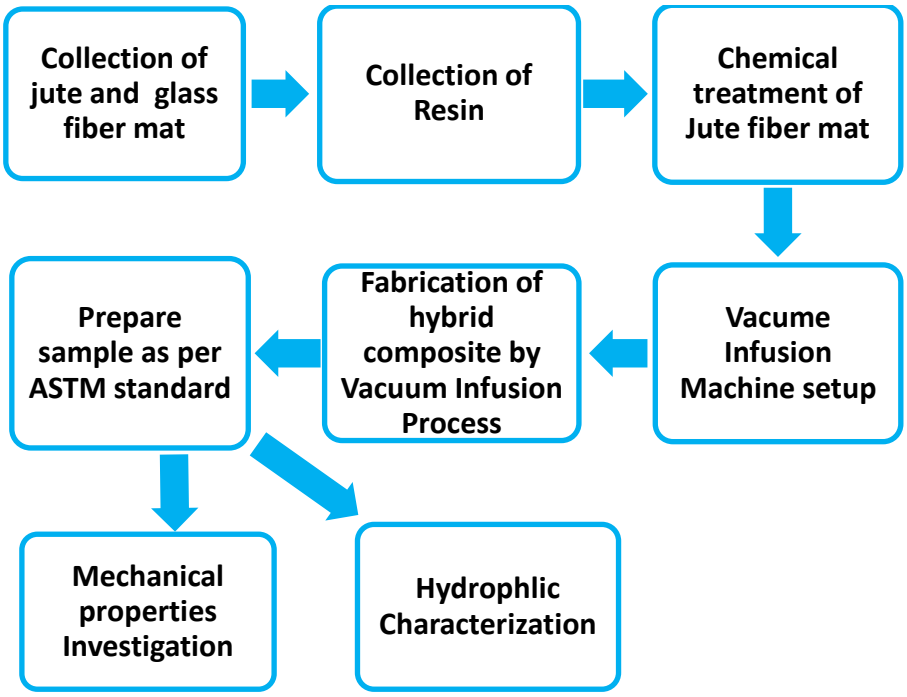


Figure 1.1 Outline of Methodology

1.5. **Scope and Limitation**

To achieve desired mechanical properties, polymer-based hybridization is the ultimate choice. Hybrid composites have emerged as a significant advancement in material science, offering superior mechanical properties. Hybrid composites encompass various categories of synthetic fiber reinforcements i.e. glass fibers, carbon fibers etc. This synthetic fiber blended hybrid composites exhibit higher mechanical properties but non-biodegradable. It will yield substantial cost but facilitates more manageable forms. Manufacturing process of hybrid composites also influences the stability of hybrid composites. The known process of manufacturing is hand Layup, Automated tape making, Injection molding, Vacuum Infusion process etc. All of these manufacturing process offers range of options, each with its own advantages for ideal applications.

Hybrid composites have attracted the academician and industrial community as viable substitutes of traditional fibers. These composites not only present themselves as sustainable and cost-effective engineering solutions but also align with the growing environmental consciousness and consumer demand for bio-based materials. The utilization of hybrid composites has emerged as a new trend in the field of materials. Natural fibers are renewable, non-abrasive, and environmentally friendly alternatives, making them widely favored as filler

materials for bio-composites. Natural fiber-based hybrid composites exhibit reasonable mechanical properties.

Several manufacturing processes are followed for fabricating hybrid composites, each with distinct effects on the strength and stability of the final products. Hand layup compression molding offers flexibility and cost-effectiveness, making it ideal for small-scale production and prototypes. In contrast, automated tape lying is a more modern, semi-automated approach suitable for high-volume production, offering advantages like repeatability, reduced labor requirements, and minimal waste generation. Injection molding is known for its ability to swiftly and cost-effectively make intricate shapes. Additionally, the vacuum infusion process (VIP) stands out for its versatility in producing lightweight, high-strength components with minimal voids. The choice of the composite manufacturing depends on several factors, including cost, production volume, part complexity, and the desired mechanical properties. Consequently, in this context, we have opted for the vacuum infusion process as the most suitable method for manufacturing hybrid composites.

Natural fiber hybrid composites exhibit meager properties due to fiber arrangements and fiber-matrix interface. However, incorporating jute fiber into glass fiber composites can significantly enhance mechanical properties, thereby mitigating the limitations of natural fiber composites. Moreover, the stacking sequence of jute and glass fiber in the composite laminate may come out with upgraded mechanical properties.

The use of polymer hybrid composite i.e. carbon and glass fiber hybrid composites offers performance but comes with complexities in manufacturing and design, as well as challenges related to variable properties and potential environmental concerns with significant cost. Proper engineering and material selection are crucial to maximize the advantages while minimizing the disadvantages in specific applications. In natural fiber and synthetic fiber hybrid composites offer advantages in terms of sustainability, cost, and lightweight properties. However, they also come with challenges related to moisture absorption, limited temperature range, variable properties, and a more limited range of applications. Careful selection and engineering are essential to maximize their benefits while mitigating their limitation. The investigation and further development of hybrid composites hold the potential for future applications.

1.6. **Outline of the Thesis**

The chapters of this report are organized as follows:

Chapter 2 reports the recent literature review regarding natural fiber like jute, hemp, or flax, with synthetic or other natural components to create versatile composite materials. It also discussed environmental sustainability, cost-effectiveness, and improved mechanical properties of composites. These composites are gaining popularity across multiple industries due to their lower weight, sustainability, and reduced environmental impact. It also describes an environment-friendly alternative to traditional synthetic composites to find applications in cars, aircraft, military, marine etc.

Chapter 3 has discussed about the material and methodology used during the experiment. It has also discussed about the fabrication of the samples, mechanical testing, and hydrophilic characterization of the manufactured hybrid composites. At the end of the chapter, the detail vacuum infusion process (VIP) for the fabrication of the specimens are also explained.

Chapter 4 has described the data reduction process which was obtained from the experiment. In this chapter mechanical properties of the hybrid composite specimens such as tensile strength, flexural strength, hardness and impact toughness data are recorded from the experiment. At the same time water absorption behavior of the hybrid composite specimens are recorded. The method of mechanical properties calculations are also incorporated in this chapter.

Chapter 5 discussed about the results obtain from the data analysis. In this chapter, mechanical characteristics are analyzed between pure glass fiber composites and jute-glass fiber based hybrid composites. Here, tensile property, flexural property, impact test, hardness test including water absorption test results are discussed on the basis of charts, graphs to find the objectives of the study.

Chapter 6 concludes the overall research with some recommendations for future studies.

Chapter 2

LITERATURE REVIEW

2.1. **Introduction**

Manufacturing natural fiber hybrid composites involves combining natural with synthetic fibers to create a composite material which exhibits improved mechanical, environmental, and cost-effective properties. The process typically involves some pre-processing of natural fibers along with preparation with special setup. Selected natural fibers should be compatibility with synthetic fibers to enhance composite performance. Thermosetting or thermoplastic resin will be used as matrix material to bind the fibers together. For hybridization, number of manufacturing process can be adopted which typically involve pressure and curing time. Testing will determine the mechanical, performance of the manufactured product. This hybridization must be sustainable, eco-friendly, reducing the environmental impact and above all cost effective. Now a day, natural fiber-based hybrid composites are gaining prominence in various industries due to their improved properties.

2.2. **Natural Fiber Reinforced Composites (NFC)**

NFCs are advanced materials that harness the strength and stability of natural fibers, such as jute, flax, hemp, or sisal, to reinforce polymer matrices. These composites are eco-friendly and lightweight, making it ideal for various applications across industries. NFCs are celebrated for their green credentials. Natural fibers are renewable resources, and their cultivation and processing typically have a lower environmental impact compared to synthetic counterparts [42]. NFCs offer a favorable strength-to-weight ratio, making them advantageous in applications where weight reduction is crucial, such as automotive components and construction materials. These composites provide excellent damping and acoustic properties, making them suitable for sound insulation and vibration-damping applications in vehicles and buildings. NFCs are biodegradable, meaning they do not contribute to long-term environmental waste, further reinforcing their ecological appeal. Natural fibers are often more cost-effective than synthetic options, contributing to cost savings in manufacturing processes. They are used in interior automotive parts, panels, and flooring, reducing vehicle weight and environmental impact [43]. In construction, NFCs are employed in building materials, reducing carbon footprints and enhancing insulation properties. Therefore, natural fiber hybrid composites are at the forefront of sustainable materials, offering a combination of strength, lightness, cost-effectiveness, and eco-friendliness [44-45].

2.3. **Matrix and Reinforcement Materials**

The synergy between the reinforcement materials and matrix in hybrid composites is a fundamental aspect that drives the overall performance and characteristics of the composite material. This combination is critical for achieving the desired properties and tailoring the material to specific applications. In a hybrid composite matrix material may also vary, and it plays an important role in determining the overall performance of the material. Common matrix materials include epoxy, polyester, and thermoplastics [46]. The matrix provides environmental protection from moisture, heat, and chemicals. Selecting the appropriate matrix material is essential to ensure that the hybrid composite can withstand the intended operating conditions. Reinforcement materials, such as fibers or particles, are chosen for their high strength and stiffness. When embedded in a matrix material, they impart these properties to the composite. The matrix material helps distribute the loads evenly across the reinforcement. The matrix material often provides durability and toughness to the composite. It protects the reinforcement materials from environmental factors, chemical corrosion, and wear. This protective role of the matrix ensures that the composite maintains its structural integrity over time [47]. Hybrid composites can be designed to balance the rigidity of the reinforcement with the matrix's ability to withstand impacts and shocks, as seen in applications like sports equipment.

In some cases, the matrix material may enhance the thermal or electrical conductivity of the composite, depending on its intrinsic properties. This synergy is vital in applications where heat dissipation or electrical conduction is required, such as in electronic components or thermal management systems. The matrix material, especially in polymer composites, contributes to the lightweight nature of the hybrid composite [48]. When combined with high-strength reinforcement materials, this results in a material with an excellent strength-to-weight ratio. Weight reduction is particularly significant where fuel efficiency and performance are critical. The choice of the matrix material can provide environmental and chemical resistance to the composite. The hybrid composites are capable of withstanding harsh environments, like offshore structures, where the matrix material helps protect the reinforcement materials from corrosion and degradation [49]. The synergy between the matrix and reinforcement materials is achieved through careful selection and design. Engineers and material scientists assess the specific requirements of the application and choose matrix and reinforcement materials that complement each other. The combination of materials allows for a tailored approach to meet the desired performance characteristics, such as strength, stiffness, durability, weight, and environmental resistance. This flexibility makes hybrid composites an optimal option for industries and various applications.

2.4. **Constituents of Natural Fibers**

Plants and animals are the source of fibers and their composition varies depending on the origin. Natural fibers, such as cotton and flax, primarily consist of cellulose, a complex carbohydrate. Cellulose are made from glucose, provide strength and flexibility. Animal-based natural fibers like silk are mainly composed of fibroin proteins, known for their remarkable tensile strength. Coir, from coconut husks, contains lignin and cellulose, offering durability and resistance.

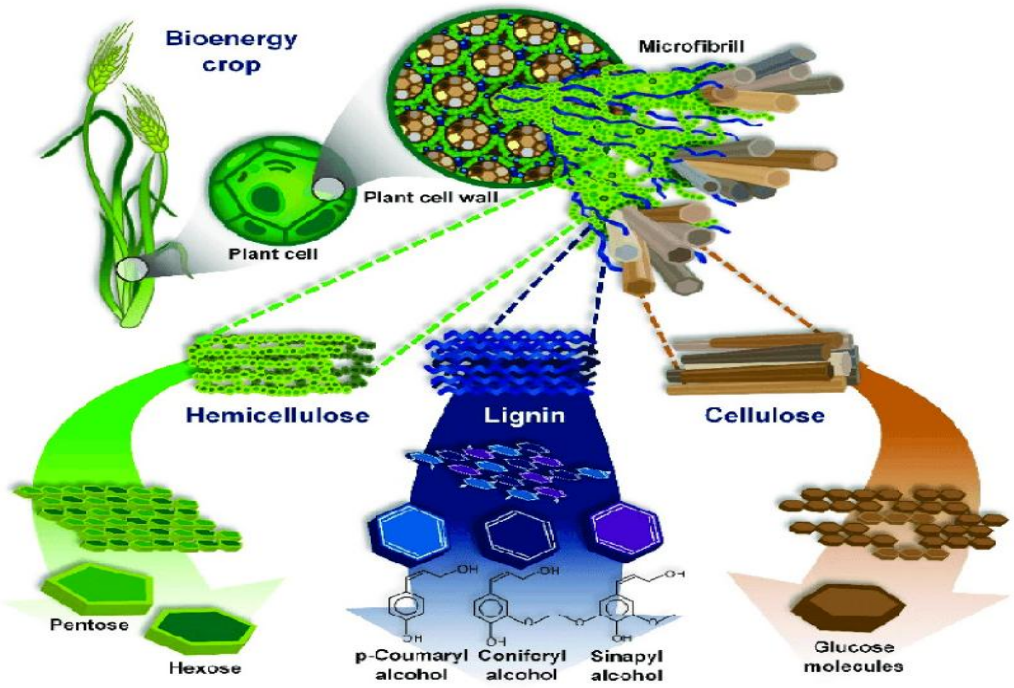


Figure 2.1. Schematic representation of the structural hierarchy in a plant fiber [50].

Each natural fiber's unique composition imparts distinct properties, making them valuable in textiles, construction, and various industrial applications, while also emphasizing their biodegradable and renewable characteristics. Plant fibers are weak in strength. The dimensional irregularities are the major cause to lower performance. Natural fiber surfaces need to be cleaned to remove impurities. The following shows different natural fibers major constituents in the Table 2.1:

Table 2.1. Properties of the natural fibers [2][29]

Fibers	Cellulose (wt%)	Hemicellulose (wt%)	Lignin (wt%)	Micro-fibrillar angle
Coir	36-43	0.03	41-43	41-45
Kenaf	72	20.3	9	9 -15

Fibers	Cellulose (wt%)	Hemicellulose (wt%)	Lignin (wt%)	Micro-fibrillar angle
Sisal	67-78	10-14	8-11	20
Flax	62-72	18.6-20.6	2.5	5-10
Cotton	83-90	5.7	<2	-
bamboo	60.8	30	32	2-10
Jute	61-71.5	13.6-21	12-26	8

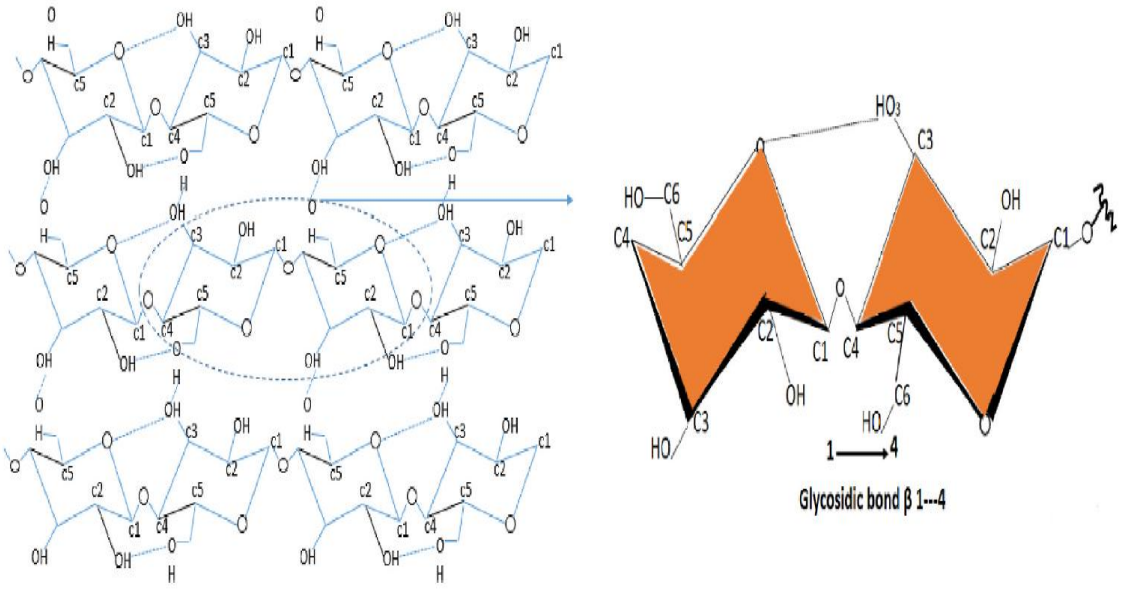


Figure 2.2. Molecular Structure of Cellulose [50]

2.5. **Jute as Natural Fiber**

Jute is a versatile natural fiber that has found increasing use in hybrid composites, combining its unique properties with those of other materials to create advanced engineering solutions [51]. Jute is obtained from the jute plant's stem, making it a renewable and environmentally friendly resource. Its key characteristics, when used in hybrid composites, contribute to several benefits. Jute fibers possess moderate tensile strength and impressive flexibility. When incorporated into hybrid composites, they complement the overall mechanical properties, enhancing both tensile and flexural strength [52]. Jute is biodegradable, which is a significant advantage in environmentally conscious industries. Hybrid composites with jute reduce the environmental impact and promote sustainability, especially in sectors like automotive, construction, and packaging. Jute is cost-effective compared to many synthetic fibers, making it an attractive choice for industries seeking to reduce material costs while maintaining performance [53-54]. However, jute fibers have limitations, such as susceptibility to moisture

and relatively lower tensile strength compared to some synthetic fibers. To overcome these limitations, hybrid composites often incorporate jute with materials like glass or carbon fibers. This combination leverages the strength and moisture resistance of the synthetic fibers while benefiting from the sustainability and cost-effectiveness of jute.



Figure 2.3. Various types of natural fibers [55]

Jute and glass fiber hybrid composites have shown higher environmental tolerance. The common matrix material is epoxy resin. Epoxy resin is costly compared to polyester resin. The bonding performance of polyester resin has no significant downside.

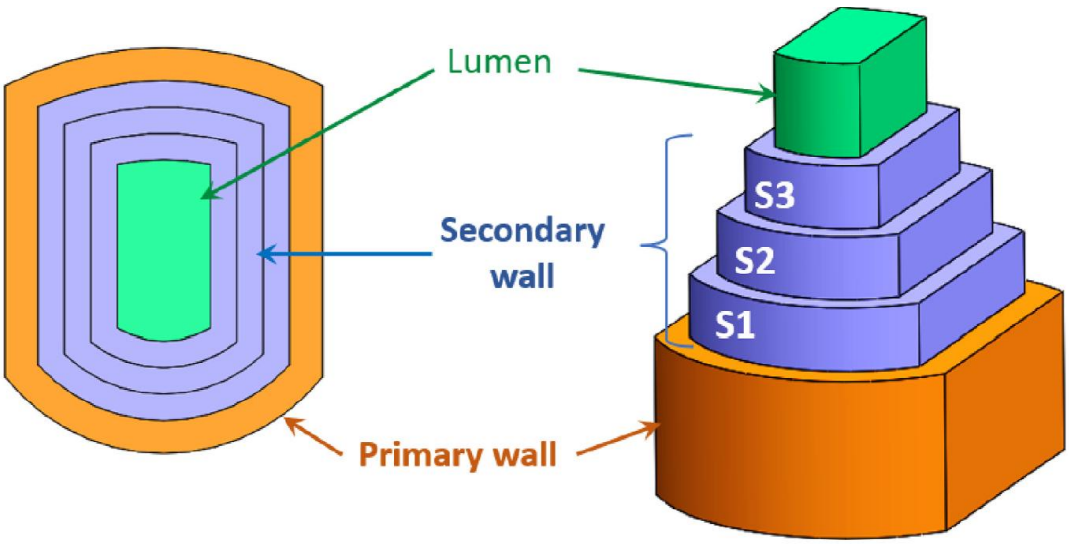


Figure 2.4. Microstructure of Natural Fibers [55]

Natural fiber like jute requires chemical treatment to eliminate any impurity. Hybrid composite are made with different techniques and process [56]. It reduces the hydroxyl group on the natural Fiber, effectively decreasing the hydrophilicity and roughens up the surface. This can lead to the overall improvement in mechanical and moisture absorption performance of the hybrid composite.

2.6. **Chemical Treatment of Natural Fibers**

Chemical treatment is essential for the natural fibers to reduce their hydrophilic nature. The natural fiber hybrid composites having lower mechanical performance. Natural fibers are water absorbent and shows lower strength than synthetic fibers. The alkali treatment is one of the viable options which is economical and powerful. The effect of the NaOH treatment had been studied by the researchers. The NaOH concentration (1, 5, and 10 %) and the submerge length (0, 24, and 48 h) had different consequences on the fiber surface morphology [57-58]. The previous study also showed that alkali and sodium bicarbonates produce higher quality compared to the raw jute fibers. The treatment ensures a neutral environment for necessary bonding with the matrix resin. If the surface of the natural fiber is not treated with NaOH, the impurity like wax and oils will be present in the fiber. The crystalline characteristics are also impacted by alkali treatment, which transforms cellulose I into cellulose II [55].

2.7. **Vacuum Infusion Process (VIP)**

The vacuum infusion process is a sophisticated and widely used manufacturing technique for producing high-quality composite materials. It involves several critical steps to ensure the proper infusion of resin into the reinforcement fibers. The process starts with the mold preparation, which shapes the composite part. Layers of reinforcing fibers, such as carbon, fiberglass, or aramid, are laid out in the mold to form the structural core of the composite part. These layers are collectively known as the "layup." In addition to fibers, core materials like foam or honeycomb may be included for added strength and stiffness. The specific orientation and arrangement of the fibers in the layup are designed to meet the mechanical and structural requirements of the final product. Once the layup is complete, a vacuum bag is placed over the entire assembly, enclosing the fibers and any core materials. Vacuum bagging materials, like release film, breather cloth, and peel ply, may also be added to the setup. A vacuum is applied to the bag, and it is sealed to the mold, creating a sealed environment. Prior to resin infusion, a network of resin distribution channels is established on top of the dry layup. This network, often created using spiral tubes or a "plumbing" system, ensures an even flow of resin throughout the layup. Liquid resin, usually an epoxy, is poured into a reservoir. This resin is specifically chosen for its compatibility with the reinforcement fibers and its ability

to provide the desired mechanical properties. A non collapsible plastic pipes are connected to the vacuum bag, and a vacuum pump is turned on. This creates a pressure differential between the bag and the ambient atmosphere. As a result, air is drawn out of the layup, creating a low-pressure environment. The vacuum also compresses the dry layup, removing any air between the fibers and compacting the materials. The low-pressure environment inside the vacuum bag helps facilitate the flow of resin into the dry layup. The resin is pulled into the fibers to saturate them fully and evenly. As the resin flows through the layup, it displaces air and fills voids, ensuring that the entire structure is impregnated with resin. After complete resin infusion, the entire setup, including the mold, layup, and vacuum bag, is placed in an oven or allowed to cure at room temperature. Curing hardens it and binds the fibers together. The curing process may take several hours or days, depending on the resin type and cure cycle. Once the composite part has fully cured, the vacuum bag is removed, and the part is carefully demolded from the mold. Any excess resin or flash is trimmed, and the final composite part is inspected for quality and dimensional accuracy.

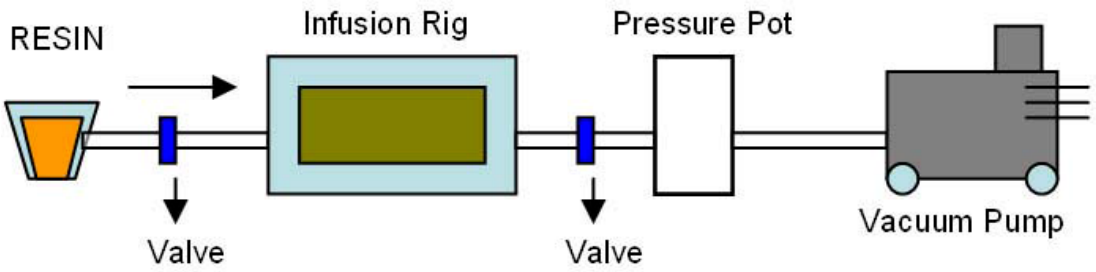


Figure 2.5. Vacuum Infusion Process (VIP) Diagram [56]

The VIP allows number of advantages. The process allows for a high fiber volume fraction, meaning that a significant portion of the composite is made up of strong, lightweight fibers. This results in excellent strength-to-weight ratios and stiffness. Vacuum infusion ensures uniform and thorough wetting of the fibers with resin. This eliminates dry spots and air voids, leading to improved mechanical properties and consistent quality. The process is suitable for creating complex, intricate, and large parts with consistent fiber placement. This flexibility is crucial in industries like aerospace and automotive. Vacuum infusion minimizes resin waste. The resin is drawn into the dry layup under vacuum, so there is less excess resin that needs to be trimmed or disposed of. Vacuum infusion results in a smooth, high-quality surface finish. The resin flows evenly over the mold surface and conforms to the mold shape, reducing the need for extensive post-processing. The process offers precise control over resin flow, infusion pressure, and temperature, allowing for customization of mechanical properties. The

reduction in resin waste and emissions make vacuum infusion a more environmentally friendly composite manufacturing method compared to other techniques. Over time, the reduced labor and material costs can make vacuum infusion a cost-effective manufacturing process, particularly for large-scale production. The resulting composite materials have excellent mechanical properties [56].

On the other hand, this process has some disadvantages with challenge. Setting up a vacuum infusion system can require a significant initial investment in equipment, including vacuum pumps, distribution systems, and curing ovens. Vacuum infusion is a relatively complex process, and it may require skilled technicians to ensure proper setup, monitoring, and control. Curing times can be relatively long, which may depend on the types of fiber and types of resin. This can impact production throughput. Infusing thick composite parts can be challenging, as resin may take longer to travel through the layup, potentially leading to variations in resin distribution. Ensuring a consistent resin infusion and quality control during the process is critical to avoid defects and variations in material properties. Resin choices are crucial, and some resins may be sensitive to environmental factors, which can impact the process or the final material properties. The vacuum infusion process is best suited for epoxy resins and some thermosetting materials. Thermoplastics are generally not compatible with this process. The vacuum system and other equipment require regular maintenance to ensure consistent and reliable performance. Overall, its ability to create lightweight, strong, and environmentally friendly composite materials makes it a valuable choice in various industries.

