

**FABRICATION AND CHARACTERIZATION OF NATURAL
FIBERS REINFORCED POLYMER COMPOSITE**

Over the past few decades, we find that polymers have replaced many of the conventional metals/materials in various applications. This is possible because of the advantages polymers offer over conventional materials. The most important advantages of using polymers are the ease of processing, productivity, and cost reduction. In most of these applications, the properties of polymers are modified using fillers and fibers to suit the high strength/high modulus requirements. Fiber reinforced polymers offer advantages over other conventional materials when specific properties are compared. These composites are finding applications in diverse fields from appliances to space-crafts. Natural fibers have recently attracted the attention of scientists and technologists because of the advantages that these fibers provide over conventional reinforcement materials, and the development of natural fiber composites has been a subject of interest for the past few years. These natural fibers are low-cost fibers with low density and high specific properties. These are biodegradable and non abrasive, unlike other reinforcing fibers. However, certain drawbacks such as incompatibility with the hydrophobic polymer matrix, the tendency to form aggregates during processing, and poor resistance to moisture greatly reduce the potential of natural fibres to be used as reinforcement in polymers. In this report, we shall review the reported work on various aspects of natural fibers reinforced composites and address some of the basic issues in development of such composites [1].

1.1 Natural Fibers

Natural fibers are fibers that are produced by geological processes, or from the bodies of plants or animals. They can be used as a component of composite materials, where the orientation of fibers impacts the properties. Natural fibers can also be matted into sheets to make paper or felt [1].

1.2 Types of Natural Fibers

Natural fibers are grouped into three types: vegetable (cellulose), animal (protein), mineral fibers as shown in figure 1.1. Some examples are cotton (seed hairs), ramie, jute, and flax (bast fibers), and sisal and abaca (leaf fibers). Of these fibers, jute, ramie, flax, and sisal are the most commonly used fibers for polymer composites. Natural fibers in the form of wood flour have also been often used for preparation of natural fiber composites. The tensile strength of glass

fibers is substantially higher than that of natural fibers even though the modulus is of the same order. However, when the specific modulus of natural fibers (modulus/specific gravity) is considered, the natural fibers show values that are comparable to or better than those of glass fibers. These higher specific properties are one of the major advantages of using natural fiber composites for applications wherein the desired properties also include weight reduction[1].

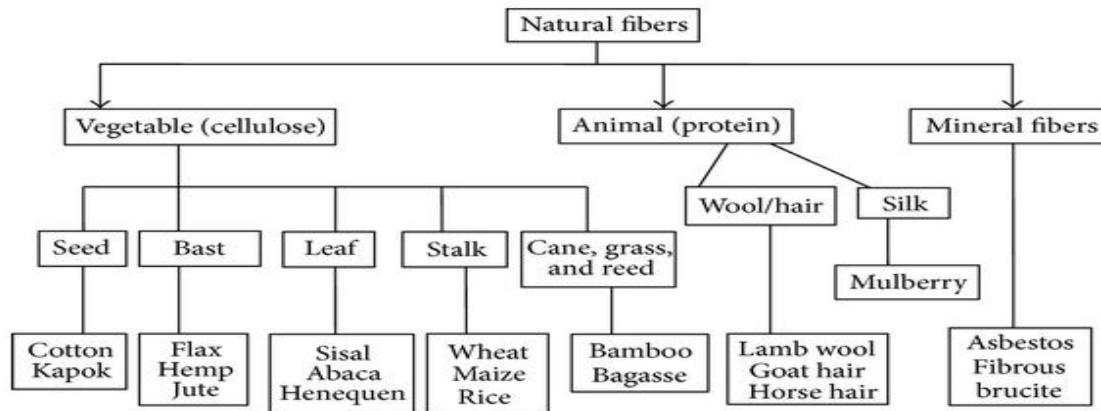


Figure 1.1 Types of natural fibers

1.3 Structure of Fibers

Natural fibers themselves are cellulose fiber reinforced materials as they consist of microfibrils in an amorphous matrix of lignin and hemicellulose. These fibers consist of several fibrils that run all along the length of the fiber. The hydrogen bonds and other linkages provide the necessary strength and stiffness to the fibers [1].

1.4 Chemical Composition of Natural Fibers

The chemical composition of natural fibers varies depending upon the type of fiber. Primarily, fibers contain cellulose, hemicellulose, pectin, and lignin. The properties of each constituent contribute to the overall properties of the fiber. Hemicellulose is responsible for the biodegradation, moisture absorption, and thermal degradation of the fiber as it shows least resistance whereas lignin is thermally stable but is responsible for the UV degradation. The percentage composition of each of these components varies for different fibers. Generally, the fibers contain 60 – 80% cellulose, 5 – 20% lignin, and up to 20% moisture[1].

1.5 Composites

Composites are simply a combination of two or more constituent materials with different physical or chemical properties. When combined, they produce a material with characteristics different from their original properties. The two main components within a composite are the matrix and fiber [2].

1.6 Natural Fiber Composites

The matrix phase plays a crucial role in the performance of polymer composites. Both thermosets and thermoplastics are attractive as matrix materials for composites. In thermoset composites, formulation is complex because a large number of components are involved such as base resin, curing agents, catalysts, flowing agents, and hardeners. These composite materials are chemically cured to a highly cross-linked, three-dimensional network structure. These cross-linked structures are highly solvent resistant, tough, and creep resistant. The fiber loading can be as high as 80% and because of the alignment of fibers, the enhancement in the properties is remarkable [3].

Thermoplastics offer many advantages over thermoset polymers. One of the advantages of thermo-plastic matrix composites is their low processing costs. Another is design flexibility and ease of molding complex parts. Simple methods such as extrusion and injection molding are used for processing of these composites. In thermoplastics most of the work reported so far deals with polymers such as polyethylene, polypropylene, polystyrene, and polyvinyl chloride. This is mainly because the processing temperature is restricted to temperatures below 200°C to avoid thermal degradation of the natural fibers. For thermoplastic composites, the dispersion of the fibers in the composites is also an important parameter to achieve consistency in the product. Thermoplastic composites are flexible and tough and exhibit good mechanical properties. However, the % loading is limited by the process-ability of the composite. The fiber orientation in the composites is random and accordingly the property modification is not as high as is observed in thermoset composites [3].

Properties of the fibers, the aspect ratio of the fibers, and the fiber – matrix interface govern the properties of the composites. The surface adhesion between the fiber and the polymer plays an important role in the transmission of stress from matrix to the fiber and thus contributes toward the performance of the composite. Another important aspect is the thermal stability of these fibers. These fibers are ligno-cellulosic and consist of mainly lignin, hemicellulose, and cellulose. The cell walls of the fibers undergo pyrolysis with increasing processing temperature

and contribute to char formation. These charred layers help to insulate the lingo cellulosic from further thermal degradation. Since most thermoplastics are processed at high temperatures, the thermal stability of the fibers at processing temperatures is important. Thus the key issues in development of natural reinforced composites are (i) thermal stability of the fibers, (ii) surface adhesion characteristics of the fibers, and (iii) dispersion of the fibers in the case of thermoplastic composites [3].

1.7 Types of Composites

As shown in figure 1.2 polymers are classified into two broad categories: according to matrix constitute and according to reinforcement form.

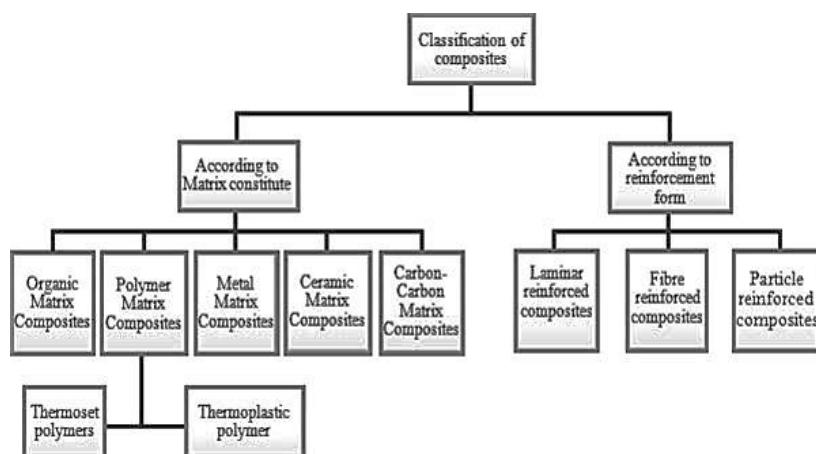


Figure 1.2 Classification of composite

1.7.1 Polymer Matrix Composites (PMCs)

The most common advanced composites are polymer matrix composites. These composites consist of a polymer thermoplastic or thermosetting reinforced by fiber (natural carbon or boron). These materials can be fashioned into a variety of shapes and sizes. They provide great strength and stiffness along with resistance to corrosion. The reason for these being most common is their low cost, high strength and simple manufacturing principles.

1.7.2 Metal Matrix Composites (MMCs)

Metal matrix composites, as the name implies, have a metal matrix. Examples of matrices in such composites include aluminium, magnesium and titanium. The typical fiber includes carbon and silicon carbide. Metals are mainly reinforced to suit the needs of design. For example, the elastic stiffness and strength of metals can be increased, while large coefficient of

thermal expansion, and thermal and electrical conductivities of metals can be reduced by the addition of fibers such as silicon carbide.

1.7.3 Ceramic Matrix Composites (CMCs)

Ceramic matrix composites have ceramic matrix such as alumina, calcium, alumina silicate reinforced by silicon carbide. The advantages of CMC include high strength, hardness, high service temperature limits for ceramics, chemical inertness and low density.

Naturally resistant to high temperature, ceramic materials have a tendency to become brittle and to fracture. Composites successfully made with ceramic matrices are reinforced with silicon carbide fibers. These composites offer the same high temperature tolerance of super alloys but without such a high density. The brittle nature of ceramics makes composite fabrication difficult. Usually most CMC production procedures involve starting materials in powder form.

There are four classes of ceramics matrices: glass (easy to fabricate because of low softening temperatures, include borosilicate and alumino silicates), conventional ceramics (silicon carbide, silicon nitride, aluminum oxide and zirconium oxide are fully crystalline), cement and concreted carbon components.

1.7.4 Carbon-carbon composites (CCMs)

CCMs use carbon fibers in a carbon matrix. Carbon-carbon composites are used in very high temperature environments of up to 6000 oF, and are twenty times stronger and thirty times lighter than graphite fibers [4].

1.8 Advantages of Natural Fiber

Natural fibers, as reinforcement, have recently attracted the attention of researchers because of their advantages over other established materials. They are environmentally friendly, fully biodegradable, abundantly available, renewable and cheap and have low density. Plant fibers are light compared to glass, carbon and aramid fibers. The biodegradability of plant fibers can contribute to a healthy ecosystem while their low cost and high performance fulfills the economic interest of industry. When natural fiber reinforced plastics are subjected, at the end of their life cycle, to combustion process or landfill, the released amount of CO₂ of the fibers is neutral with respect to the assimilated amount during their growth. The abrasive nature of

fiber is much lower which leads to advantages in regard to technical process and recycling process of the composite materials in general. Natural fiber-reinforced plastics, by using biodegradable polymers as matrices, are the most environmental friendly materials, which can be composed at the end of their life cycle. Natural fiber composites are used in place of glass mostly in non-structural applications. A number of automotive components previously made with glass fiber composites are now being manufactured using environmentally friendly composites. Although natural fibers and their composites are environmental friendly and renewable (unlike traditional sources of energy, i.e., coal, oil and gas), these have several bottlenecks. These have: poor wettability, incompatibility with some polymeric matrices and high moisture absorption. Composite materials made with the use of unmodified plant fibers frequently exhibit unsatisfactory mechanical properties. To overcome this, in many cases, a surface treatment or compatibilizing agents need to be used prior to composite fabrication. The properties can be improved both by physical treatments (cold plasma treatment, corona treatment) and chemical treatments (maleic anhydride organosilanes, isocyanates, sodium hydroxide permanganate and peroxide). Mechanical properties of natural fibers are much lower than those of glass fibers but their specific properties, especially stiffness, are comparable to the glass fibers [5].

1.9 Applications of Composites

1.9.1 Automobile Application

PMCs are consumed in a large amount in the automotive industry because of their lightweight and less cost. PMC's mechanical characteristics are very significant for designing vehicles to an extent that they meet all of the requirements, including a deduction in the automobile's weight, therefore promoting the fuel efficiency, and also reducing the emission of exhaust, thus lessening the air pollution. According to the estimation, if there is a 25% reduction in the weight of the car, 250 million barrels of crude oil can be saved, while if there is a 10% reduction in car's weight, there can be a 6-8% increase in the fuel efficiency. Although, when trying to achieve this, the safety of the passengers should not be sacrificed. So, when the vehicle is being designed, the most significant factors are three, including, the safety of the passenger, fuel efficiency, and lightweight.

Because of their biodegradability, low cost of production, resistance to abrasion and corrosion, vibration and noise reduction, high impact energy absorption, design flexibility, high stiffness,

high strength, and lightweight, the perfect materials for such applications are natural fiber polymer composites. PMCs are utilized at some of the various parts in the manufacturing of automobiles. Some of those parts are body stiffener, chassis, parcel shelves, fire engine, pedal box system, seatback, spoiler, dashboard, connecting rod, refrigerated truck linens, boot liner, engine cover, bumper system, and door panel.

In some parts of automobiles, the usage of natural fiber polymer composites (NFPC) has some problems like high flammability and high moisture absorption, making it difficult to address these issues for preventing these complications to occur during service. Therefore, they combine with synthetic fibers via techniques of hybridization for making hybrid composites. These hybrid composites are comparatively more cost-effective and have more remarkable structural and mechanical characteristics. According to several analysts and researchers, the usage of hybrid polymer composites in the automobile can reduce weight to 20-40%, lasts 10 years longer as compared to the conventional vehicles, therefore resulting in a new trend in the selection of materials for applications in automobiles.

Recently, an investigation was done on the utilization of recycled waste plastics in automobiles for arresting the pollution problems that the waste plastics emanates. According to the research, the bio-filler-recycled waste plastic-based composites were best suited for most automobile interiors like floor panel or door sills, as there is a requirement of moderate water resistance, good wear, and mechanical characteristics. According to the work, the developed bio-composite will easily degrade after reuse because of the aging, after it is disposed off [6].

1.9.2 Aerospace Application

The aerospace industry uses advanced composites in huge amounts. In the United States, 50% of the total advanced composites are consumed by the aerospace industry. The reason for the aerospace industry using advanced composites this much is the same as the reason for the automotive industry to use it. In the aerospace industry, the three main concerns are radiation shielding, cost savings, and weight reduction. The most crucial concern is weight reduction as it affects various factors like increasing range, maneuverability, number of assembled parts, speed, and fuel efficiency. Fuel savings and weight reduction are the two biggest benefits given by lightweight polymers to the aerospace industry.

According to Koniuszewska and Kaczmar, a fleet of almost 600 planes is operated by American Airlines. If they lessen 1 pound from the weight of every aircraft then they can save almost

11,000 gallons of fuel per year. In the production of aircraft, the process can be made cheap by making some changes, for instance, lessen the tooling cost, instead of metal alloys the fiber-reinforced polymer composites should be used, lessen the number of assembled parts, therefore making it less expensive as there will be no need to join several parts together, and there will be no need of maintenance. Also, because of the variations in the condition of the environment in advanced PMCs, property variations can be obtained [6].

1.9.3 Marine Application

Because of the remarkable engineering characteristics of advanced composites, the marine industry has been using them extensively in recent times. The major drivers for its extensive usage in the marine industry are its environmental sustainability, cost savings, and weight. Manufacturers were forced to make and use new innovative processes and materials while also keeping in mind the product's life cycle for developing high-performance engineering components simultaneously, therefore ensuring an eco-friendly environment. It's because of such demands that the biodegradable polymer matrix composites' (eco-composites) incorporation was needed as they help in reducing the hazardous and toxic materials, helps in recycling of the materials and also helps in reducing the waste and polluting air emission, meanwhile giving excellent mechanical characteristics too [6].

1.9.4 Biomedical Application

One of the leading industries in using polymer composite materials is the medical field. They are being used in the applications of biomedicine because of their excellent characteristics, including their compactness, biomimicry, biocompatibility, bioresorbability, precise control, biodegradability, and compatible mechanical strength. Because of the bio-compatibility of the biopolymer materials, the living material's morphological properties can be smartly imitated by the biopolymer materials. Some of their application areas are surgical implants, antimicrobial materials, blood vessels, ligament and bones application, regenerative medicine, drug delivery, protein immobilization, oral tissues, dental usage, tissue engineering, medical devices, and wound dressing.

Synthetic polymers and natural polymers are used in the field of biomedicine. This field also uses fibers as its reinforcement's major form. Synthetic polymers that are included here, are polyester -amides (PEA), poly lactic-co-glycolic acid (PLGA), polycaprolactone (PCL), polylactic acid (PLA), polyglycolic acid (PGA), polyamide (PA). The included natural

polymers are cellulose, starch, pullulan, psyllium, pectin, agar, alginates, guar gum, collagen, and chitosan. The polymer composites are also utilized widely in biomedical applications as soft (skin) and hard (bone) tissues [6].

1.9.5 Bones

Many constituents like the blood vessels, collagen fibers, mucopolysaccharides, bone cells, and hydroxyapatite (HA) nanocrystals form the bone. The animal's waste bones can easily give off hydroxyapatites, which are utilized continuously for grafts and bone fillers. Their continuous usage is inclusive of their osteo conductivity characteristics which allow for the osteoprogenitor cell's quick development. Therefore, serving as bone fillers to help in repairing the bone fracture, which is the most common sensitive disorder to bones.

For repairing the bone, both synthetic and natural degradable polymer composites are utilized as scaffolds in a broad range because of their remarkable biological and mechanical characteristics. Despite these materials being good for biomedicine, the environmental impact and sustainability were also measured, and therefore, for HA synthesis, environmentally sustainable processes are being developed and utilized for the formation of hydroxyapatite powders (HAp). Right now, all the manufacturing processes are being done to synthesize hydroxyapatite powders (HAp) from both animals and plants.

Being the body's first immune system organ, the skin is the body's one of the most major parts. The skin prevents the antigens and pathogens from entering the body as it has layers. Still, there are many conditions that they are exposed to. Some of them are necrosis, burns, and skin infections.

Researchers are very interested in using biocompatible and biodegradable polymer composites for skin regeneration. Polymeric materials are utilized as drug delivery materials as they are very appropriate and ideal for drug delivery systems. For example, the polymer-based hydrogels are utilized as carriers for the drug molecules like antifungal, antibiotic, and anticancer drugs. They are also utilized for providing a shield to the site of the wound and aid in quickening the process of healing as well as for tissue engineering so that the damaged or lost tissue can be reproduced by helping in the development of new cells [6].

1.9.6 Other Applications

In aircraft, the usage of fiber-reinforced polymer (FRP) composites is very beneficial because of its tri-biological, electrical, and mechanical characteristics. Other commendable benefits in utilizing the fiber-reinforced polymer composites in aircraft are its resistance to fracture, characteristics of vibration-damping, decreased noise level, durability, improved impact and damage tolerance, resistance to heat and flame for interior panels, improved stiffness and strength, enhanced resistance to fatigue and corrosion, lessened scrap, and design flexibility. Such characteristics make the polymer composites suitable for the components like tail assemblies, food tray arms, vertical fins, fittings, airframe, aircraft wing boxes, fuselage, brackets, rotors, window frames, bulkheads, and aircraft brakes [6].

Reinforced polymer composites are gaining significant attention in material science, driven by their sustainability, cost-efficiency, and favorable specific properties. Natural fibers used as reinforcement are biodegradable, low-cost, non-abrasive, and exhibit low density combined with high specific strength and stiffness. Notably, natural fiber-reinforced composites have shown performance characteristics comparable to those of traditional synthetic fiber composites [5].

2.1 Natural Fiber-Reinforced Composites

Natural fiber-reinforced composites represent a rapidly growing field in polymer science due to their sustainability, cost-effectiveness, and desirable specific properties. These fibers are low-cost, biodegradable, non-abrasive, and possess low density with high specific strength and stiffness. Natural fiber composites have demonstrated performance levels comparable to those of conventional synthetic fiber composites. However, their practical application is often hindered by certain limitations, including poor interfacial bonding between fibers and matrix, as well as high moisture absorption. These drawbacks critically affect the durability and mechanical properties of the composites. This review highlights recent advancements in natural fiber-reinforced composites, with special emphasis on the types of fibers used and their implications on composite performance [5].

2.2 Work in Polymer Composites

Polymer composites have emerged as one of the most promising classes of engineering materials in the 21st century. The use of fibers, both synthetic and natural, as reinforcement has significantly enhanced the performance of these materials. Fiber-reinforced polymer (FRP) composites offer several advantages including a high strength-to-weight ratio, excellent durability, superior stiffness, enhanced damping, good flexural strength, and resistance to wear, corrosion, fire, and impact. These properties make FRP composites highly suitable for aerospace, automotive, marine, construction, and sports applications [7].

2.3 Literature Review

The advancement in polymer composites has been a focal point of research due to the increasing demand for sustainable, lightweight, and high-performance materials. Various studies have explored material selection, processing techniques, reinforcement strategies, and predictive modeling to enhance the performance of polymer composites.

D.K. Rajak et al. (2019) conducted an extensive review of composite manufacturing techniques with the objective of identifying optimized fabrication methods that reduce processing defects and improve durability. The study emphasized the importance of selecting appropriate reinforcement types and processing parameters to achieve desirable mechanical performance. The authors concluded that fiber-reinforced composites (FRCs), due to their favorable strength-to-weight ratio and adaptability, are particularly promising for high-demand applications such as the automotive industry, where lightweight yet durable materials are crucial [8].