2.8. **Previous Studies**

Composite materials are superior materials created by two or more distinct fibers to obtain enhanced properties. Composites offer benefits like improved strength-to-weight ratios, corrosion resistance, and tailored characteristics. These ongoing advances continually expand the applications and environmental benefits of composites. Conventional composites like metal matrix composites enhance strength and stiffness of metals by ceramics or carbon fibers. This combination results in materials that are both lightweight and incredibly strong, making them ideal for applications that demand a high strength-to-weight ratio i.e. aerospace, automotive, and sporting industries. Advance composites are synthetic fiber-reinforced composites such as carbon, glass, or aramid. The synthetic fibers contribute to the composite's strength and stiffness, while the polymer matrix imparts flexibility and durability. Carbon fiber composites are renowned for their exceptional strength and low weight, making them a top choice for applications like high-performance sports equipment, aircraft components, and automotive parts. Glass fiber composites are known for their cost-effectiveness and are often

used in boat hulls, wind turbine blades, and construction materials. Presently, NFCs are gaining popularity in industries. Hybrid composites offer optimum mechanical properties, thermal insulation, and a reduced carbon footprint. Their biodegradability also makes them a responsible choice for reducing waste and pollution.

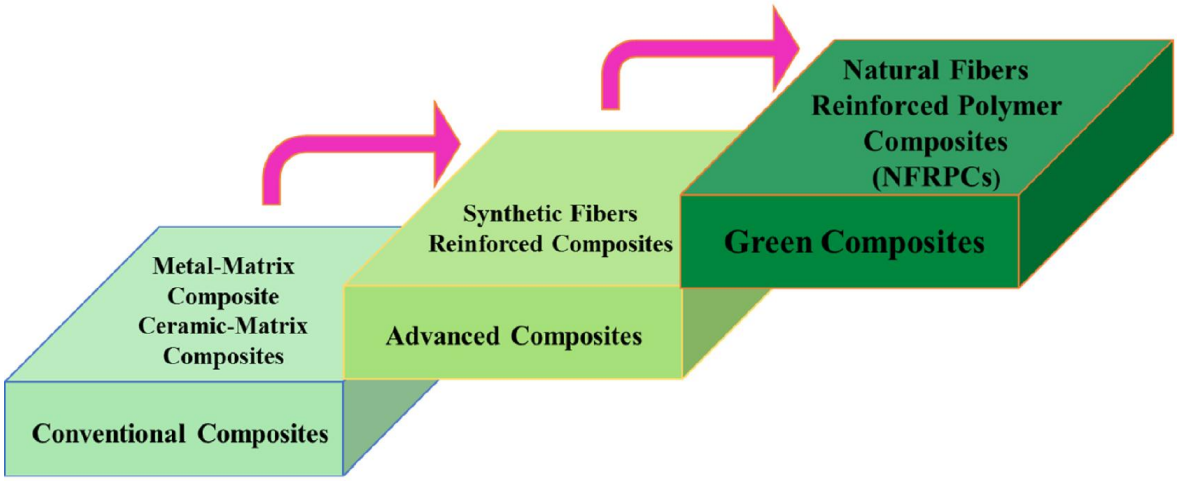


Figure 2.6. Advancements in composite materials [59].

Green composites' recyclability is one of the major motivators, with less environmental impact and with less associated energy consumption during processing. The release of CO_2 is less during the processing. In Kyoto Protocol, composites are declared as non-greenhouse gases.

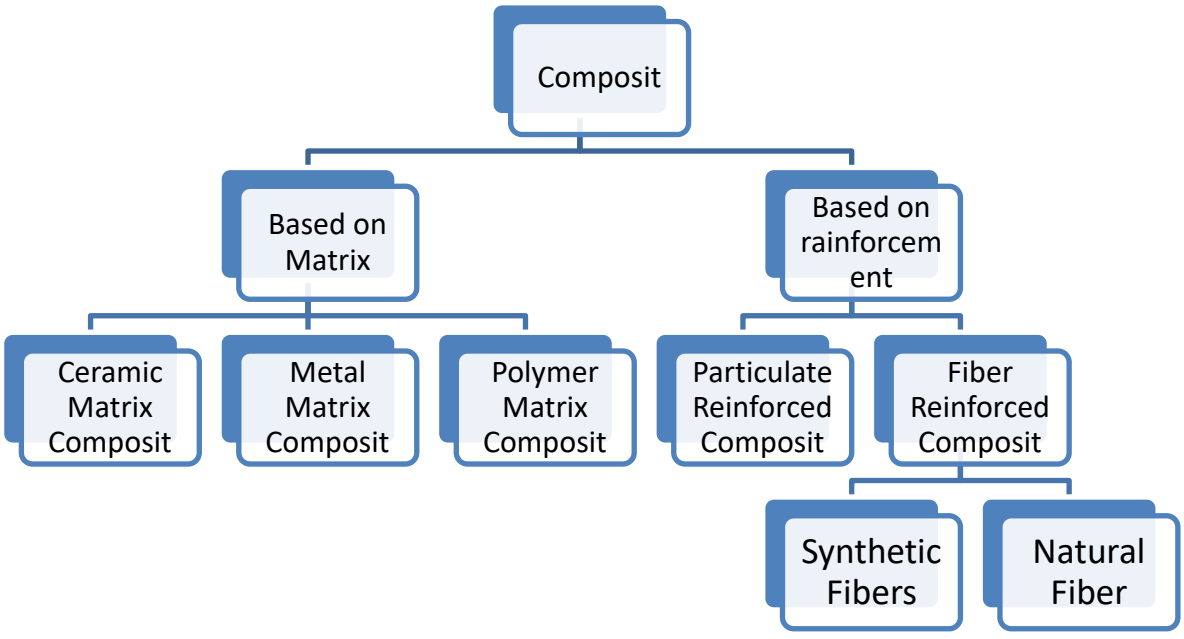


Figure 2.7. Classification of Composites [23]

In the study Yusoff et al. [60] has developed kenaf, bamboo, and coir hybrids composites by hot press technique. These fibers were arranged to create two configurations: high modulus and brittle (HMB) fibers (kenaf-bamboo-coir/PLA) and low modulus and ductile (LMD) fibers (coir-bamboo-kenaf/PLA) shown in Figure 2.8. The study revealed that the linear increase in the tensile strength and modulus reached up to 158 MPa and 7 GPa, respectively. The inclusion of HMB fibers in the outermost layers enhanced the flexural strength up to 49% compared to the LMD fibers. Conversely, the impact strength was 21% higher when LMD fibers were placed in the outermost layers. The water absorption capacity reached 39%, attributed to the increased fiber content.

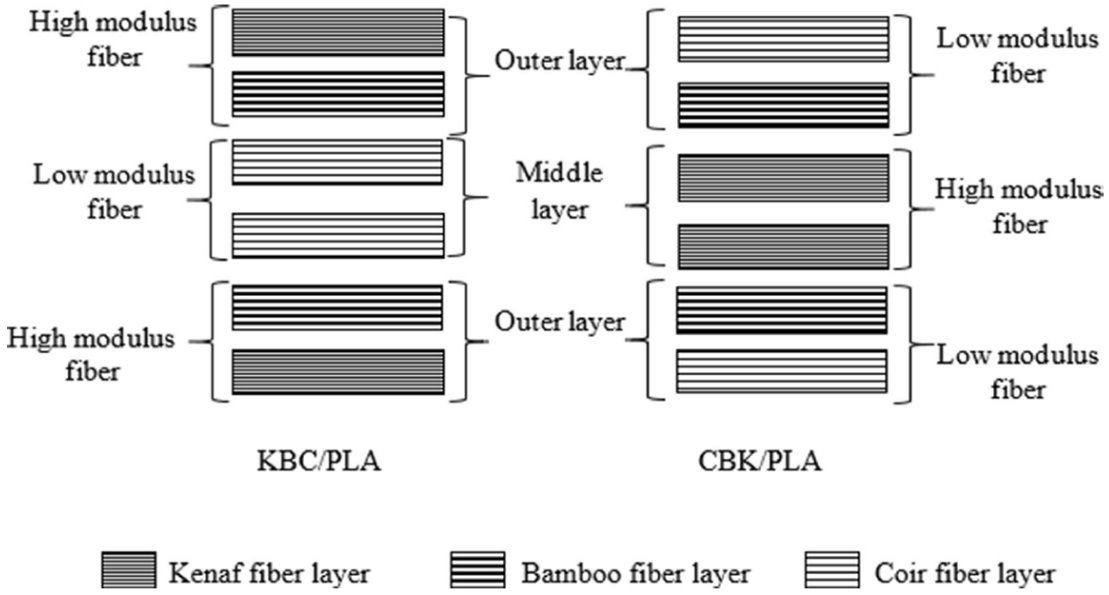


Figure 2.8 Hybrid composites [60]

Senthilkumar et al. [61] has developed pineapple leaf fiber (PALF) hybrid composite by hot press technique, demonstrating superior flexural strength of 44.39 MPa and a flexural modulus of 4.82 GPa. Incorporating olive tree leaf (OTL) powder into the epoxy matrix resulted in reduced flexural properties. It shows that pineapple leaf fiber hybrid composites have better mechanical properties. Figure 2.9 shows increasing the PALF content enhanced impact strength by 3 to 8 times.

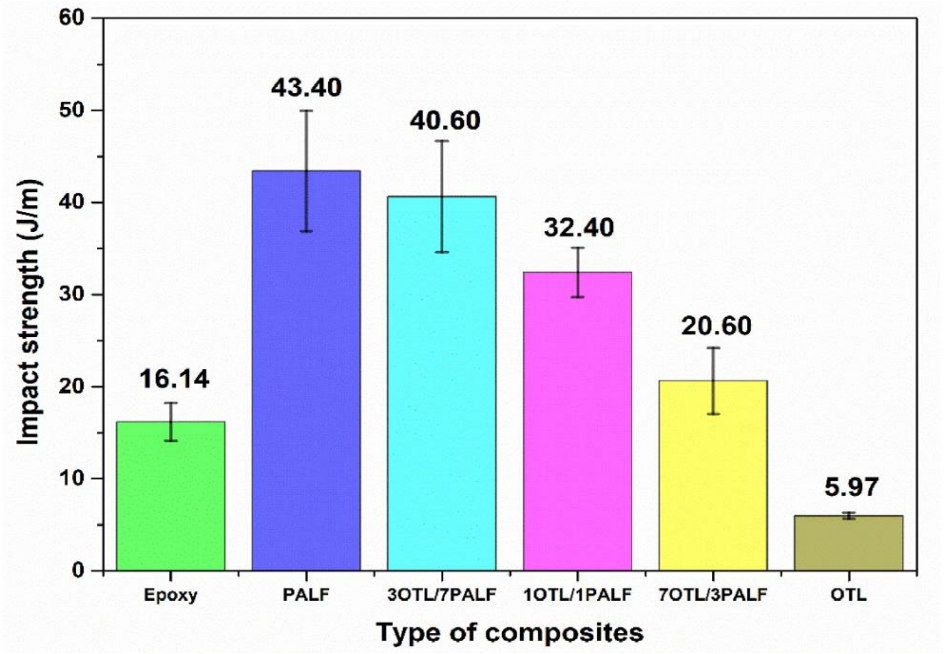


Figure 2.9. Impact strength of PALF/OTL fiber reinforced composites [61]

Nadondu et al.[62] has developed hybrid composite composed of glass fiber (5 wt%), carbon fiber (10 wt%), durian skin fiber (10 wt%), and polylactic acid (75 wt%) by injection molding process. It exhibited a tensile strength of 77.686 MPa, an impact strength of 26.761 kJ/m², and a hardness of 74.159 on the E scale (Rockwell). The study found that the tensile strength was highest when the glass fiber was at the center of the lamina. On the other hand, while increasing the carbon and durian skin fiber contents would reduce hardness.

Ramesh et al. [63] fabricated sisal/GFRP and jute/GFRP hybrid composites using the hand layup process. The sisal/GFRP composite exhibited superior tensile strength of 68.55 MPa. Meanwhile, the jute/GFRP composite demonstrated higher flexural performance of 1.03 kN, slightly higher than the sisal/GFRP sample. The study finds that sisal/GFRP composites are better suited for tensile loading, whereas jute/GFRP composites perform more effectively under flexural loading.

Lekrine et al. [64] developed hybrid bio-composite materials incorporating biochar (Bi) and WF fibers to analyze the effects of different treatment durations (24, 48, 72, 120, and 168 hours) with 10% sodium bicarbonate ($NaHCO_3$). Among the studied bio-composites, PLA/BiWF-72 exhibited the highest tensile strength (37.41 ± 0.91 MPa) and flexural strength (61.89 ± 2.89 MPa). However, at a 168 hours treatment duration, the flexural strength decreased to 51.53 ± 1.92 MPa, and the tensile strength dropped to 33.46 ± 0.86 MPa, indicating that longer processing times reduce both tensile and flexural strength. The highest

impact resistance was observed in the bio-composite (3.453 ± 0.197 kJ/m²). Beyond 24 hours of treatment, impact resistance gradually declined as shown in fig 2.10.

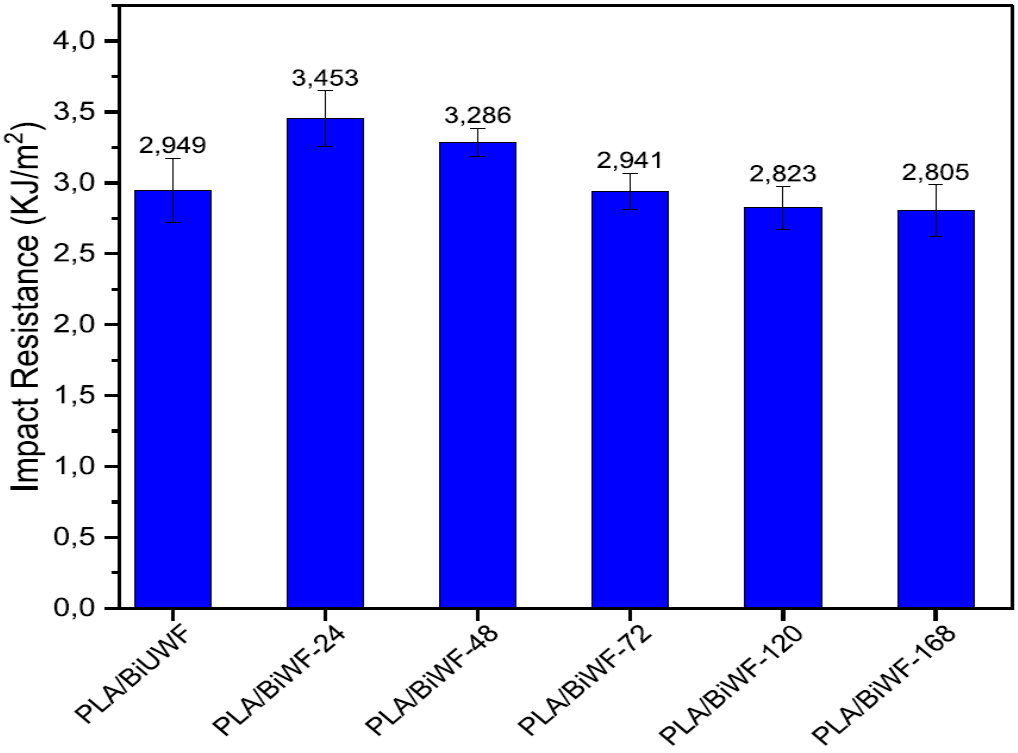


Figure 2.10 Impact resistance of hybrid bio-composite[64]

Batu et al. [65] studied false banana fiber and glass fiber (B/G) reinforced hybrid composites by varying fiber orientation and fiber volume which was fabricated by hand layup process. The experiment indicates that fiber orientation significantly impacts mechanical properties i.e. with the 0° direction (fibers aligned along the load direction) yielding the best performance. Among the tested volume fractions, B/G: 10/40 (the lowest false banana fiber content) exhibited the highest value. The highest compressive strength recorded was 35.687 MPa for the B/G: 10/40 composite, whereas the lowest tensile strength of 9.29 MPa was observed at a B/G: 40/10 ratio. The highest tensile modulus (1355.6 MPa) was also found in the B/G: 10/40 composite, while the lowest tensile modulus (293.71 MPa) was recorded for B/G: 40/10. These results suggest that higher glass fiber content enhances tensile strength and modulus of elasticity. Overall, the study found that as the false banana fiber content increases, the composite's mechanical strength decreases.

Supian et al. [66] fabricated date palm fiber-reinforced epoxy composites and date palm/bamboo hybrid composites using hand lay-up technique. As shown in Figure 2.11, the date palm fiber (DPF) specimens exhibited the highest tensile values (DPF-G: 6.32 GPa, DPF-AA: 5.96 GPa, DPF-L: 5.91 GPa, and DPF-A: 5.58 GPa). The bamboo composite specimen

(B) followed with a tensile modulus of 5.46 GPa, while the lowest values were observed in the date palm fiber/bamboo hybrid composites (DPF-A/B: 5.30 GPa, DPF-L/B: 5.18 GPa, DPF-AA/B: 5.02 GPa, and DPF-G/B: 5.01 GPa). According to Figure 2.12, the bamboo composite exhibited the highest flexural strength (B: 68.19 MPa), followed by the hybrid composites (DPF-A/B: 61.10 MPa, DPF-AA/B: 61.09 MPa, DPF-L/B: 60.81 MPa, and DPF-G/B: 60.56 MPa). The date palm fiber composites recorded the lowest flexural strength (DPF-G: 58.20 MPa, DPF-A: 55.22 MPa, DPF-AA: 48.86 MPa, and DPF-L: 40.34 MPa). These results suggest that bamboo fibers enhance the flexural properties of date palm fiber composites when hybridized. Findings from Figure 2.13 indicate that the bamboo composite specimen had the highest impact strength (B: 13.87 J/m), followed by the hybrid composites (DPF-L/B: 12.70 J/m, DPF-AA/B: 12.33 J/m, DPF-G/B: 12.09 J/m, and DPF-A/B: 11.56 J/m). The date palm fiber composites exhibited the lowest impact strength (DPF-AA: 10.69 J/m, DPF-L: 9.18 J/m, DPF-A: 8.61 J/m, and DPF-G: 8.56 J/m). Figure 2.13 also highlights that hybrid composites with a 50:50 date palm fiber/bamboo fiber ratio achieved higher impact strength than pure date palm fiber composites. Overall, the results suggest that lower modulus fibers correspond to higher elongation values.

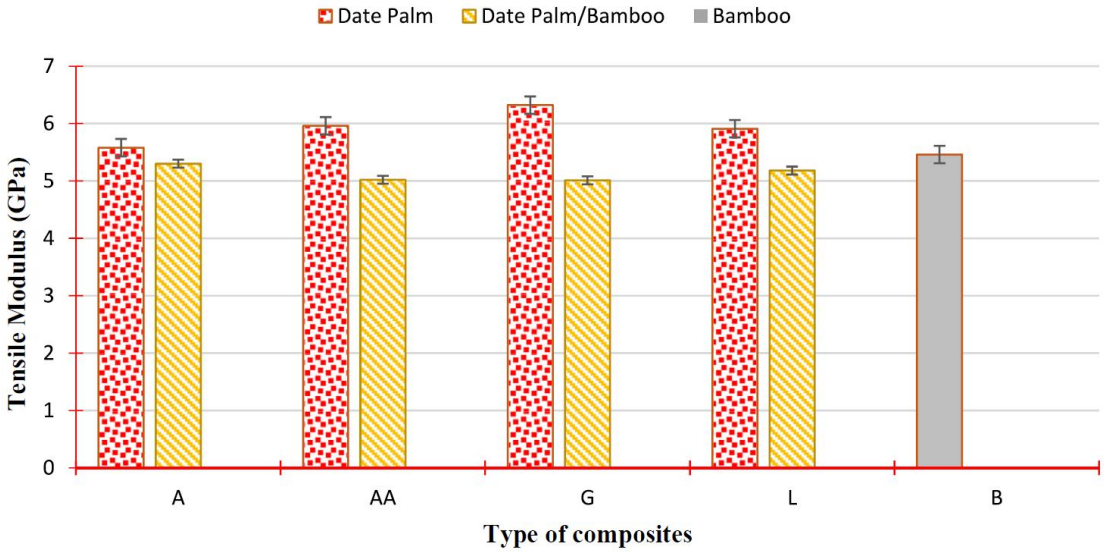


Figure 2.11 Tensile modulus of different composite [66]

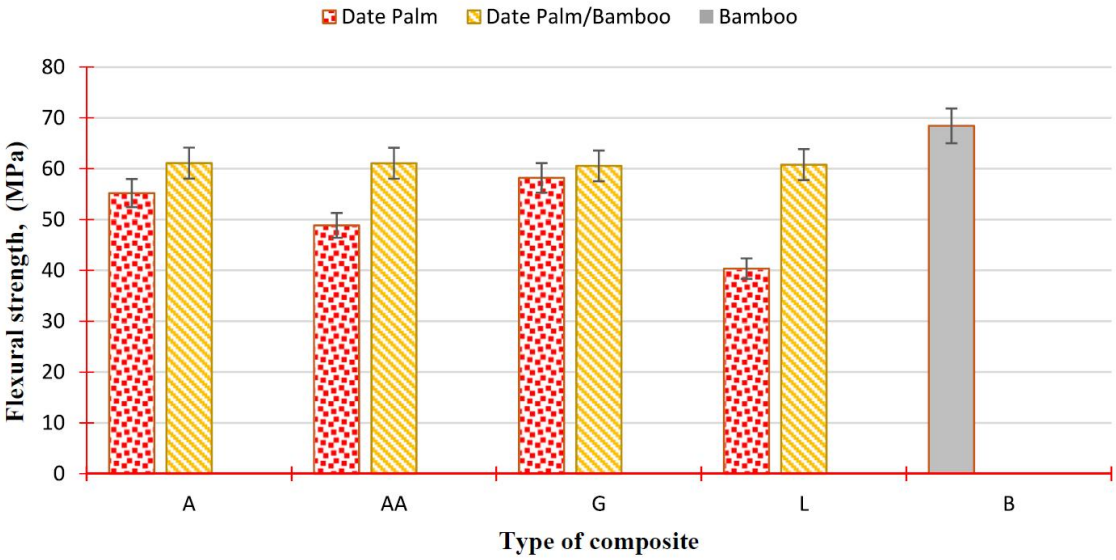


Figure 2.12 Flexural strength of different composites [66]

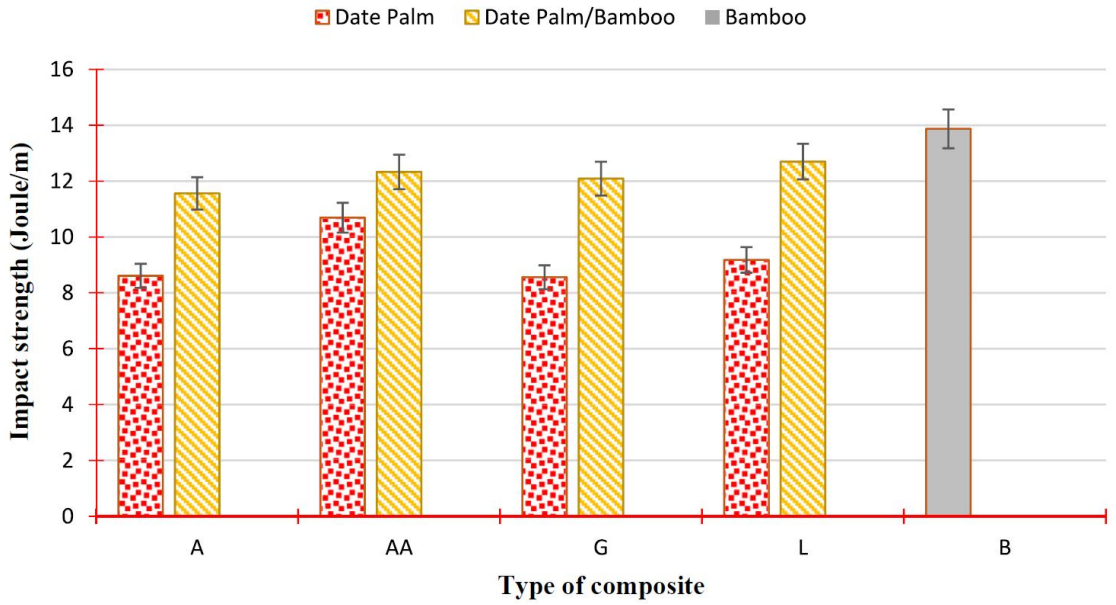


Figure 2.13 Impact strength of different composite [66]

In this study Munshi et al. [67] hybrid composites were manufactured by using rattan fiber, carbon fiber, jute fiber, and epoxy resin as matrix materials. The fabrication is done by hand lay-up method. The results indicated that composites reinforced with plain weave rattan fiber R3C2 & R3J2, compared to R5 composites, the tensile strength of these samples increased by 104.36% and 349.68%, respectively. Additionally, the flexural strengths of R3C2 and R3J2 composites improved significantly by 218.41% and 90.9%. It has been found that the hybrid

composites with rattan fibers demonstrate enhanced physical, mechanical, and thermal properties.

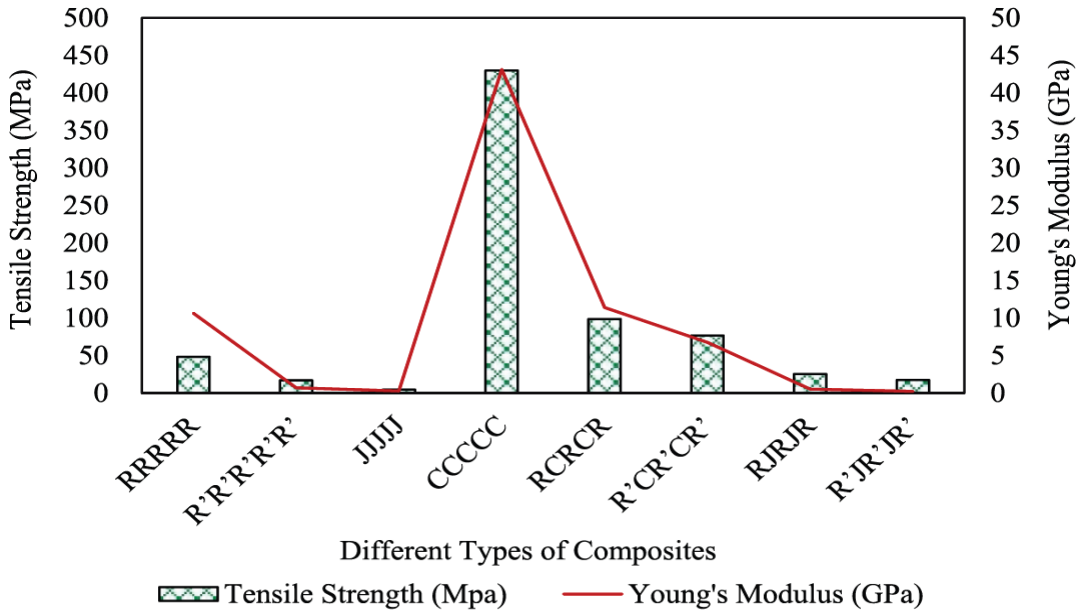


Figure 2.14 Tensile behavior of hybrid composite [67]

In this study of hybridization in bio-composite development by Baigh et al. [68], the jute fiber reinforced polymer (JFRP) composites have showed superior tensile strength of 35.16 MPa, while hybrid composites showed a maximum of 32.16 MPa. Among the manufactured hybrid composites, jute layers on the outer plies exhibited the highest tensile modulus of 1.315 GPa. Additionally, a hybrid composite with three jute layers alternating with jute-pineapple plies demonstrated the greatest elongation at 15.94%. In terms of flexural strength, an alternating jute/PALF ply arrangement achieved 44.36 MPa, comparable to JFRP (44.91 MPa), with a 78.57% increase in flexural modulus.

In this study Hossain et al. [69], jute and glass fiber were used to make a graphene-based composite and manufactured by hand layup with mechanical press. In comparison to the composite reduced graphene oxide (without rGO), the composite's (prepared with rGO) tensile strength was increased by 146%, flexural strength by 122%, impact energy by 144%, thermal conductivity by 108.33%, and electrical conductivity by 127.21%.

In the study Tewelde et al. [70] has found that the tensile strength has relation with volume fraction. The hybrid composites manufactured by hand lay up process have the maximum tensile strength of 223.83 MPa at ratio of 20WH/30GF. On the other hand, tensile strength is the lowest 106.5 MPa at 30WH/20GF. The composite 20WH/30GF has the highest compressive strength, which is of 63.52 MPa. The composite 30WH/20GF has the lowest

compressive strength 44.88 MPa. The result shows that the compressive strength of WH /GF composite varies with the change in fiber volume fraction.

The hybrid composites were developed by Marichelvam et al. [71] using by hydraulic press. The polyester resin is used as a matrix. The fibers were marcarized with 5% sodium hydroxide (NaOH) solution. The treated composite sample ratio of Hibiscus cannabinus fiber, Madar, Gongura fiber (40:20:40) exhibits a tensile strength of 34.720 N/mm^2, flexural strength of 77.957 MPa, and flexural modulus of 1548.588 GPa. The average water absorption of the sample is 2.45%.

In the study Oyewo et al. [72] chose polyester resin and hand lay-up technique. It was found that banana and coir fiber had different tensile strength. The tensile strength of the BBC was 76.3 while the BCB was 71.5 MPa. Among the manufacturing processes, hand lay-up is economical; other methods like compression, injection etc., are efficient for large-scale production.

Shifa et al. [73] developed hybrid composites consisting of glass fiber and wheat straw by hand lay-up method. 30 wt % fiber exhibits a greater tensile stress (54.4 MPa) than 20 wt % or 10 wt % respectively. So, tensile stress increases with increasing fiber content. Flexural stress boosts with enhancing the fiber loading i.e. 30 wt% of treated fiber contains the highest flexural strength (88.76 MPa) compared to other types of composites

In this study Rao et al. [74] has investigated tensile, flexural and impact strength of untreated and treated CA fiber/BF epoxy hybrid composites. The tensile strengths of the CA fiber/BF composite (CA1+BF1) were measured at 59.79 MPa for the untreated sample, 63.83 MPa for the PLA-coated sample, 67.26 MPa for the alkali-treated sample, and 70.42 MPa for the PLA-coated + alkali-treated CA fiber/BF composite.

In this study Gupta et al. [75], the jute glass fiber hybrid composite with polyester resin is used. The glass fiber/polyester composite (S1) experienced a tensile strength and Young's modulus of 374.9 MPa and 6.44 GPa respectively, while the jute fiber/polyester composite structure (S5) experienced a tensile strength and Young's modulus of 41.8 MPa and 3.86 GPa, respectively.

In this study Queiroz et al. [76] fabricated composite panels using carbon fiber and jute fiber by compression molding technique. Figure 2.15 shows the stacking sequence of the composites. Tensile strength of JFRP shows 63.13 MPa, AC1 94.56 MPa, AC2 141MPa, C1 188 MPa, C2 288 MPa and CFRP 641 MPa. Young's modulas of JFRP shows 6.07 GPa,

AC1 10.31 GPa, AC2 12.75 GPa, C1 16.22 GPa, C2 25.02 GPa and CFRP 65.66 GPa. Maximum strain observed AC2 that is 0.016 mm/mm. Minimum strain observed in AC1 is 0.010 mm/mm. The bonded joint strength was significantly improved when compared to pure JFRP.

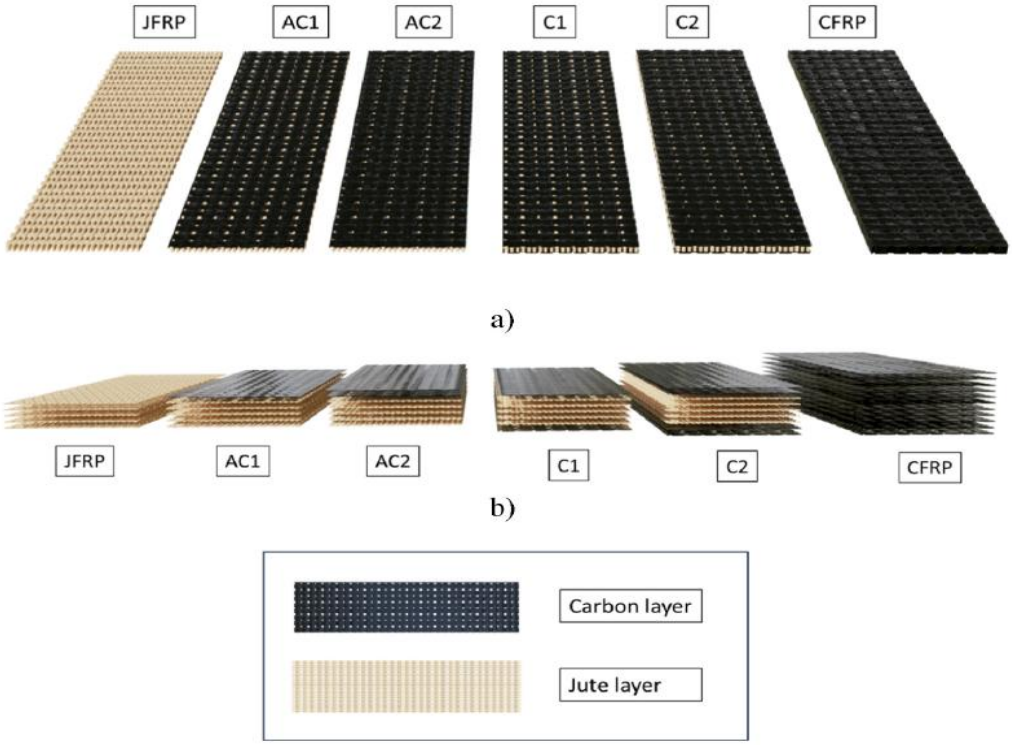


Figure 2.15 Manufactured composites a) Top View b) Side view [76]

The findings of Wang et al. [77] suggested that the chemical treatment of natural jute fibers has an important influence on fiber adhesion. The chemical treatment of jute fibers consequently improves the tensile properties of the composites shown in the figure 2.16. The chemical treatment of jute fiber has a significant impact on the formation of voids in the composites as well as the mechanical properties of jute fiber composites.

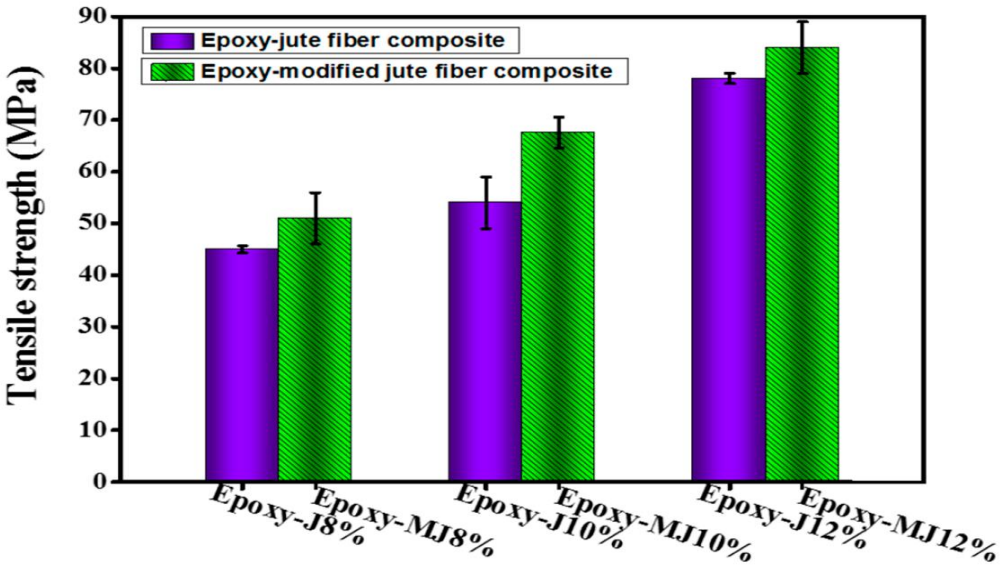


Figure 2.16 Effect of fiber loading on the tensile strength [77]

In the study Hasan et al. [78], the hybrid composites of jute and glass fibers were fabricated by hand layup technique. It can be seen (figure 2.17) that Type A (J +J +G +J +J) could bear the highest tensile load of 99 MPa. The 4-layer composites have shown better tensile strength i.e. 122 MPa to 133 MPa. This may be due to a lack of glass-fiber and the absence of jute fiber.

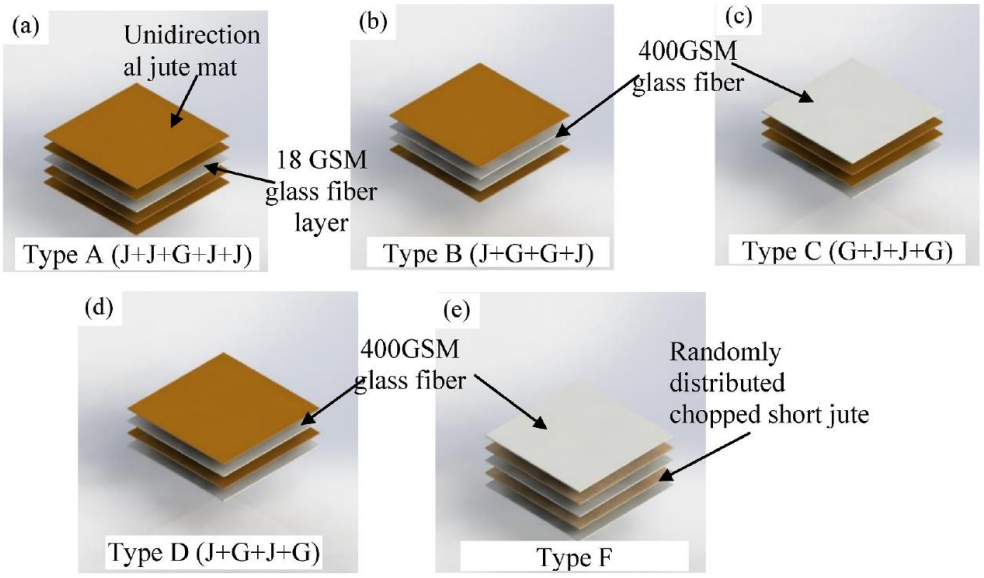


Figure 2.17 Stacking sequence of Hybrid Composite fibers [78]

In this study, Type C (G + J + J + G) and Type B (J + G + G + J) have similar impact strength (375 MPa), which is above average and shown in the Figure 2.18.

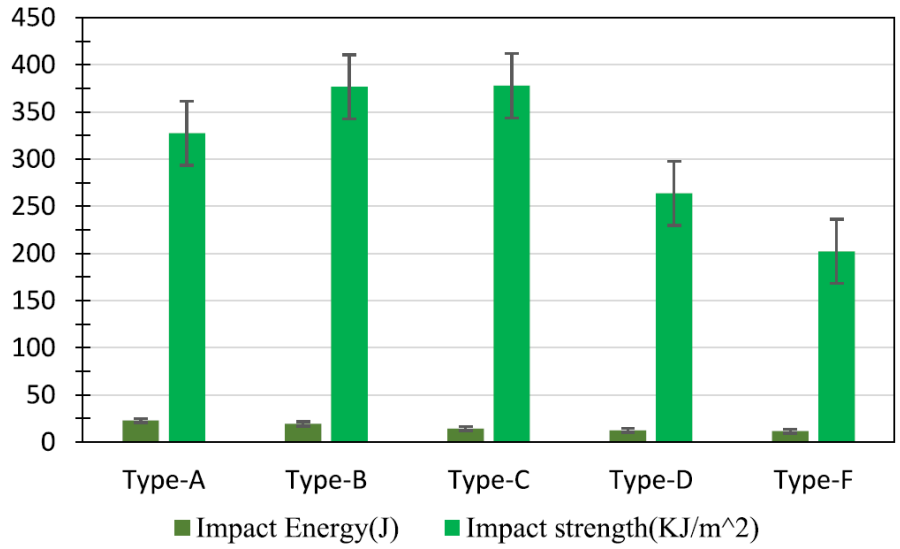


Figure 2.18 Impact energy and impact strength of the fabricated composites [78]

Alvy et al.[79] studied the impact of jute and carbon fiber hybrid composite with different stacking sequences. In this experiment, four layers of jute and carbon fibers were considered. Stacking sequence C/J/J/C shows the highest performance i.e. tensile strength (306.87 MPa). C/J/J/C has a higher bending modulus among other composites manufactured with the same configuration but change of layering sequences. Carbon layers C/J/J/C exhibit maximum bending quality. In J/C/C/J, jutes are in the outermost layers, which create poor adhesion, excessive voids and thereby reduced strength. In J/C/C/J, maximum water absorption is observed. C/J/J/C has shown lower water absorption than to J/C/C/J. Therefore, C/J/J/C arrangement shows more suitability than that of J/C/C/J.

Bhuiyan et al.[80] studied Jute and Kevlar hybrid composites. Here, arrangement A(0◦) had the maximum tensile and flexural stress of 66.541 MPa and 84.36 MPa. Arrangement A(90◦) showed the minimum strength of 6.736 MPa and 12.16 MPa. So, the direction of fibers has an effect on the mechanical properties of manufactured hybrid composites. Similarly, fiber layering order has an effect on the mechanical properties of the composites. The highest tensile and flexural properties were observed when Kevlar fiber on the outer side. All jute fiber layers showed hydrophilic characteristics i.e. absorbed water while immersed in the water for a certain duration.

In the study Bekele et al. [81] had manufactured composites by palmyra palm leaf stalk fiber and sisal fiber. Here, fiber and matrix volume fraction used 10/90, 15/85, 20/80. The highest tensile strength is found at 20/80. It has been found that the impact and toughness value reduced when increased natural sisal fiber. Sisal fiber has superior tensile strength but reduced impact strength.

In the study Venkatesh et al. [82] has introduced Glass (E), Kenaf (KF) and sisal fiber (SF) hybrid composite by hand layup process. The fiber volume 70E/10KF/20SF had the highest tensile and flexural strength of 57.9 MPa (approx.) and 78.65 MPa (approx.). The impact strength increases by increasing natural fibers 29.4 kJ/m^2.

In the study Pramanik et al. [83], jute fiber reinforced composites were manufactured with five layers of jute fibers by hand layup process. The fiber to resin volume fraction has an influence on the mechanical properties of the manufactured composite. Therefore, a careful selection of fiber layers and matrix material, along with fiber to resin volume fraction, will regulate the characteristics of the composite.

In the study, Turjo et al. [84] has fabricated hybrid composite by combining jute and glass fiber by the hand lay-up process. Vacuum Infusion Process maintains less void (3%) in the hybrid composites, which increases the mechanical strength of the composites. Laminate JGJG hybrid composite produces a maximum tensile strength 83.02 MPa. Laminate JJJJ composite produces tensile strength 65.9 MPa. Corrosive environment has a significant effect on the ultimate tensile strength (UTS). Laminate JJJJ has higher bonding between the fiber and the matrix. Laminate JAAJ hybrid composite tensile stress 46.3 MPa which is a combination of aluminum foil and jute fiber. More water absorption occurs due to loose bonding between the foil and the matrix. Therefore, the hybrid manufacturing process has superior control over the quality of the composites. The Vacuum Infusion Process (3% void), along with other production processes with their void contents, are shown in Figure 2.19.

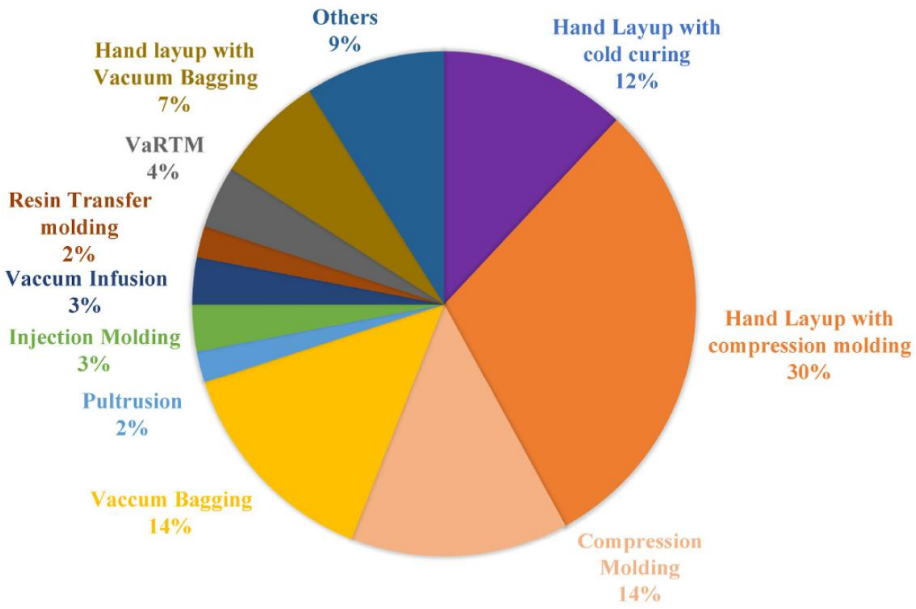


Figure 2.19 Void content in composite manufacturing process [84]

The analytical results of Biswas et al. [85], jute and bamboo hybrid composites have been produced by the vacuum infusion process. The tensile strength of manufactured hybrid composites was 216 MPa and 392 MPa. The Young's Modulus of manufactured hybrid composites was 31 GPa and 29 GPa. Therefore, jute fiber composites have a higher Young's Modulus value. Jute fiber composite has 158 ± 18.90 MPa flexure strength and 18 ± 1.92 GPa flexural modulus where bamboo fiber composite has flexure strength 226 ± 25.13 MPa and flexural modulus 19 ± 1.32 GPa. Jute fiber reinforced composites showed lower flexure strength than that of bamboo fiber reinforced composites.

Symington et al. [86] have shown in the study that the tensile strength of Flex, Abaca, and Kenaf have almost similar failure strengths 70 MPa. On the other hand, Sisal has a higher tensile strength 80 MPa and Hemp has a lower tensile strength 60 MPa (shown in Figure 2.20). Hemp and Kenaf composites has significant modulus values of 13.7 and 11.9 GPa. The composites of Abaca and Sisal exhibit similar properties to each other in the region of 8 GPa. When comparing Young's modulus of the composites to other materials in Figure 2.21, Hemp and Kenaf have higher strength compared to oak. From the study, it has been determined that the composites do not show the same order of mechanical properties as base fibers.

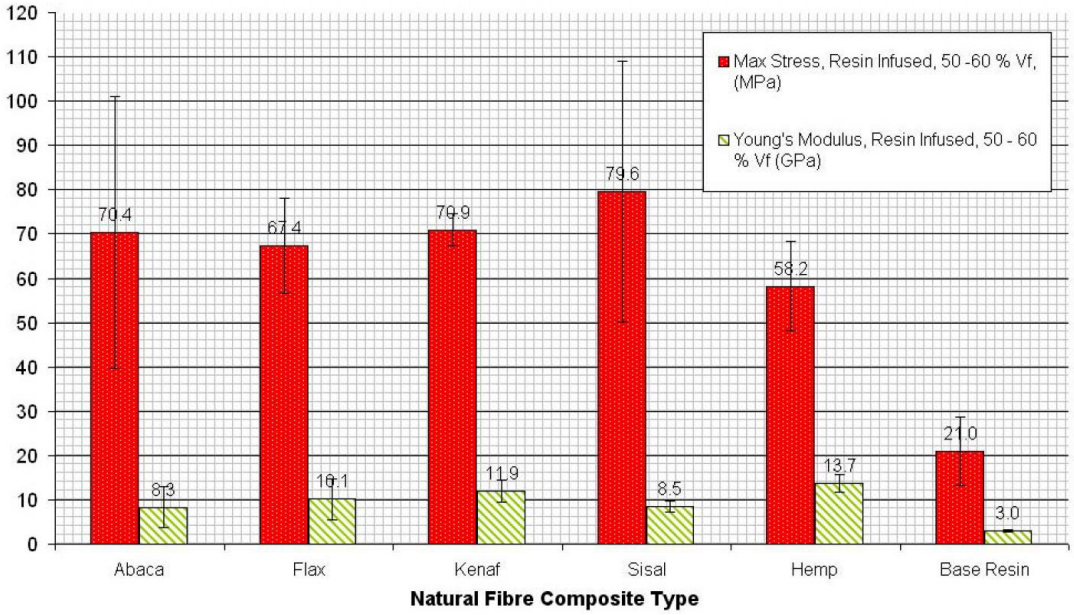


Figure 2.20 Bio-composites by vacuum infusion process

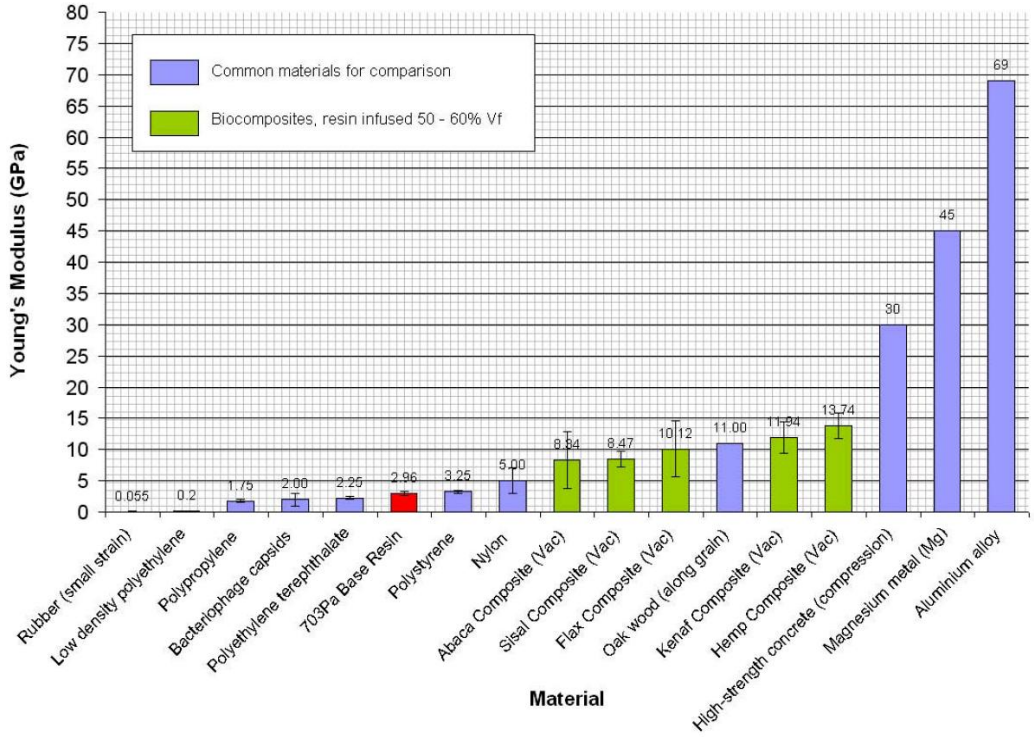


Figure 2.21 Young's modulus comparison between manufactured composites and other common materials.

In the study Kim et al.[87] has highlighted the mechanical properties and failure mechanisms of manufactured GFRP hybrid composites. Vacuum infusion processed manufactured GFRP has higher UTS 428 MPa and Young's Modulus 17.73 GPa than the hand layup processed UTS 277.2 MPa and Young's Modulus 13.43 GPa. In compression test, vacuum infusion processed manufactured GFRP has a larger ultimate strength 324.1 MPa and modulus 25.9 GPa than the hand layup process. This is due to the maintenance of less void content in the VIP than HL.

In the study, Sujon et al. [88] used VIP process and manufactured jute carbon fiber hybrid composite. Carbon fiber 4 layers and jute fiber 3 layers are arranged unidirectionally in different stacking sequences. J3C4J3 showed the maximum tensile strength 571 MPa. However, C2J6C2 showed the maximum flexural strength 455 MPa. From the study, it has been observed that stacking sequences of the fibers have a significant effect on the strength of the composite.

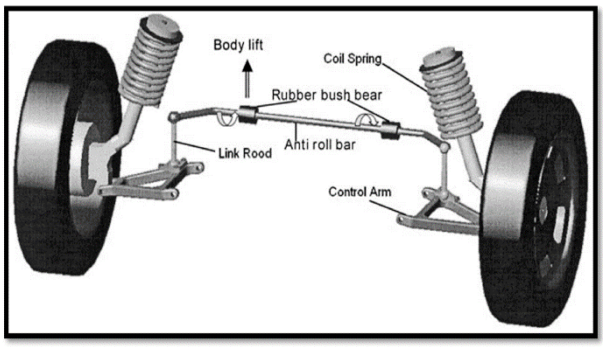
2.9. **Application of Natural Fiber Hybrid Composite**

Hybrid composites have continued to see significant technological developments and applications across various industries. It has gained wide acceptance among the tech giants due to its environment-friendliness, low cost, and usability for a variety of applications. Automotive industries are shifting their modes from metal to composites to gain a better

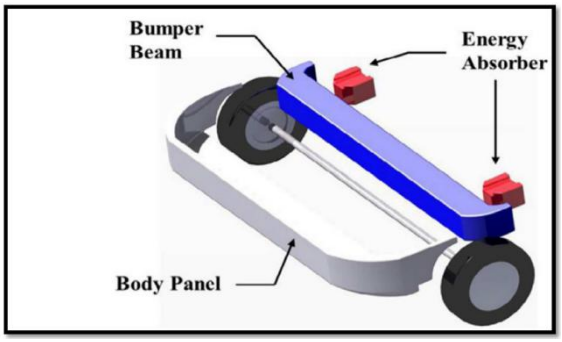
power-to-weight ratio. On the other hand, natural fibers like jute, cotton, etc., are available in nature which are low-cost and environmentally friendly. Natural fibers have some inherent disadvantages (1) thermal stability, (2) compatibility etc. This study focuses on the effects of natural fiber hybrid composite made different automotive components [43].