D. Abliz (2013) focused on the curing mechanisms in polymer composites and provided insights into various curing technologies such as thermal, UV, and microwave curing. The study underscored that the selection of a suitable curing process should account for material compatibility, curing kinetics, penetration capability (especially with complex fiber architectures), ease of processing, and cost-effectiveness. Abliz highlighted that the curing technique significantly affects the final properties of the composite, and improper curing may lead to internal stresses and delamination [9].

Zhang et al. explored the use of artificial neural networks (ANNs) for predicting the properties of polymer composites. Their findings demonstrated that ANNs, being capable of learning from data without requiring explicit physical models, are highly effective in modeling non-linear and complex interactions between matrix and reinforcement. The study marked a shift toward data-driven modeling techniques in composite material design, reducing dependency on traditional analytical models with restrictive assumptions [10].

K. Mao (2007) developed a novel test rig designed for the continuous measurement of wear in polymer composite gears. His experimental and theoretical work focused on thermal wear and fatigue behaviors, offering valuable insights into gear failure mechanisms. This continuous wear monitoring approach enables more accurate life predictions of polymer gears, especially in automotive and mechanical applications, where thermal stress is a key concern [11].

J.H. Du (2007) investigated the integration of carbon nanotubes (CNTs) into polymer matrices. The study concluded that CNTs offer significant improvements in both mechanical strength and electrical conductivity, making them suitable for multifunctional composite applications. However, Du noted that challenges such as poor dispersion and weak interfacial bonding hinder their full potential, suggesting the need for further research on functionalization and alignment techniques [12].

K. Friedrich (2018) analyzed the effects of various nano-fillers and fibers on the tribological performance of polymer composites under dry sliding conditions. His work showed that incorporating nanoscale reinforcements like silica, alumina, or carbon-based fillers could significantly reduce wear and friction coefficients. The study was particularly relevant for applications involving adhesive wear and contact mechanics, such as bearings and seals [13].

Y. Swolfs (2014) provided a comprehensive review of fiber hybridization strategies in polymer composites. He identified three fundamental mechanisms—residual stresses, altered failure progression, and dynamic effects—that influence hybrid composite behavior. Swolfs highlighted that hybridization, especially with fibers like carbon/glass or carbon/aramid, offers a promising way to tailor properties and overcome limitations of individual fibers [14].

Y.C. Yuan (2008) examined self-healing mechanisms in polymer composites. He discussed both intrinsic and extrinsic approaches, concluding that extrinsic methods—such as microcapsules or hollow fibers embedded with healing agents—are more scalable for large-scale industrial use. These systems enhance service life by enabling autonomous repair of micro-cracks, especially in aerospace and civil infrastructure [15].

L. Mohammed (2015) studied natural fiber-reinforced polymer composites, emphasizing their benefits such as low density, cost-effectiveness, biodegradability, and good mechanical strength. His work supported the increasing adoption of natural fibers like jute, hemp, and flax in commercial applications such as automotive interiors, construction panels, and packaging, as substitutes for synthetic fibers [16].

T. Kuilla (2010) reviewed recent developments in the modification of graphene and its use in graphene-based polymer nanocomposites. The author highlighted graphene's exceptional electrical, thermal, and mechanical properties, making it an ideal filler for applications in conductive materials, flexible electronics, and barrier films. Challenges associated with dispersion and interfacial bonding were also discussed [17].

N.M. Nurazzi (2021) evaluated the mechanical performance of CNT-reinforced polymer composites. The study emphasized the importance of uniform dispersion and strong filler–matrix interaction to enhance properties. Nurazzi noted that CNTs tend to agglomerate, which adversely affects load transfer and results in performance degradation, highlighting the need for surface functionalization and advanced dispersion techniques [18].

P.J. Herrera Franco (2004) investigated the effect of fiber surface treatments on the mechanical performance of unidirectional henequen fiber composites. His findings showed that surface treatments, including the application of silane coupling agents, significantly improve fiber–matrix interfacial bonding by increasing surface roughness and exposing cellulose microfibrils. The study concluded that optimizing surface chemistry is key to improving mechanical reinforcement efficiency [19].

S. Arjula (2006) studied the erosion behavior of polymers and polymer composites, noting that elastomers exhibited low erosion efficiency (below 0.1%), while natural fiber-based composites like bamboo fiber eco-composites (BFEC) showed superior erosion resistance. This makes such composites suitable for environments involving high-velocity particle impact, such as in mining or aerospace applications [20].

M. Chan (2011) proposed a new experimental setup for preparing nanoclay-reinforced epoxy composites. The study found that as the nanoclay content increased, both tensile strength and Young's modulus improved. The work emphasized that conventional injection molding is not suitable for achieving full exfoliation, and that the nanoclay cluster effect plays a critical role in reinforcing thermosetting polymers [21].

K. Okubo (2004) examined the mechanical performance of bamboo fiber-based eco-composites. He observed significant enhancements in tensile strength (15%) and Young's modulus (30%) over conventional composites. The study reinforced the value of sustainably sourced natural fibers in developing high-performance, environmentally friendly materials [22].

Sachin G Ghalme (2021) studied the improving mechanical properties of rice husk and straw fiber reinforced polymer composite through reinforcement optimization. He concluded that the addition of 05 and 08 wt% of RS and RH fiber respectively in bio epoxy resin presents rice straw and husk reinforced polymer composite with improved tensile and flexural strength simultaneously [23].

Similarly Xinzhen Liu (2023) et al conducted study on epoxy resin composite reinforced with rice straw fiber. He observed that when the straw fiber filling was 15%, the best performance of the composites was achieved by the alkali treatment, with tensile strength and tensile modulus reaching 1.89 KN and 3.92 MPa, bending strength and bending modulus reaching 2.00 KN and 81.65 MPa, average water absorption reaching 2.77%, and density reaching 0.957 g/cm³ [24].

The reviewed literature highlights the influence of the resin-to-hardener ratio on the mechanical behavior of epoxy-based natural fiber composites. Studies indicate that epoxy-rich systems tend to exhibit brittle behavior due to the formation of a rigid macromolecular network. In contrast, hardener-rich systems display fracture characteristics typical of materials with greater deformation capacity. This ductile behavior is attributed to the presence of unreacted sites on the hardener molecules and the incorporation of flexible segments with rotational mobility within the polymer network. Based on this literature review, several research gaps have been identified, which are discussed in the following section.

2.4 Research Gap

Despite significant advancements in polymer composite research, several critical areas remain underexplored or inadequately addressed:

- The synergistic effects of hybridizing different natural fibers within a single composite system are not yet fully understood.
- There is a lack of comprehensive studies evaluating the effect of varying natural fiber compositions on the mechanical and thermal properties of composites.
- Limited research exists on the influence of resin and hardener compositions, especially in conjunction with diverse fiber types and their ratios.
- Systematic optimization of matrix-to-reinforcement ratios for enhanced composite performance remains a challenge.
- Research translating lab-scale findings into industry-ready composite products using combinations of natural fibers is still at a nascent stage.

2.5 Objectives

Based on the above research gaps, the following objectives have been defined for the present study:

1. To utilize agricultural waste as reinforcement material for the development of eco-friendly polymer composites.
2. To fabricate polymer composites using different types of reinforcements and evaluate their mechanical.
3. To optimize the composition of reinforcement and polymer matrix to achieve superior composite performance.

3.1 Polymer Composite Fabrication

Before fabricating a polymer composite, several essential preparatory steps must be undertaken to ensure the final product meets the required performance standards. The process begins with the selection of an appropriate polymer matrix and reinforcement material, based on the intended application and the desired mechanical, thermal, or chemical properties. The matrix may be a thermosetting resin (e.g., epoxy) or a thermoplastic polymer, while the reinforcement can be natural fibers (such as jute, flax, or hemp) or synthetic ones (such as glass or carbon fibers). Once the materials are selected, fiber preparation becomes a crucial step—particularly for natural fibers, which typically require chemical or physical treatments to improve interfacial adhesion with the matrix and to reduce moisture absorption. The fiber length, orientation, and volume fraction must be carefully considered, as they significantly influence the composite's mechanical behavior.

Mold design is another critical factor, as it dictates the shape and dimensional accuracy of the final composite product. The mold must be fabricated to withstand the processing conditions and maintain consistent geometry. Before initiating the fabrication process, material characterization is performed to evaluate the mechanical and thermal properties of both matrix and reinforcement materials. This includes tests such as tensile strength, impact resistance, thermal stability, and fiber–matrix compatibility.

Finally, the processing technique must be selected according to the production scale, complexity of the part, and cost-effectiveness. Common techniques include hand lay-up, vacuum-assisted resin transfer molding (VARTM), compression molding, and injection molding. These preparatory steps are fundamental to achieving composites with optimized structural integrity, durability, and functional performance.

3.2 Mold Making

The process of mold fabrication, specifically the creation of multi-cavity molds on an aluminum plate (dimensions: 100 mm × 100 mm)—was carried out using a Computer Numerical Control (CNC) machine, ensuring high precision and repeatability. The procedure begins by firmly mounting the aluminum workpiece on the CNC machine's worktable using clamps or fixtures to eliminate movement during machining. The mold cavity design is prepared using Computer-

Aided Design (CAD) software, and the design is then converted into G-code, which guides the CNC machine's toolpaths. Next, appropriate cutting tools (such as end mills, drills, or ball nose cutters) are selected based on the required cavity geometry and complexity. The machining begins with a roughing operation to remove bulk material, followed by finishing passes to achieve fine surface quality and dimensional accuracy. Coolants and lubricants are employed to minimize tool wear and thermal deformation.

The cavities are arranged in a predefined pattern, typically a grid, to maximize material usage and mold productivity. Post-machining, the mold is thoroughly inspected for dimensional accuracy and surface finish using metrological instruments. This process ensures the reliable and efficient production of multiple mold cavities, making it suitable for mass production, prototyping, and experimental fabrication of composite samples.

3.2.1 Multi-Cavity Mould

A multi-cavity mold is a sophisticated mold design that incorporates multiple identical cavities within a single mold plate. It is widely used in injection moulding and thermoset molding processes where high-volume production is required. Each cavity is designed to produce the same component simultaneously in a single cycle, thereby enhancing production efficiency, reducing unit costs, and ensuring uniformity across products. The mold layout is optimized to ensure balanced material flow, proper venting, and uniform cooling, which are critical for avoiding defects such as short shots, warping, or incomplete fills. Although the initial design and manufacturing of multi-cavity molds are more complex and expensive, the long-term benefits include reduced cycle time, consistent product quality, and greater scalability, making them economically viable for mass production in sectors such as consumer goods, packaging, medical devices, and automotive components.

3.2.2 Split Pattern Mould

A split pattern mold used in simple molding is a basic but effective design in which the mold is divided into two sections: the top and bottom halves. This type of mold is typically used in processes like sand casting or other low-pressure molding techniques. The pattern, which is a replica of the part to be made, is placed inside the mold cavity. Once the pattern is positioned, the two halves of the mold are brought together to form a closed cavity. The material—whether it's metal, plastic, or another substance—is then poured or injected into the cavity to take the shape of the pattern. After the material has cooled or hardened, the two halves of the mold are separated, and the finished part is removed. This type of split pattern mold is widely used

because it is simple to make and cost-effective, while still allowing for the production of detailed parts. The ability to split the mold into two sections makes it easier to remove the finished part without damaging it, and the design can be reused for multiple productions.

3.3 Fabrication Process of Polymer Composites

The fabrication of natural fiber-reinforced polymer composites involves a series of well-defined stages to ensure the production of high-quality materials with desired mechanical and physical properties. The major steps are outlined below:

3.3.1 Selection of Materials

The preparation of the polymer matrix begins by mixing the selected resin and hardener in the appropriate ratios, following the manufacturer's specifications. This ensures the proper chemical reaction and curing process. Depending on the desired properties of the composite, additives such as accelerators, pigments, or plasticizers may be incorporated to enhance specific characteristics, like improving curing time, providing color, or increasing flexibility. For thermosetting polymers like epoxy, the combination of the resin and hardener triggers the curing reaction, which will harden the material once it sets. Manual stirring is then carried out to ensure a homogeneous mixture, allowing the fibers to be evenly distributed throughout the polymer matrix. This thorough mixing is crucial to achieve consistent mechanical properties in the final composite material. Reinforcement materials are key to improving the mechanical properties of the polymer matrix in composite materials. These reinforcements, which can be either synthetic or natural fibers, play a vital role in increasing the strength, stiffness, and durability of the composite. Synthetic fibers, such as glass, carbon, and aramid (like Kevlar), are widely used because of their high strength, resistance to wear, and ability to withstand fatigue. In contrast, natural fibers like cotton, jute, banana, coconut, abaca, and hemp are gaining popularity due to their sustainability, being biodegradable, and offering renewable resources. These fibers can be used in different forms, depending on the needs of the application, including continuous fibers for added strength, chopped fibers for better processability, woven fibers for structural reinforcement, or powdered fibers for uniform distribution within the matrix. The selection of reinforcement type and form plays an essential role in determining the overall properties and effectiveness of the composite material in various industrial uses.

Reinforcement Materials: These are used to enhance the mechanical properties of the matrix.

3.3.2 Preparation of Reinforcement

The preparation of natural fibers for use as reinforcement in composites involves several important steps to ensure their effectiveness. First, the fibers are chopped into short lengths, which make them easier to handle and integrate into the polymer matrix. Next, the fibers undergo grinding, often using a mixer grinder or ball mill, to achieve the desired particle size. This process helps break down the fibers into finer particles that can better blend with the matrix material. After grinding, the fibers are sieved to obtain uniform particles, ensuring consistency in the mixture and uniform reinforcement throughout the composite. Finally, the fibers are dried, usually by exposing them to sunlight, to reduce moisture content. Drying is crucial because excess moisture can interfere with the bonding between the fibers and the polymer matrix, reducing the overall performance of the composite. Each of these preparation steps is essential to ensure that the natural fibers can effectively enhance the mechanical properties of the composite material.

3.3.3 Polymer Matrix Preparation

The preparation of the polymer matrix begins by mixing the selected resin and hardener in the appropriate ratios, following the manufacturer's specifications. This ensures the proper chemical reaction and curing process. Depending on the desired properties of the composite, additives such as accelerators, pigments, or plasticizers may be incorporated to enhance specific characteristics, like improving curing time, providing color, or increasing flexibility. For thermosetting polymers like epoxy, the combination of the resin and hardener triggers the curing reaction, which will harden the material once it sets. Manual stirring is then carried out to ensure a homogeneous mixture, allowing the fibers to be evenly distributed throughout the polymer matrix. This thorough mixing is crucial to achieve consistent mechanical properties in the final composite material.

Composite Fabrication Methods

The following manufacturing techniques were considered, although resin casting (hand lay-up) was used in this study. In the hand lay-up process, fibers are manually placed in molds and resin is poured. It is simple and cost-effective for small-scale production. In this study, resin moulding using epoxy-hardener systems was employed for all fiber composites with varying weight fractions. The samples were cured at room temperature and post-cured for 48 hours.

3.4 Selection of Matrix Material

Selection of the matrix is crucial as it governs the overall mechanical and thermal behavior of the composite. The matrix should possess good adhesion with fibers, adequate toughness, and thermal stability. Some commercially available epoxy systems considered which are presented below.

Table 3.1 Properties of different polymers

Epoxy System	Hardener	Key Features	Applications
LY556	HY951	Excellent thermal properties, good wetting of fibers, low crystallization	Aerospace adhesives, structural parts
SW404	HY2404	High mechanical strength, good chemical and abrasion resistance	Molds, patterns, foundry tools
Araldite AW106	HV953 IN	Superior toughness, peel strength, and moisture resistance	General industrial bonding, structural adhesives
Aradur 450	–	Excellent bonding with wet concrete, slight flexibility	Protective coatings, civil structures

In the present study, Araldite AW106 epoxy resin and HV953 IN hardener were selected for all fiber-reinforced composites due to their good compatibility, industrial usability, and proven toughness.

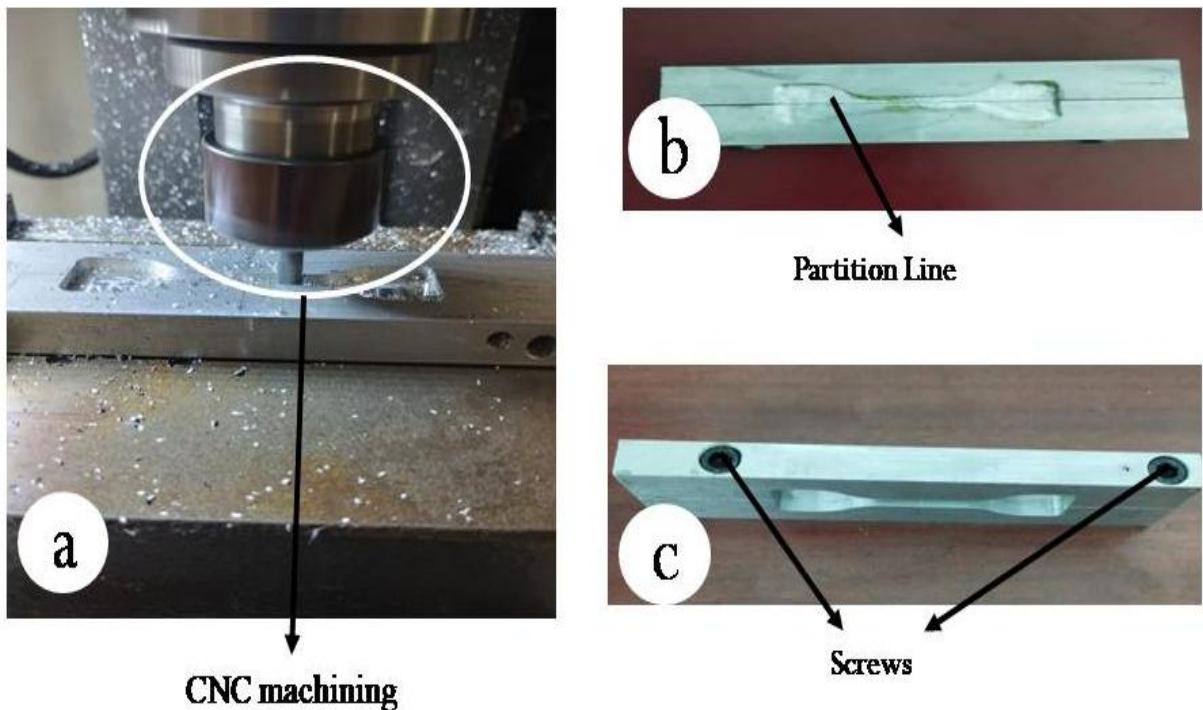


Figure 3.1 Split mold (a) cnc machining (b) front view of mold (c) top view of mold

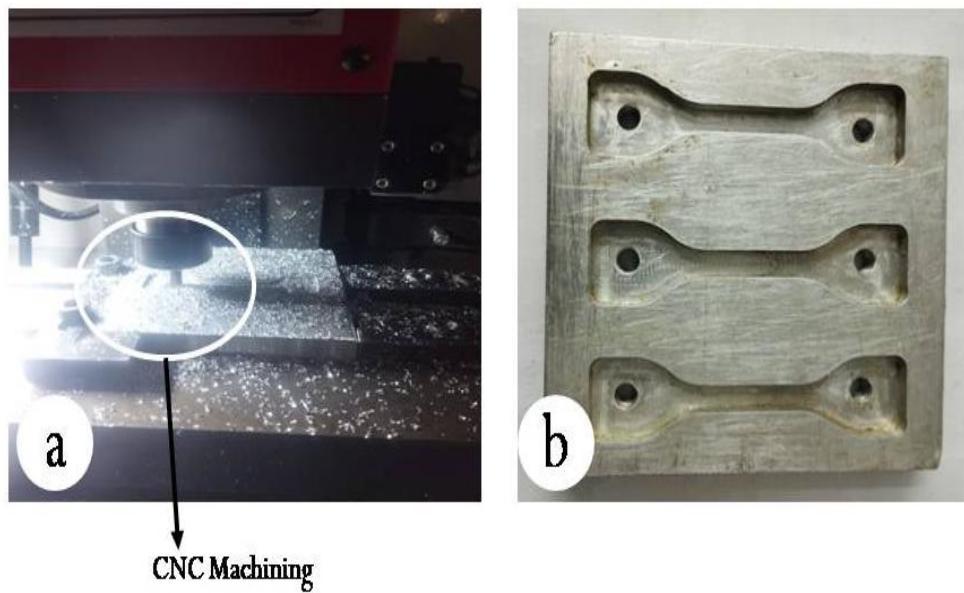


Figure 3.2 Multi cavity mold (A) cnc machining (B) front view of mold

3.5 Perpetration of Samples

3.5.1 Hardener and Resin

First of all, samples are prepared by taking resin AW106 and hardener HV953IN in different compositions and the compositions used as shown in Table 3.2. The fabricated samples is shown in Fig. 3.3.

Table 3.2 Weight content for resin and hardener

Sample No.	Resin (wt. in gram)	Hardener (wt. in gram)
1	20	16
2	19.46	16.54
3	18.95	17.05
4	18.46	17.54
5	18	18



Figure 3.3 Samples made from different quantities of hardener and resin

3.5.2 Rice Straw Fiber-Reinforced Polymer Composite

Rice straw, a byproduct of rice cultivation, is gaining attention as a viable reinforcement material in natural fiber-reinforced polymer composites due to its abundant availability, renewability, and cost-effectiveness. Being a widely produced agricultural residue, rice straw offers a sustainable and eco-friendly alternative to synthetic reinforcements such as glass fibers. Its utilization in composites addresses multiple environmental and economic concerns by reducing agro-waste, minimizing the need for landfill disposal or open-field burning—which contributes to air pollution, and providing value-added applications in material science.

In terms of composition, rice straw is primarily made up of cellulose, hemicellulose, and lignin, which impart it with decent mechanical strength and stiffness when appropriately treated. Its low density helps maintain the lightweight nature of the composite, an essential factor in sectors like automotive, aerospace, and construction, where reducing component weight is critical for energy efficiency and performance.

When processed correctly, typically through cutting, grinding, drying, and surface treatment—rice straw fibers can form strong interfacial bonds with polymer matrices, particularly epoxy-based systems. This results in composites that exhibit enhanced tensile strength, flexural properties, and dimensional stability, making them suitable for moderate structural applications. Moreover, rice straw is non-toxic, biodegradable, and naturally renewable, ensuring that the resulting composites align with modern sustainability goals and reduce the carbon footprint associated with conventional composite materials.

The preparation of rice straw fibers for composite fabrication involves a series of processing steps to ensure uniformity and compatibility with the polymer matrix. Initially, the rice straw is collected in its raw, unprocessed form, as shown in Figure 3.4(a). It is then manually cut into small fragments using scissors to reduce its size, as illustrated in Figure 3.4(b). These smaller pieces are further processed using a mixer grinder, as seen in Figure 3.4(c), to achieve finer, more consistent particle sizes. The result of this grinding process is a coarsely ground fiber. Finally, the fibers are thoroughly dried to eliminate any residual moisture, yielding the fine, dry rice straw fibers suitable for composite fabrication, as shown in Figure 3.4(d). The mixture of resin, hardener and rice straw is then poured into mold as shown in figure 3.4(e). the samples obtained after curing is shown in figure 3.4(f).The use of rice straw in polymer composites not only supports waste valorization but also opens new pathways for the development of low-cost, sustainable, and biodegradable materials tailored for both structural and non-structural applications.

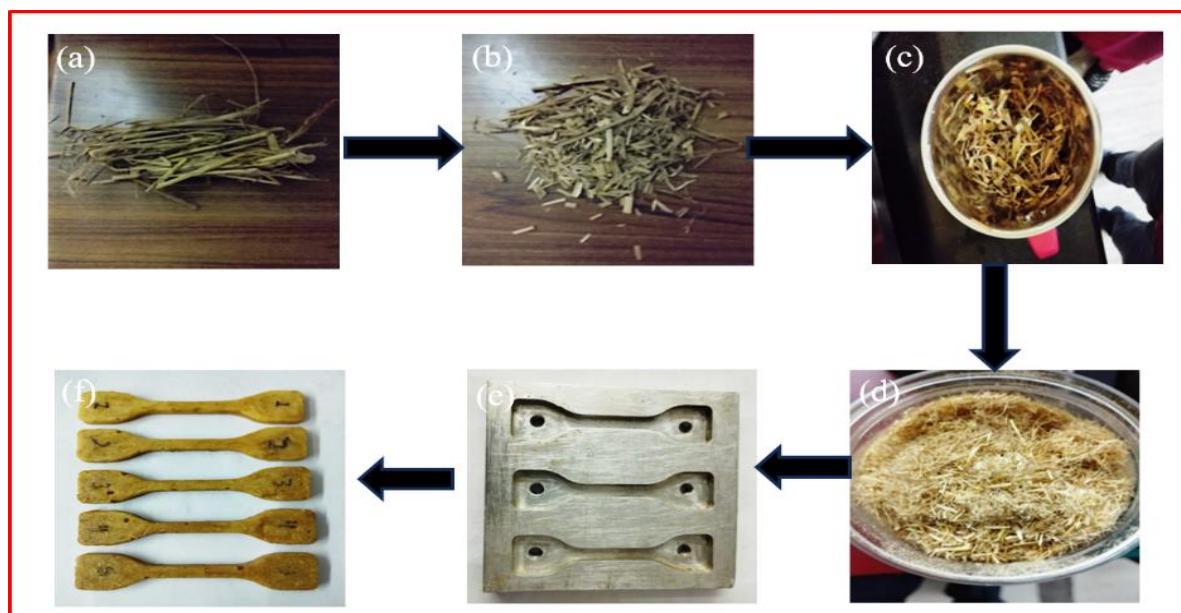


Figure 3.4 Rice straw composite boards produced using the hybrid resin formulation

Table 3.3 Weight content for resin, hardener and rice straw

Sample No.	Resin (wt. in grams)	Hardener (wt. in grams)	Rice straw (wt. in gram)
1	5.88	5.88	0.24
2	5.76	5.76	0.48
3	5.64	5.64	0.72
4	5.52	5.52	0.96
5	5.40	5.40	1.20
6	5.28	5.28	1.44
7	5.10	5.10	1.80
8	4.80	4.80	2.40
9	4.50	4.50	3.00

3.5.3 Jute-Reinforced Polymer Composite

Jute is one of the most economically important and widely used natural fibers, valued for its exceptional mechanical properties, cost-effectiveness, and biodegradability. It possesses high tensile strength, stiffness, and abrasion resistance, which make it particularly effective as a reinforcement material in polymer composites. These favorable characteristics are primarily attributed to jute's high lignin and cellulose content, which contribute to its natural rigidity, thermal stability, and durability. The use of jute in polymer composites has gained significant traction in recent years, especially in sectors that prioritize eco-friendly and sustainable alternatives to synthetic materials. Jute-reinforced composites are now commonly employed in various industrial applications such as automotive interiors, construction panels, furniture, biodegradable packaging, and other structural and semi-structural components. Their growing popularity is driven not only by performance advantages but also by the environmental benefits they offer, as jute is a renewable, biodegradable, and abundantly available agricultural by-product.

In the present study, jute was procured in rope form from local sources and subjected to a systematic preparation process to convert it into a suitable form for composite reinforcement. The rope was manually untwisted, and individual fibers were carefully separated. These fibers were then chopped into short lengths to facilitate further processing. The chopped fibers were initially ground using a mixer grinder to reduce their size and partially homogenize the material. To achieve a finer and more uniform particle size, the partially ground fibers were further refined using a ball milling process, which was carried out continuously for four days at a rate

of six hours per day. The resulting jute powder was then sieved to ensure consistency in particle size, which is essential for uniform dispersion within the matrix. The processed jute powder was subsequently mixed with an epoxy resin and hardener system to fabricate the composite specimens. This thorough preparation ensured improved fiber–matrix adhesion, homogeneity in the composite structure, and enhanced mechanical performance in the final product.

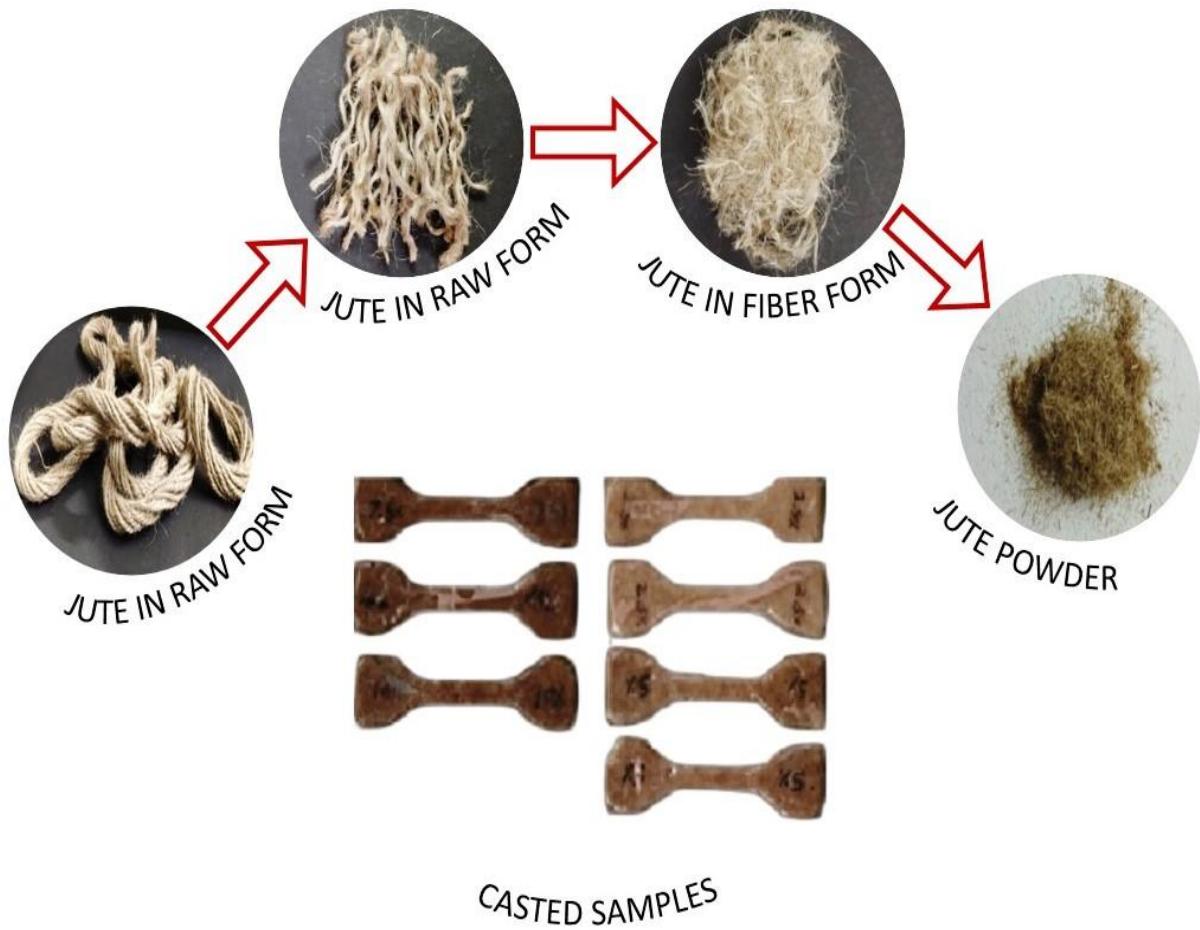


Figure 3.5 Different stages of making jute fibers

Table 3.4 Weight composition for resin, hardener and jute

Sample No.	Resin (g)	Hardener (g)	Jute (g)
1	5.850	5.850	0.300
2	5.700	5.700	0.600
3	5.550	5.550	0.900
4	5.400	5.400	1.200
5	5.250	5.250	1.500

Sample No.	Resin (g)	Hardener (g)	Jute (g)
6	5.100	5.100	1.800
7	4.800	4.800	2.400

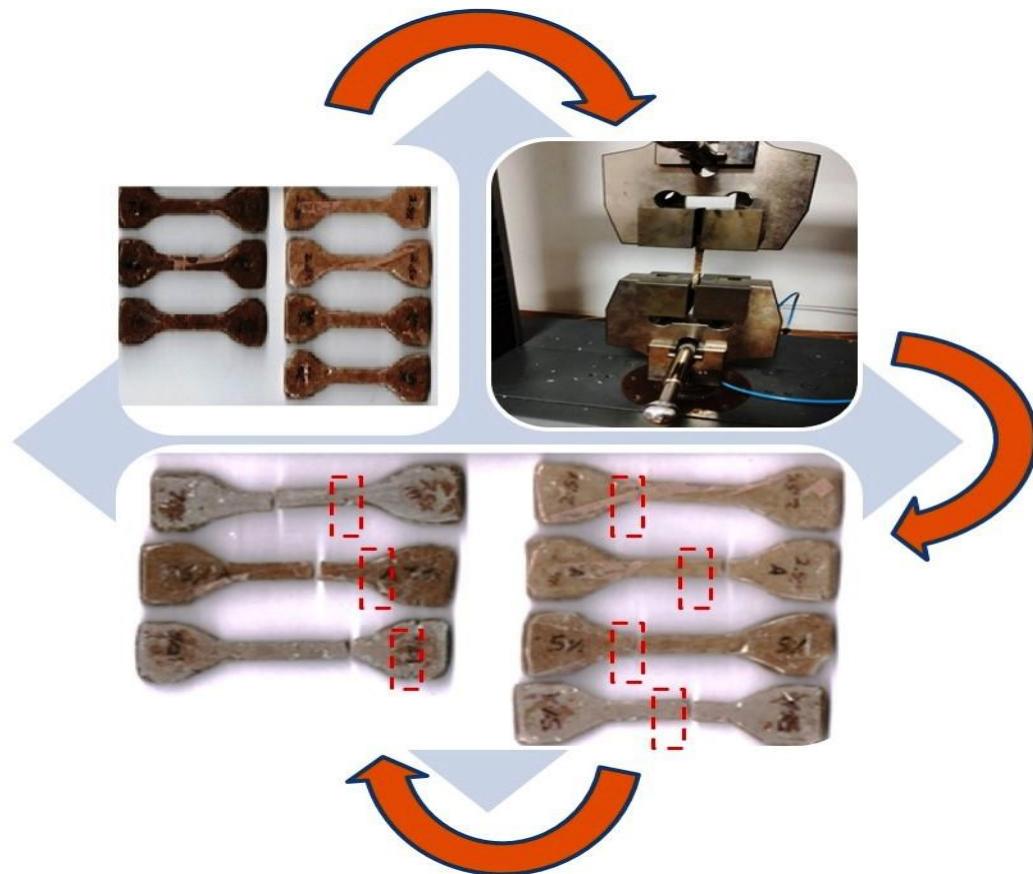


Figure 3.6 Tensile testing of specimen

3.5.4 Banana Fiber-Reinforced Composite

Banana fiber, extracted from the pseudostem of banana plants, is recognized for its excellent tensile strength, flexibility, and biodegradability, making it a promising reinforcement material in the development of natural fiber polymer composites. As a by-product of banana cultivation, banana fiber contributes to agricultural waste valorization and supports the principles of a circular economy by converting organic waste into high-value functional materials. The integration of banana fiber into polymer matrices enhances key mechanical properties such as impact resistance, stiffness, and dimensional stability, thereby making it well-suited for a range of applications in sectors like automotive interiors, agricultural equipment, and eco-friendly packaging materials.

In this study, the preparation of banana fiber for composite fabrication involved a series of carefully executed steps. The raw banana fibers were initially sourced in rope form from local suppliers. These ropes were manually chopped into smaller segments and subsequently processed in a grinding machine to break down the fiber structure. The ground fibers were then sieved using a coarse mesh to ensure uniformity in particle size and remove oversized fragments. This sieved banana fiber powder was subsequently blended with epoxy resin (AW106 IN) and hardener (HV953 IN) in pre-determined ratios. The mixing was carried out manually to ensure even dispersion of fiber throughout the resin-hardener matrix. This prepared mixture was then used for molding composite samples, with different fiber loadings evaluated for their mechanical performance after post-curing.



Figure 3.7 Different stages in making banana fiber samples

Table 3.5 Weight composition for resin, hardener and banana fiber

Sample No.	Resin (g)	Hardener (g)	Banana Fiber (g)
1	5.88	5.88	0.24
2	5.76	5.76	0.48
3	5.64	5.64	0.72
4	5.52	5.52	0.96
5	5.40	5.40	1.20

Sample No.	Resin (g)	Hardener (g)	Banana Fiber (g)
6	5.28	5.28	1.44
7	5.10	5.10	1.80
8	4.80	4.80	2.40
9	4.50	4.50	3.00
10	4.20	4.20	3.60

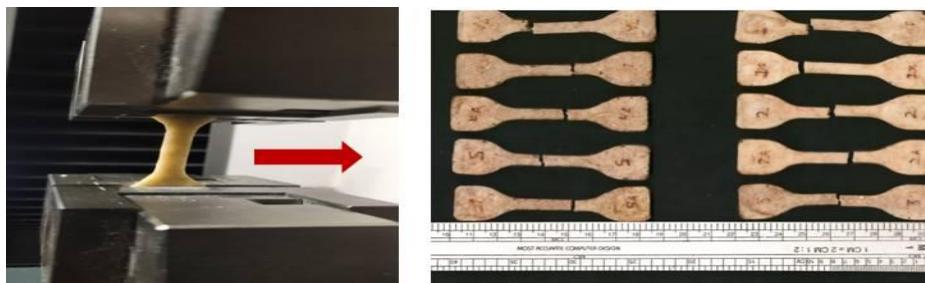


Figure 3.8 Tensile testing of specimen

The polymer composites are fabricated by resin moulding technique. Composite specimens with different fiber loading (1%, 2%, 3%, 4%, 5%) were prepared and subjected to post curing for 48 hours at room temperature.

3.5.5 Abaca Fiber

Abaca fiber, derived from the leaf stalks of the abaca plant—a species of banana native to the Philippines—is increasingly being explored as a reinforcement material in natural fiberpolymer composites due to its unique combination of strength, durability, and environmental sustainability. Known for its exceptional tensile strength and resistance to wear and tear, abaca fiber is well-suited for demanding applications such as automotive components, marine products, and industrial textiles. When incorporated into a polymer matrix, abaca fibers significantly enhance the mechanical performance of the composite, contributing to increased stiffness, tensile strength, and impact resistance. In addition to these mechanical advantages, abaca is a biodegradable, eco-friendly, and renewable resource, offering a viable alternative to synthetic fibers that pose environmental concerns. The cultivation of abaca also supports sustainable agricultural practices, as the crop requires minimal inputs, thrives in tropical climates, and can be harvested annually. Furthermore, abaca fiber is lightweight and cost-effective, making it suitable for large-scale, environmentally conscious composite manufacturing.

In this study, abaca fiber was sourced locally and used as a reinforcement material. Epoxy resin AW 106 IN and the corresponding hardener HV 953 IN were employed as the matrix binder. The raw abaca fiber was initially obtained in sheet form, as shown in figure 3.9(a), and then manually cut into small pieces, depicted in figure 3.9(b). These chopped fibers were subsequently ground into a fine powder using a mixer grinder, as illustrated in Figure 3.9(c). The powdered fibers were then filtered using a coarse sieve to ensure uniform particle size and remove larger fragments. The sieved abaca fiber powder was used in the composite fabrication process. A resin-hardener mixture was prepared in the recommended ratio and manually blended with the abaca fiber powder to ensure uniform distribution. This prepared mixture was then cast into molds as shown in figure 3.10 to form the composite samples. The resulting abaca-reinforced composites as shown in figure 3.11 are expected to exhibit improved structural and environmental performance, supporting the development of sustainable material alternatives.

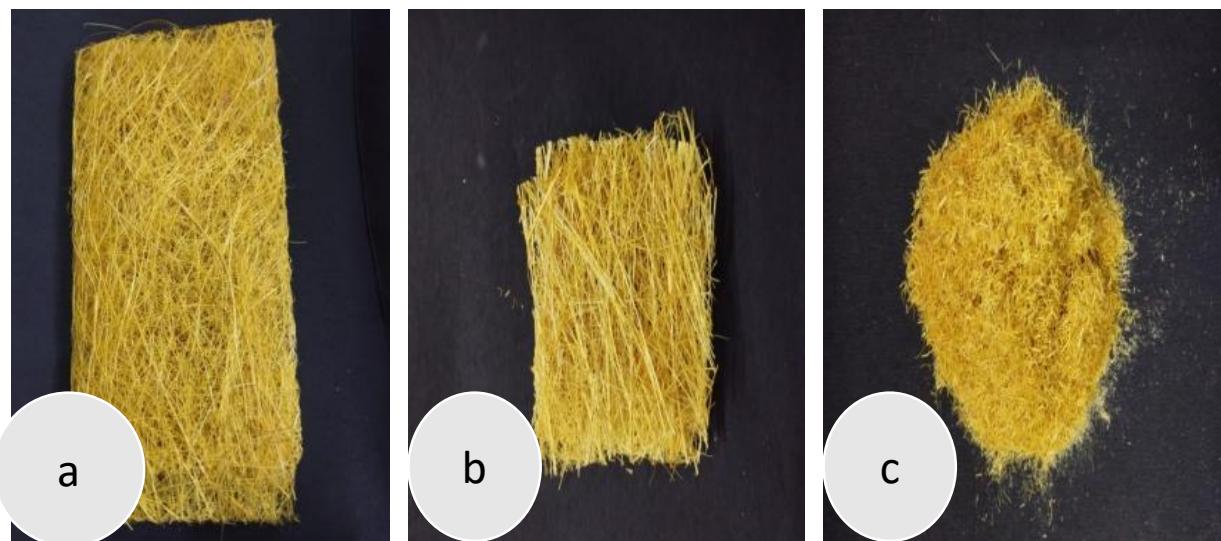


Figure 3.9 Different stages in making abaca powder

Table 3.6 Weight content for hardener, resin and abaca fiber powder

S.No.	RESIN(gram)	HARDENER(gram)	ABACA FIBER(gram)
1	7.84	7.84	0.32
2	7.60	7.60	0.80
3	7.36	7.36	1.28
4	7.20	7.20	1.60
5	6.80	6.80	2.40

6	6.40	6.40	3.20
7	6.00	6.00	4.00

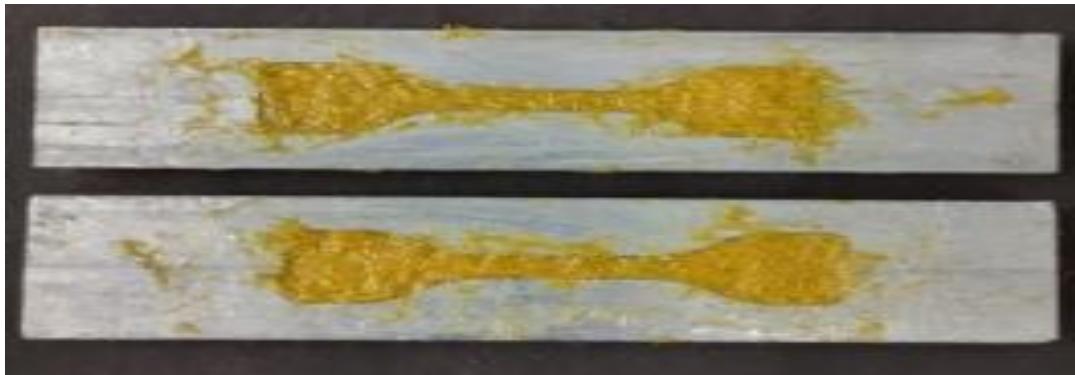


Figure 3.10 Mixture of resin, hardener and abaca powder in mold



Figure 3.11 Samples made from different quantities of resin, hardener and abaca powder

3.5.6 Hemp Fiber

Hemp fiber is increasingly used as a reinforcement in natural fiber polymer composites due to its outstanding mechanical properties, sustainability, and versatility. Hemp fibers are known for their high tensile strength, durability, and resistance to environmental factors like UV radiation and moisture, making them ideal for reinforcing composites in industries such as automotive, construction, and packaging. When integrated into a polymer matrix, hemp fibers significantly improve the composite's overall strength, stiffness, and impact resistance, while maintaining a lightweight structure. Beyond its mechanical advantages, hemp is also an environmentally friendly material. It is a fast-growing, renewable resource that requires minimal pesticides and water, making it a more sustainable alternative to synthetic fibers. Hemp fibers are biodegradable and non-toxic, contributing to a lower environmental footprint.

compared to petroleum-based materials. The use of hemp fiber as reinforcement not only enhances the performance of natural fiber composites but also supports the growing demand for eco-friendly, renewable, and cost-effective materials in a variety of industrial applications. This makes hemp an attractive option for companies seeking to reduce their environmental impact while maintaining high-quality performance in their products. Hemp fiber has been obtained from local sources as reinforcing material. Epoxy resin AW 106 IN and corresponding hardener HV 953 IN used as a binder.