These composites find use in numerous fields, offering unique advantages and performance characteristics. The car industry is one of the major users of natural fiber based hybrid composites. These materials are used for both interior and exterior components to increase the performance of the vehicles. Applications includes manufacturing of dashboard panels, door panels, and interior trim components. These materials provide a lightweight alternative to traditional plastics, reducing overall vehicle weight. Bumpers, fenders, and other exterior components are also produced using natural fiber composites, contributing to weight reduction while maintaining structural integrity. In the quest for sustainability, natural fiber hybrid composites are employed to create bio-based car parts. These composites can replace traditional plastics in various applications.

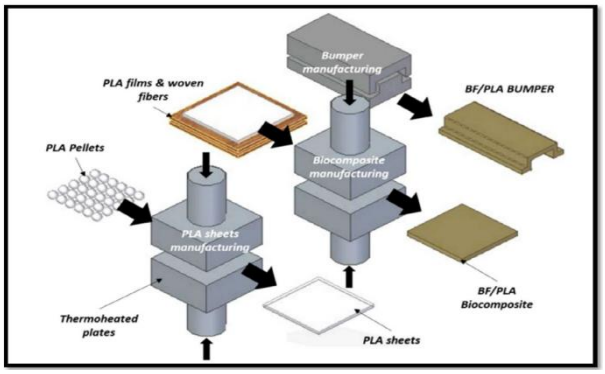
In construction Industry, natural fiber hybrid composites are employed to create materials that offer both structural stability and insulation properties. Some common applications include: Hybrid composites containing natural fibers act as thermal insulation in walls, roofs, and floors, reducing energy consumption and enhancing the environmental sustainability of buildings. Natural fiber hybrid composites are used to create lightweight and durable facade panels, which offer both aesthetic appeal and thermal performance. In some cases, hybrid composites are used in structural elements such as beams and columns to reduce weight and improve sustainability [89]. In the aerospace industry, where weight reduction and performance are critical, natural fiber hybrid composites find applications in non-structural components [90]. Composites made from natural fibers are used in non-structural interior components like cabin panels, overhead bins, and seat backs to reduce overall aircraft weight and improve fuel efficiency. Some natural fiber composites are employed for noise insulation in aircraft interiors. Bio-based hybrid composites are utilized in the manufacture of various sports and leisure equipment, offering a balance between performance and sustainability. Hybrid composites are used to create bicycle frames and components, making them lighter and more eco-friendly. These sports equipment items incorporate natural fiber composites for their lightweight, strength, and flexibility. Hybrid composites are used to create watercraft that are both lightweight and durable. Outdoor furniture manufacturers use natural fiber hybrid composites to create eco-friendly, weather-resistant products.



(a) Structure of anti roll bar [14]



(b) Automotive bumper beam



c) Bumper bio composite



(d) Composite Leaf Spring

Figure 2.22. Composite material is used in the automotive industries [43]



Bullet-resistant vests



Helmets



Riot shields



Vehicle protection against roadside bombing of military vehicle



Vehicle protection in inside integrated ballistic armor in helicopter

Figure 2.23. Fiber composites for ballistic protection and energy absorption [91]

The composites are well accepted in the marine sector, mostly in boat and ship building. This sector mostly relied upon fiberglass composites, which is shifting towards hybrid composites. Fiberglass consists of glass fiber and resin as matrix material [92]. Fiberglass construction is easier, and raw materials are available in the local markets. At present, many advanced materials like Kevlar or carbon fiber with higher strength have been invented and used in boat manufacturing industries.

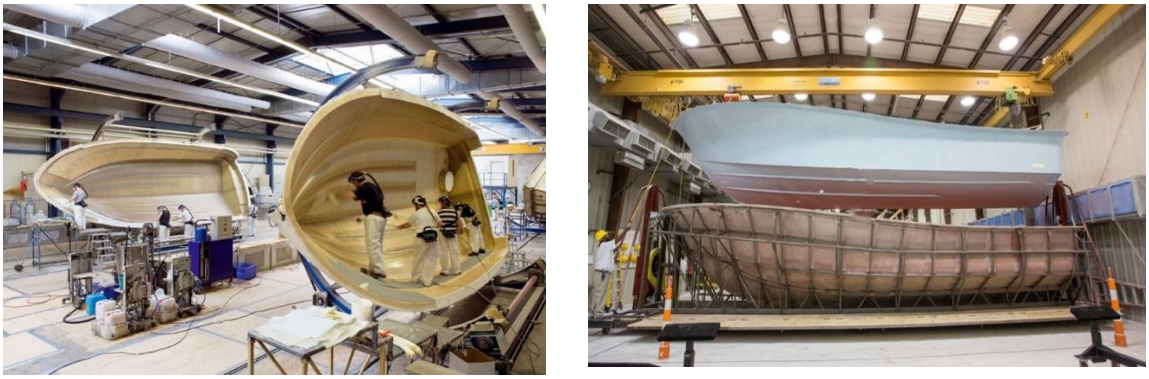


Figure 2.24. Boat manufacturing process by composite material

Composite materials are commonly used in naval ships due to their higher mechanical properties. Composites like fiberglass-reinforced polymer (FRP) significantly reduce the overall weight of ships compared to traditional steel or aluminum. Composites do not rust, making them ideal for marine environments. High resistance to impact, fatigue, and environmental stress improves the vessel's lifespan. Composites are often used in ship superstructures to lower the center of gravity, enhancing stability [93]. Modular construction using composites simplifies assembly and maintenance. Composites with radar-absorbing materials (RAM) are used in naval vessels to reduce radar cross-section, enhancing stealth capabilities. Composite propellers reduce weight and noise, improving fuel efficiency and stealth. Non-magnetic composites prevent interference with magnetic mines, making them ideal for minehunters. Composite pipes and tanks are resistant to corrosion from seawater and chemicals, reducing maintenance. Lighter ships require less fuel, lowering operating costs and emissions. Corrosion-resistant composites minimize the need for repairs, reducing downtime and lifecycle costs. Advances in composite technology i.e. natural fiber-based hybrid composites include efforts to make materials more sustainable and recyclable. Composites can be more expensive to produce and fabricate than traditional materials. While composites are engineered to be fire-resistant, ensuring compliance with naval safety standards can be challenging. Composite materials are revolutionizing naval shipbuilding, allowing for lighter, more efficient, and technologically advanced vessels. Their use continues to expand as innovation addresses current limitations [94-95].



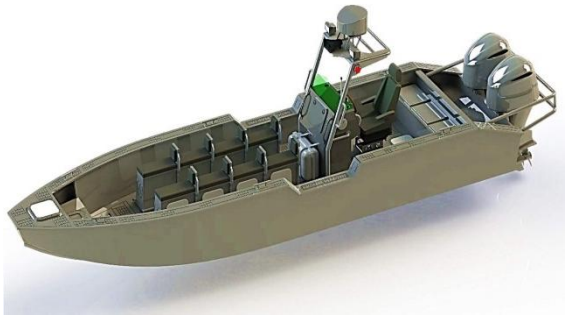
(a) US advanced electric ship



(b) USS Zumwalt Destroyer



(c) Patrol Boat Chaser 1600 B6-Jet



(d) Patrol Boat Harpoon 850-S

Figure 2.25. Naval ship and boat builder using advanced composite material

composites play a critical role in military aircraft design, offering unmatched advantages in performance, efficiency, and stealth. Continued advancements in material science are expected to push these benefits even further, shaping the future of military aviation [90].



(a) Fighter Jet F-35 Lightning II



(b) Helicopter AH-64 Apache



(c) Stealth Bomber B-2 Spirit



(d) Eurofighter Typhoon

Figure 2.26. Modern fighter jets (a),(b),(c) and (d) are using composite materials

In the consumer goods sector, various products are made from natural fiber hybrid composites due to their aesthetic appeal and eco-friendliness: furniture like chairs, tables, and other furniture items are crafted using these composites for their aesthetics, lightweight nature, and sustainability. Some electronic device casings, like laptop shells, are made from natural fiber composites to reduce weight and environmental impact. Natural fiber hybrid composites are used to create lightweight and sustainable components for shoes and sandals. The marine industry utilizes natural fiber hybrid composites for their lightweight, corrosion-resistant properties. Hybrid composites are used in boat construction to reduce weight and improve the environmental footprint. Life vests and buoyancy aids may incorporate these materials for their lightweight and buoyant characteristics. In the packaging industry, natural fiber hybrid composites are employed to create sustainable and biodegradable packaging materials. Hybrid composites are used to make trays, containers, and packaging materials that decompose more easily than traditional plastics, reducing environmental impact. Natural fiber hybrid composites are applied in various infrastructure projects to enhance sustainability and longevity. Some bridge components, like railings and decking, are constructed using hybrid composites to reduce maintenance needs and enhance environmental friendliness.

Hybrid composites made of natural fibers are used in the renewable energy sector. Wind Turbine Blades are constructed using natural fiber composites, combining lightweight materials with structural integrity [96]. The housing and frames of solar panels can be made from natural fiber hybrid composites, contributing to their environmental sustainability. Agriculture and horticulture benefit from natural fiber hybrid composites in various ways. Biodegradable planting pots and containers made from these materials are used in nurseries and gardening. Agricultural structures and animal housing use these composites for their insulating properties and sustainability.

Therefore, natural fiber hybrid composites are gaining prominence across multiple industries due to their sustainability, lightweight nature, and cost-effectiveness. Their versatility allows them to be used in diverse applications, from automotive components to consumer goods, renewable energy products to military hardware. While they offer numerous advantages, there are some limitations like moisture absorption and processing considerations.

2.10. **Summery**

Natural fiber-based hybrid composites are advanced materials that combine natural fibers, like jute, hemp, or flax, with synthetic or other natural components to create versatile composite materials. These composites offer a balanced blend of environmental sustainability, cost-effectiveness, and improved strength. The process of manufacturing natural fiber hybrid composites involves careful selection and preparation of the natural fibers, as well as choosing a compatible matrix material, often a thermosetting or thermoplastic resin. Hybridization with synthetic fibers can be useful to increase specific mechanical properties like strength and stiffness. The hybrid manufacturing process requires a controlled environment, like maintenance of temperature and pressure, and time to cure. Composites' desired specifications and industry standards are maintained through strict quality control. These composites are gaining popularity among the different sectors of the industry. They have a better future due to increased environmental awareness among the people. Natural fiber-based hybrid composites are an eco-friendly alternative to traditional synthetic composites. They are widely used in car industry, construction materials, the aviation industry, the household products etc., which is environmentally conscious and cost-efficient materials in today's industrial landscape.

Chapter 3

MATERIALS AND METHODS

3.1. **Introduction**

Material and methodology will be discussed followed during the experiment. It will also discuss about the fabrication of the composites, mechanical testing and hydrophilic characterization.

3.2. **Matrix Material**

3.2.1. **Polyester Resin**

In this experimental setup, the primary material serving as the matrix is polyester resin ("GRADE # 3330W, Brand Name # NORSODYNE"). Polyester is a type of synthetic resin that is commonly used. It is a thermosetting resin, meaning that it hardens or cures when exposed to heat or chemical catalysts, forming a rigid and durable material. Polyester Resin and MEKP hardener were collected from local supplier Metacenter Ltd, Dhaka. Polyester resin characteristics, used in this experiment are shown in Table 3.1.

Table 3.1. Characteristics of the resin

Parameters	Value
Appearance	Clear
Colour	Pale Yellow
Viscosity at 30^0 C	430 mPa.s
Gel Time at 30^0 C	25 min



Figure 3.1. Norsodyne 3330W polyester resin (200 liters container)

3.2.2. **Hardener**

Methyl Ethyl Ketone Peroxide (MEKP) is a kind of hardener. It is a type of organic peroxide commonly used as curing agent. These resins are widely employed in various industries, including boat building, automotive, aerospace, and construction.

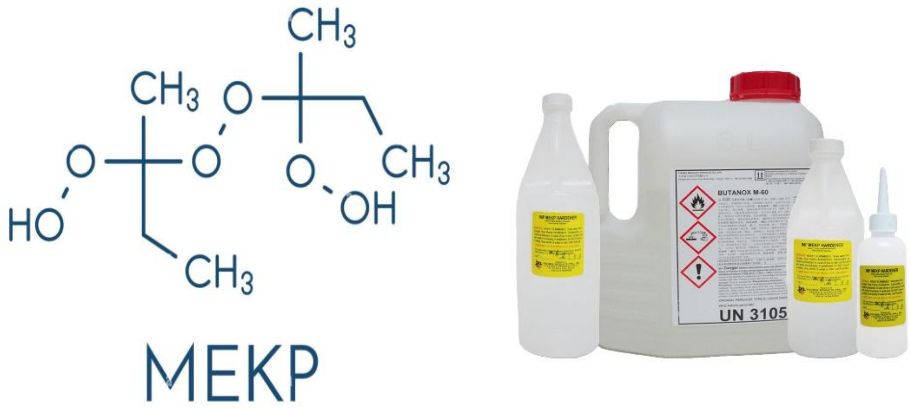


Figure 3.2. MEKP in a containerized form

MEKP acts as a hardener in the curing process of the resin, initiating the polymerization which converts the resin liquid state to a solid state. When MEKP is mixed with the resin, it decomposes, releasing free radicals that initiate the polymer chains in the resin, resulting in a hardened and cured product. MEKP is highly reactive and potentially hazardous chemical. It can be sensitive to heat, shock, and friction and is classified as a hazardous material due to its potential for explosive decomposition. Therefore, it must be handled with care, and safety precautions, including appropriate protective equipment and storage, should be followed when working with MEKP.

3.2.3. **Reactions**

The chemical reaction between the resin and the MEKP is an important step in the curing process of polyester resin. This reaction results in the conversion of the liquid resin into a solid, rigid material. Initially, MEKP hardener is mixed into the polyester resin in a specific ratio based on the formulation. When subjected to an appropriate amount of heat (often generated by ambient temperature or added accelerators), MEKP begins to decompose. The decomposition of MEKP is initiated by heat and yields two methyl ethyl ketone (MEK) molecules and two highly reactive free radicals (R•).

MEKP → 2 MEK + 2 R•

In the above reaction, two free radicals are strongly reactive with unpaired electrons. These free radicals react with the unsaturated polyester resin's molecular structure. The unsaturated double bonds are typically located along the polymer backbone of the resin. The reaction between the free radicals (R•) and the unsaturated polyester chains results in the formation of new chemical bonds, creating cross-links between polymer chains. This cross-linking process continues as more and more free radicals interact with the resin, ultimately forming a three-dimensional network of chemical bonds. As a result, the liquid resin becomes increasingly viscous and eventually solidifies.

(Polyester chain with unsaturated double bonds) + 2 R• → Cross-linked network

The cross-linking process continues until the free radicals are either consumed or reach a stable state. At this point, the curing reaction is considered complete, and the polyester resin has hardened into a solid mass. Any remaining free radicals may undergo termination reactions, where they combine with each other or react with other species present in the resin.

3.3. **Fibers**

For the experiment, two types of glass fiber mat were used i.e. (1) Glass Fiber Woven Roving Mat 600 g/m^2 (2) Glass Fiber Chopped Strand Mat (CSM) 450 g/m^2 and (3) jute fiber mat 400 g/m^2 as reinforcing materials. E-glass fiber mats were purchased from local supplier Metacenter Ltd, Dhaka, Bangladesh. The Jute fiber mats were collected from local market. Both the jute and glass fiber mat were prepared by cutting 12 inch x 12 inch square size shape for the sample preparation. The jute fiber mats were modified using Sodium Hydroxide (NaOH) chemical treatment. 5% NaOH alkali solution was used for the surface treatment of the jute fiber mat. The fibers were soaked in a NaOH solution for 24 hours [81- 83]. Finally, the jute fibers were washed by fresh water and dried.

Fibers are 2 types i.e. natural fibers and synthetic fibers. Natural fibers are found in the animal, plant or mineral. Synthetic fibers are formed by the organic and inorganic fibers. Following flow chart shows the fiber types:

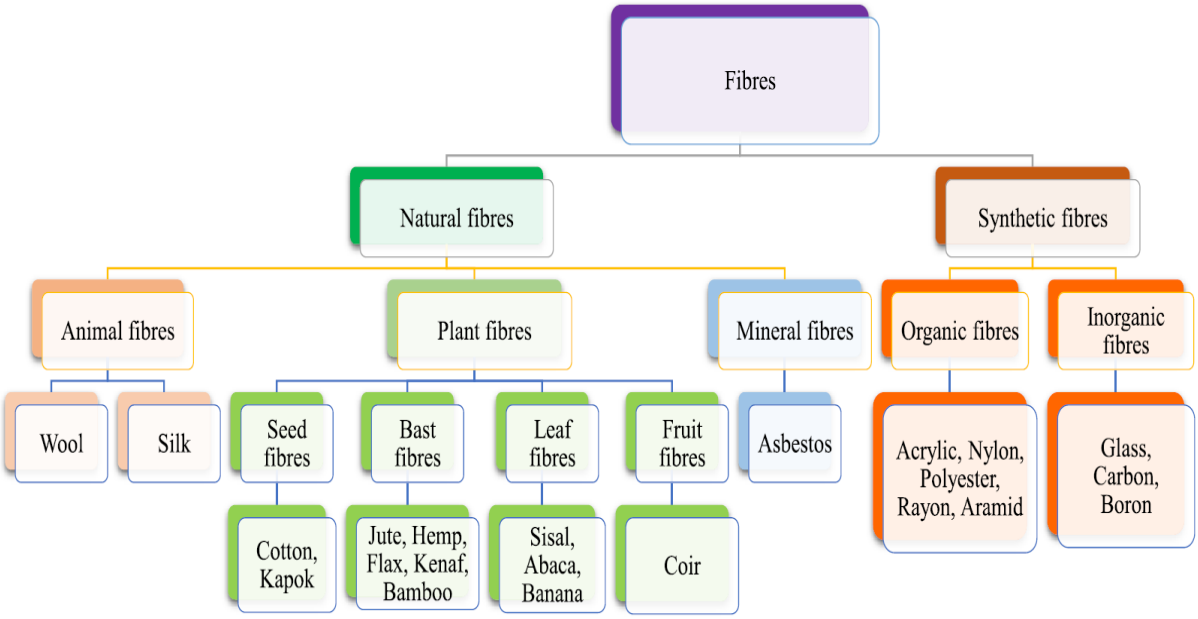


Figure 3.3. Classification of fibers [97]

3.3.1. **Glass Fibers**

Glass fiber is a type of fiber used in different applications, including composites, insulation, and reinforcement. Glass fibers are primarily made from silica-based materials. The key raw materials used

Table 3.2. Comparative properties with natural fibers and synthetic fibers [98]

Plant Fibers	***Density(g/cm^3)***	***Tensile Strength(MPa)***	***Specific Strength (GPa/g/ cm^3)***	***Elongation at Break (%)***
Flax	1.5	345-1100	0.2-0.7	2.7-3.2
Hemp	1.14	690	0.6	1.6
Cotton	1.5-1.6	287-800	0.2-0.5	7.0-8.0
Jute	1.3-1.4	393-773	0.3-0.5	1.16-1.5
E-glass	2.5	2000-3500	0.8-1.4	2.5
S-glass	2.5	4570	1.8	2.8

in the construction of glass fibers include silica sand, soda ash, limestone, and other additives. These materials are melted together in a furnace to form a glass composition suitable for fiber production. The raw materials are heated to high temperatures, typically exceeding 1700°C (3092°F), in a furnace to melt them and form a molten glass. The specific composition of the

glass is carefully controlled to ensure desired properties in the resulting fibers, such as electrical insulating properties and mechanical strength. Once the glass has been melted and formed into a molten mass, it is drawn into thin fibers. This process involves extruding the molten glass through tiny orifices (spinnerets) to create fine, continuous filaments. The filaments are rapidly cooled to solidify them. After solidification, the fibers are treated with a chemical sizing. It helps to protect the fibers from abrasion and damage. The individual fibers are gathered into strands and wound onto bobbins or spools for further processing and use. These strands are the basic building blocks for E-Glass fiber products. Depending on the intended use, the E-Glass fibers may be cut into specific lengths or processed further to create different products, such as woven fabrics, roving, chopped strands, or mats.

3.3.2. **Woven Roving**

Woven Roving a type of glass fiber, with a weight of 600 g/m² (grams per square meter) has been used to fabricate composite material. In this experiment, 12 inch x 12 inch Glass Fiber Woven Roving was cut to maintain uniform sample size. Woven Roving consists of continuous strands of Glass fibers together into a heavy and robust fabric. The woven roving E-glass fibers are known for its electrical insulating properties and mechanical strength. It provides excellent tensile strength [99-100]. It is used to reinforce the polymer matrix in composites, such as fiberglass, to enhance their mechanical properties. Woven Roving is relatively dense, which means it provides a high fiber-to-resin ratio in composite laminates. This results in increased strength and rigidity. Woven Roving is a thicker and heavier fabric compared to other reinforcement materials, such as woven fabrics or chopped strand mat. This thickness allows for the quick build-up of composite layers, making it suitable for applications where a high fiber content is desired. Woven Roving typically has a plain or leno weave pattern. This balanced construction makes it suitable for applications where bidirectional reinforcement is needed. Glass Fiber Woven Roving is used in various applications, including boat and ship construction, automotive parts, aerospace components, and infrastructure projects like the manufacturing of large pipes and tanks. It's often employed in hand lay-up, spray-up or vacuum infusion processes. Woven Roving is compatible with resin. It is a heavy, bidirectional reinforcement material made from Glass fibers woven together. It is used to provide strength and stiffness to composite materials and is suitable for applications where high mechanical performance and quick buildup of composite layers are essential.

3.3.3. **Chopped Strand Mat (CSM)**

Chopped Strand Mat (CSM) is a kind of glass fiber with a weight of 450 g/m² (grams per square meter) was used to fabricate composite material. In this experiment, 12 inch x 12 inch CSM was cut to maintain uniform sample size. CSM is a non-woven reinforcement material made up of randomly oriented chopped glass fibers held together with a binder. Here, the glass fibers in the CSM are not continuous but rather cut into short lengths. GlassFiber CSM are known for their excellent electrical insulating properties, high tensile strength, and good chemical resistance. CSM provides strength in multiple directions and is used to add stiffness to composite laminates. Selected 450 g/m² CSM refers to the weight of the Chopped Strand Mat per square meter. In this case, the CSM has a weight of 450 grams for every square meter of material. The weight of CSM is an indication of its thickness and density. CSMs with higher weights are thicker and denser, offering more reinforcement per unit area. CSM 450 g/m² is commonly used as a reinforcement material in fiberglass composites. The random orientation of the chopped fibers in the CSM helps to provide strength. Glass fibers are cost-effective and versatility in a wide range of industries.

3.3.4. **Jute Fibers Mat**

Jute fibers, derived from the jute plant, have been used for centuries in various applications, primarily for their strength, durability, and biodegradability [101]. The jute plant, belonging to the genus Corchorus, can grow up to 3 meters tall and thrives in humid, warm climates. Harvesting typically occurs when the plants are around four to six months old. The process begins with cutting the stalks close to the ground, followed by retting, where the stalks are soaked in water for several days.

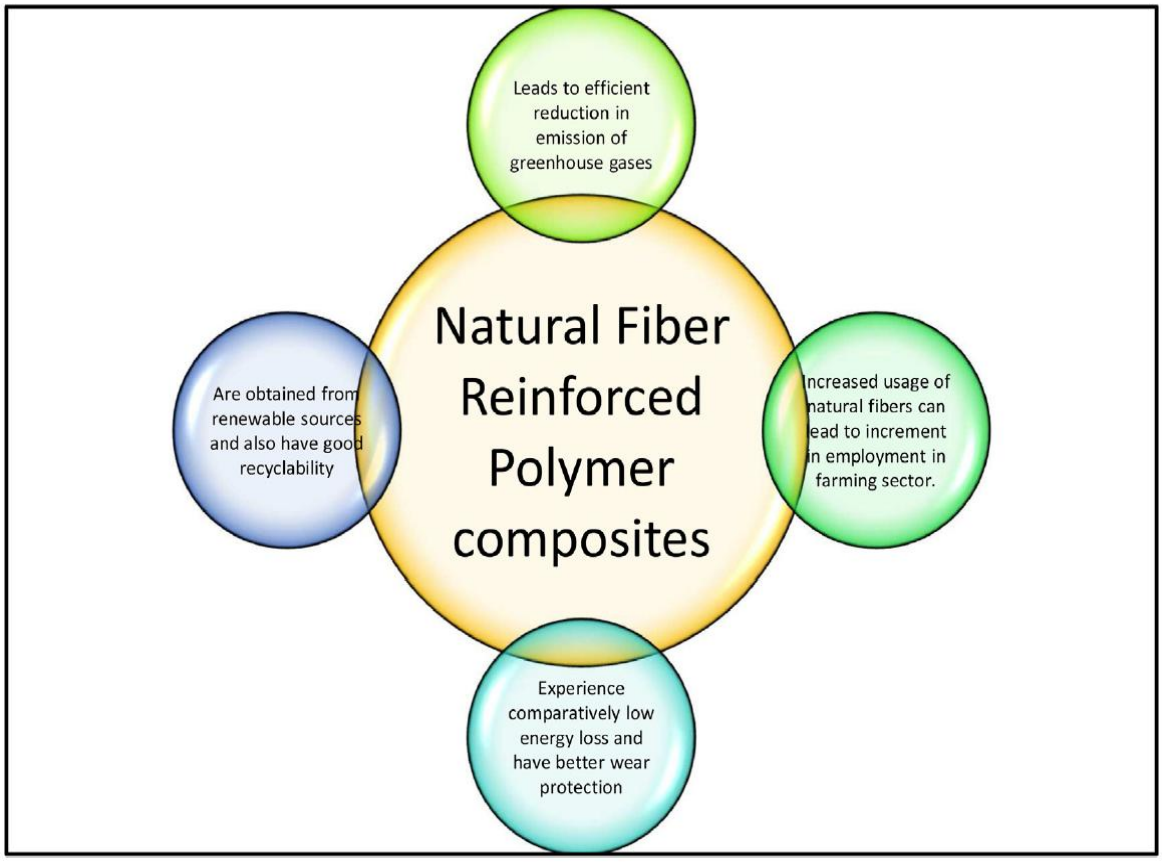


Figure 3.4. Factors validating the use of natural fibers [43]

This process helps separate the fibrous material from the woody core. After retting, the fibers are extracted, washed, dried, and then spun into yarn. Once processed, jute fibers are spun into yarns and woven or tufted into mats. The natural golden color of jute adds an aesthetic appeal, and the fibers can be dyed in various colors for decorative purposes. One of the key properties of jute fiber mats is their strength. Jute has a high tensile strength, making these mats suitable for heavy foot traffic areas. Additionally, jute is highly breathable and moisture-absorbent, which helps in maintaining a comfortable indoor environment [102]. These mats are naturally resistant to wear and tear, and their durability ensures they can last for years with proper care. In an age where environmental concerns are paramount, jute fiber mats offer a sustainable alternative to synthetic mats made from plastics or other non-biodegradable materials. Jute grows fast and require less care. End of its life, jute mats decay naturally. The production of jute has a lower carbon footprint compared to synthetic fibers [103]. By choosing jute mats, consumers contribute to sustainable practices that support farmers and promote eco-friendly materials.