Figure 3.12(a) shows hemp fiber was in rope form. Figure 3.12(b) shows rope is then cut into small pieces by manual cutting. Fig 3.12(c) shows separation of fibers from these small pieces. Then these fibers are crushed in a grinding machine. Figure 3.12(d) shows fibers obtained after grinding in mixer grinder. The grinded hemp fibers are filtered with a coarse sieve. The filtered coarse sieve particles then used for making composite. To make the composite a mixture of resin and hardener are used. This combination of resin and hardener are used multiple purpose application and thus used for this work. The coarse fibers of hemp are then mixed with a combination of mixture of resin and hardener and then properly mix them by manual stirring.



Figure 3.12 Different stages in making hemp powder

Table 3.7 Weight content for hardener, resin and hemp fiber powder

S.NO.	RESIN(gram)	HARDENER(gram)	HEMP FIBER(gram)
1	7.84	7.84	0.32
2	7.68	7.68	0.64
3	7.52	7.52	0.96
4	7.36	7.36	1.28
5	7.20	7.20	1.60
6	7.04	7.04	1.92
7	6.80	6.80	2.40

8	6.56	6.56	2.88
9	6.32	6.32	3.36
10	6.08	6.08	3.84
11	5.84	5.84	4.32
12	5.60	5.60	4.80



Figure 3.13 Mixture of rein, hardener and hemp powder in mold

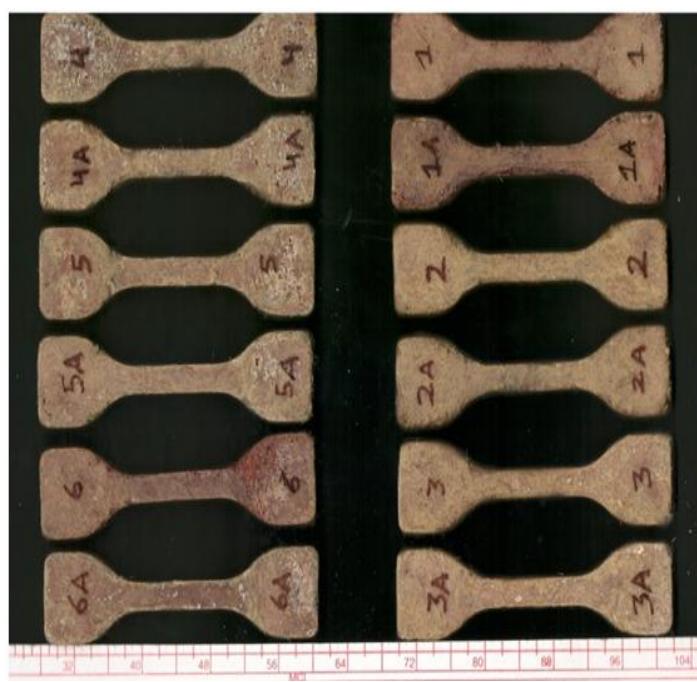


Figure 3.14 Samples made from different quantities of resin, hardener and hemp powder

4.1 Tensile Properties of Fabricated Composites

4.1.1 Resin-Hardener Combinations

Figure 4.1 illustrates the mechanical behavior of polymer composites fabricated with varying resin-to-hardener ratios, as revealed through tensile testing. The stress–strain curves provide key insights into both elastic and plastic deformation responses of the materials. Figure 4.2 compares the Young’s modulus for each formulation, highlighting the effect of hardener content on composite stiffness. Figures 4.3 and 4.4 further show the variation in tensile strength and elongation at break, respectively, for composites prepared using Araldite AW106 resin and HV953 hardener. The results demonstrate a systematic change in mechanical properties with increasing hardener content while keeping the resin content fixed.

At a resin-to-hardener ratio of 100:80, the composite exhibits the highest stiffness and strength, with a Young’s modulus of 1024.30 MPa, a tensile strength of 47.84 MPa, and an elongation at break of 5.02%. This combination indicates an optimal cross-linking density that results in a rigid and strong material with limited ductility. When the hardener content is slightly increased to a 100:85 ratio, both the Young’s modulus and tensile strength decrease to 679.33 MPa and 39.26 MPa, respectively, while the elongation at break increases modestly to 6.30%. This shift reflects a slight reduction in stiffness and strength but a marginal gain in flexibility, likely due to alterations in the epoxy network [25].

Further increasing the hardener ratio to 100:90 results in a more pronounced reduction in mechanical performance, with the Young’s modulus decreasing to 404.84 MPa and tensile strength falling to 23.80 MPa. The elongation at break remains relatively constant at 5.64%, indicating that although the material becomes softer, it does not significantly improve in flexibility. At a 100:95 ratio, this downward trend continues, with the Young’s modulus dropping to 381.10 MPa and tensile strength to 20.14 MPa, along with a slight decrease in elongation to 5.37%, signifying a more compliant yet structurally weaker material [26].

Interestingly, at an equal resin-to-hardener ratio of 100:100, the material demonstrates a marked shift in behavior. While the Young’s modulus reaches its lowest value of 308.41 MPa, indicating a significant reduction in stiffness, the tensile strength increases to 33.83 MPa and

elongation at break peaks at 8.08%. This suggests a transition to a highly flexible material with moderate strength, potentially due to the plasticization effect of excess hardener which may enhance chain mobility within the cured matrix.

This figure shows stress-strain curves for a material with varying ratios of resin and hardener, represented by the labels 100:80, 100:85, 100:90, 100:95, and 100:100% [27]. Each subfigure, labeled from "a" to "e," presents the stress-strain relationship for different mixtures. In each curve, the stress increases with strain, indicating elastic deformation at lower strains, where the material can return to its original shape. As the strain continues, the material begins to experience plastic deformation, particularly in the curves marked with higher hardener content. The curves labeled with higher ratios of hardener, such as 100:95 (d) and 100:100% (e), show a more pronounced rise in stress, suggesting that the material becomes stiffer or stronger as the hardener content increases. At the 100:80 (a) and 100:85 (b) ratios, the material exhibits a lower increase in stress, indicating that it is more pliable compared to those with higher hardener content. The general trend suggests that increasing the amount of hardener enhances the material's resistance to deformation, leading to higher stress values at corresponding strains. These stress-strain curves illustrate how different resin-to-hardener ratios can affect the mechanical properties of the material, particularly in terms of strength and flexibility.

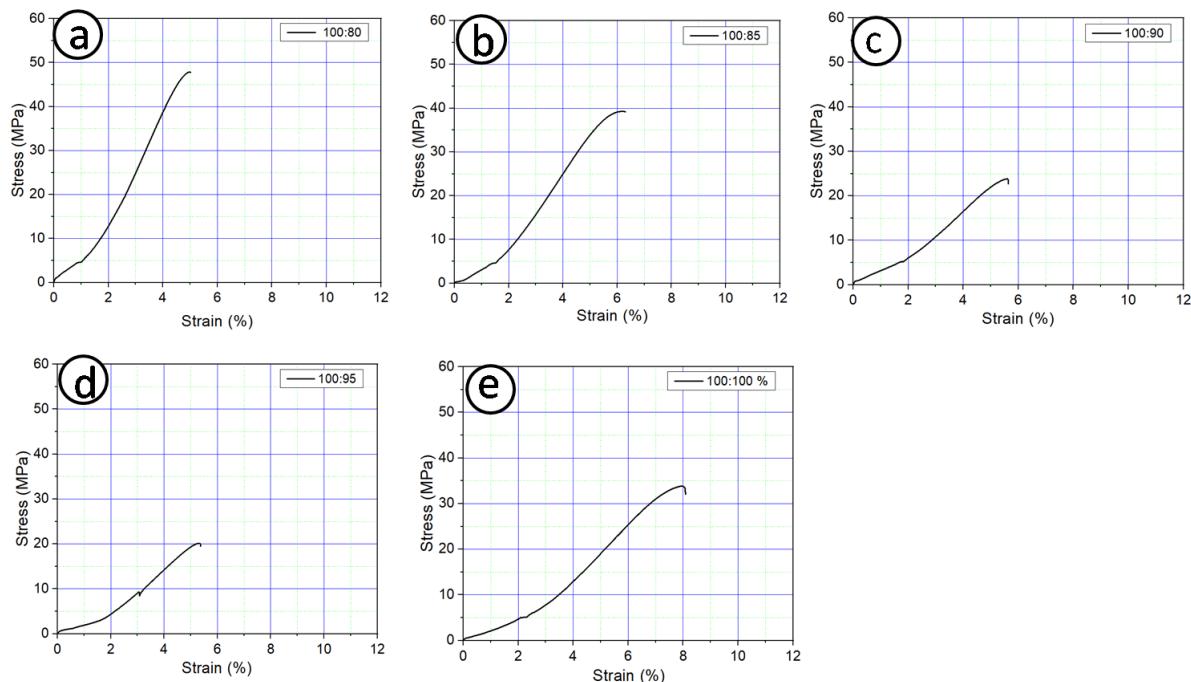


Figure 4.1 Stress-strain diagrams

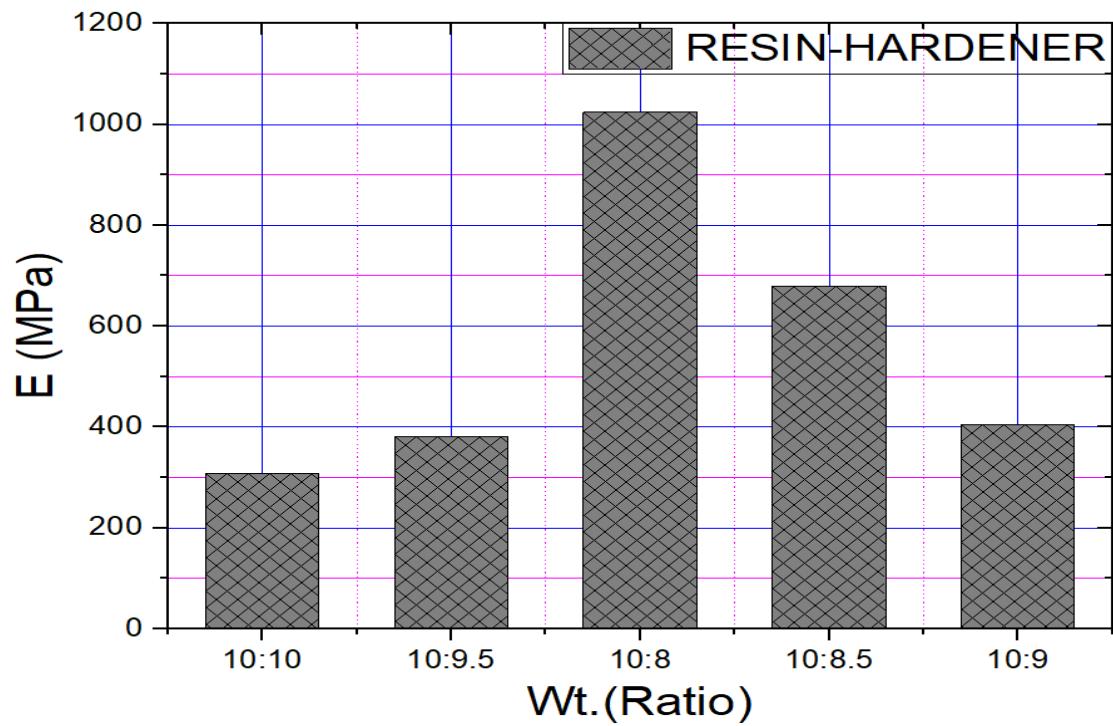


Figure 4.2 Young's modulus of different composition of polymer

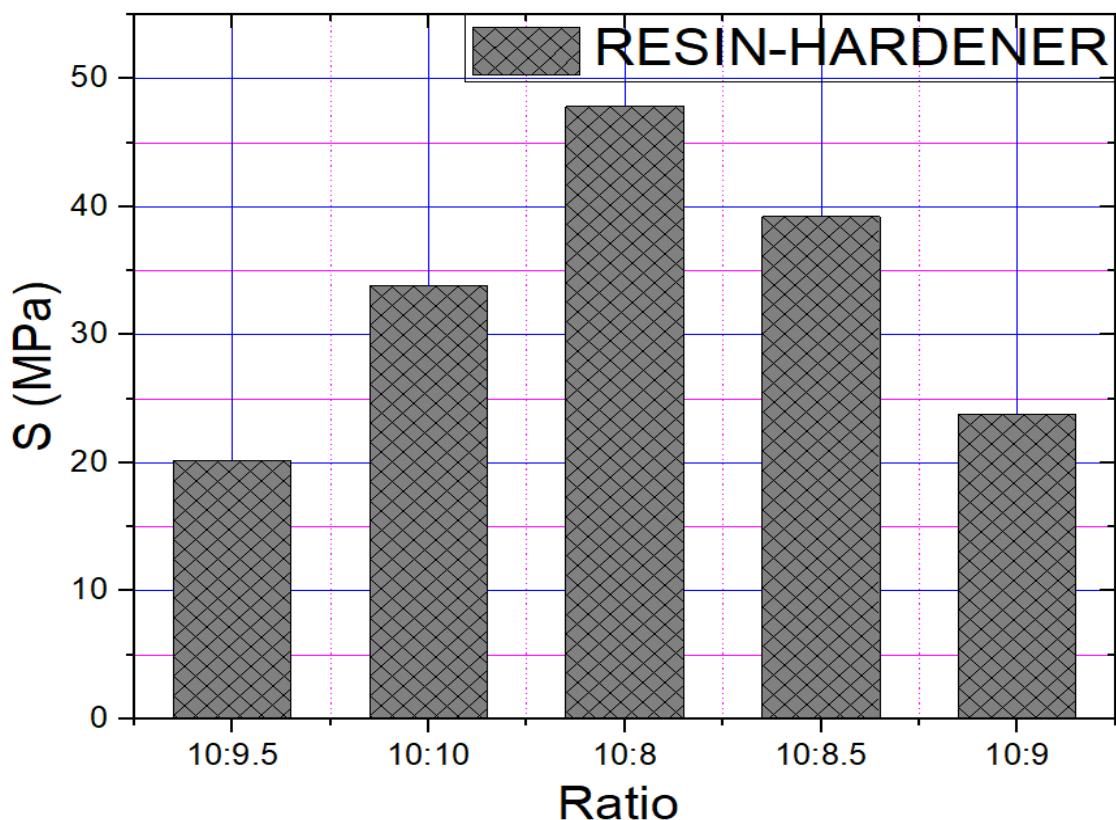


Figure 4.3 Strength of polymer

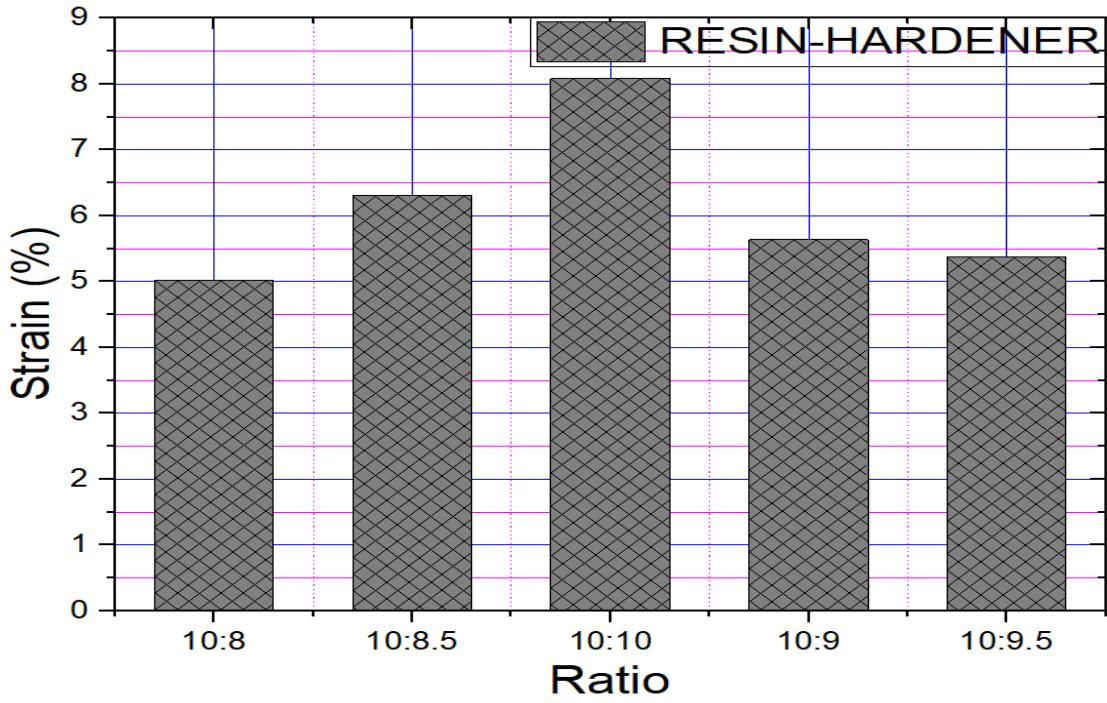


Figure 4.4 Elongation at failure

4.1.2 Rice Straw Reinforced Polymer Composite

Figure 4.5 illustrates the mechanical behavior of rice straw reinforced polymer composites fabricated with varying resin-to-hardener ratios, as revealed through tensile testing. The stress-strain curves provide key insights into both elastic and plastic deformation responses of the materials. Figure 4.6 compares the Young's modulus for each formulation, highlighting the effect of hardener content on composite stiffness. Figures 4.7 and 4.8 further show the variation in tensile strength and elongation at break, respectively, for composites prepared using Araldite AW106 resin and HV953 hardener. The results demonstrate a systematic change in mechanical properties with increasing hardener content while keeping the resin content fixed.

The graph illustrates the mechanical properties of rice straw-reinforced composites at varying rice straw content, combined with resin AW 106 and hardener HV 953. As the percentage of rice straw increases, distinct changes in the material's properties are observed. At 2% rice straw, the composite shows a relatively low Young's modulus of 96.83 MPa, strength of 22.37 MPa, and an elongation of 10.39%. As the rice straw content increases to 4%, the Young's modulus nearly doubles to 222.46 MPa, while strength increases slightly to 23.59 MPa, and elongation decreases to 6.36%. At 6% rice straw, both Young's modulus and strength rise further to 231.35

MPa and 25.23 MPa respectively, but elongation stays relatively similar at 6.69%. When the rice straw content reaches 8%, the composite achieves a significant increase in strength to 35.95 MPa, with a Young's modulus of 235.76 MPa and elongation at 7.78%. At 10%, the material shows substantial improvement in rigidity, with a Young's modulus of 395.27 MPa and a strength of 41 MPa, though elongation reduces to 5.69%. This trend continues at 12% rice straw, with the composite exhibiting the highest values for Young's modulus (479.40 MPa) and strength (52.24 MPa), and elongation at 6.34%. However, at 15%, a notable drop in Young's modulus to 167.12 MPa and strength to 25.59 MPa occurs, while elongation increases to 7.96%. The material properties continue to deteriorate with higher rice straw percentages; at 20%, Young's modulus and strength drop further to 142.55 MPa and 27.18 MPa, with elongation remaining around 7.62%. Finally, at 25% rice straw, the composite shows a sharp decline in both Young's modulus (81.70 MPa) and strength (9.59 MPa), while elongation increases to 8.00%. These results suggest that while the addition of rice straw improves the material's strength and stiffness up to a certain point, excessive amounts seem to reduce its mechanical properties, especially its rigidity and strength, while elongation remains relatively stable or slightly increases at higher rice straw concentrations [28].

This figure displays a series of stress-strain curves corresponding to different strain percentages, ranging from 2% to 25%. Each graph, labeled from "a" to "i," shows how the material's stress responds as strain increases [29]. At the lower strain levels, such as 2% in (a) and 4% in (b), the material shows minimal stress, indicating that it is still in the elastic region where deformation is reversible. As the strain increases, like at 6% (c), 8% (d), and 10% (e), the stress begins to rise more significantly, showing the material entering the plastic region where it undergoes permanent deformation. The curves continue to show greater increases in stress at higher strains, especially at 12% (f) and 15% (g), which suggests that the material is becoming stiffer and more resistant to deformation. At 20% strain (h), the material continues to show increased stress but at a reduced rate, indicating it is nearing its maximum capacity. Finally, at 25% strain (i), the curve exhibits a sharp drop in stress after reaching a peak, signifying the onset of failure or fracture, where the material can no longer maintain its strength. These stress-strain curves provide a comprehensive overview of the material's behavior under different strain conditions, showcasing its elastic and plastic deformation characteristics and its ultimate failure at higher strains.

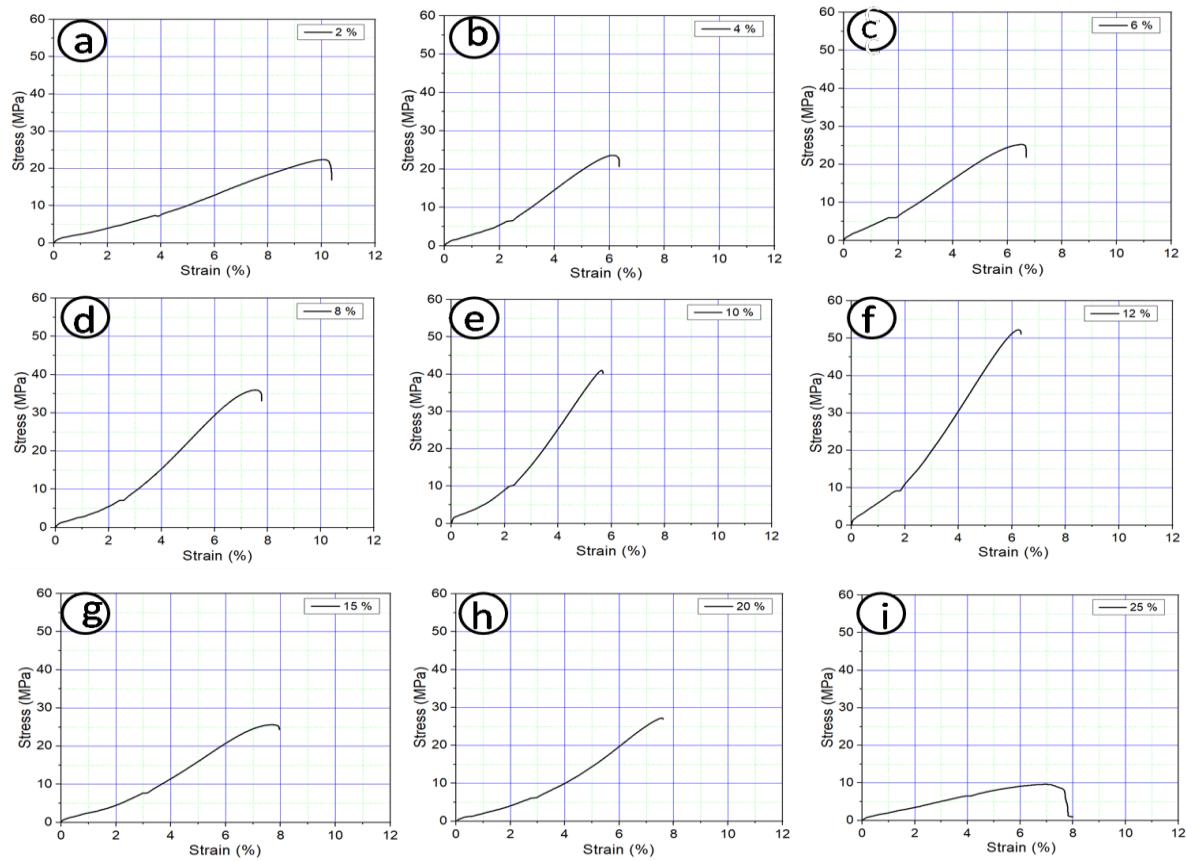


Figure 4.5 Stress-strain diagrams

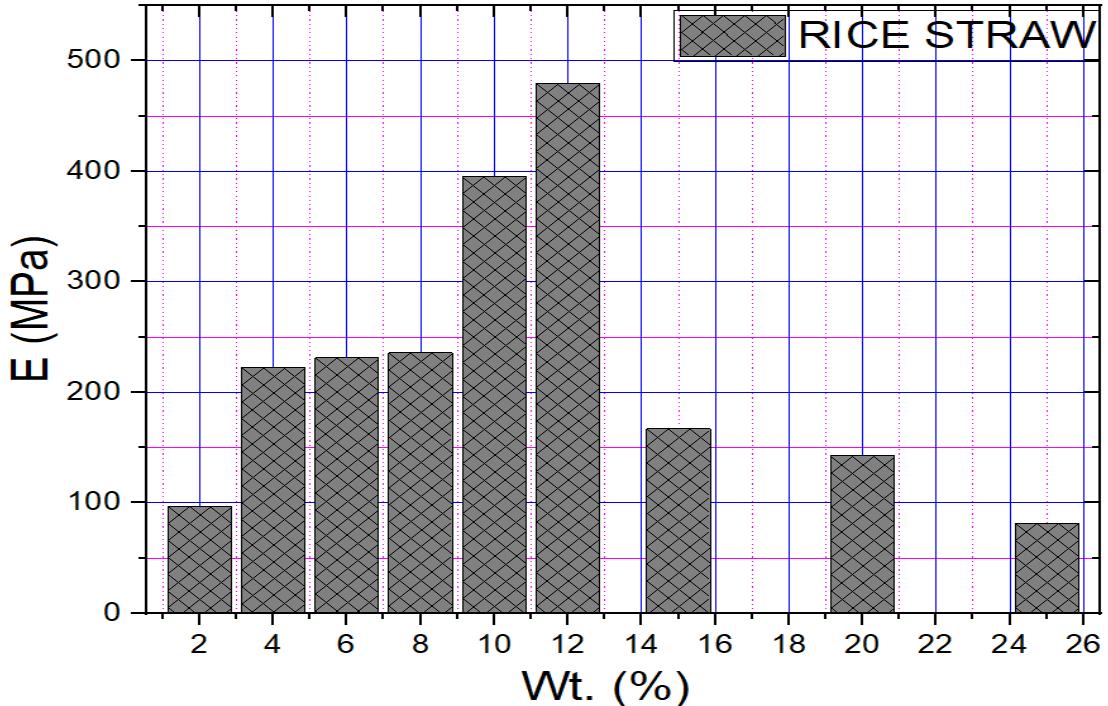


Figure 4.6 Young's modulus of different composition of polymer

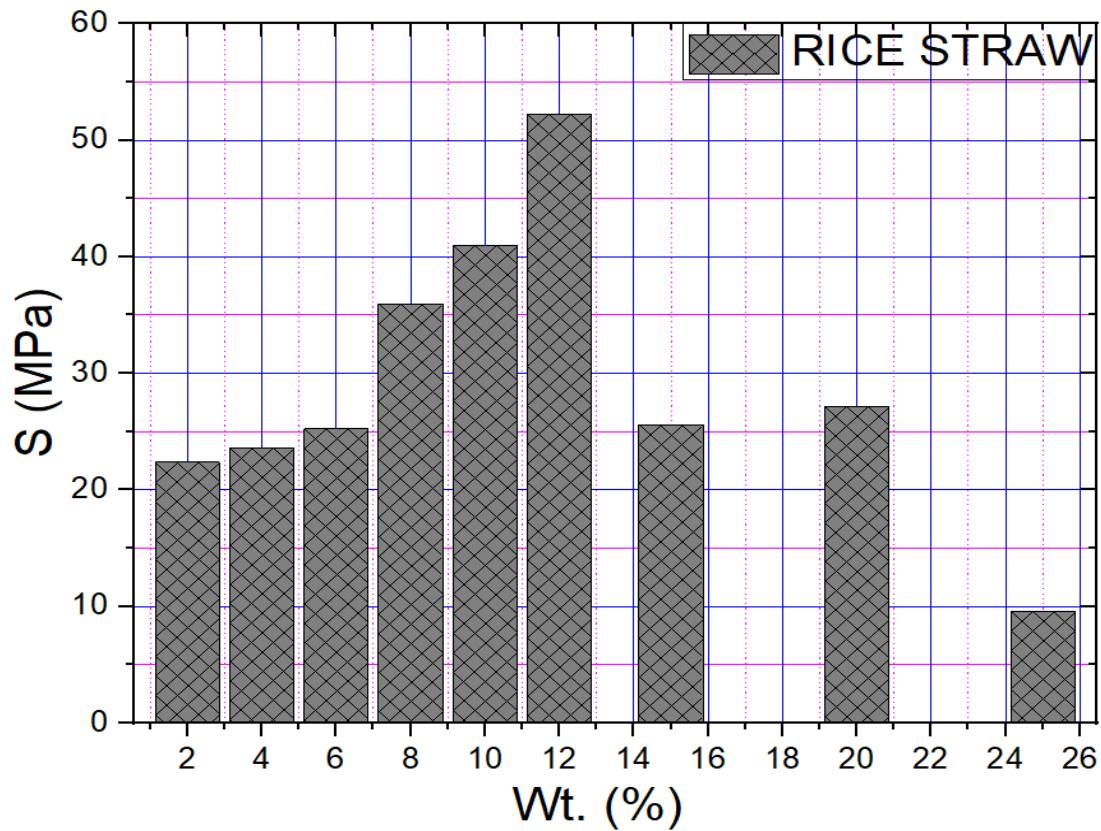


Figure 4.7 Strength of polymer

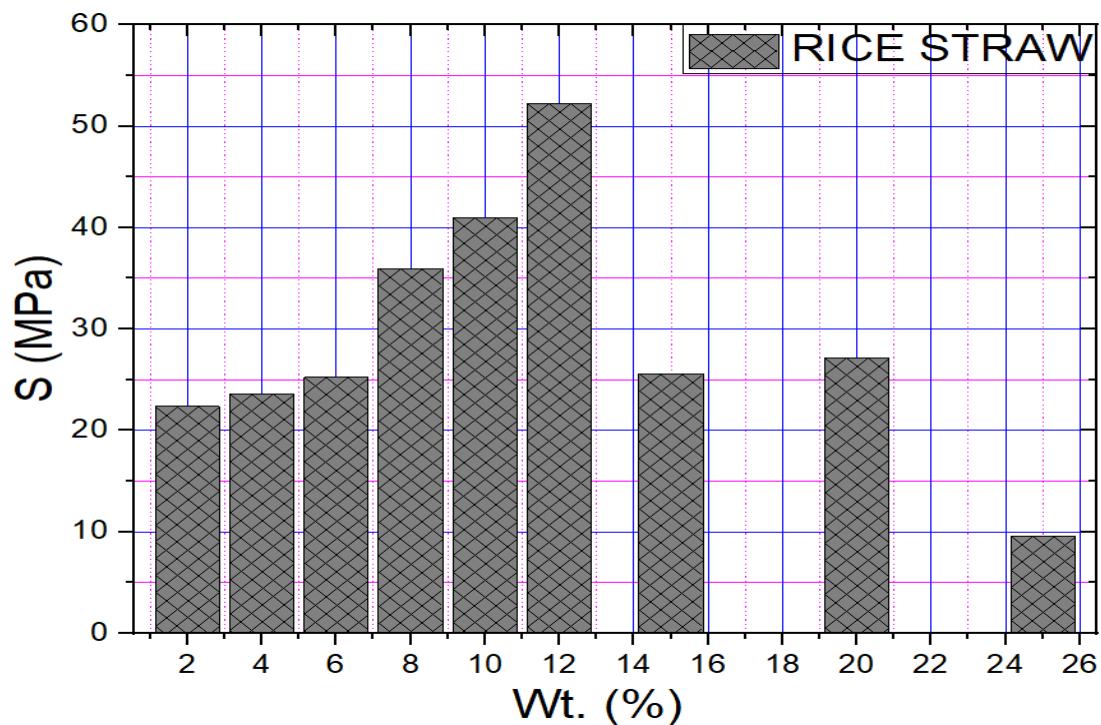


Figure 4.8 Elongation at failure

4.1.3 Jute Reinforced Polymer Composite

Figure 4.9 illustrates the mechanical behavior of jute reinforced polymer composites fabricated with varying resin-to-hardener ratios, as revealed through tensile testing. The stress-strain curves provide key insights into both elastic and plastic deformation responses of the materials. Figure 4.10 compares the Young's modulus for each formulation, highlighting the effect of hardener content on composite stiffness. Figures 4.11 and 4.12 further show the variation in tensile strength and elongation at break, respectively, for composites prepared using Araldite AW106 resin and HV953 hardener. The results demonstrate a systematic change in mechanical properties with increasing hardener content while keeping the resin content fixed.

The graph shows the mechanical properties of jute-reinforced composites with varying percentages of jute fibers, combined with resin AW 106 and hardener HV 953. At 2.5% jute, the composite exhibits a Young's modulus of 126.49 MPa, strength of 18.05 MPa, and elongation of 5.86%. As the jute content increases to 5%, the composite demonstrates a significant increase in stiffness, with Young's modulus rising sharply to 451.89 MPa, while strength increases to 30.26 MPa. However, elongation decreases to 4.14%, suggesting a more brittle nature. At 7.5% jute, the material experiences a decline in Young's modulus to 127.56 MPa, but strength increases dramatically to 50.42 MPa. Elongation also improves to 10.73%, indicating that the composite becomes more flexible. At 10% jute, the composite regains a high level of stiffness with a Young's modulus of 490.62 MPa, but strength slightly decreases to 46.67 MPa, and elongation drops again to 5.12%, indicating increased rigidity but reduced flexibility. At 12.5% jute, the composite shows a noticeable reduction in Young's modulus to 242.49 MPa, while strength rises to 53 MPa, and elongation improves to 8.40%, showing better flexibility. At 15% jute, the material exhibits a high stiffness with a Young's modulus of 459.20 MPa, but the strength reduces slightly to 50.14 MPa, and elongation stays relatively stable at 5.84%. Finally, at 20% jute, the composite shows a sharp drop in stiffness with Young's modulus falling to 80.44 MPa, strength decreasing to 18.40 MPa, and elongation increasing again to 8.52%, suggesting that excessive jute content significantly weakens the composite's structural integrity while increasing its flexibility. These results demonstrate that jute enhances the material's strength and stiffness at moderate concentrations, but higher fiber contents seem to reduce the composite's overall mechanical performance, especially in terms of stiffness and strength [30].

This figure displays a series of stress-strain curves for a material under different strain percentages, illustrating how the material responds to varying levels of strain. The curves are labeled from "a" to "g" and cover strain values from 2.5% up to 20% [31]. At the lower strain levels, such as 2.5% (a) and 5% (b), the stress response is relatively low, indicating the material remains in the elastic region where the deformation is reversible. As the strain increases to 7.5% (c) and 10% (d), the material begins to show higher stress values, indicating it is undergoing more significant deformation, potentially entering the plastic region. At these strain levels, the material can still return to its original shape if the stress is removed, but it is closer to the yield point. With further increases in strain, like at 12.5% (e) and 15% (f), the material shows even more pronounced stress increases, demonstrating more substantial plastic deformation. At the highest strain value of 20% (g), the material continues to exhibit an increase in stress but at a more moderate rate, signaling that the material is nearing its ultimate tensile strength, where it could fail or rupture if the strain continues. These stress-strain curves provide valuable insights into the material's mechanical properties, highlighting the relationship between stress and strain as the material progresses through elastic and plastic deformation stages before ultimate failure.