3.4. **Chemical Treatment of Jute Fibers**

The water absorption rate of jute and glass fiber hybrid composites depend on many factors. For the successful reinforcement among the fibers and matrix, the surface treatment of jute fiber mat is very important.

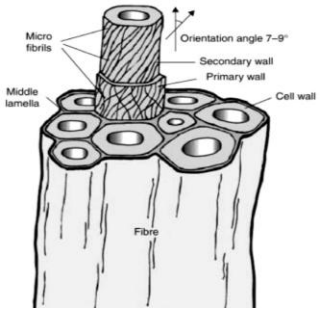


Figure 3.5. Morphology of jute fiber [97]

Mercerization is the process of alkali treatment of natural fibers to clean any impurity. The jute fiber shows low mechanical properties even after composite manufacturing with synthetic fibers. Natural fibers are water absorbent and has low mechanical properties.

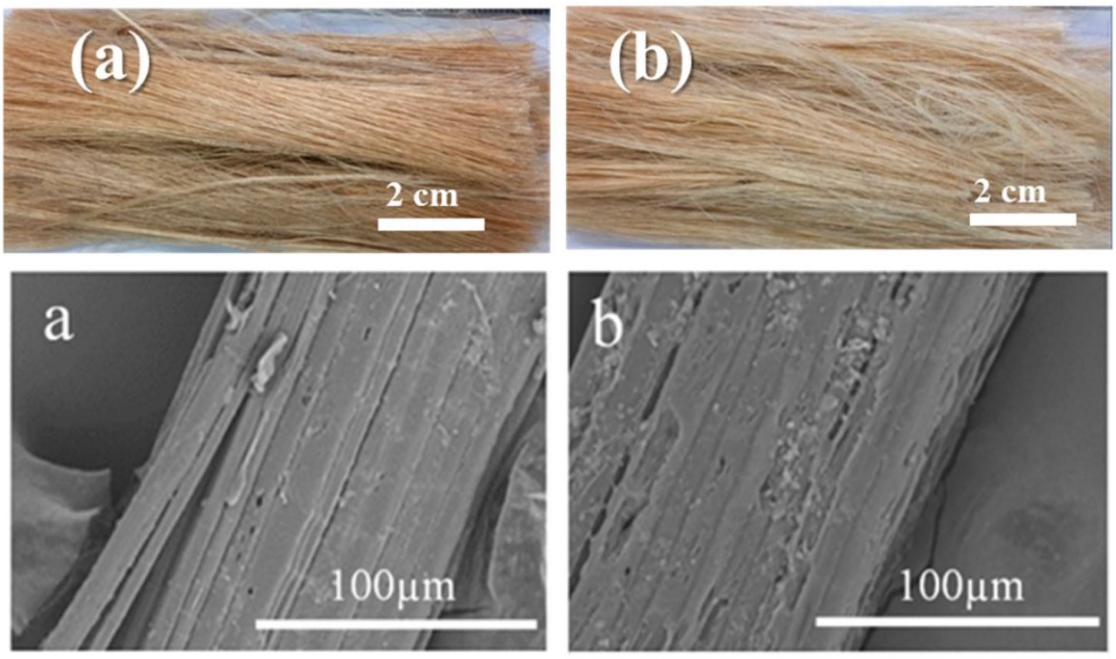


Figure 3.6. (a) Jute Fibers (b) Jute Fiber (Mercerized) -1000x magnification [77]

In this experiment, pre-treatment processes is adopted to improve the compatibility of jute fibers with polymer matrices and to enhance the mechanical characteristics of the composites. The 12 inch x 12 inch size jute fiber mat were dipped and washed into 5% NaOH solution for 24 hours (at 30^0C). The jute fiber mats were dried naturally under sunlight.

3.4.1. **Mercerization**

Mercerization of jute fiber involves a chemical process that alters the structure and properties of the cellulose in the jute fiber, primarily through treatment with sodium hydroxide (NaOH) [104]. The mercerization process enhances jute fibers quality.

3.4.1.1. **Process Overview**

- Jute fiber mat (size: 12 inch x 12 inch).
- This treatment is typically done at a concentration of around 5% NaOH, under controlled temperature and tension, to prevent the fibers from shrinking.
- After treatment, the fibers are rinsed, neutralized and then dried.

3.4.1.2. **Chemical Reaction**

The primary chemical reaction during the mercerization of jute fibers involves the modification of cellulose in the fiber. When sodium hydroxide is applied, it causes a structural transformation in the cellulose. Cellulose in jute is a polymer made of glucose units, and its chemical formula can be simplified as $(C_6H_{10}O_5)_n$, where **'n'** represents the number of repeating glucose units. Cellulose $(C_6H_{10}O_5)$ reacts with sodium hydroxide (NaOH) in water:

Cellulose $(C_6H_{10}O_5)$ n+NaOH⟶ Sodium cellulose alkoxide + water (H_2O)

This reaction causes the cellulose fibers to swell and undergo structural changes, making the cellulose chains more disordered (less crystalline).The sodium cellulose alkoxide formed is more reactive and can retain its high affinity for dyes, as the amorphous regions make it easier for dye molecules to bind to the cellulose. Removal of non-cellulosic materials like pectin and hemicellulose improves the smoothness and surface appearance of the fibers.

3.4.1.3. **Chemical Changes During Mercerization**

- The sodium hydroxide (NaOH) dissociates in water to form hydroxide ions (OH^-), which interact with the cellulose in the jute fiber.
- The sodium hydroxide also degrades the hemicelluloses and pectin that are present in the fiber, which helps remove the non-cellulosic materials that contribute to the rough texture of jute.
- The swelling and structural changes cause the cellulose to become more reactive and more accessible to dye molecules.

3.4.1.4. **Effect of NaOH on Jute**

1. Swelling of the cellulose: NaOH causes the cellulose to swell by disrupting the hydrogen bonding between the cellulose chains, resulting in an expansion of the fiber.
2. Improvement in dye affinity: The more open structure of cellulose after mercerization allows dyes to penetrate the fiber more effectively.
3. Reduction in amorphousness: The mercerization process creates a more crystalline cellulose structure, improving the fiber's strength and luster.

3.4.1.5. **Neutralization**

After the fibers have undergone the mercerization process, they are typically rinsed with water and then neutralized with a mild acid (like acetic acid or sulfuric acid) to remove any residual NaOH. This prevents further chemical reactions and helps restore the fiber to a neutral pH. In this experiment, only rinsing with water has been carried out.

3.4.1.6. **Final Properties of Mercerized Jute**

1. Increased Strength: The mercerized fiber becomes more robust due to the enhanced crystalline structure of the cellulose.
2. Improved Luster: The surface of the fiber becomes smoother, contributing to a shiny appearance.
3. Enhanced Dyeability: The fiber becomes more receptive to dyes, resulting in more vibrant and uniform coloring.
4. Improved Durability and Resistance to Water: The fiber is more resistant to wear and tear and absorbs moisture more effectively due to the changes in cellulose structure.

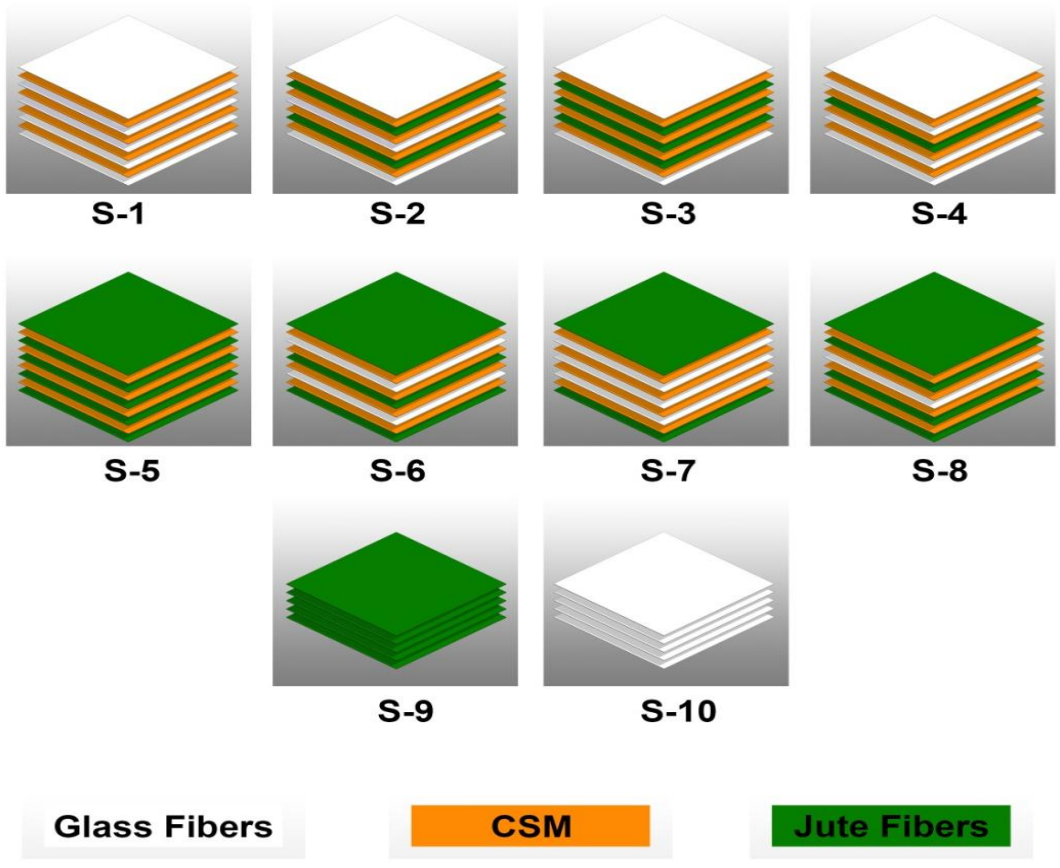
3.5. **Experimental Design**

The experimental design of jute fiber hybrid composites depends on the properties desired of the final product, production volume, and part complexity. Most popular composite manufacturing process are Hand Layup (HLU), Compression Molding, Resin Transfer Molding (RTM), Vacuum Infusion Process (VIP), Pultrusion Process, Spray up Process, 3D Printing of Hybrid Composite etc. Hand lay-up is easy for creating composite parts. This process involves layering dry fibers in a mold, followed by the manual application of resin, which is left to cure. Vacuum infusion is a process in which fibers are stacked one above another in the mold. Resin is introduced into the fiber stacking under vacuum pressure. It is known for producing high-quality parts with minimal voids and resin waste. RTM is a closed-mold process where resin is injected into the cavity under pressure. The process is used for producing high-strength composite parts in medium to large production volumes. In

compression molding, a fixed amount of resin and fibers are placed in the mold. The mold gives final shape of the composites. In spray-up process, mixture of resin and chopped fibers are injected on the mold surface. It is primarily used for large, complex parts and is particularly popular for boat hulls and other large components. 3D printing or additive manufacturing is an emerging technology used to fabricate hybrid composites by extruding layers of resin and fiber (natural or synthetic) in a controlled manner., considering fibers properties, size, shape and the product quality Vacuum Infusion Process (VIP) has been adopted in this experiment for the fabrication of hybrid composite.

3.5.1. **Stacking Sequence**

Ten stacking sequences were adopted to make the hybrid composite. Two of the stacking sequences are made entirely of glass fibers S-1(9 layers) and S-10 (5 layers). Another jute stacking sequence i.e. S-9 (5 layers) is selected only with jute fibers laminate. In other Stacking sequences S2 to S8 jute fibers are carefully designed and placed at different layers within the glass fibers. The stacking sequences are made to compare the mechanical properties of the fabricated hybrid composites. Figure 3.7 shows the stacking sequence of the prepared samples.



Sample Number	Stacking Sequence	Sample Number	Stacking Sequence
S-1	GCGCGCGCG	**S-6**	JCGCJCGCJ
S-2	GCJCGCJCG	**S-7**	JCGCGCGCJ
S-3	GCJCJCJCG	**S-8**	JCJCGCJCJ
S-4	GCGCJCGCG	**S-9**	JJJJJ
S-5	JCJCJCJCJ	**S-10**	GGGGG

Figure 3.7. Stacking Sequence of the prepared samples

3.5.2. **Vacuum Infusion Process (VIP)**

The VIP is a process to manufacture composite material by using vacuum pressure [105]. At the preparatory stage, a mold is prepared with a dry stack of jute fiber mats and glass fiber mats arranged in the desired layup configuration. In this experiment, Vacmobile MODULAR 4S series of vacuum system (Made by New Zealand) was used to fabricate composite material. The major components of the vacuum system used in the experiment is shown in the figure:

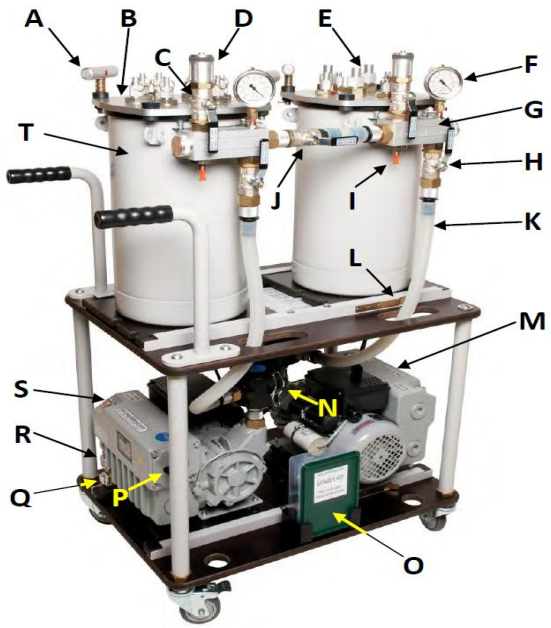


Figure 3.8. VACMOBILE MODULAR 4S series Vacuum System (Reference: Vacmobile OEM catalogue)

Key Components of the Vacuum System (Figure 3.8)	
A - Resin trap lid handle	*K - Vacuum pump hose*
B - Resin trap lid	*L - Panel latch*
C - Isolation valve for vacuum regulator	*M – Two Vacuum pump*
D - Vacuum regulator	*N - Pump inlet filter*
E - O-ring sealed vacuum tubing gland	*O - Spare parts box*
F - Vacuum gauge (glycerin filled)	*P - Vacuum pump exhaust port*
G - Manifold block	*Q - Oil drain plug*
H - Vacuum pump isolation valve	*R - Oil level indicator*
I - Absolute pressure gauge connection	*S - Oil filler plug*
J - Trap interconnect valve	*T - Resin trap outer body*

The Vacmobile MODULAR 4S is a vacuum system consists of two vacuum pump, non-collapsible plastic resin feed tube, resin infusion, resin trap, vacuum bagging, vacuum pressure gauge, flow valves etc. Initially, a mould is prepared with stacking of samples. Mould is covered with vacuum bagging. In this setup two vacuum pump were used with two 12 liters resin catch pot. Vacuum pump operated by 230 V, 50 Hz AC supply. An absolute pressure gauge is used for precision vacuum measurement. One of the vacuum pump is used for resin infusion inside the vacuum bag and other vacuum pump is used to suck back excess resin from the vacuum bag. Following is the process diagram of vacuum Infusion process.

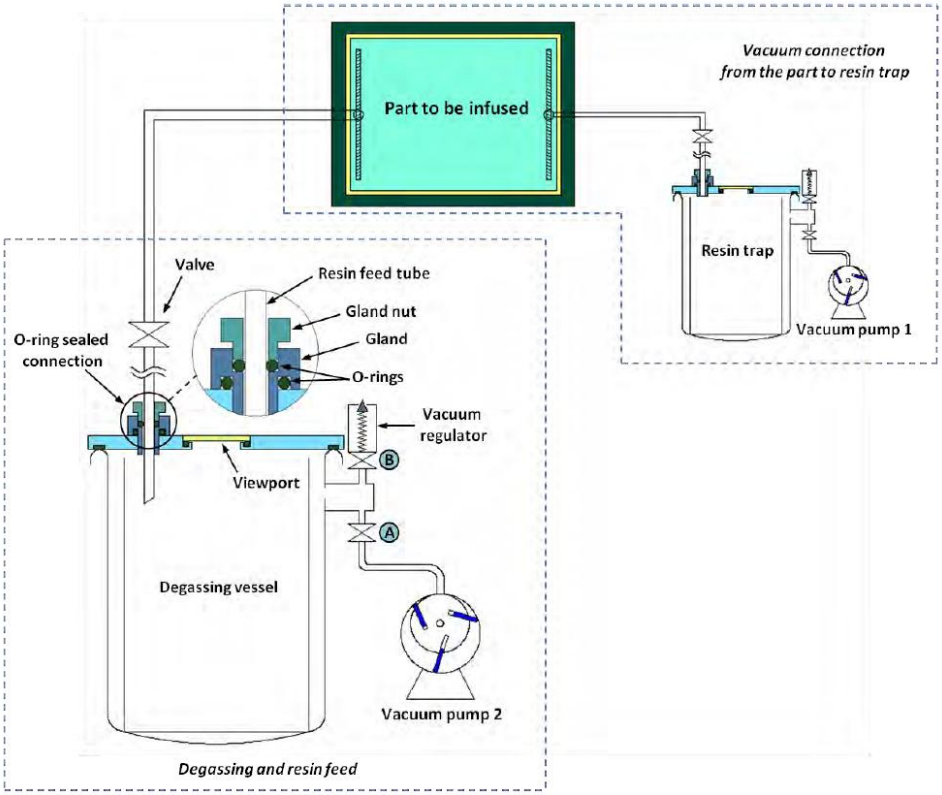
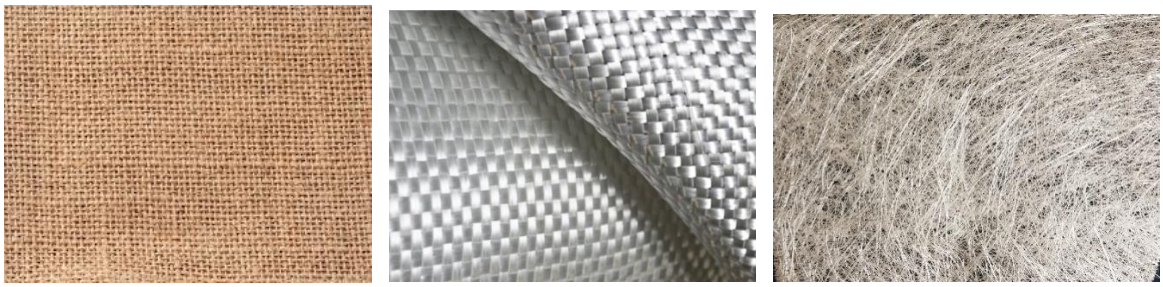


Figure 3.9. Resin feed and resin trap by Vacuum System (https://vacmobiles.com/feeding-degassed-resin/)

3.5.3. **Step-By-Step Process Flow**

3.5.3.1. **Fibers Reinforcement**

This is the prime requirements for the composite which provide ultimate strength. To increase the attachment between the natural fiber jute with woven roving and CSM has been introduced in this experiment.



(a) (b) (c)

Figure 3.10. (a) Jute Fiber Mat (b) Glass Fiber Fabric (Woven Roving) (c) Chopped Strand Mat

3.5.3.2. **Resin and Hardener**

Resin is the binding agent that bonds with the fibers to create a solid composite. Epoxy and polyester are the commonly used resins. In this experiment, Polyester Resin ("GRADE # 3330W, Brand Name # NORSODYNE") with hardener MEKP are used.

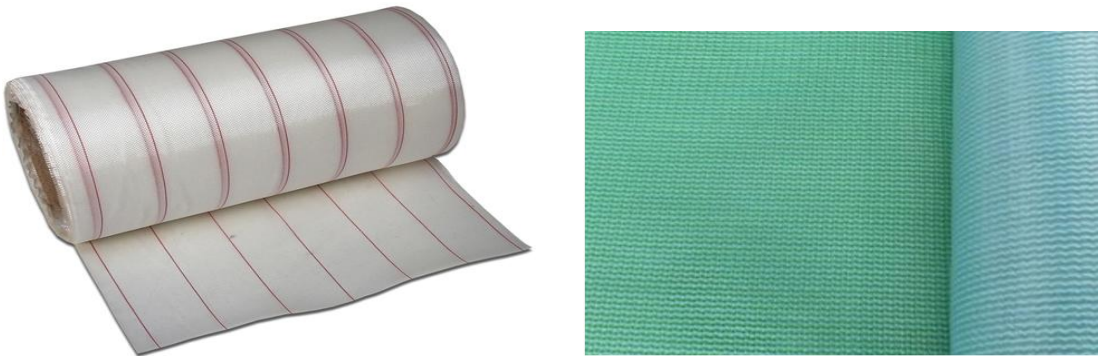


(a) (b)

Figure 3.11 (a) Polyester Resin (b) MEKP

3.5.3.3. **Peel Ply and Release Film**

A synthetic fabric layer is used that prevents resin from sticking to the vacuum bag, making it easier to remove the bag once curing is complete. The release film layer, on the other hand, prevents any excess resin from sticking to the infusion mesh, making it easier to remove once the infusion process is complete.



(a) (b)

Figure 3.12. (a) Peel Ply and (b) Release Film

3.5.3.4. **Breather Fabric**

A breather fabric (polyester) layer is used, which ensures vacuum distribution, excess resin to suck back and ensures resin flow. Breather cloth also allows trapped air inside the mold to escape.



Figure 3.13. Breather Fabric

3.5.3.5. **Vacuum Bagging**

A flexible, airtight bag that covers the entire mold and materials, allowing the vacuum to be pulled, compressing and compacting the materials as the resin flows. The vacuum bag is a sealing arrangement that ensures uniform resin flow through the fibers, eliminating voids that could compromise the material's structural integrity.

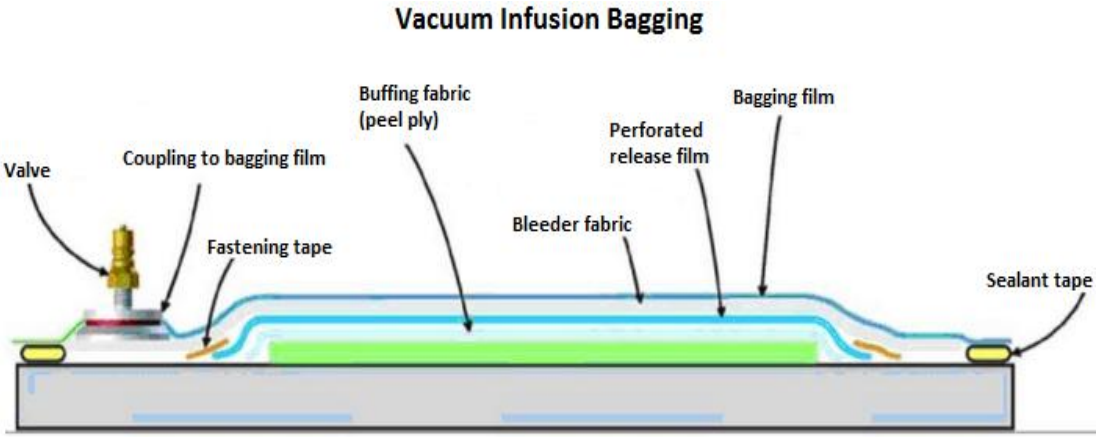


Figure 3.14. Vacuum Infusion Bagging (https://kevra.fi/guides/vacuum-infusion)

3.5.3.6. **Flow Media**

This material promotes even resin distribution throughout the reinforcement fibers by creating a pathway for the resin to flow once the vacuum is applied.

3.5.3.7. **Sealant Tape**

Used to create an airtight seal during vacuum bagging, prevents any air leakage during the infusion process.

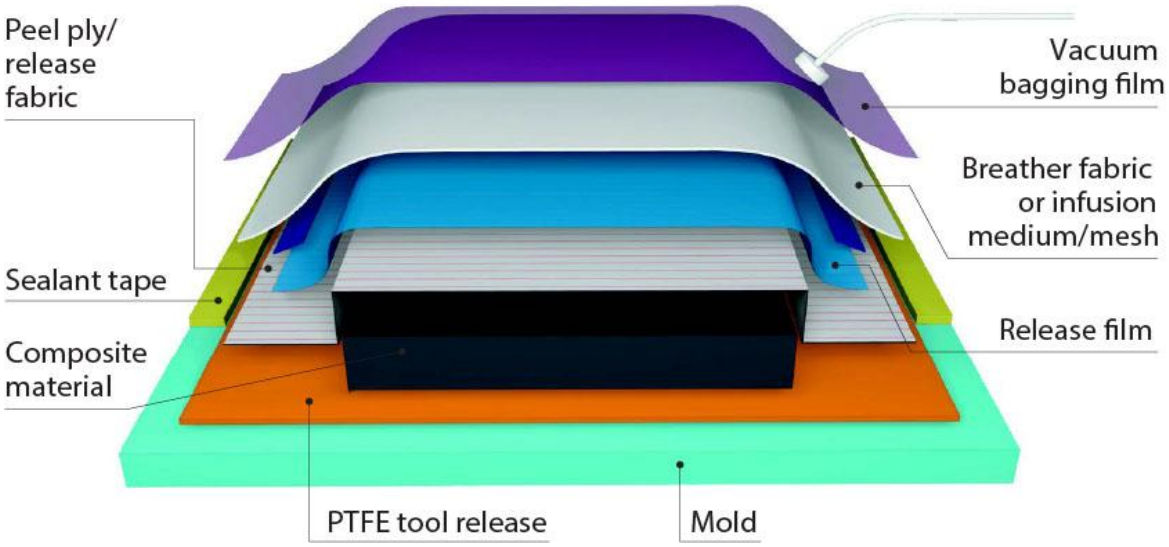


Figure 3.15. Vacuum bagging layers
(https://www.compositesone.com/vacuum-baggin-films)

3.5.4. **Fabrication of Samples**

3.5.4.1. **Prepare the Mold**

- Mold is prepared that will shape the composite part. The mold is usually cleaned and waxed to ensure easy release of the final product and prevent resin from sticking.
- In this experiment, a piece of ply wood has been taken to prepare the mould. Fibers sample were placed on top of the ply wood surface. A bag is prepared by stitching a nylon net (Release Film) where all round plastic tube is placed for infusion resin from the vacuum pump to vacuum bag. Finally, a transparent plastic bag is placed on top of net and locked all over to seal the environment.