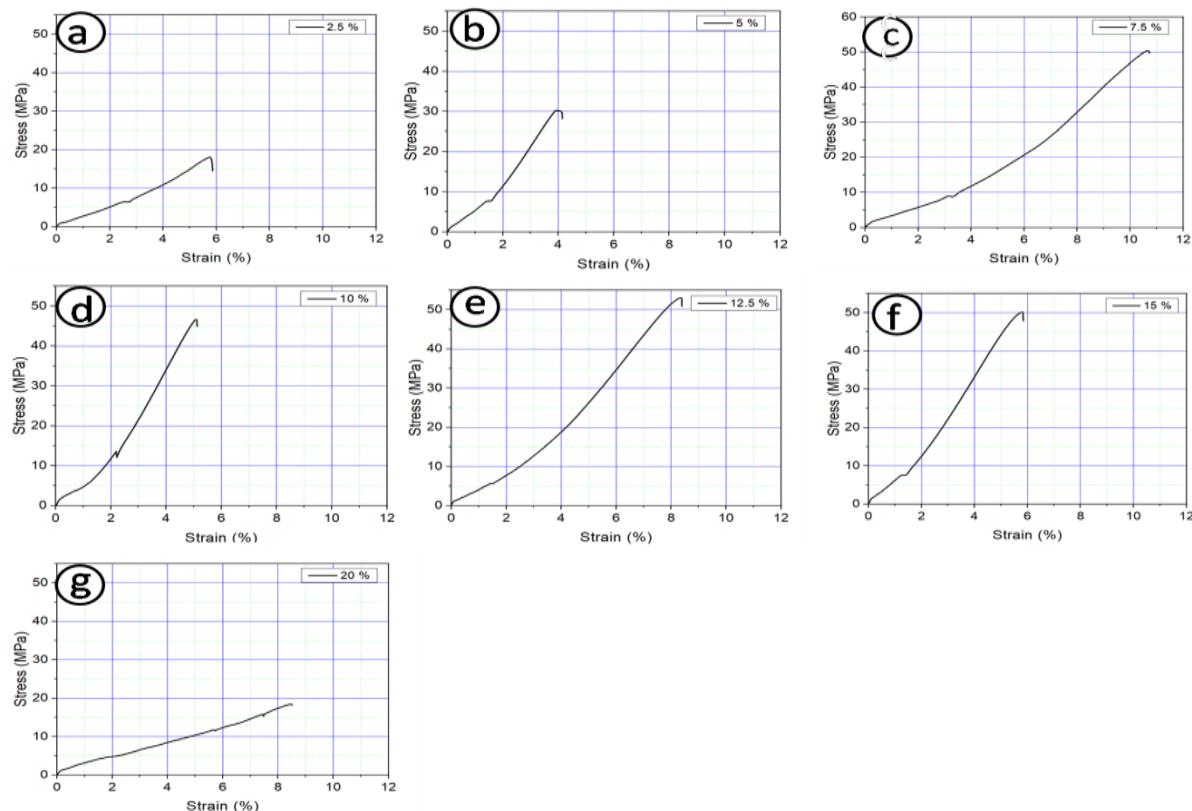


Figure 4.9 Stress-strain diagrams

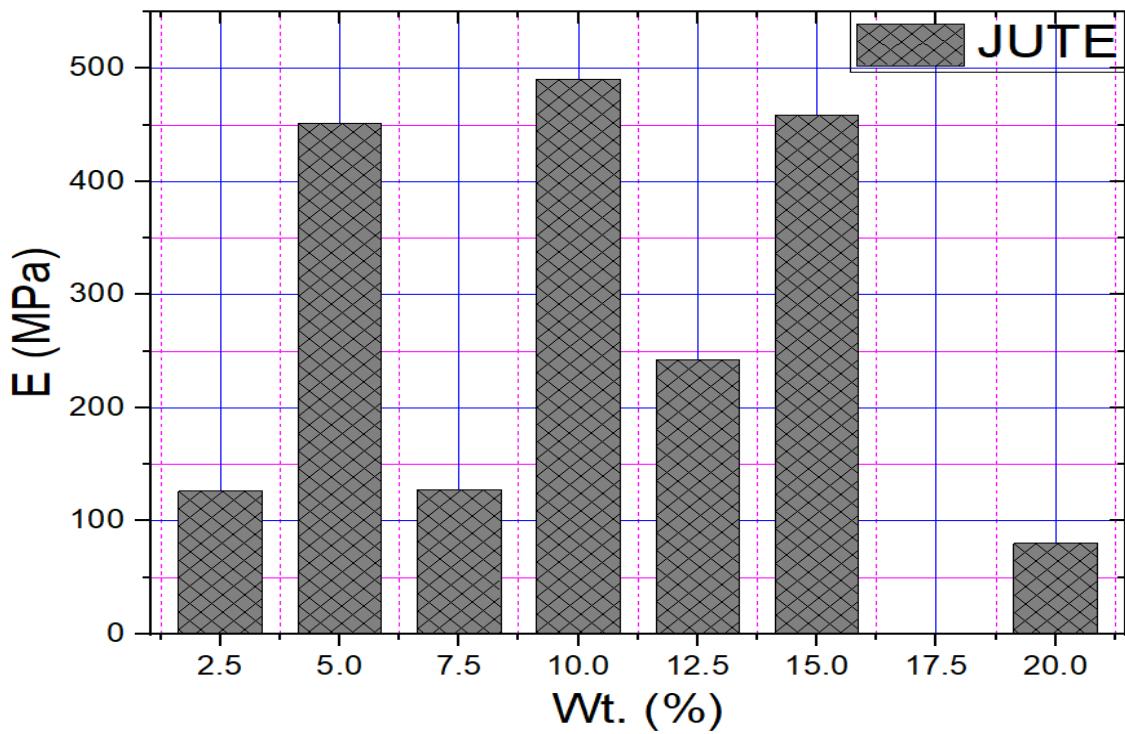


Figure 4.10 Young's modulus of different composition of polymer

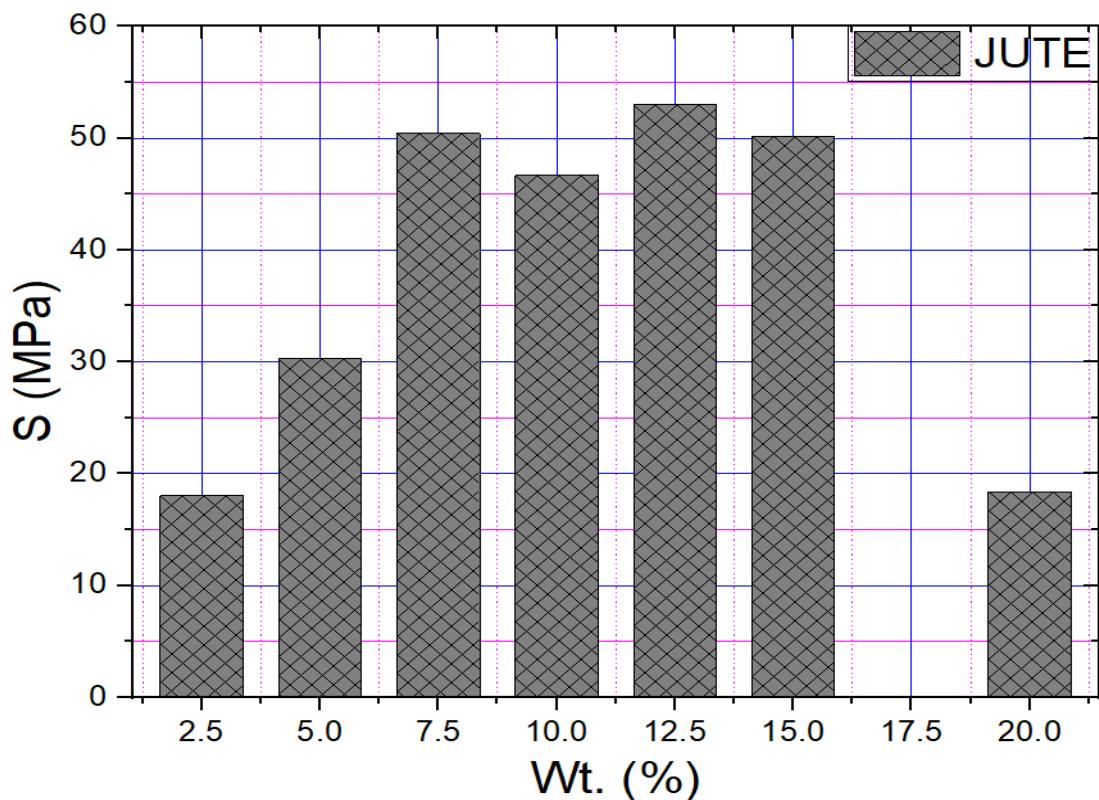


Figure 4.11 Strength of polymer

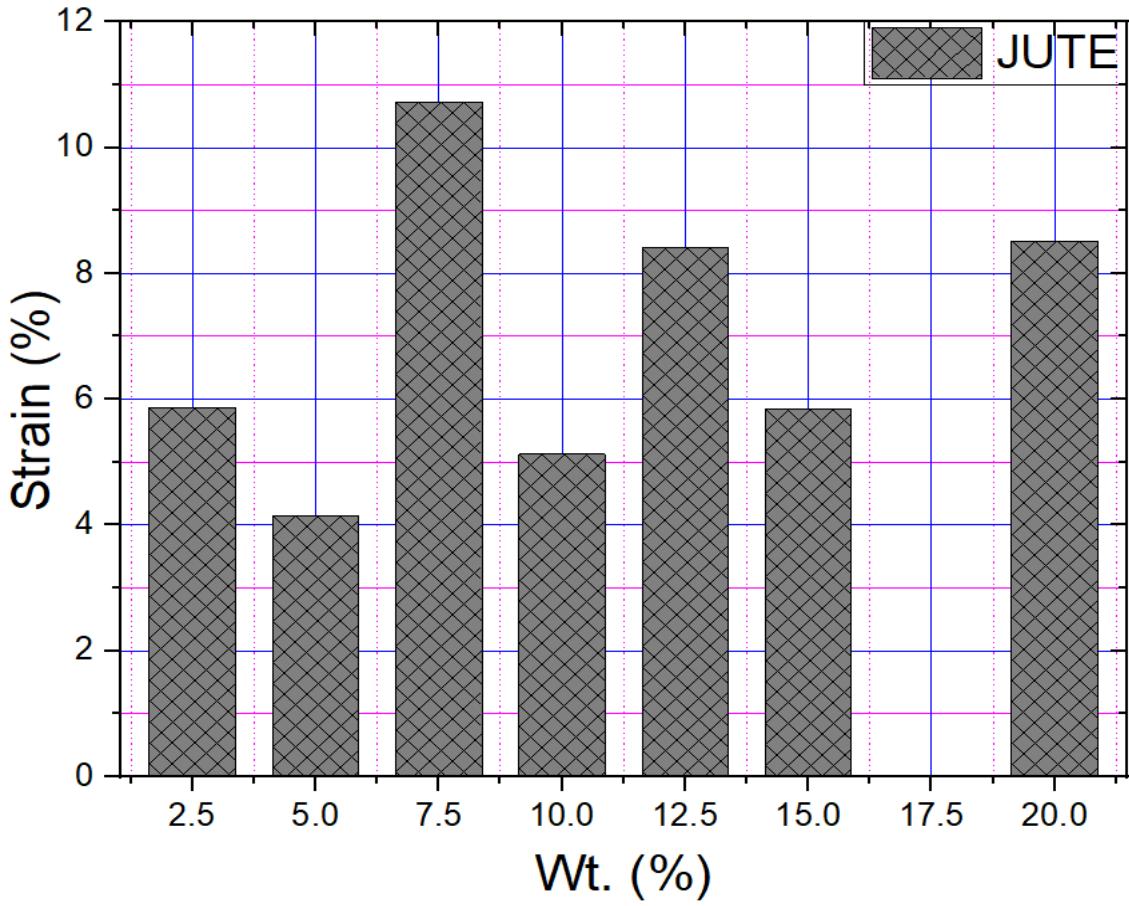


Figure 4.12 Elongation at failure

4.1.4 Banana Fiber Reinforced Polymer Composite

Figure 4.13 illustrates the mechanical behavior of banana fiber reinforced polymer composites fabricated with varying resin-to-hardener ratios, as revealed through tensile testing. The stress-strain curves provide key insights into both elastic and plastic deformation responses of the materials. Figure 4.14 compares the Young's modulus for each formulation, highlighting the effect of hardener content on composite stiffness. Figures 4.15 and 4.16 further show the variation in tensile strength and elongation at break, respectively, for composites prepared using Araldite AW106 resin and HV953 hardener. The results demonstrate a systematic change in mechanical properties with increasing hardener content while keeping the resin content fixed.

The graph demonstrates the mechanical properties of banana fiber-reinforced composites with varying percentages of banana fiber, using resin AW 106 and hardener HV 953. At 2% banana fiber, the composite exhibits a high Young's modulus of 177.75 MPa, strength of 47.25 MPa, and elongation of 5.64%, indicating a balanced material with good stiffness and strength. As

the banana fiber content increases to 4%, the composite shows a slight decrease in Young's modulus to 166.75 MPa, but strength increases to 50.26 MPa, and elongation improves slightly to 5.97%. At 6% banana fiber, the material's Young's modulus rises again to 170.94 MPa, while strength increases more significantly to 62.49 MPa, and elongation also improves to 7.04%, suggesting that the composite becomes stronger and more flexible. At 8% banana fiber, the Young's modulus reaches a peak of 220.87 MPa, with strength at 68.57 MPa and a slight reduction in elongation to 6.27%. As the fiber content increases to 10%, the Young's modulus drops to 151.97 MPa, while strength continues to rise to 75.10 MPa and elongation increases again to 8.09%, indicating a shift towards greater flexibility. At 12%, the composite shows a moderate increase in strength to 81.00 MPa, with a slight drop in Young's modulus to 165.74 MPa and elongation at 7.74%. At 15% banana fiber, there is a noticeable reduction in stiffness, with Young's modulus dropping to 135.42 MPa, and strength decreases to 65.42 MPa, while elongation slightly improves to 7.39%, indicating a trade-off between flexibility and mechanical performance. At 20%, the composite experiences a sharp decline in Young's modulus to 73.08 MPa, while strength remains relatively high at 68.24 MPa, and elongation significantly increases to 12.43%, showing increased flexibility but lower stiffness. At 25%, the Young's modulus recovers somewhat to 162.30 MPa, and strength drops to 58.81 MPa, with elongation at 7.30%, indicating a more balanced composite with moderate stiffness and strength. Finally, at 30%, both Young's modulus (129.74 MPa) and strength (33.42 MPa) decrease further, while elongation drops to 5.62%, indicating that higher fiber content reduces the composite's mechanical properties, leading to lower strength and stiffness with moderate flexibility. These results suggest that banana fiber significantly enhances the material's strength and stiffness at moderate concentrations, but beyond a certain point, excessive fiber content leads to a reduction in overall mechanical performance, with increased flexibility but compromised rigidity and strength [32].

The image presents a series of stress-strain curves, labeled from (a) to (j), showing the behavior of a material under increasing strain levels, ranging from 2% to 30% [33]. In graph (a), with just 2% strain, the stress increases slowly, indicating that the material is still in the elastic range, where it deforms but will return to its original shape once the load is removed. As the strain increases to 4% in graph (b), there is a more noticeable increase in stress, suggesting the material is beginning to experience some permanent deformation, though it remains largely elastic. At 6% strain in graph (c), the stress rises more sharply, indicating that the material is entering the plastic deformation stage, where permanent changes in the structure of the material

begin to occur. In graph (d), with 8% strain, the curve shows further progression into the plastic region, with stress increasing at a faster rate. By graph (e), at 10% strain, the material is undergoing more significant plastic deformation. The curve continues to show a steady increase in stress as the material experiences more permanent changes. In graph (f), at 12% strain, the material continues to deform plastically, with the curve showing a more defined shape indicating the ongoing plastic deformation. At 15% strain in graph (g), the material shows continued deformation, with the stress continuing to increase sharply. As the strain reaches 20% in graph (h), the material is experiencing substantial plastic deformation, with the curve showing a clear bend, possibly signaling localized necking. In graph (i), at 25% strain, the material is undergoing even more deformation, with a significant rise in stress. Finally, in graph (j), at 30% strain, the curve reaches its maximum deformation before the material likely fails, showing signs of fracture or rupture. In summary, the series of graphs illustrates the material's progression from elastic to plastic deformation, eventually leading to failure as strain increases.

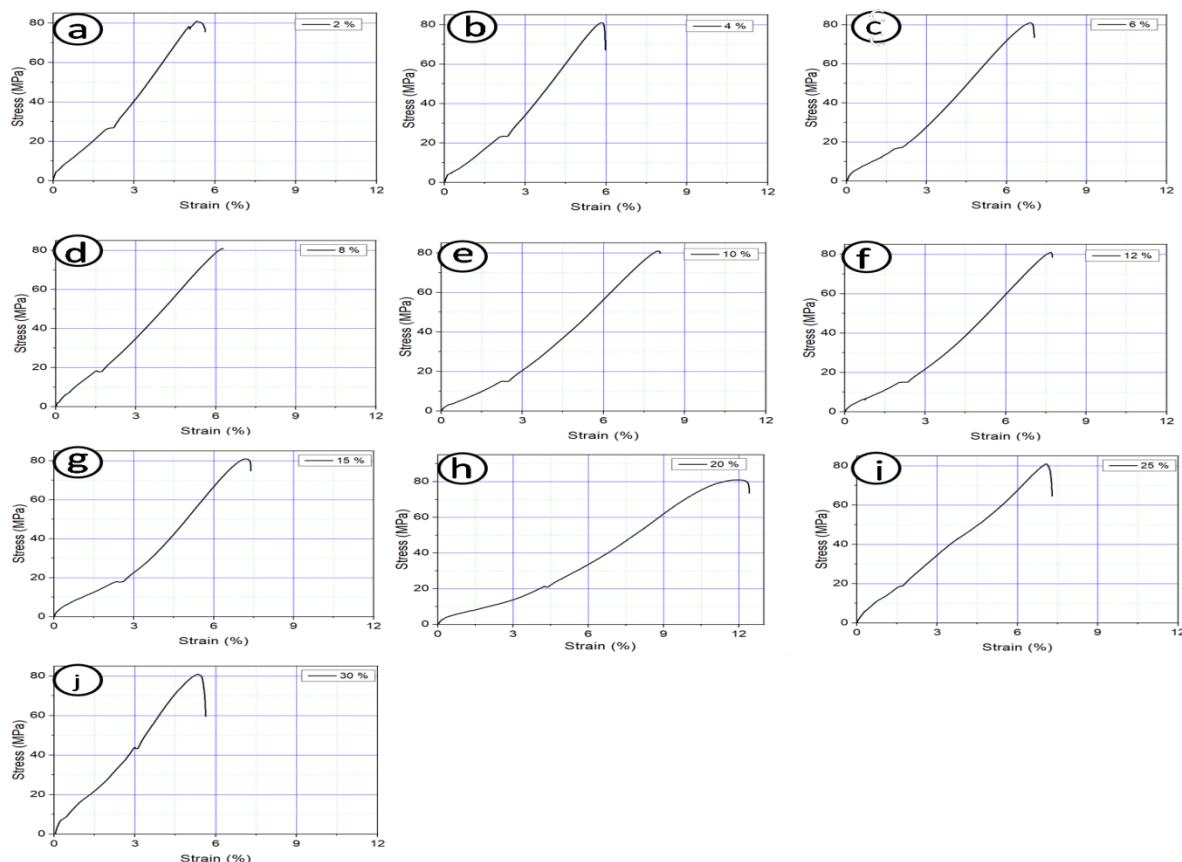


Figure 4.13 Stress-strain diagrams

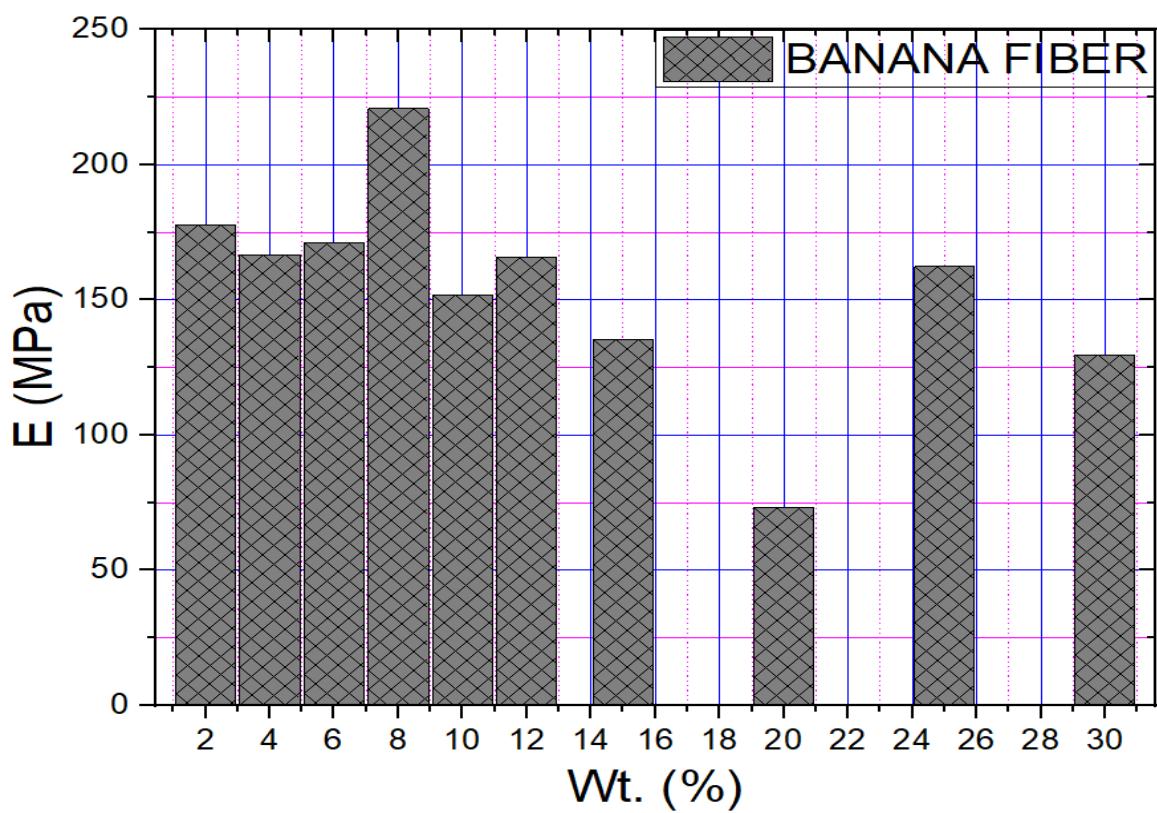


Figure 4.14 Young's modulus of different composition of polymer

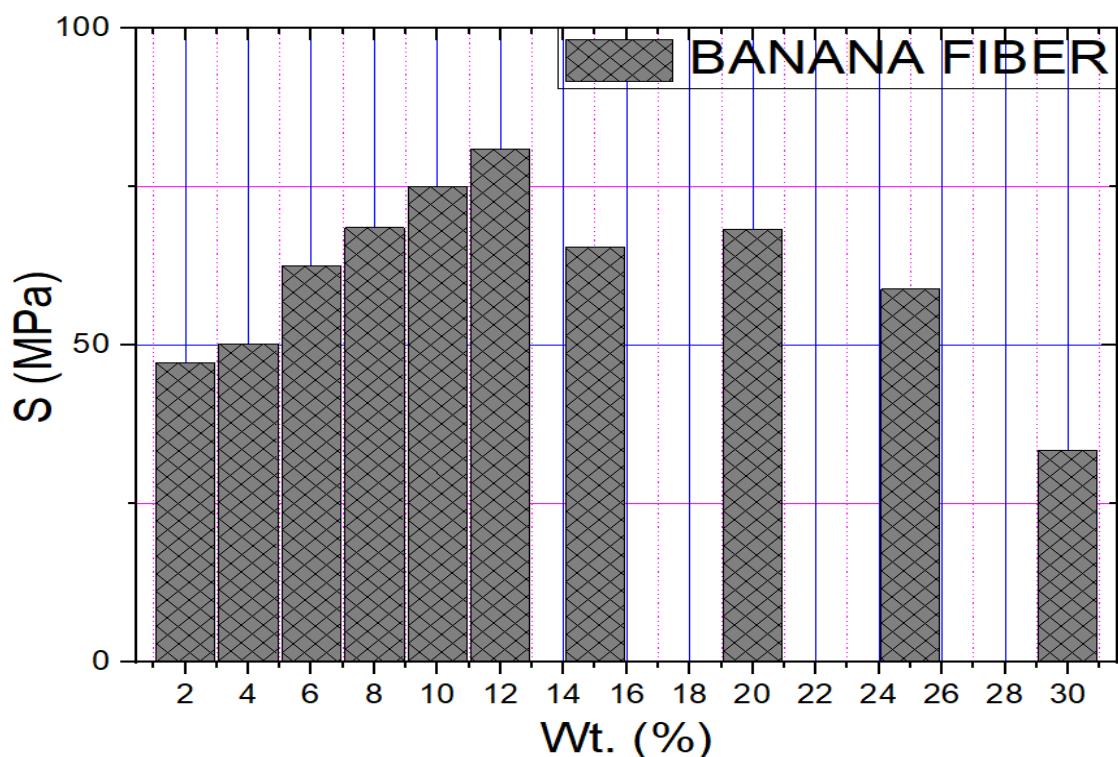


Figure 4.15 Strength of polymer

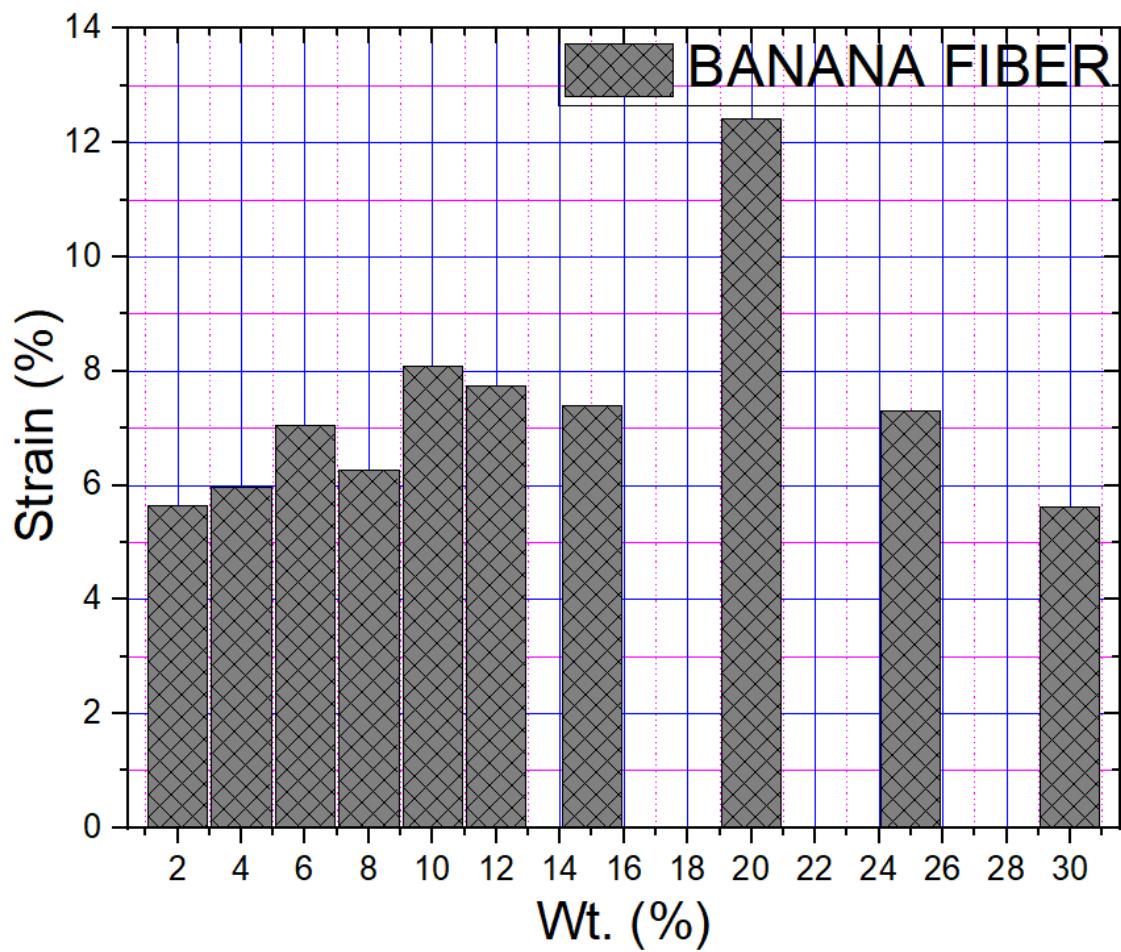


Figure 4.16 Elongation at failure

4.1.5 Abaca Reinforced Polymer Composite

Figure 4.17 illustrates the mechanical behavior of abaca fiber reinforced polymer composites fabricated with varying resin-to-hardener ratios, as revealed through tensile testing. The stress-strain curves provide key insights into both elastic and plastic deformation responses of the materials. Figure 4.18 compares the Young's modulus for each formulation, highlighting the effect of hardener content on composite stiffness. Figures 4.19 and 4.20 further show the variation in tensile strength and elongation at break, respectively, for composites prepared using Araldite AW106 resin and HV953 hardener. The results demonstrate a systematic change in mechanical properties with increasing hardener content while keeping the resin content fixed.