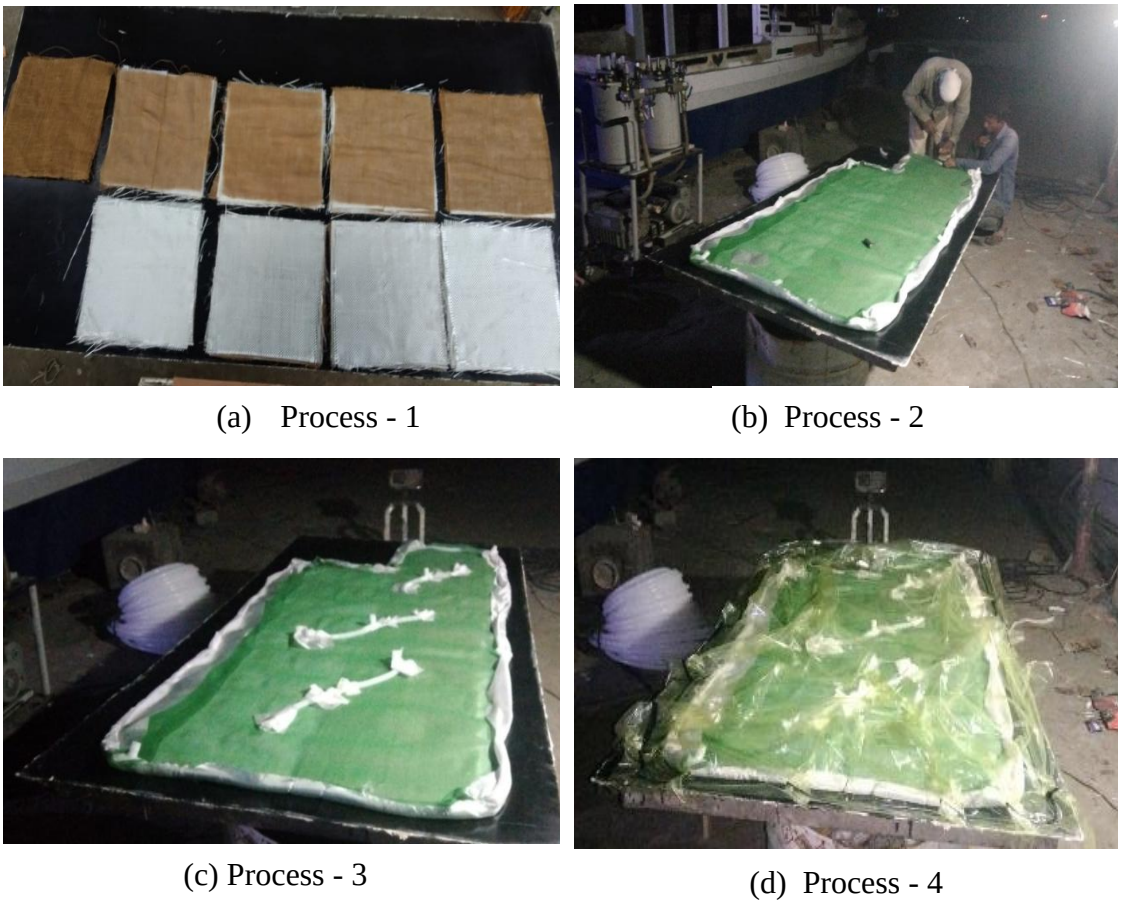
3.5.4.2. **Lay Out the Reinforcement**

- Layers of reinforcement fibers (jute and glass fibers) are carefully placed in the mold according to the desired orientation. The arrangement of these fibers can impact the strength and flexibility of the finished part.
- Peel ply, breather fabric, and flow media are added on top of the reinforcement layers to aid in the resin infusion and curing process.

3.5.4.3. **Apply Vacuum Bagging**

- A transparent plastic sheet is spread over the mold, ensuring enough space to accommodate resin flow. The edges of the bag are sealed to the mold with sealant tape, creating an airtight environment.

- Vacuum hoses are attached to the bag, allowing air to be drawn out from the system.



(a) Process - 1 (b) Process - 2

(c) Process - 3 (d) Process - 4

Figure 3.16. Mold to vacuum bagging process flow

3.5.4.4. **Pull the Vacuum**

- A vacuum pump is activated, creating a vacuum within the bag. This vacuum compresses the fiber layers, holding them tightly against the mold surface.
- By removing air, the vacuum also minimizes voids, ensuring a more solid and uniform composite structure.

3.5.4.5. **Introduce the Resin**

- Resin is introduced into the setup through a resin inlet.
- The resin flows through the glass and jute fibers. Flow media and breather fabric help control the speed and direction of resin flow to ensure even distribution. Figure 3.17 shows the vacuum infusion process system setup.



(a) Process - 1



(b) Process - 2



(c) Process - 3



(d) Process - 4

Figure 3.17. Vacuum Infusion Process System Setup

3.5.4.6. **Curing**

- Curing is the process for drying the mold. Curing depends on other factors, including quality of the resin.
- The resin hardens, bonding with the fibers to form a rigid composite material during this stage.

3.5.4.7. **Demolding and Finishing**

- After curing, the vacuum bag, peel ply, and breather fabric are removed, exposing the finished composite part.
- The part is carefully separated from the mold and may undergo additional finishing steps such as trimming, sanding, and coating, depending on the application. Figure 3.18 shows curing and demolding of composite fabricated samples.

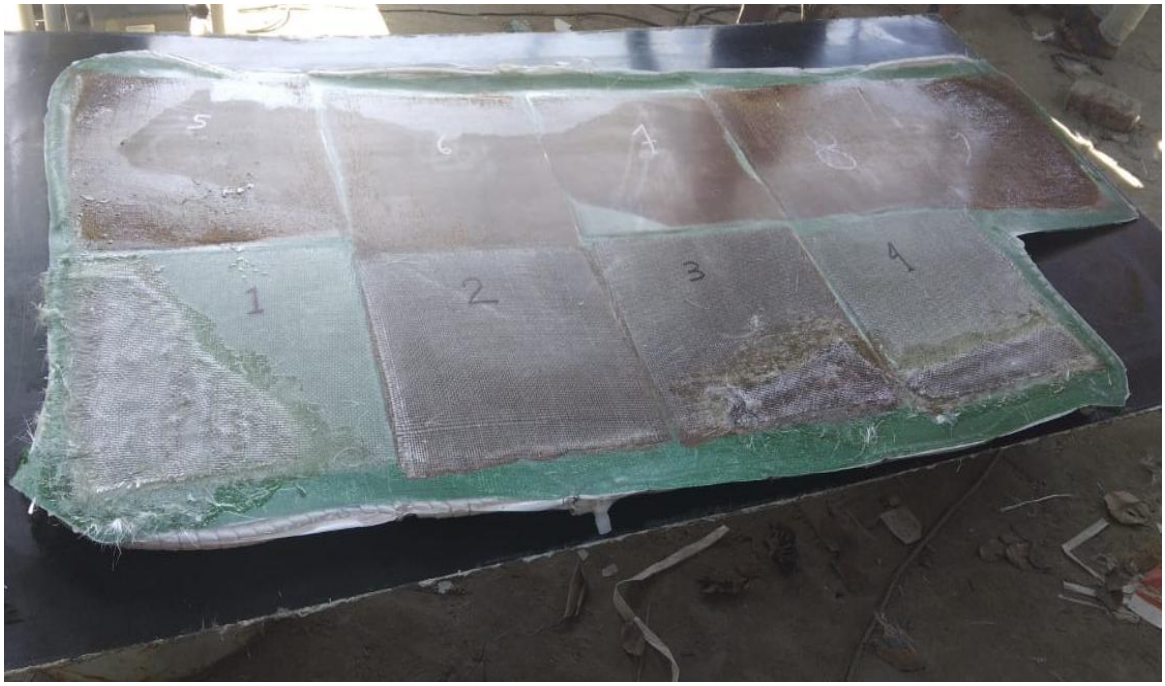


Figure 3.18. Curing and demolding of composite fabricated samples

3.6. **Flowchart of Methodology**

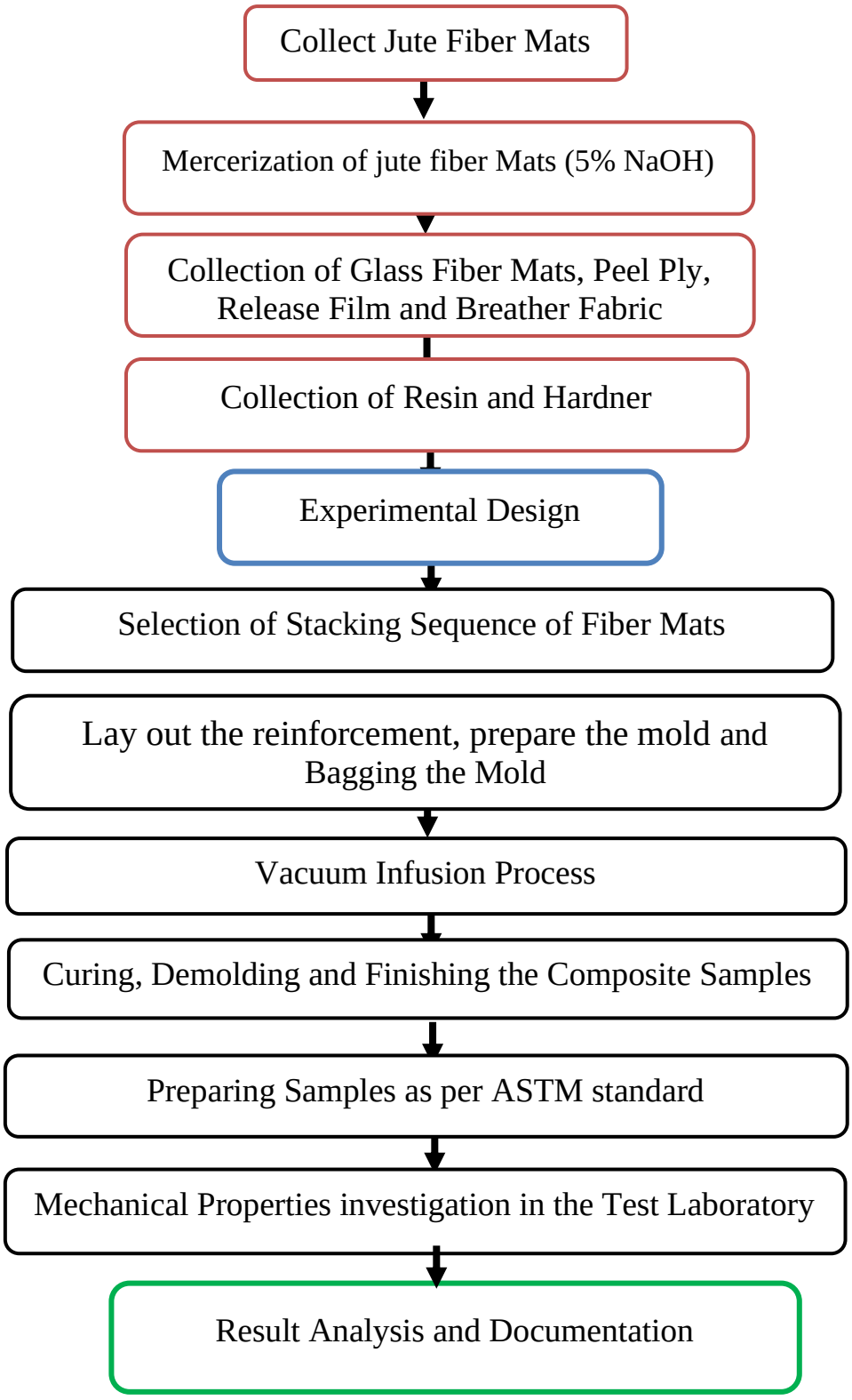


Figure 3.19. Flow Chart of Methodology

Chapter 4

DATA REDUCTIONS

4.1. **Introduction**

Data reduction chapter involves with mechanical properties testing of the fabricated hybrid composite samples. Water absorption test of the hybrid composites has been conducted and results are accumulated. The method to calculate the state of mechanical properties and hydrophilic characteristics are also discussed.

4.2. **Tensile Properties**

The tensile test is a crucial mechanical examination that assesses how materials behave under uniaxial tensile loading. It quantifies a material's capacity to endure stress. The elastic and plastic behaviors of the composite samples are investigated. At first, sample is kept under tensile loading where it experiences elongation. Continue application of stress, test sample goes for plastic deformation. Young's modulus, or the modulus of elasticity, describes the relationship between stress and strain. It indicates how much a material will deform under a specific applied stress. Once yielding starts, considerable dislocation motion takes place within the metal grains. The movement of dislocations is impeded by grain and phase boundaries, alongside other obstacles. As dislocations encounter more hindrances, the stress needed for continued movement rises.

The ASTM D3039 standard test specimens were prepared and tested in the universal testing machine (UTM) as per figure 4.1. In this experiment, hybrid composite samples S1-S10 are cut by CNC plasma cutting machine shown in figure 4.2 and 4.3. The test helps researchers to understand the tensile properties of fabricated jute-glass fiber based hybrid composite.

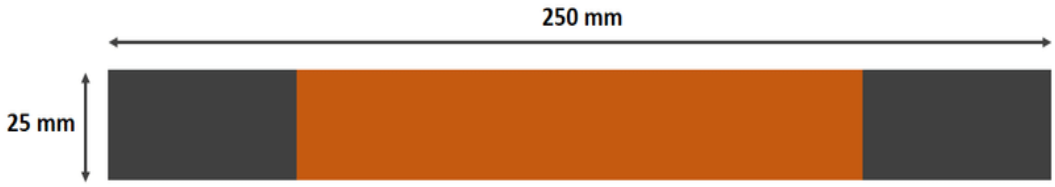


Figure 4.1 Tensile test specimen according to ASTM D3039



Figure 4.2. Tensile and Flexural Test Specimen Cutting by CNC Machine

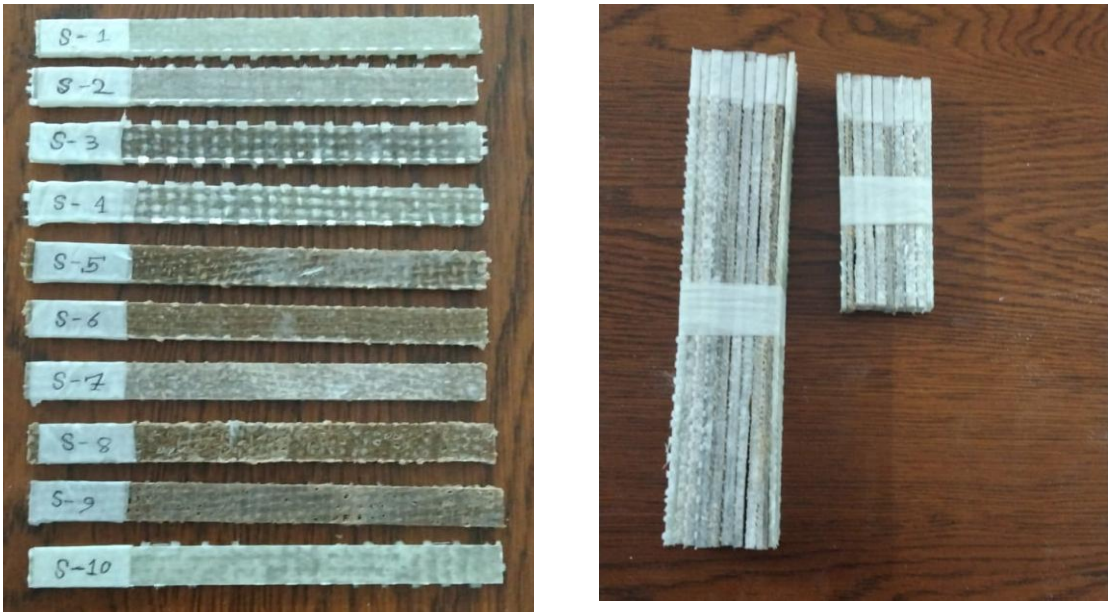


Figure 4.3. Tensile and Flexural Test Specimen



Figure 4.4. Specimen Under Tensile Test

In test Procedure, the sample is clamped in the machine's grips. A uniaxial tensile force is applied slowly, pulling the sample apart. The machine records the applied force and elongation in real-time. The test continues until the material breaks, capturing the ultimate tensile strength and elongation at fracture. Tensile test ascertains ultimate strength, elasticity, plasticity, ductility, and toughness of the composite. The formula related to the tensile test are appended below:

- **Young Modulus**: The ratio of stress and strain. It is proportional to the stiffness of the material.
- **Ultimate Tensile Strength**: The Highest stress that a material withstands or resist without failure.
- **Elongation at Break**: The maximum increase in length after failure which is expressed as percentage elongation.

$$\textbf{\textit{Applied Stress}}: \quad \sigma = \frac{F}{A} \qquad \text{.....(4.1)}$$

$$\textbf{\textit{Strain}}: \quad \varepsilon = \frac{\Delta l}{l} \qquad \text{.....(4.2)}$$

$$\textbf{\textit{Young Modulus}}: \quad E = \frac{\sigma}{\varepsilon} \qquad \text{.....(4.3)}$$

$\boldsymbol{\sigma} = Applied\ Stress$ $\boldsymbol{\varepsilon} = Strain$ $\Delta \boldsymbol{l} = Change\ in\ Length$

F = Applied Force $\boldsymbol{l} = Gauge\ length$ **A** = Cross Sectional Area

$\boldsymbol{E} = Modulus\ of\ Elasticity$

Following data have been observed from the tensile test and are arranged in Table 4.1.

Table 4.1. Tensile Test Data

Sample	*Fiber Sequence*	*Force, kN*	*Stress, MPa*	*Tensile Strain, %*	*Young Modulus, GPa*	*Displacement, mm*
S1	GCGCGCGCG	26.0994	293.378	8.91778	3.289809796	8.026
S2	GCJCGCJCG	14.4773	145.186	6.17958	2.349447697	5.56163
S3	GCJCJCJCG	13.5322	129.065	6.11486	2.110677922	5.50338
S4	GCGCJCGCG	16.6934	172.484	6.28361	2.744982582	5.65525
S5	JCJCJCJCJ	9.38781	81.5534	5.2025	1.567580971	4.68225
S6	JCGCJCGCJ	15.7598	144.457	5.3754	2.687372103	4.83788
S7	JCGCGCGCJ	15.0847	138.116	5.1145	2.70047903	4.60313
S8	JCJCGCJCJ	10.0794	90.2449	4.7954	1.881905576	4.31588
S9	JJJJJ	1.86984	24.1656	2.77389	0.871180905	2.4965
S10	GGGGG	12.9175	213.287	7.71889	2.763182271	6.947

4.3. **Flexural Properties**

Flexural test or bending test, evaluates a material's behavior when subjected to bending stress. Unlike tensile or compression testing, which focuses on uniaxial forces, flexural testing reveals how materials respond to a combination of tension (on one side) and compression (on the opposite side) when bent.

In flexural test, the stress is concentrated on the upper and lower surfaces at the midpoint between the two supports. Typically, a three-point or four-point bending test is used , where a sample is supported at two points and loaded at one (three-point) or two (four-point) points. Measurements of stress, strain, and deflection are taken until the sample fails, providing data on flexural strength, modulus, strain, and toughness. Figure 4.5 shows flexural test procedure. The ASTM D790 standard test specimens were prepared for the 3(three) points bending test.

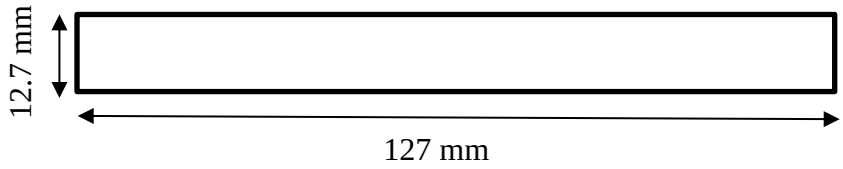


Figure 4.5 Flexural test specimen according to ASTM D790

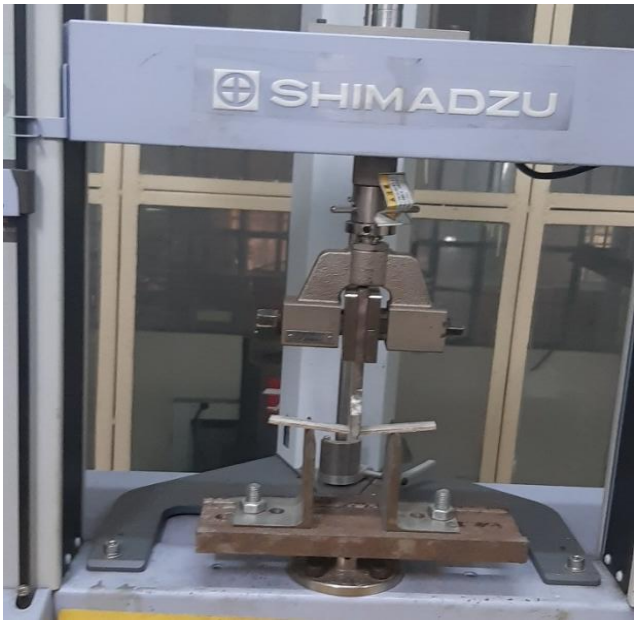


Figure 4.6. Flexural test procedure

In the experiment, the sample is kept on supports with the distance between them to meet specific test requirements. In the three-point bending test(figure 4.6), a machine head applies a vertical force gradually. As the force increases, the deflection at the midpoint is recorded. This data helps calculate stress, strain, and other properties. The test continues until the material fractures or reaches a specified deflection. The fracture pattern can provide insights into material toughness.

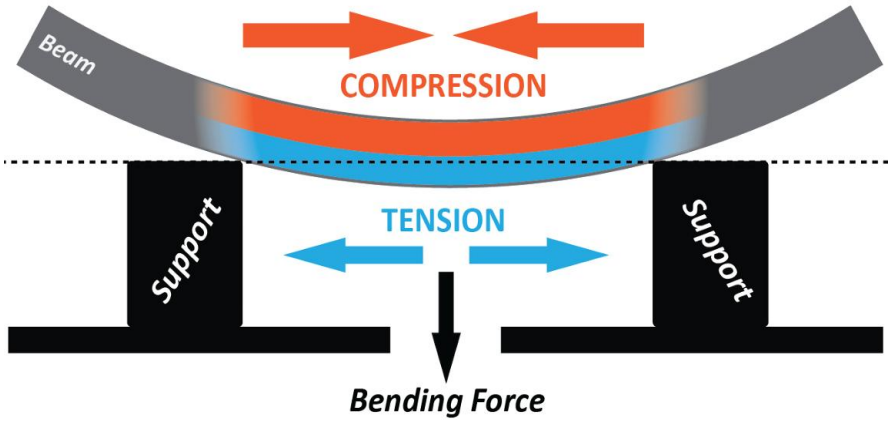


Figure 4.7. Bending stress - tension on one face and compression on the opposite face.

- **Flexural Modulus (Bending Modulus):** Flexural modulus (bending modulus) informs about material's stiffness in bending. It describes how much a material will bend under a given load. A high flexural modulus indicates that the material is stiff and will deform less under bending loads, while a low flexural modulus implies the material will flex more easily.
- **Flexural Strength:** Flexural strength (modulus of rupture) represents the maximum stress a material can withstand in bending before it fails or fractures. This property is crucial for assessing materials that will experience bending forces. The formulas to calculate flexural strengths are appended below:

$$\sigma_f = \frac{3FL}{2bh^2}$$

$$\varepsilon_f = \frac{6yh}{L^2}$$

$$E_f = \frac{\sigma_f}{\varepsilon_f}$$

$\sigma_{f=Flexurul\ Stress}$ $F = Applied\ load$ $h = Thickness\ of\ the\ specimen$

$\varepsilon_{f=Flexural\ strain}$ $L = Two\ supports\ distance$ $b = Width\ of\ the\ Specimen$

$E = Flexural\ modulus$ $y = deflection\ at\ mid\ point$

The Shimadzu tensile tester provides the applied force and the displacement of the jaw which were converted into flexural stress and flexural strain, respectively.

Following data have been observed from the flexural test are arranged in Table 4.2.