The graph presents the mechanical behavior of abaca fiber-reinforced composites with varying percentages of abaca fiber, combined with resin AW 106 and hardener HV 953. At a low abaca content of 2%, the composite exhibits a Young's modulus of 24.02 MPa, strength of 24.51

MPa, and elongation of 5.03%. Increasing the abaca content to 5% results in a significant improvement in both stiffness and strength, with Young's modulus rising to 98.96 MPa and strength reaching 58.66 MPa, accompanied by a notable increase in elongation to 13.13%. Further addition of abaca to 8% leads to a slight increase in Young's modulus to 106.45 MPa and strength to 63.98 MPa, while elongation also increases slightly to 13.66%. At 10% abaca, the composite shows further gains in stiffness and strength with Young's modulus at 153.56 MPa and strength reaching 94.99 MPa; however, elongation decreases to 8.29%. The trend continues with 15% abaca, where the material achieves the highest recorded values of Young's modulus at 251.51 MPa and strength at 119.05 MPa, while elongation slightly declines to 8.16%. When the abaca content increases to 20%, a minor reduction in stiffness and strength occurs, with Young's modulus falling to 243.34 MPa and strength to 99.75 MPa, and elongation decreasing to 6.95%. Finally, at 25% abaca, the composite experiences a more pronounced decrease in mechanical properties, with Young's modulus dropping to 156.20 MPa, strength to 62.82 MPa, and elongation reducing to 5.73%. These results indicate that incorporating abaca fibers significantly enhances the composite's stiffness and strength up to optimal fiber content around 15%, beyond which the mechanical performance starts to decline, accompanied by a general decrease in elongation as fiber content increases [34].

The image presents a sequence of stress-strain curves, labeled from (a) to (g), each showing how a material responds to different levels of strain, ranging from 2% to 25% [35]. In the first graph, (a), with just 2% strain, the material experiences only a slight increase in stress, which suggests that it is still behaving elastically and will return to its original shape once the stress is removed. As the strain increases to 5% in graph (b), the stress increases at a faster rate, indicating that the material is beginning to undergo some permanent deformation while still remaining mostly elastic. At 8% strain in graph (c), the material exhibits more noticeable plastic deformation, with stress rising sharply, signaling that the material is nearing its yield point. In graph (d), with 10% strain, the stress increases significantly, indicating that the material is moving further into the plastic deformation region, where the changes become permanent. In graph (e), at 15% strain, the curve continues to bend, showing that the material is now in the plastic zone and close to reaching its ultimate tensile strength. By graph (f), at 20% strain, the curve shows more pronounced bending, suggesting that localized necking may be occurring, indicating that the material is nearing failure. Finally, in graph (g), with 25% strain, the material undergoes a substantial amount of deformation, suggesting that it has either already failed or is

very close to fracture. Overall, the image illustrates the material's transition from elastic deformation to plastic deformation and, eventually, to failure as strain increases.

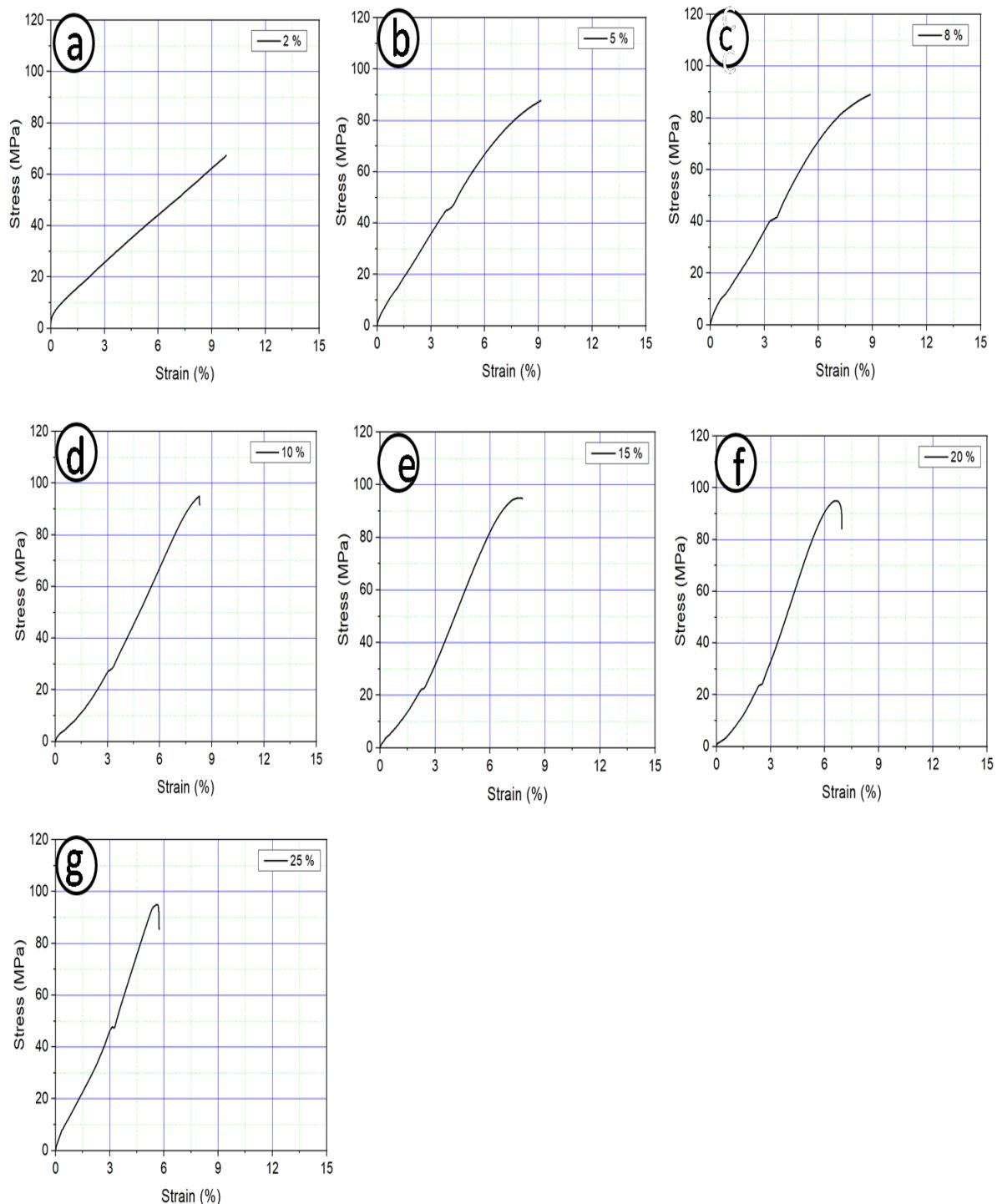


Figure 4.17 Stress-strain diagrams

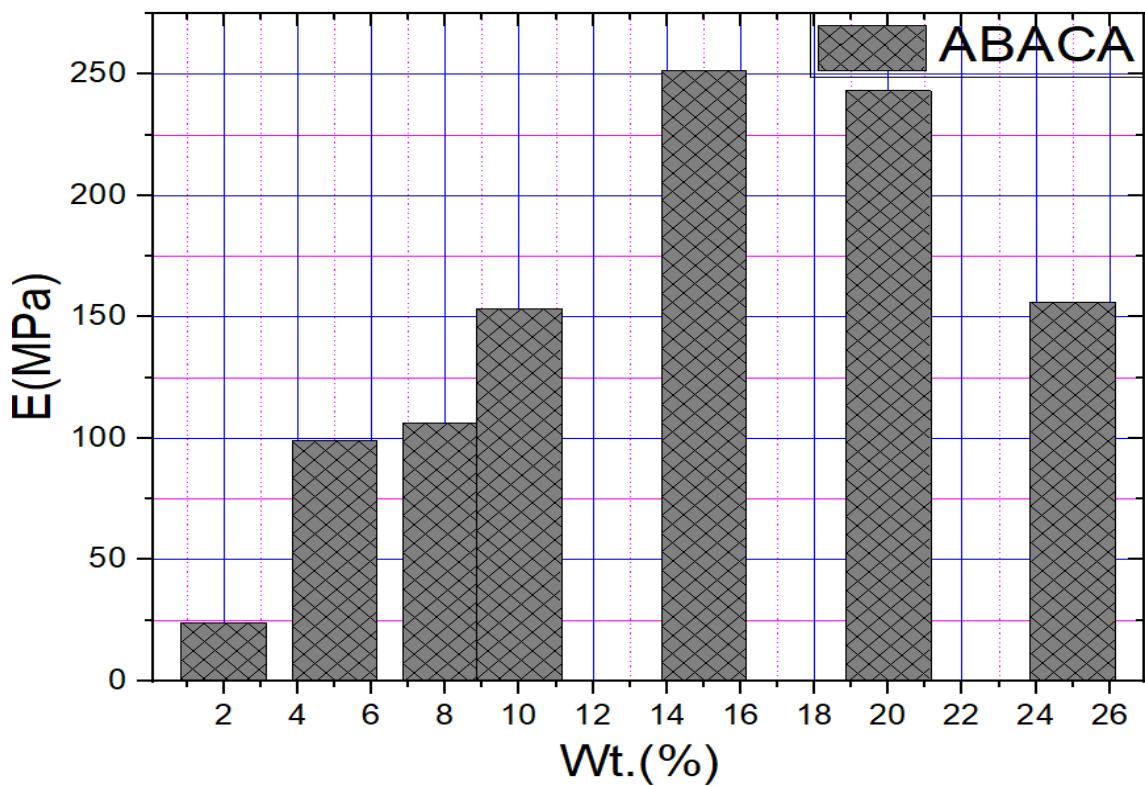


Figure 4.18 Young's modulus of different composition of polymer

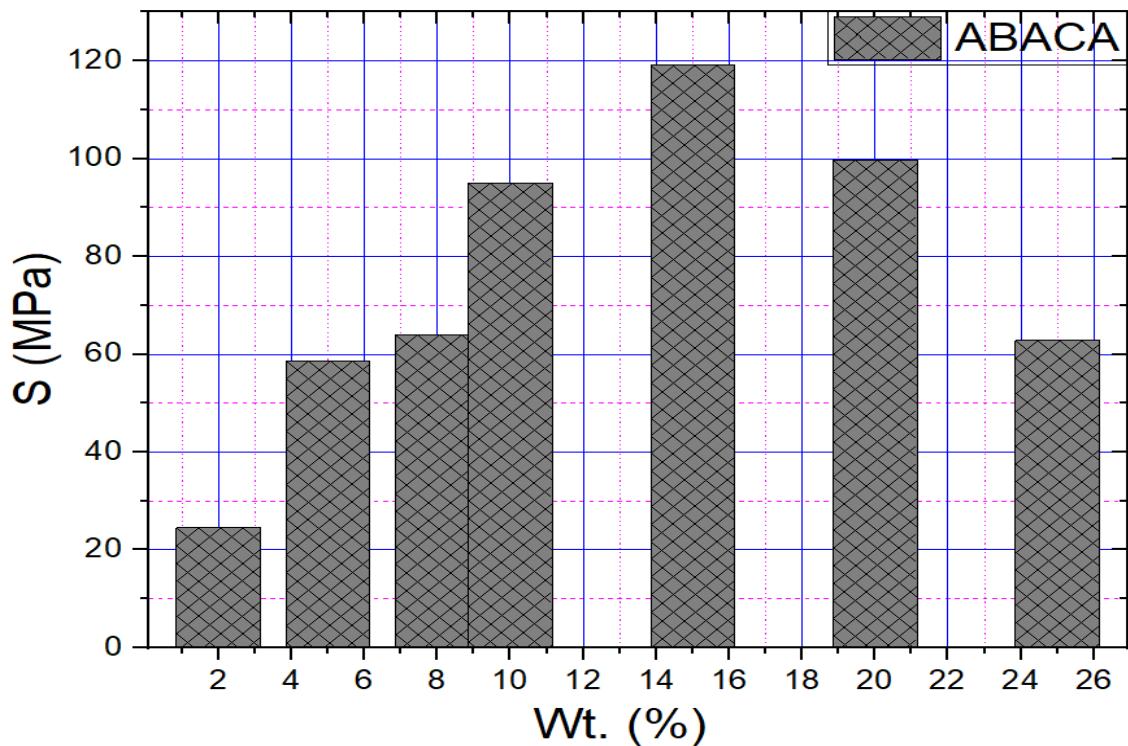


Figure 4.19 Strength of polymer

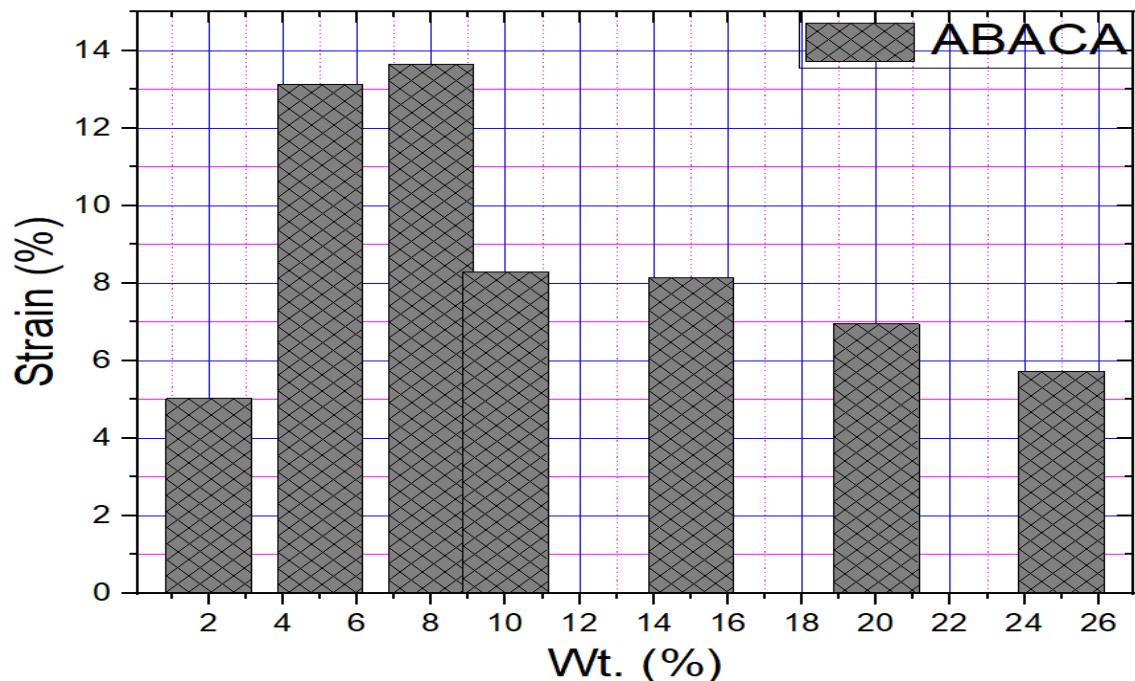


Figure 4.20 Elongation at failure

4.1.6 Hemp Reinforced Polymer Composite

Figure 4.21 illustrates the mechanical behavior of hemp fiber reinforced polymer composites fabricated with varying resin-to-hardener ratios, as revealed through tensile testing. The stress-strain curves provide key insights into both elastic and plastic deformation responses of the materials. Figure 4.22 compares the Young's modulus for each formulation, highlighting the effect of hardener content on composite stiffness. Figures 4.23 and 4.24 further show the variation in tensile strength and elongation at break, respectively, for composites prepared using Araldite AW106 resin and HV953 hardener. The results demonstrate a systematic change in mechanical properties with increasing hardener content while keeping the resin content fixed.

The graph presents the mechanical properties of hemp-reinforced composites with varying hemp content, combined with resin AW 106 and hardener HV 953. At 2% hemp, the composite exhibits a relatively high Young's modulus of 186.68 MPa, strength of 36.85 MPa, and elongation of 4.56%. As the hemp content increases to 4%, the material becomes less stiff, with Young's modulus dropping to 98.80 MPa, but the strength increases slightly to 38.83 MPa. Elongation significantly improves to 12.45%, suggesting increased flexibility. At 6% hemp,

the Young's modulus increases to 144.34 MPa, while strength rises to 42.32 MPa, and elongation decreases to 9.05%, indicating a balance between stiffness and flexibility. The trend continues at 8% hemp, where Young's modulus falls to 116.94 MPa and strength increases to 48.78 MPa, with elongation improving further to 9.89%. At 10%, the composite shows a slight decrease in both Young's modulus (112.37 MPa) and elongation (8.55%), while strength continues to increase to 50.65 MPa. The material properties further stabilize at 12% hemp, with Young's modulus rising again to 191.88 MPa and strength increasing to 53.97 MPa, while elongation decreases slightly to 7.70%. At 15% hemp, the composite shows a modest decrease in stiffness (151.21 MPa) but an increase in strength to 59.16 MPa, with elongation at 7.18%. The trend of increasing strength continues at 18% hemp, where the composite achieves strength of 59.91 MPa, with Young's modulus remaining steady at 191.79 MPa and elongation decreasing to 6.62%. At 21% hemp, the composite exhibits a drop in Young's modulus to 163.99 MPa, but strength increases significantly to 70 MPa, and elongation improves again to 8.39%. As the hemp content rises further to 24%, the Young's modulus decreases sharply to 82.09 MPa, while strength remains high at 59.56 MPa, and elongation increases significantly to 14.60%, indicating greater flexibility. At 27% hemp, the material experiences another reduction in Young's modulus to 133.09 MPa, strength drops to 43.57 MPa, and elongation remains at 9.39%, signaling a loss in rigidity but sustained flexibility. Finally, at 30% hemp, the composite shows a slight reduction in Young's modulus to 120.79 MPa and strength to 48.25 MPa, with elongation at 8.10%. These results demonstrate that hemp content initially enhances the material's stiffness, strength, and flexibility up to a certain point, but as the hemp percentage continues to rise, the composite becomes more flexible but loses some of its mechanical strength and rigidity [36].

The figure presents stress-strain curves for a material subjected to different strain percentages, showing how the material's stress response changes as strain increases. The graphs are arranged in a grid from top left to bottom right, with each subfigure labeled from "a" to "l," corresponding to varying strain levels ranging from 2% to 30% [37]. At lower strain percentages, such as 2% (a) and 4% (b), the material shows a relatively low stress response, indicating elastic deformation with minimal plastic deformation. As the strain percentage increases, the stress response also rises, demonstrating the material's ability to endure more stress before reaching the yield point. In the middle range (e.g., at 8% in (d), 10% in (e), and 12% in (f)), the curve starts to exhibit a more pronounced plastic deformation phase, where the material undergoes significant changes in structure. As the strain continues to rise (e.g., at 15% in (g), 18% in (h),

and 21% in (i)), the material's stress continues to increase, but some curves exhibit a softening effect, indicating that the material has reached or is nearing its breaking point. For higher strain levels, such as 24% in (j), 27% in (k), and 30% in (l), the stress response tends to flatten or drop, signaling that the material has reached its ultimate tensile strength and is approaching failure. These curves provide insights into the material's mechanical properties, including its elastic modulus, yield strength, and tensile strength. The gradual increase in stress with strain indicates that the material undergoes both elastic and plastic deformations, culminating in a fracture or failure at higher strain levels.