Table 4.2. Flexural Test Data

Sample	*Sequence*	*Force, N*	*Break Force, N*	*Stress, MPa*	*Flex Modulus, Gpa*	*Displacement, mm*
S1	GCGCGCGCG	524.047	489.786	304.02	8.52	6.92923
S2	GCJCGCJCG	474.732	421.536	202.019	5.54	6.1902
S3	GCJCJCJCG	528.326	377.428	202.381	8.97	3.62457
S4	GCGCJCGCG	578.341	561.424	271.044	7.01	6.7172
S5	JCJCJCJCJ	350.035	263.917	136.644	3.85	5.62023
S6	JCGCJCGCJ	474.649	401.345	185.289	5.54	5.29753
S7	JCGCGCGCJ	361.129	307.234	169.246	4.13	7.1162
S8	JCJCGCJCJ	263.529	230.319	93.5336	2.32	6.29987
S9	JJJJJ	38.9989	35.8765	22.1154	0.45	9.4139
S10	GGGGG	190.04	182.756	311.473	16.73	6.14323

4.4. **Impact Toughness**

Impact strength refers to protection against sudden impact load applied for a very short period of time. It measures how much energy the material can absorb before breaking when subjected to a load. This property is crucial in materials expected to endure sudden forces, such as in automotive, aerospace, and construction applications. It's typically quantified as the amount of energy (in joules) a material absorbs upon impact until it breaks. The higher the impact strength, the more resilient the material is to sudden forces. Charpy is a common testing method adopted in this experiment. The test sample is prepared as per ASTM 256 which is as follows:

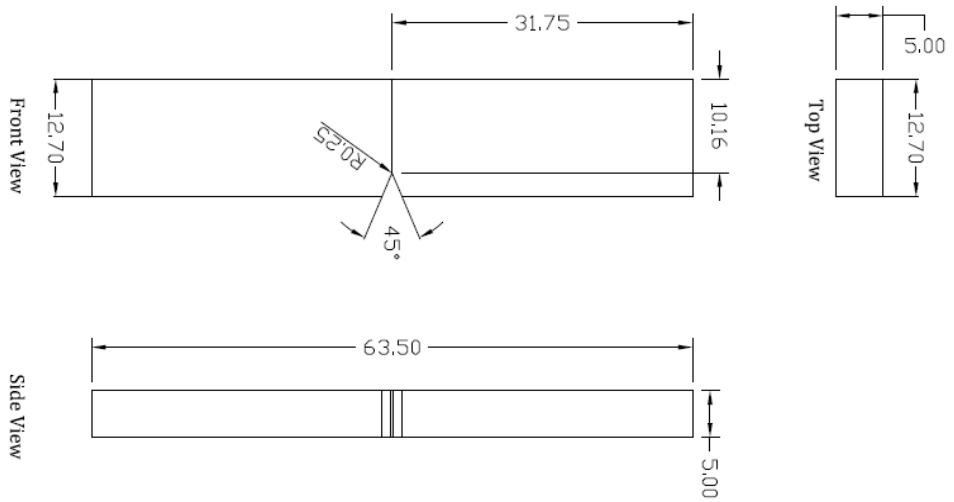


Figure 4.8. Test Specimen Design as per ASTM 256 Standard



Figure 4.9. Test Specimen Before and After Impact Test



Step 1: Measuring Specimen



Step 2: Setting up machine



Step 3: Impacting Specimen



Step 4: Impact Angle

Figure 4.10. Impact Test by Charpy method at the Mechanical Lab of CUET

Different materials exhibit varying impact strengths. Generally, metal exhibits high impact strength due to ductility, especially in alloys. Composite materials have high impact strength. Ceramics and Glass shows lower impact strength due to brittleness. Impact strength often decreases at lower temperatures, especially for materials like plastics that become brittle in cold conditions. High impact strength is critical in applications where materials face dynamic

=forces. In this study, Charpy test on 30 notched specimens of 10 different hybrid composite samples were prepared and an experiment was carried out. The machine, along with experimental sequence, is shown in the Figure 4.8. The impact strength (Joule/m^2) is calculated as per the following equation:

Mass, m = 2.5 kg

Arm radius, R = 0.345 m

Energy Absorbed, $E_K = mgR(Cos\beta - Cos\alpha)$ ……... (4.7)

Impact Strength, $U_C = \frac{E_k}{A}$ ……... (4.8)

The ASTM D256 standard test specimens were impact tested by Charpy method. Following data have been found from the experiment:

Table 4.3 Impact Strength Data

Sample	***Fiber Sequence***	***Energy Absorbed, J***	***Impact Strength, kJ/ m^2***
S1	GCGCGCGCG	2.35624967	39.27082783
S2	GCJCGCJCG	0.292430043	5.667248893
S3	GCJCJCJCG	0.614575265	11.32231512
S4	GCGCJCGCG	0	0
S5	JCJCJCJCJ	2.199005071	39.65028978
S6	JCGCJCGCJ	0.658318245	18.28661791
S7	JCGCGCGCJ	0.847101507	16.80756958
S8	JCJCGCJCJ	3.576672475	64.560875
S9	JJJJJ	0.092556133	2.098778532
S10	GGGGG	0.614575265	26.39928113

4.5. **Hardness Number**

Hardness is the resistance of material to deform from its original shape. Hardness testing is crucial to assess the durability, strength, and wear resistance of materials. The hardness test depends on the material's type, structure, and application requirements. Rockwell is fast and ideal for metals; Vickers is highly precise for a wide range of materials; Knoop is best for thin, brittle specimens; Shore is suited for soft polymers; and Mohs is most applicable in mineralogy. Each method offers distinct advantages for specific materials and applications. The hardness test is for the material's property, the accuracy required, and the specific application. Each test provides different insights, with tests like Rockwell and Brinell suited for metals, and Knoop and Shore for brittle and soft materials, respectively. The Hardness test

specimen were cut from the hybrid composite samples according to ASTM E10 -18 standard (Figure 4.11.).

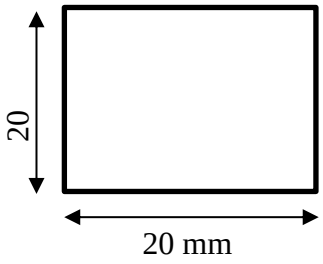


Figure 4.11. Test specimen (as per ASTM E10 -18)

In a hardness test, a steel or carbide ball is loaded into the material's surface with a preset load. The indentation diameter is measured. Hardness (HB) is measured by dividing applied load by indentation surface area. This test method is suitable for materials with coarse structures, like cast metals. The depth of the indentation is used to determine hardness. The depth of indentation is converted into a Rockwell hardness number (HRL) on scales. This hardness number is widely used for testing metals and alloys, as it provides quick and repeatable results without needing to measure the indentation directly. Figure 4.12 shows the 1/4" steel ball pressede against test sample.

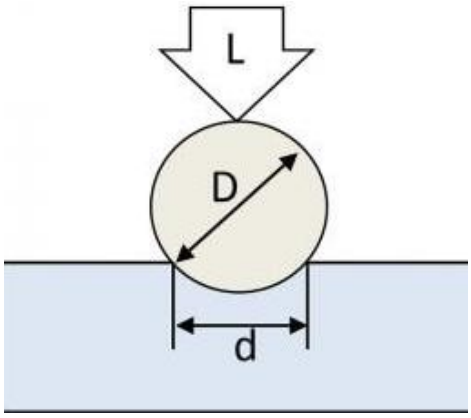


Figure 4.12. Brinell Hardness Test

Table 4.4. Rockwell hardness test specifications

Scale	Indentor	Load (Kgs)	Dial	Application
L	1/4" Ball	60	Red	Plastic and composite material

In this study, Rockwell/Brinell combined system (P.A HILTON Ltd) is used to find out the Rockwell Hardness number of the hybrid composite. The steps are discussed below:

Step 1: The Rockwell/Brinell combined system machine was setup with 60 Kg load. The specimen samples were arranged and rough surfaces of the specimens were finished with emery paper for uniform load distribution during test.



Figure 4.13. Test Specimens for hardness test



Step 1: Machine Setup



Step 2: $\frac{1}{4}^{"}$ Ball with 60 Kg load set



Step 3: Specimen under load



Step 4: Hardness number in HRL

Figure 4.14. Rockwell Hardness Test of 10 specimen at the Mechanical Lab of CUET

Step 2: The vertical spindle of the machine was set with 1/4" Ball (figure 4.12). The test specimens were placed above the lower spindle. The rotating handle of the spindle was rotated anti-clockwise twice to raise the spindle with specimen and pressed against the ball from the upper spindle.

Step3: The load (60 Kg) is applied by rear to front movement of the load lever. Indicator pointer of the dial gauge rotated clockwise to show the hardness number**.**

Step 4: The reading of the hardness number has been found directly from the gauge. The readings of hardness numbers are noted and kept for further analysis.

The ASTM E10-18 standard test specimens were tested by Rockwell hardness tester. Following data have been found from the experiment:

Table 4.5. Rockwell hardness (HRL) number of samples

Sample	***Fiber Sequence***	***Rockwell Hardness (HRL) Number***
S1	GCGCGCGCG	106
S2	GCJCGCJCG	86
S3	GCJCJCJCG	81
S4	GCGCJCGCG	92
S5	JCJCJCJCJ	82
S6	JCGCJCGCJ	82
S7	JCGCGCGCJ	84
S8	JCJCGCJCJ	79
S9	JJJJJ	67
S10	GGGGG	90

4.6. **Water Absorption Test**

Natural fiber, due to its inherent characteristics, is hydrophilic because of the higher intervening space between fiber cells. Water content in fiber makes the composite weaker and decreases the fatigue life. The water test is commonly used to measure the amount of moisture/water can be absorbed by the specimen in a particular period. It's useful in evaluating the porosity, durability, and overall quality of construction materials like concrete, bricks, stones, and wood. The test essentially determines the degree to which a material will absorb water, which can impact its performance, especially in environments exposed to moisture. The water absorption test for the fabricated composites are designed to assess how much water the fiber reinforced composite materials can absorb under specified conditions. This test is essential for composites used in applications where moisture or water exposure can influence mechanical performance, durability, and dimensional stability. Composite materials, especially those used in marine applications, require low water absorption to maintain their mechanical properties and avoid potential degradation. For water absorption test, test specimens were made as per ASTM D570 standard size: 20 mm x 20 mm. Dry the sample thoroughly (often at 50–100°C) for next 12 to 24 hours. Weigh the dry sample accurately to obtain the dry mass $\boldsymbol{W_{Dry}}$. Immerse the samples in the fresh water and salt water at room temperature for 24 Hours. Figure 4.15 shows the test specimen dimension according to ASTM D570 which was cut as per the design from the manufactured hybrid samples.

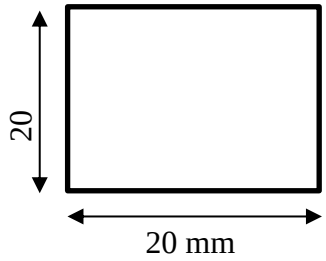


Figure 4.15. Water absorption test specimen according to ASTM D570



(a) Fresh water and salt water



(b) Specimen soaking for 48H

Figure 4.16. Fresh water and salt water absorption test

After the soaking period, remove the sample from the water and blot it gently to remove excess surface water. Avoid pressing too hard, as this might cause the sample to lose some of the absorbed water. Immediately weigh the sample to obtain the saturated mass ($\boldsymbol{W_{wet}}$).



(a) Weighing scale initializing



(b) Weighing of a sample

Figure 4.17. Weighing scale for the measurement of dry and wet weight of the samples

Following formula will be observed to calculate water percentage:

$$\textbf{Water Absorption (\%)} = \frac{\boldsymbol{W_{wet} - W_{dry}}}{\boldsymbol{W_{dry}}} \times 100 \quad \text{.....(4.9)}$$

W_{wet}= $weight\ of\ the\ sample\ after\ immersion$

W_{dry}=$Initial\ weight\ of\ the\ dry\ sample\ before\ immersion$

- **Interpreting High Absorption**: A high water absorption percentage may lead to swelling, loss of mechanical strength, and even degradation of the matrix-fiber bond, making the composite less durable.
- **Interpreting Low Absorption**: Lower water absorption generally indicates better moisture resistance and stability, making the composite suitable for humid or marine environments.

The ASTM D570 standard 20 (twenty) test specimens were made from all 10 fabricated hybrid composite samples. Among them, 10 (ten) samples were soaked in fresh water for 24 hours. Rest 10(ten) specimens were soaked in saltwater solution for 24 hours. Both samples were dry-weighted and wet-weighted. The following data have been found from the experiment:

Table 4.6. Water Absorption Test Data

Ser	Sequence of Fibers	Fresh Water Test			Salt Water Test		
		Dry Weight, g	Wet Weight, g	Absorption %	Dry Weight, g	Wet Weight, g	Absorption %
S1	GCGCGCGCG	2.88	2.88	0.00	2.70	2.70	0.00
S2	GCJCGCJCG	2.35	2.35	0.00	2.34	2.34	0.00
S3	GCJCJCJCG	2.46	2.46	0.00	2.43	2.43	0.00
S4	GCGCJCGCG	3.25	3.25	0.00	3.42	3.42	0.00
S5	JCJCJCJCJ	2.23	2.26	1.35	2.13	2.14	0.47
S6	JCGCJCGCJ	2.33	2.35	0.86	2.19	2.20	0.46
S7	JCGCGCGCJ	2.15	2.23	3.72	2.50	2.54	1.60
S8	JCJCGCJCJ	2.39	2.42	1.26	2.28	2.30	0.88
S9	JJJJJ	1.18	1.23	4.24	1.16	1.18	1.72
S10	GGGGG	1.32	1.32	0.00	1.07	1.07	0.00

4.7. **Summery**

The data reduction processes associated with this work have been briefly discussed in the present chapter. The equations which carry out desired results have been listed here also. The findings from these processes and equations are discussed in the following chapter.

Chapter 5

RESULTS AND DISCUSSIONS

5.1. **Introduction**

Glass fiber composites have higher properties compared to natural fiber-based hybrid composites. Pure glass fiber composites typically offer higher tensile strength, stiffness, impact resistance, fatigue resistance, and durability than jute fiber-based hybrid composites. Glass fiber composite shows lower hydrophilic characteristics than to natural fiber-based hybrid composites. In search of cost effectiveness, natural fiber-based hybrid composites are cheaper options than pure glass fiber composites. Therefore, the strength of hybrid composites may be designed based on durability and cost effectiveness. In this chapter, mechanical characteristics of fabricated hybrid composites will be investigated for this study.

5.2. **Hybrid Composite Laminates**

To study the mechanical properties of hybrid composites ten (10) samples were fabricated with different stacking sequence. The fiber mats were arranged $0^0/90^0$ orientation. In the hybrid manufacturing, glass fiber mats (E- Glass Fiber and CSM) and jute fiber mats were used. In hybrid composite laminates, fiber layers are expressed by the alphabet G, C and J where G = Glass Fiber Mat, C = Chopped Strand Mat (CSM) and J = Jute Fiber Mat. In this study, S9 composite sample is made up of five (5) layers of pure jute fiber mats and S10 is made up of five(5) layers of glass fiber mats.

5.3. **Tensile Properties**

The test specimens of hybrid composite laminates were tensile tested. For analyzing the data, different combinations of composite samples made up of glass and jute fibers in different layering sequences, have been tested under this study by the universal testing machine (UTM).

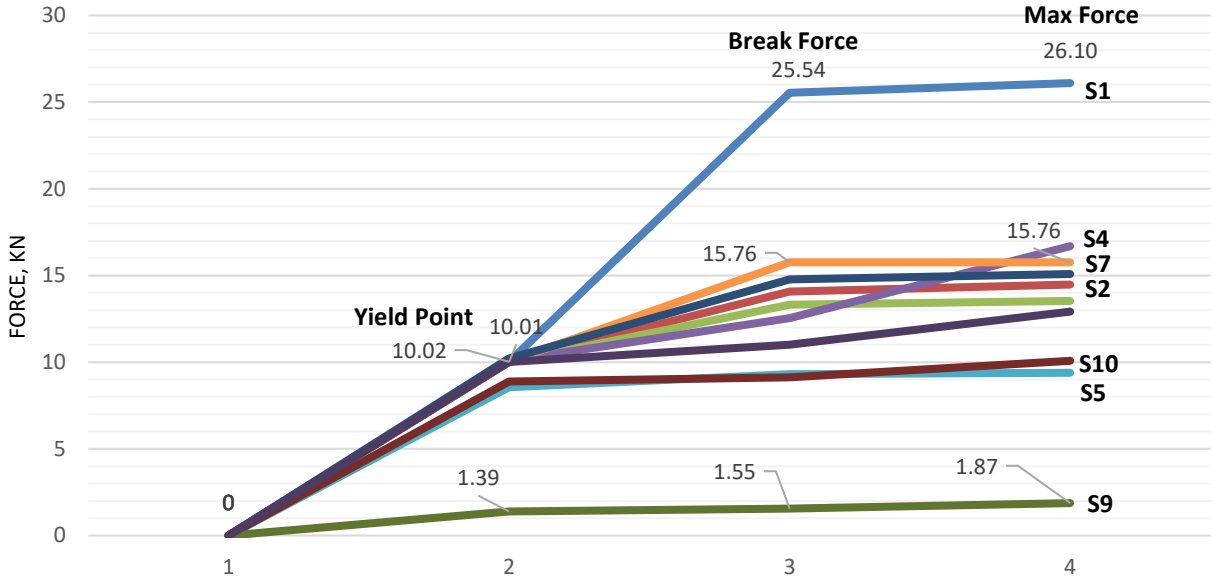


Figure 5.1. Different forces acted upon hybrid composite laminates

Figure 5.1 shows that pure glass fiver laminate S1 possesses highest tensile force of 26.10 kN where it breaks at 25.54 kN. The addition of single jute fiber layer at the center of S4, tensile force reduced to 16.69 kN and breaking force reduced to 12.55 kN i.e. tensile force reduced to 36% by adding 11.11 % volume of jute fiber. In S2, tensile force reduces to 44.67% by adding two (2) jute fiber layers. Again, tensile force farther reduces to 48.16% by adding three(3) jute fiber layers in S3. From the experiment, it has been observed that increase in jute fiver volume fraction in the hybrid composite reduces tensile force. This may be resulted of poor bonding between fibers and matrix. The stacking sequence revels that two jute fiber layers at the outer periphery of S7 exhibits higher tensile load than two jute fiber layers at the inner core at S2. The finding is inline with the findings of Yusoff et al. [60], the inclusion of low modulus and ductile (LMD) fibers in the outermost layers significantly enhanced the tensile strength. It is evident from the data that jute and glass fiber hybrid composite samples S2 to S7 having different yield point, breaking force and tensile force. All these yield point, breaking force and tensile force lies within the range of pure glass composite (S1) to pure jute composite (S9). It indicates that the stacking sequence of jute and glass fibers has an effect on the overall strength of the hybrid composites.

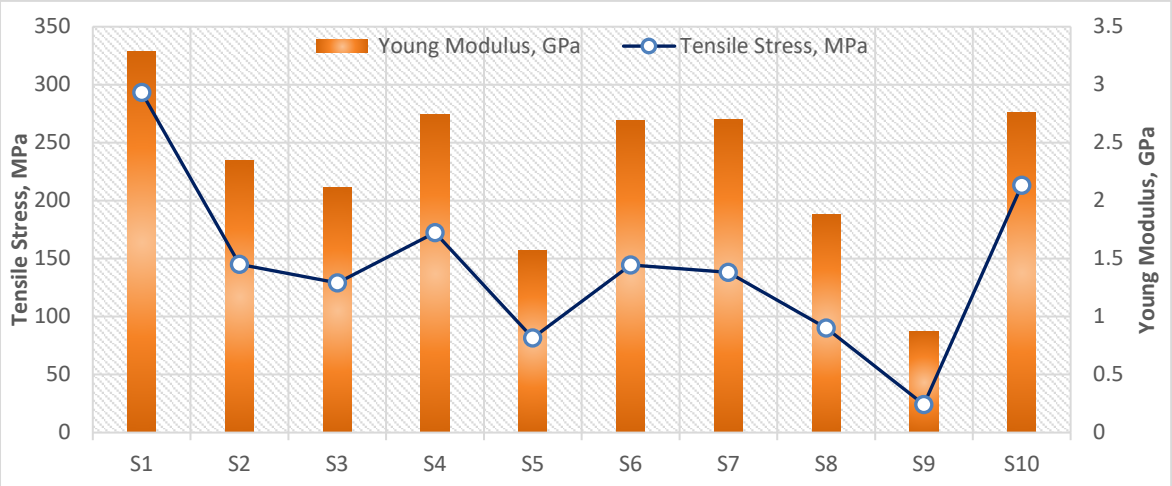


Figure 5.2. Tensile Stress vs. Young's Modulus curve of hybrid composite laminates

The figure 5.2 shows that the 5 layers pure glass fiber GFRP sample S10 has higher tensile stress 213.28 MPa and Young's Modulus 2.76 where 5 layers pure jute fiber JFRP sample S9 has the lowest tensile stress 24.17 MPa and Young's Modulus 0.87 GPa. The jute glass fiber hybrid composite has maximum tensile stress 172 MPa. The finding is supported by Turjo et al. [84] who has fabricated hybrid composite by hand lay-up process. The findings are JGJG hybrid composites tensile stress 83.02 MPa which is less than the tensile stress 172 MPa. As hand layup process has considerable amount of void space than to vacuum infusion process. Therefore, vacuum infusion process manufactured jute glass fiber hybrid composite has come out with better tensile stress than hand layup manufactured hybrid composite. Moreover, blending of both jute and glass fiber hybrid composites (S2 to S7) stress taking ability increases than to pure jute fiber composites.

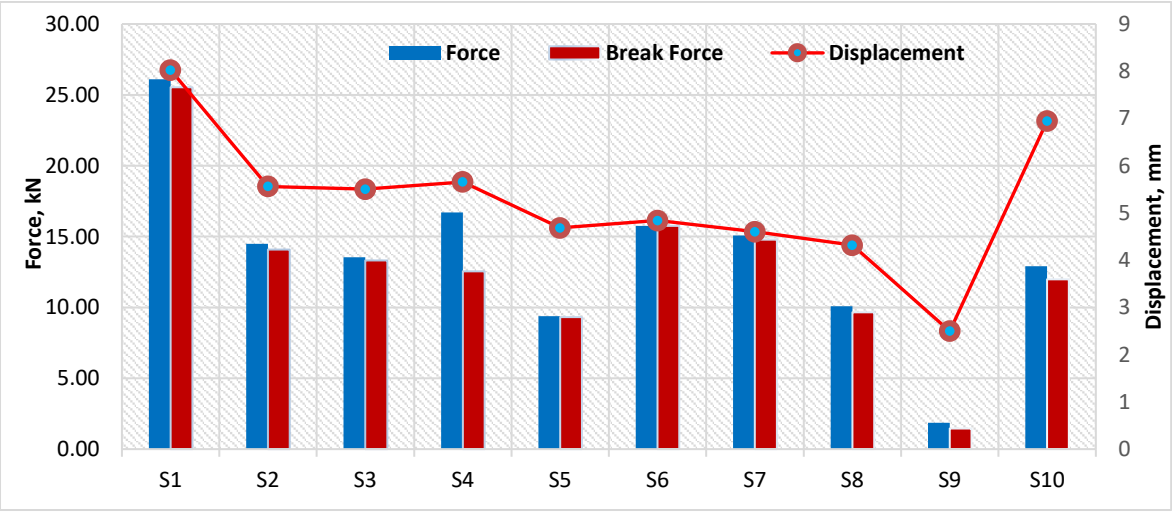


Figure 5.3. Force, Breaking Force and Displacement Curve of Hybrid Composite Laminates

Figure 5.3 indicates that pure glass fibers composite S1 is more resistant to tensile force 26 kN than to pure jute fibers S9 composite is 1.86 kN. The manufactured hybrid composite samples tensile force lies in between glass fiber composites and jute fiber composites. The tensile force of the hybrid composites remain within 9.38 kN to 16.69 kN. The addition of jute fiber layers in the hybrid composites S2 to S7, stiffness decreases and ductility increases. The stacking sequence of the 3 jute fibers and 6 glass fiber layers in S3 and S6 showed that S3 breaks at less load 13.53 kN than 15.75 kN of S6. The outer layers of Jute fiber in S6 exhibits more elongation before rapture. It indicates that stacking sequences of S3 made this composite more ductile than S6. This study identifies that the hybrid manufacturing process and fiber stacking sequence have a substantial effect on the tensile performance of the composites.

5.4. **Flexural Properties**

Flexural Strength is the maximum bending stress a material can withstand. Flexural modulus measures the stiffness and is a measure of how much it will deform under stress before reaching the breaking point. In figure 5.4, pure jute fiber composite sample JJJJJ (S9) shows low flexural strength (22.12 MPa) and low flexural modulus (0.45 GPa). On the other hand, pure glass fiber composite GGGGG (S10) shows high flexural strength (311.47 MPa) and high flexural modulus (16.73 GPa). The hybrid composite samples S2 to S7 flexural stress lies in between 93 MPa to 271 MPa. The result of Batu et al. [65] on false banana/glass fiber (B/G) reinforced hybrid composites shows flexural stress 35.69 MPa which is more than pure jute fiber S9 composite of 22.12 MPa. The pure jute fiber composite will break or fracture with the application of small amount of force due to jute fiber's low flexural modulus. A higher flexural modulus means the glass fiber resists deformation more effectively under bending loads. Moreover, fiber matrix bonding is better in vacuum infusion process which yield better flexural property.

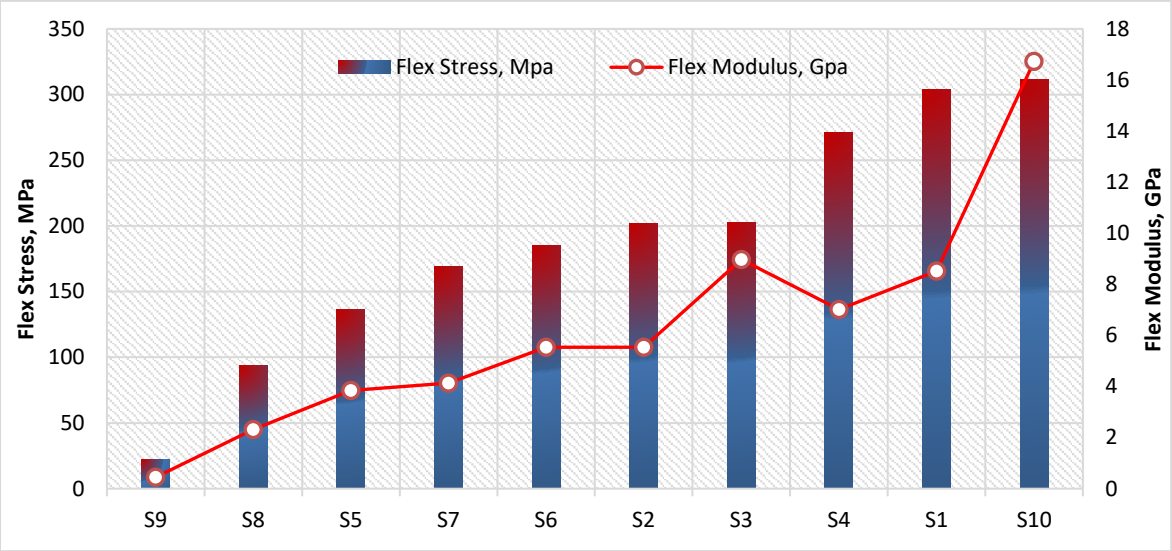


Figure 5.4. Flexural properties of Jute Glass Fiber Hybrid Composite

Figure 5.4 also shows that, sequencing 2 jute fibers lamina at the inner core of hybrid composite sample S2 has exhibited high flexural strength 202.019 MPa and high flexural modulus 5.54 GPa. On the other hand, 2 jute fibers lamina at the outer core S7 exhibited low flexural strength 169.246 MPa and low flexural modulus 4.13 GPa. Sequencing jute fibers lamina at the inner core shows higher flexural strength and modulus than that of the jute fibers lamina at outer core. This experimental result express that jute glass fiber orientation during hybrid manufacturing has impact on the strength of the composite material. In composites, both jute and glass fibers share the applied load based on their stiffness and bonding with the matrix. In jute-matrix interaction, Jute fibers often have weaker adhesion with the matrix. This can lead to early fiber pull-out or debonding, contributing to higher displacement before complete failure. The natural ductility of jute allows it to stretch significantly before breaking. Jute fibers contribute to the composite's ability to deform plastically and absorb energy, leading to higher overall displacement from 6 mm to 9 mm.

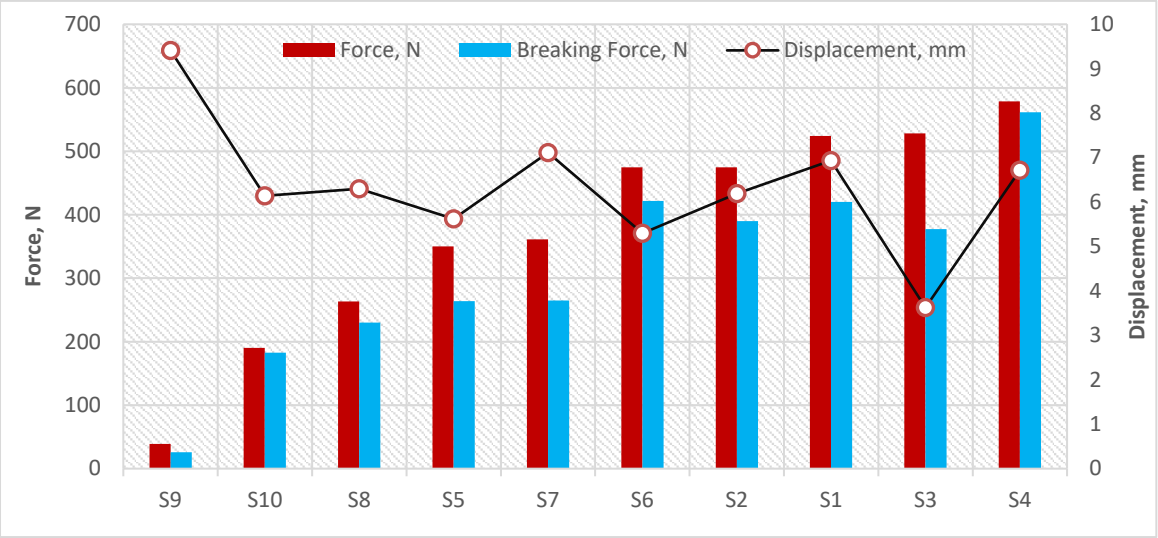


Figure 5.5. Force verses Displacement curve of hybrid composite samples

Figure 5.5 shows that sample S9 has low breaking force 35.87 kN but high displacement 9.41 mm for the jute fibers intrinsic mechanical properties and their interactions with the matrix. Pure glass fibers S1 has 304.02 MPa flexural strength, enabling them to bear higher breaking forces 489.78 kN before failing. Introduction of single jute fiber lamina at the center of glass fiber composite S4 exhibits higher strength 271.04 MPa and load bearing capacity 578 kN. Glass fibers are more brittle and fail with minimal elongation, contributing less to overall displacement. On the other hand, pure Jute fiber composite S9 has a lower flexural strength 22.11 MPa compared to glass fibers composite of S10 is 311.47 MPa. Jute fibers leads to their failure at a lower force with higher displacement. Jute fibers (weaker and less stiff) experience higher strains and fail earlier under lower loads. In the jute glass fibers hybrid construction, jute fibers fail first because of their lower strength. Glass fibers (stronger and stiffer) take over the load after jute fibers fail, preventing catastrophic failure of the fiber layers. The natural ductility of jute allows it to stretch significantly before breaking. Jute fibers contribute to the composite's ability to deform plastically and absorb energy, leading to higher overall displacement. Therefore, in hybridization, after jute fiber lamina fails, the load is redistributed to the glass fibers and the matrix, which continue to resist the applied force.

5.5. **Impact Properties**

The impact strength (IS) of pure jute fiber composite, pure glass fiber composite along with jute-glass fiber hybrid composites are presented in the figure 5.6 . Pure 9 layers glass fiber composite S1 has IS of 39.27 kJ/m^2 where as pure 5 layers of jute fiber composites S9 has IS of 2.10 kJ/m^2. It indicates that jute fiber has low impact absorbing capacity. Again, 9 layers of hybrids variants starting from S2 to S8 show different impact strength and energy absorption quality. Jute fibers have a relatively high ability to deform and absorb energy under

impact due to their natural viscoelastic properties. This enhances the composite's ability to dissipate the energy of an impact without immediate failure.

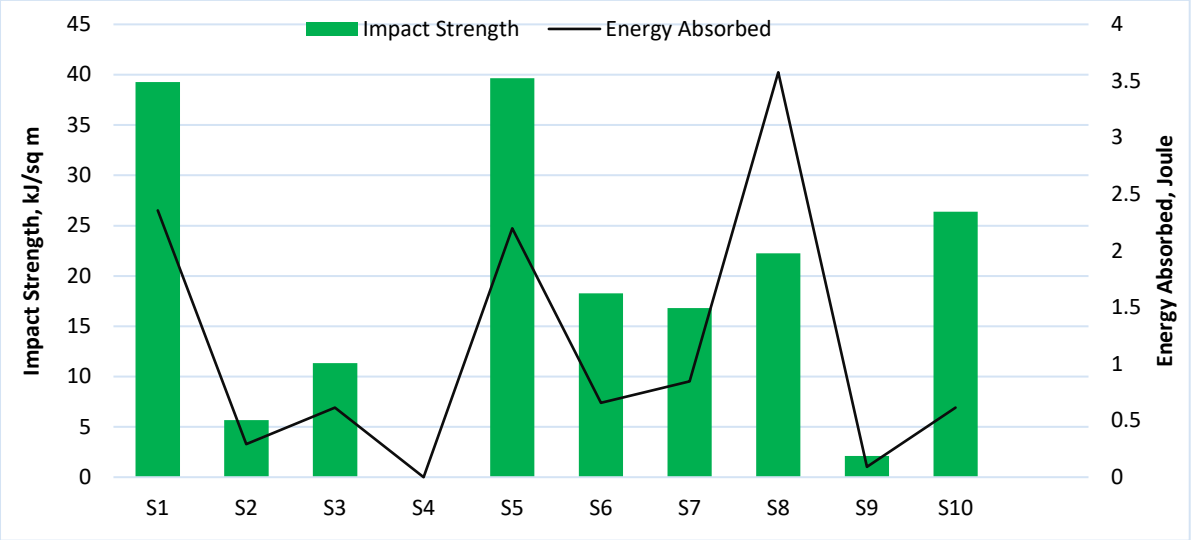


Figure 5.6. Impact strength vs Energy Absorbed of hybrid composite laminates

Glass fibers are more brittle and less effective at absorbing impact energy, leading to localized cracking or failure under sudden loads. It has been found that 3 layers of jute fiber mat GCJCJCJCG (S3) at the inner core has IS of 11.32 kJ/m^2 and 1 layer jute fiber mat at the center and 2 layers jute fiber mats at the outer surface JCGCJCGCJ (S6) of the hybrid composite has IS of 18.29 kJ/m^2 . Again, 5 layers of jute fiber layers JCJCJCJCJ(S5) i.e. 55% jute fibers have IS of 39.65 kJ/m^2 where as 100% glass fiber composite GCGCGCGCG(S1) shows almost similar IS of 39.27 kJ/m^2. The study result of Sujon et al. [88] also agrees with the findings that hybrid composite C2J6C2 has IS of 30 kJ/m^2 . Jute fibers are more likely to deflect cracks and slow their propagation, further improving impact resistance. The bonding between jute fibers and the matrix can be less stiff compared to glass fibers. Jute fibers are more ductile. This ductility allows the jute fibers to stretch and absorb energy before failure. While higher jute content improves impact strength, it may reduce other properties, such as tensile strength, because jute fibers generally have lower strength and stiffness than glass fibers. Therefore, the composition is chosen based on the specific requirements of the application. On the other hand, stacking sequence of jute fiber has significant effect on the overall performance of the impact strength of the hybrid composite.

5.6. **Hardness Number**

The Rockwell Hardness Number for jute-glass fiber hybrid composite is dependent on some important factors like matrix, fiber type, fiber arrangements, processing method etc. Jute-glass

fiber hybrid composites are a blend of natural and synthetic fibers. Here, jute fibers give green benefits and glass fiber improves mechanical properties. The Rockwell Hardness values are measured on scale Rockwell L. From Figure 5.7, the introduction of jute fiber in hybrid composites significantly improves the composite's property. In this study, sample S1 was constructed with 9-layer pure glass fiber composite, whose Rockwell Hardness(HRL) number is 106. Addition of single jute fiber layer at the center of the hybrid composite S4 reduces the Rockwell Hardness(HRL) number to 92, i.e. hardness reduction to 13.20%. In sample S2, 2 jute fiber layers are placed at the inner core of the hybrid construction, with Rockwell Hardness(HRL) number is 86. In Sample S7, 2 jute fiber layers are kept at the external surface of the hybrid construction where Rockwell Hardness(HRL) number is 84.

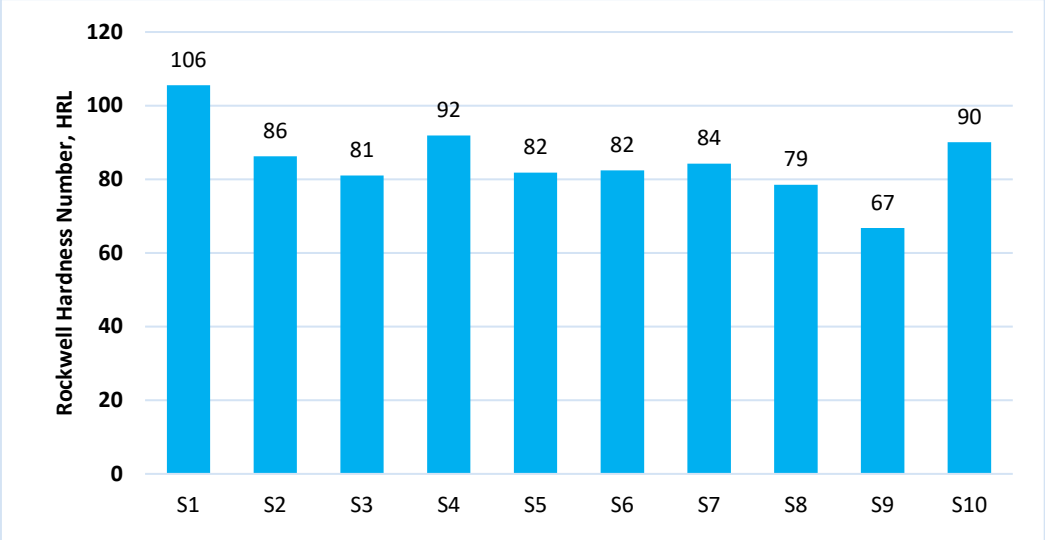


Figure 5.7. Rockwell hardness (HRL) number of jute-glass fiber hybrid composite samples

In sample S5, alternate layers of jute and glass fibers JCJCJCJCJ provide better load distribution where Rockwell Hardness (HRL) number of 82. The finding of the study of Nadondu et al.[62] is inline with the hybrid composite by the injection molding process, where the hardness number is 74.16. Random or poorly aligned jute fibers lead to more significant drops in hardness. Jute fibers, being natural fibers, are less stiff and harder compared to glass fibers. When jute fibers are introduced into a composite, the overall hardness of the hybrid composite tends to decrease relative to a pure glass fiber composite. This happens because jute fibers have lower modulus and strength, resulting in softer regions within the hybrid composite. Although jute fibers reduce the composite's hardness, they can improve toughness and impact resistance. This trade-off often leads to better energy absorption during deformation and Balanced properties, which can be optimized for applications requiring a mix of moderate hardness and toughness. However, the extent of hardness reduction can be

managed by optimizing the fiber ratio, surface treatments, and fiber sequencing in the hybrid composite.

5.7. **Water Absorption**

The water absorption test is carried out for the fabricated hybrid composite material. The water absorption test is very important as it affects the physical and mechanical properties of the material. To ascertain the amount of water absorbed by the composites under specific conditions. The composites were immersed for a period of 24 hours in fresh water and in salt water separately. The water absorption behavior of the composite is influenced by their natural fiber content, matrix material, and composite structure. Jute fibers, being natural lignocellulosic fibers, are water absorbing. Glass fibers are hydrophobic and non-porous. Polyester resin is inherently hydrophobic and acts as a barrier to water ingress. When exposed to water, jute fibers absorb moisture, causing swelling. Figure 5.8 indicates that pure glass fiber composite samples S1 and S10 do not absorb any water during fresh water or salt water immersion for 24 hours period. Glass fiber composite shows pure hydrophobic character. The layering sequence of jute and glass fibers hybrid composite show water absorption. Manufactured composites where glass fibers are at the outer layers i.e. S2, S3 and S4 are not absorbing water due to the barrier provided by the glass fiber. Farther analysis shows that 2 outer jute fiber layers of S7 absorb maximum 3.72% fresh water and 1.6% salt water. Pure jute fiber composite S9 shows highest fresh water 4.24% and salt water 1.72% absorption. Jute fibers, being hydrophilic, absorb water. Moreover, it has been observed that absorption of fresh water is more than that of salt water.

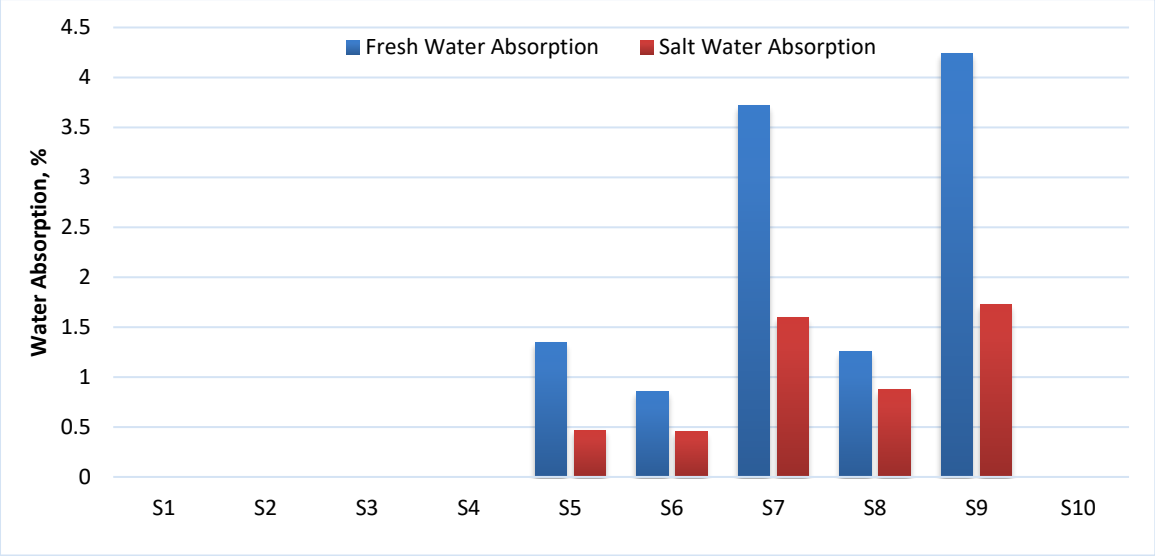


Figure 5.8. Water absorption pattern of jute and glass fiber hybrid composites

In freshwater, there are no dissolved salts, so the water absorption depends on the natural affinity of the jute fibers and any matrix porosity or defects. Saltwater generally leads to lower overall water absorption due to the dissolved salts, which reduce the activity of water molecules and their ability to penetrate the composite material. Defects in the polyester matrix (like voids or cracks) allow both fresh and saltwater to penetrate the laminate of the composite. Freshwater promotes more direct swelling of jute fibers due to its higher free water activity. Saltwater's osmotic effect may limit swelling but it may still degrade untreated fibers over time. For durability in marine applications, protective treatments (like fiber surface treatments or barrier coatings) are essential to mitigate the effects of both fresh and saltwater.

5.8. **Comparative Study**

Mechanical Properties Investigation and Hydrophilic Characterization of Vacuum Infusion Processed hybrid composites are investigated in this experiment. The Effect of stacking sequences on mechanical properties like tensile, flexural, hardness, impact resistance, and hydrophilic characterization of manufactured hybrid composite is studied. The study of Turjo et al. [84] shows that among all hybrid manufacturing processes, the Vacuum Infusion Process maintains 3% void in the hybrid construction, which increases the mechanical performance of the hybrid composites. Therefore, to validate the statement the experimental result of this vacuum infusion process manufactured hybrid composite can be compared with other similar studies of different manufacturing process.

- In this study, 9 fiber layers of hybrid composites samples S2 to S8 were examined in different stacking sequences. In S2 (GCJCGCJCG) and S7 (JCGCGCGCJ) both have 2 layers of jute fiber and 7 layers glass fibers in the hybrid manufactured sample. Result of S2 and S7 finds tensile stress 145.186 MPa and 138.116 MPa i.e. jute fiber in the inner layer of hybrid composite has more tensile strength. In S3(GCJCJCJCG) and S6(JCGCJCGCJ), both have 3 layers of jute fiber in the hybrid manufactured sample. Here, S3 and S6 have tensile stress 129.065 MPa and 144.46 MPa i.e. S6 hybrid of 1 jute fiber layer at the center and other 2 jute fiber layers on the outer surface exhibits more strength. S5(JCJCJCJCJ) and S8(JCJCGCJCJ) shows tensile strength 81.55 MPa and 90.24 MPa respectively. In S4, a single jute layer was introduced at the center of the glass fibers, has highest tensile stress 172.48 MPa. A similar study of Hasan et al. [78] finds that hand layup processed jute glass fiber 4 layered hybrid composite sample B(JGGJ), C(GJJG) and D(JGJG) have tensile stress 121.134 MPa, 115.28

MPa and 109.904 MPa, has highest tensile stress 121.134 MPa. The study of Mahmud et al. [106] shows that hybrid composites GJJG has the tensile strength 67.83 MPa.

- In S2 (GCJCGCJCG) and S7 (JCGCGCGCJ) both have flexural stress 202.019 MPa and 169.246 MPa i.e. jute fiber in the inner layer of hybrid composite has more flexural strength. In S3(GCJCJCJCG) and S6(JCGCJCGCJ), both have 3 layers of jute fiber flexural stress 202.381MPa and 185.289MPa respectively i.e. S3 hybrid arrangement is better in bending stress situation. S5(JCJCJCJCJ) and S8(JCJCGCJCJ) shows tensile strength 136.644 MPa and 93.5336 MPa respectively. In S4, a single jute layer was introduced at the center of the glass fiber layers, has highest flexural stress 271.044 MPa. A similar study of Hasan et al. [78] finds that hand layup processed jute glass fiber 4 layered hybrid composite sample B(JGGJ), C(GJJG) and D(JGJG) have flexural stress 109.459 MPa, 217.467 MPa and 147.681 MPa, has highest flexural stress 217.467 MPa. The study of Mahmud et al. [106] shows that hybrid composites GJJG have achieved 103.28 MPa flexural strength.
- In S2 (GCJCGCJCG) and S7 (JCGCGCGCJ) both have impact strength 5.667248893 kJ/m^2 and 16.80756958 kJ/m^2 i.e. jute fiber in the outer layer of hybrid composite has more impact strength. In S3(GCJCJCJCG) and S6(JCGCJCGCJ), both have 3 layers of jute fiber impact strength 11.32231512 kJ/m2 and 18.28661791 kJ/m2 respectively i.e. S6 hybrid arrangement is better in impact loading condition. S5(JCJCJCJCJ) and S8(JCJCGCJCJ) shows impact strength 39.65028978 kJ/m^2 and 64.560875 kJ/m^2 respectively. Study of Hasan et al. [78] finds that hand layup processed jute glass fiber 4 layered hybrid composite sample B(JGGJ), C(GJJG) and D(JGJG) have impact strength 375 kJ/m^2, 378 kJ/m^2 and 365 kJ/m^2 .
- In S2 (GCJCGCJCG) and S7 (JCGCGCGCJ) both have Rockwell Hardness 86 HRL and 84 HRL respectively i.e. jute fiber in the inner layer of hybrid composite has more hardness. In S3(GCJCJCJCG) and S6(JCGCJCGCJ), both have 3 layers of jute fiber with hardness 81 HRL and 82 HRL respectively. S5(JCJCJCJCJ) and S8(JCJCGCJCJ) shows 82 HRL and 79 HRL respectively. S4 with single layer of jute fiber exhibits hardness of 92 HRL. In the study of Nadondu et al. [62] finds that glass (5%), carbon(10%) and Durian skin(10%) fibers hybrid composite manufactured by injection molding process has hardness of 74.159 Rockwell E scale.
- As S2 (GCJCGCJCG), S3(GCJCJCJCG) and S4(GCGCJCGCG) are hydrophobic due to glass fiber on the outer layer of the hybrid composite. S5(JCJCJCJCJ), S6(JCGCJCGCJ), S7 (JCGCGCGCJ) and S8(JCJCGCJCJ) hybrid composite absorb fresh water (1.35%, 0.86%, 3.72% and 1.26%) and salt water (0.47%, 0.46%. 1.60% and 0.80%) in varying amount according to their construction. In the study, Sujon et al. [88] employed vacuum assisted resin infusion process to manufacture composites by woven jute fibers (six

layers) and carbon fibers (four layers). He has adopted 4 different stacking sequences and 3 different fiber orientations, water absorption rate was 3.8%.

From the above comparison, it has been reveled that single jute fiber layer within the 9 layers jute-glass fibers hybrid composite S4 will have maximum tensile and flexural characteristics. Similarly, in 2 jute fiber layers hybrid composite S2 exhibit next higher values of tensile and flexural strength. In 3 jute fiber layers hybrid composite S6 shows considerable tensile strength and S3 shows considerable flexural strength. Impact strength increases with the increase of jute fiber layers and maximum value obtained in S8. Hardness value maximum in S4 and decreases by increasing jute fiber layers in the hybrid composites. The best hydrophobic characteristics observed in the hybrid sample S2, S3 and S4 with no absorption of water.

Chapter 6

CONCLUSIONS AND RECOMMENDATIONS

6.1. **Conclusions**

Hybrid composite is one of the new trends in the field of production engineering. In this study, glass fibers are used due to cost effectiveness than carbon or aramid fibers. The use of natural fibers like jute is used as filler or reinforcement in hybrid composites due to its availability. Among several types of resins, polyester resin has been used in the composite manufacturing due to its cost-effectiveness. Here, hybridization of fiber is achieved through combining glass fibers with jute fibers. Reinforcement of fibers become load bearing components where load is transferred through matrix. Hybrid composites offer good mechanical properties compare to pure natural fiber composites. Hybrid composites are cost saving, improvement of fractural toughness, good impact resistance, and longer fatigue life.

- Hybrid composite with single layer of jute fiber S4 exhibited highest tensile force 16.69 kN, tensile stress 172.48 MPa and tensile modulus 2.744 GPa. Jute-glass fiber hybrid composite with two layers of jute fiber S2 showed tensile force 14.48 kN, tensile stress 145.18 MPa and tensile modulus 2.349 GPa. The addition of jute fiber reduces tensile strength of the manufactured composites. Jute fiber has a lower load-bearing capacity compared to glass fibers. However, blending jute and glass fibers enhances the composite's overall strength and stress bearing ability than to pure jute fiber composite. The volume fraction of jute fibers and their stacking sequence in hybrid composite laminates significantly influences the tensile strength.
- Hybrid composite with a single layer of jute fiber mat at the center of the glass fiber layers, S4 exhibited the highest flexural stress 271.044 MPa and flexural modulus 7.01 GPa. Jute-glass fiber hybrid composite with two layers of jute fiber S2 showed flexural stress 202.019 MPa and flexural modulus 5.54 GPa. Pure jute fiber composite shows low flexural modulus. In jute glass fiber hybridization, jute fibers fail first because of it’s lower strength and ductility. Glass fibers (stronger and stiffer) take over the load after jute fibers fail, preventing catastrophic failure of the composite structure. The natural ductility of jute allows it to stretch significantly before breaking. Therefore, in hybridization it has been observed that after jute fiber lamina fails, the load is redistributed to the glass fibers and the matrix, which continue to resist the applied

force. The combination makes the composite suitable for applications requiring a balance of load-bearing capacity and deformation before failure.

- The impact strength of the jute/glass fiber hybrid composite increases which increases the ability to withstand sudden impact load. Jute fibers are more ductile allows it to stretch and absorb energy before failure. Higher jute content improves impact strength but reduces other properties like tensile strength or stiffness. Therefore, jute/glass fiber hybrid composite S8 with 4 layers of jute fibers shows highest impact strength 64.56 kJ/m^2 and energy absorption 3.58 J.

- In the hardness test, hardness value maximum in S4 is 92 HRL which decreases by increasing jute fiber layers in S2 is 86 HRL. Jute fiber based hybrid composites hardness reduces with the increase of jute fiber layers in the composite stacking. Jute fibers have lower modulus and strength, resulting in softer regions within the hybrid composite. Although jute fibers reduce the composite's hardness, they can improve toughness and impact resistance. This trade-off often leads to better energy absorption during deformation, which can be optimized for applications requiring a mix of moderate hardness and toughness.

- In hybrid composite S2, S3 and S4 are hydrophobic due to outer layers are glass fiber. Hybrid composites S5, S6, S7 and S8 absorb fresh water (1.35%, 0.86%, 3.72% and 1.26%) and salt water (0.47%, 0.46%. 1.60% and 0.80%) in varying amount according to the layering sequence of jute and glass fibers in the composite. It has been observed that absorption of fresh water is more than that of salt water. Freshwater promotes more direct swelling of jute fibers due to its higher free water activity. Saltwater osmotic effect may limit swelling but may still degrade untreated fibers over time.

The stacking sequence has a dominating effect on the mechanical performance of the hybrid composites. The composite shows higher tensile and flexural properties. It happens when the glass fiber is placed on the outer surface of the composites. The increased impact toughness of the hybrid composite is the reason for the natural fiber ability to endure the maximum sudden high-impact loading. The hydrophilic nature of jute regulates the overall quality of the composites. However, research is needed to improve hybrid composites as a sustainable and cost-effective material.

6.2. **Recommendations**

Future research recommendations are:

- Optimization of fiber volume fractions by investigating the ratio of jute to glass fibers to maximize mechanical properties.
- Explore stacking sequences with fiber orientations to improve tensile, flexural, and impact performance by developing advanced laminate configurations.
- Investigate the influence of resin systems on fiber-matrix bonding and overall composite performance.
- Study the biodegradability and end-of-life management of hybrid composites and develop methods for recycling or safe disposal.

The recommendations will make the headway for the development of innovative, sustainable, and high-performance jute-glass fiber hybrid composites tailored to meet the demands of modern world.

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