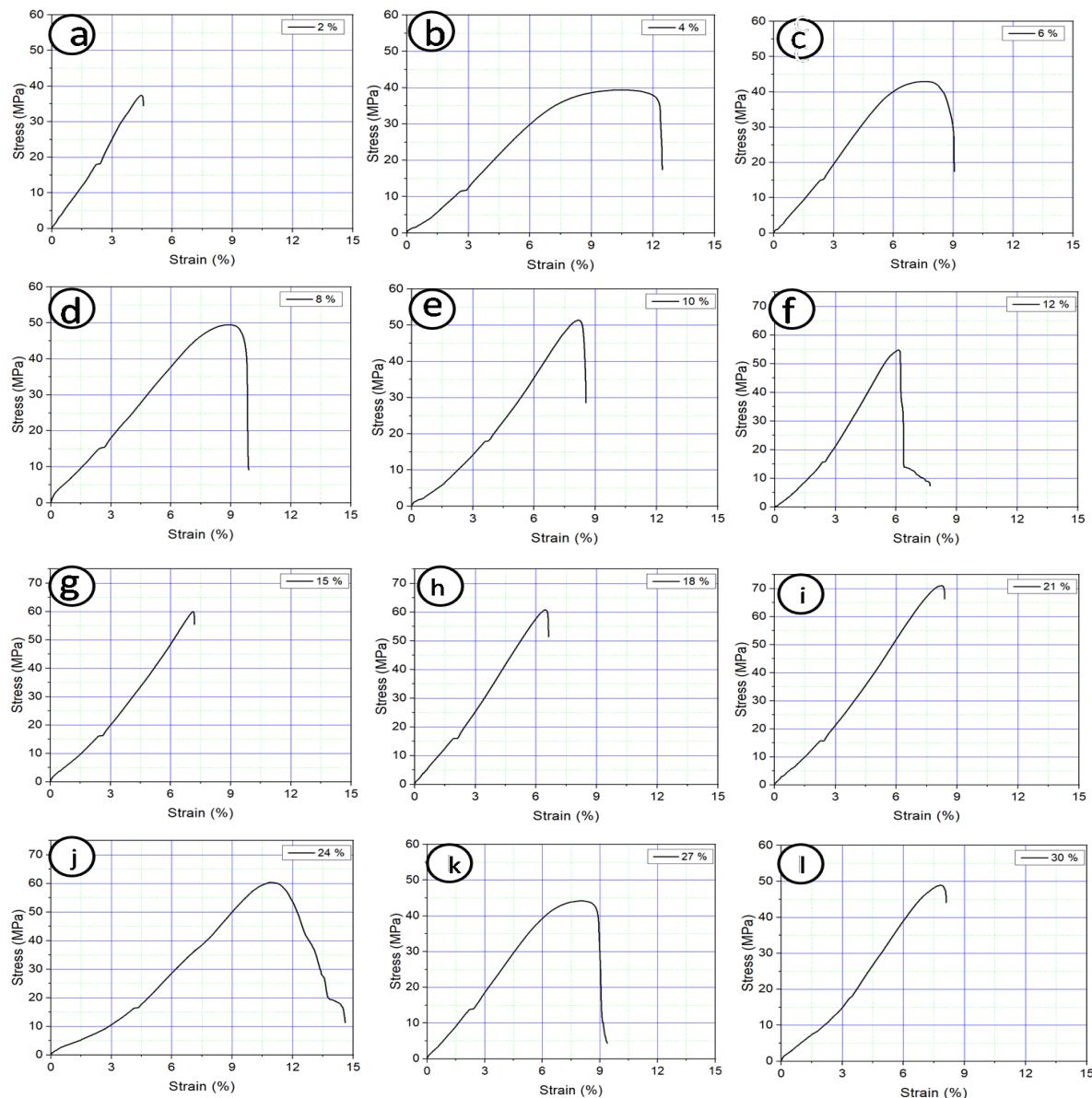


Figure 4.21 Stress-strain diagrams

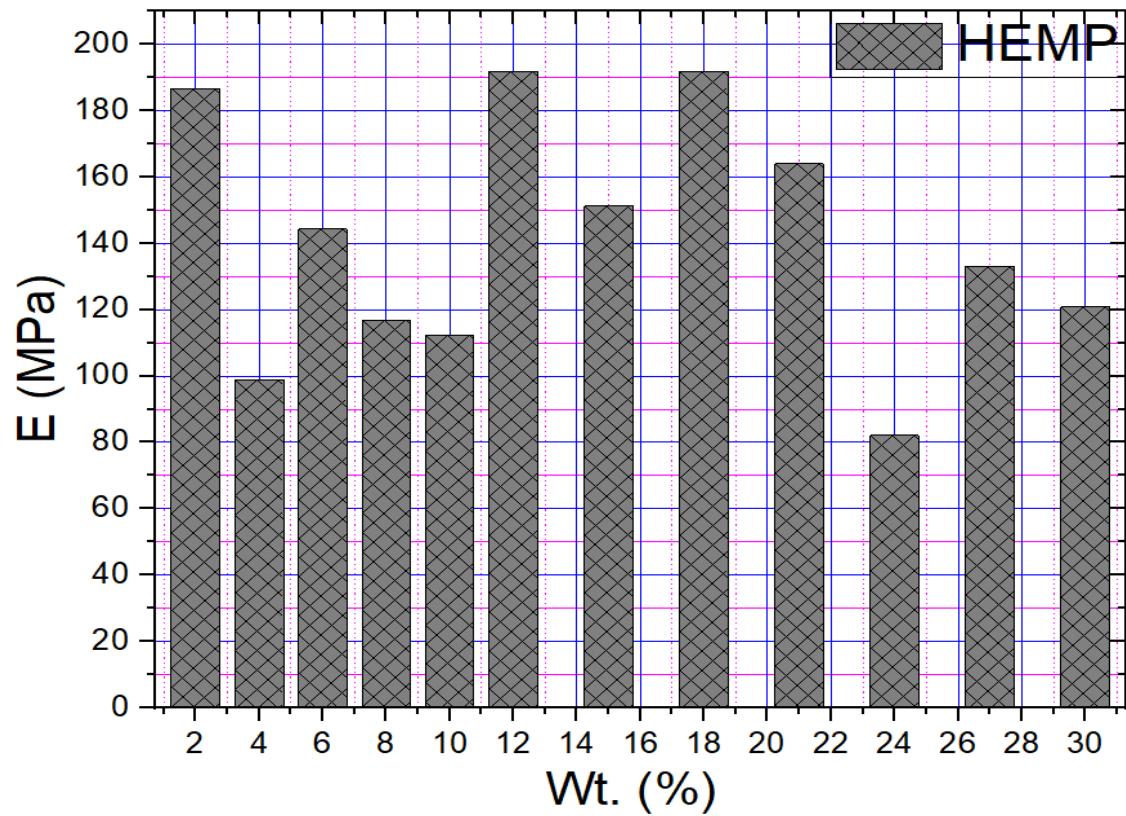


Figure 4.22 Young's modulus of different composition of polymer

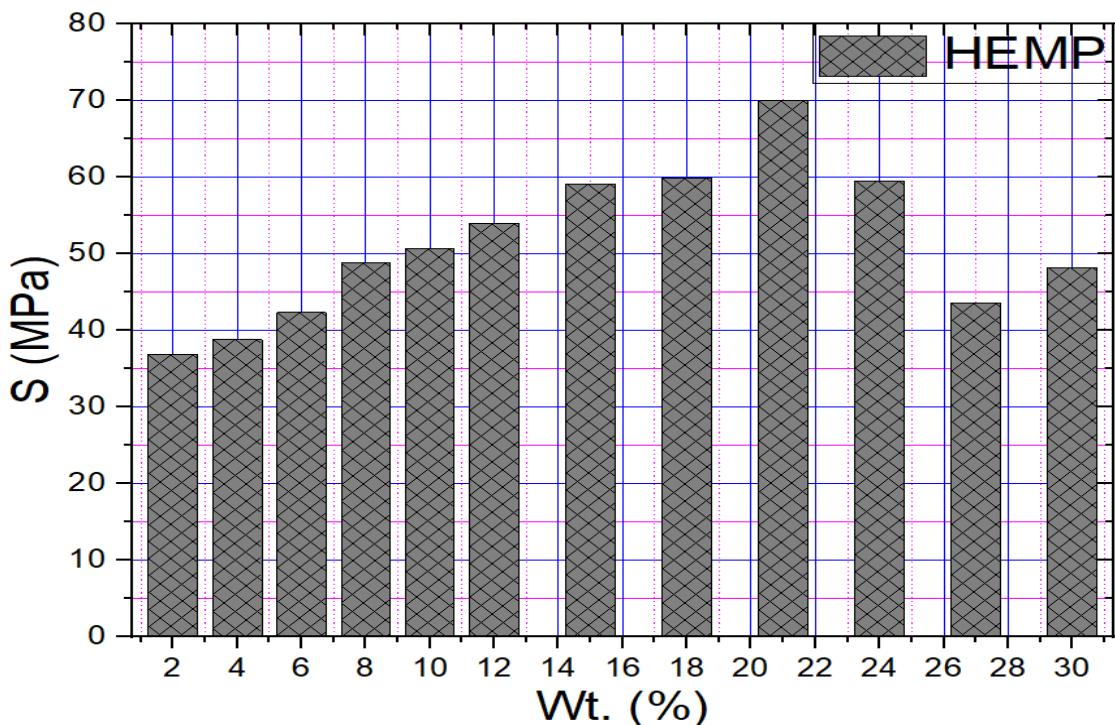


Figure 4.23 Strength of polymer

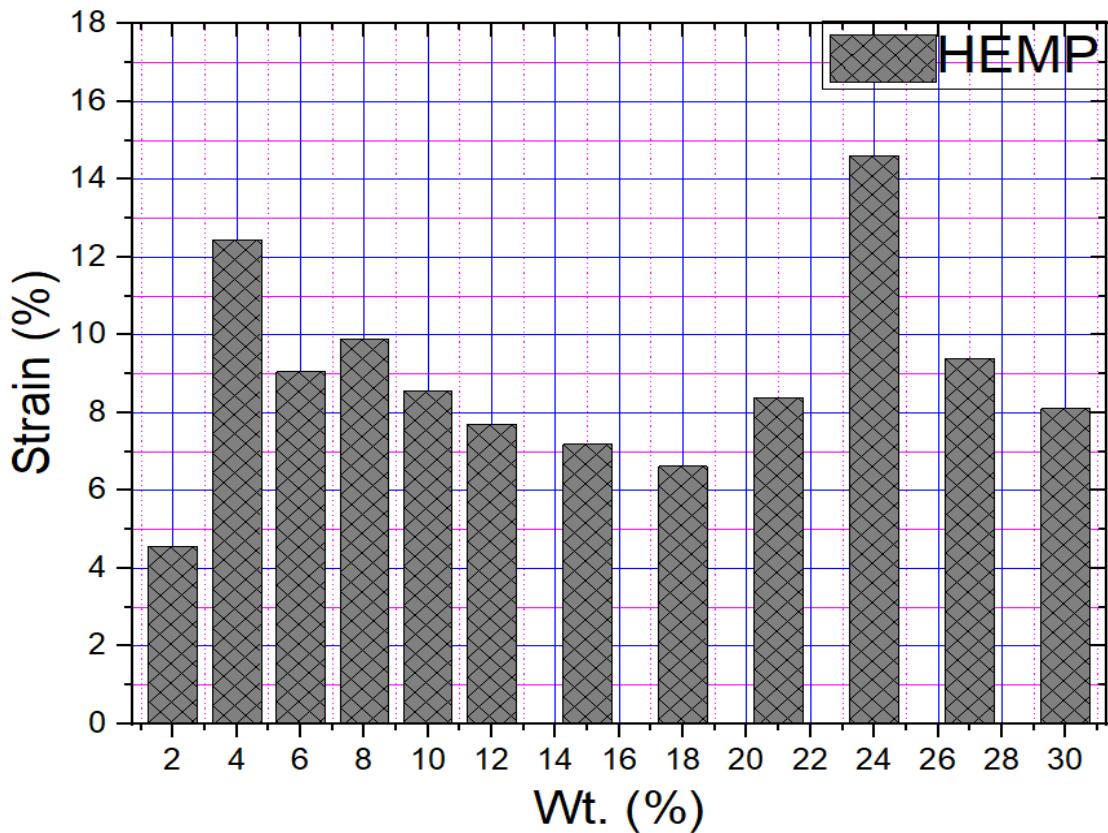


Figure 4.24 Elongation at failure

4.2 Fractography of Tensile Tested Samples

4.2.1 Resin Hardener Polymer

The figure provides detailed images of the fracture characteristics of a polymer composite made from resin AW 106 and hardener HV953 in a 100:95 ratio. In the first image figure 4.25(a), at a lower magnification (46x), the overall fracture surface is visible, showing a rough texture with some large voids and micro-cracks. These voids indicate the presence of weak regions within the composite, where the resin and hardener mixture may not have bonded fully, leading to areas of low strength. The second image 4.25(b) zooms in at a magnification of 500x, where more detailed features such as smaller voids and cracks become apparent. These features suggest localized regions where the polymer matrix has undergone microfracture, further contributing to the composite's overall failure. In the third image 4.25(c), at a magnification of 1000x, the surface shows a mixture of large and small voids, along with debris from broken polymer fragments. This indicates that the composite experienced significant plastic deformation before fracture, with the hardener possibly contributing to the brittleness of the material in these regions. Finally, the fourth image 4.25(d), magnified to 2500x, reveals the

fine details of the fracture, showcasing sharp edges, brittle fractures, and evidence of delamination between layers. The presence of these brittle features implies that the composite's failure was driven by a combination of poor adhesion between the resin and hardener components, as well as possible overloading of the material, leading to a catastrophic failure at the microstructural level. These images collectively provide insight into how the material's fracture behavior is influenced by the resin-to-hardener ratio, highlighting areas of weakness that may need to be addressed to improve the composite's mechanical properties.

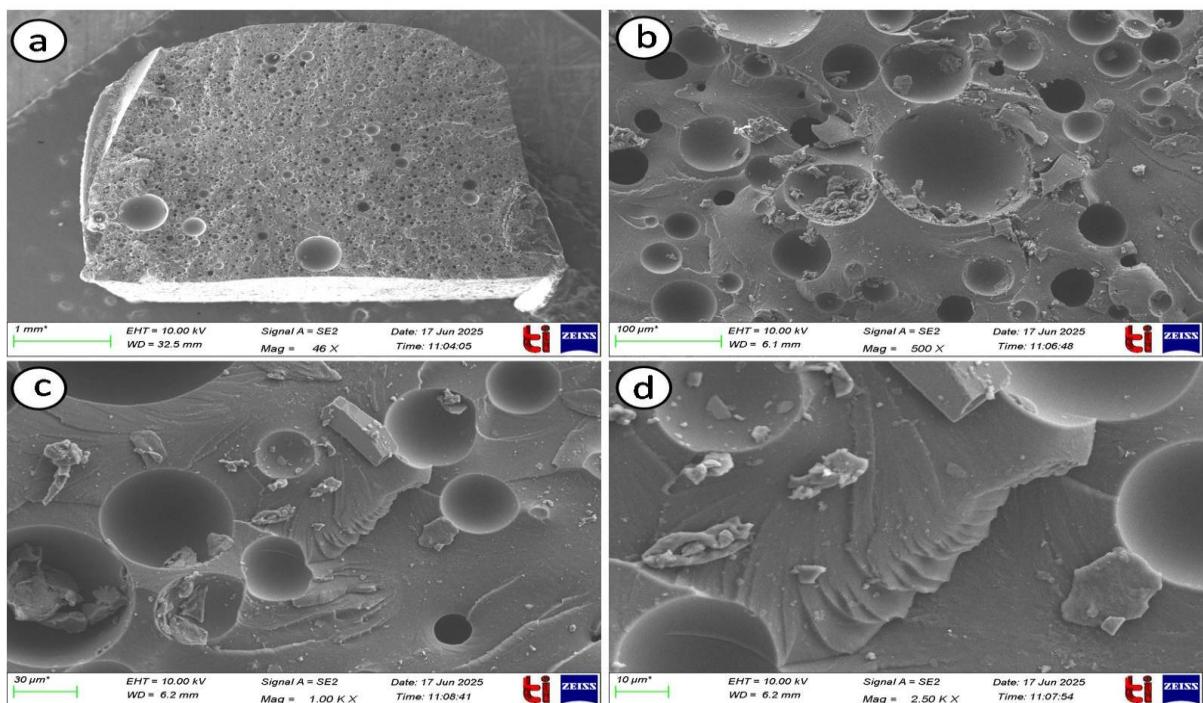


Figure 4.25 Fracture surfaces of resin hardener polymer

4.2.2 Rice Straw Reinforced Polymer Composite

The figure displays the fracture characteristics of a polymer composite reinforced with 5% rice straw, made from resin AW 106 and hardener HV953. In the first image 4.26(a), captured at a magnification of 46x, the fracture surface of the composite is observed, showing the presence of rice straw particles that are well-distributed throughout the polymer matrix. There are areas with voids around the rice straw particles, suggesting that the interaction between the resin and the rice straw is not entirely optimal, leading to weak points where cracks can initiate. The second image 4.26(b), taken at a magnification of 500x, zooms in on the surface, highlighting cracks propagating along and around the rice straw particles. This indicates that the rice straw may act as a stress concentrator, which leads to crack formation at the interface between the

particles and the polymer matrix. At the 1000x magnification in image 4.26(c), the fracture becomes more detailed, revealing significant crack propagation and a fractured surface that shows some brittle characteristics, particularly where the rice straw particles are embedded. These fractures likely originate from the weak bond between the rice straw and the matrix, which exacerbates the composite's susceptibility to failure under stress. In the final image 4.26(d), taken at 2000x magnification, the fine details of the fracture surface reveal deeper cracks and delamination occurring along the interface between the rice straw and the resin. These features further indicate that while the rice straw may reinforce the material, it also creates areas of weakness due to imperfect bonding with the resin. Overall, these images illustrate that the addition of 5% rice straw to the polymer composite influences the material's fracture behavior by providing reinforcement, but also introduces sites where cracks can develop, leading to a brittle failure mechanism.

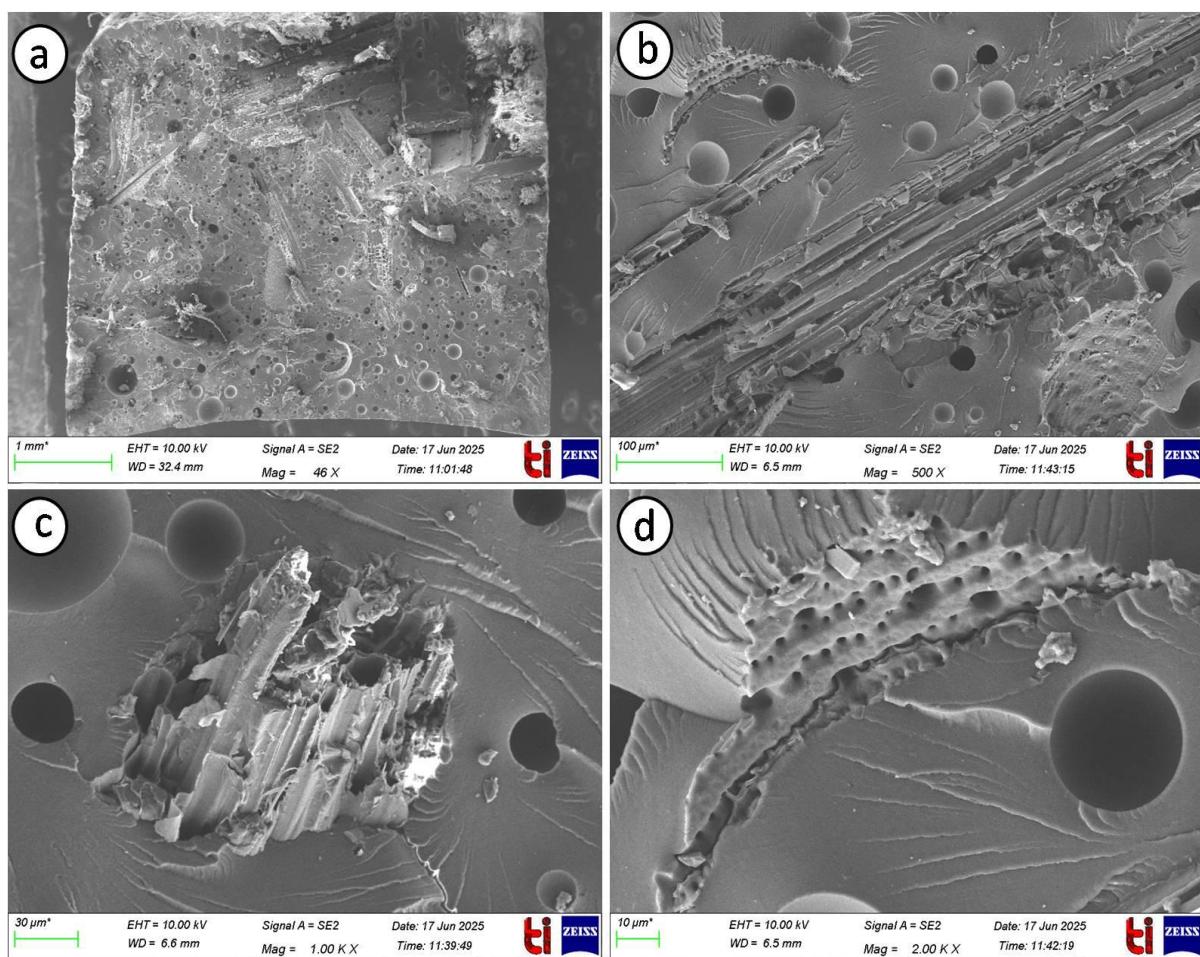


Figure 4.26 Fracture surfaces of rice straw reinforced polymer composite

4.2.3 Jute Reinforced Polymer Composite

The images above show the fracture characteristics of jute fiber-reinforced composite samples made with hardener HV 953 IN and resin AW 106 IN. Captured using scanning electron microscopy (SEM) at different magnifications, these images provide detailed insights into how the jute fibers interact with the resin matrix during fracture.

In image 4.27(a), at a magnification of 200x, the fractured surface reveals exposed jute fibers surrounded by areas of rough resin and voids. These voids indicate regions where the resin may not have properly bonded with the fibers, potentially creating weak points in the composite material. In image 4.27(b), at a magnification of 500x, the fibers are more clearly visible, with some fibers partially pulled out of the resin matrix. This suggests that the resin did not provide a strong enough bond to the fibers, causing the fibers to detach under stress.

Image 4.27(c), captured at a magnification of 750x, shows further details of the interaction between the fibers and the resin. The surface reveals cracks and voids around the fibers, indicating failure in the resin matrix. This suggests that the matrix could not support the fibers sufficiently, resulting in localized matrix failure. In image 4.27(d), at the highest magnification of 2,000x, the individual jute fibers show clear signs of breakage, and the surrounding resin matrix exhibits localized cracking. This indicates that the composite's failure was caused by both fiber fracture and resin matrix breakdown.

These SEM images indicate that the jute fiber-reinforced composite exhibits weak bonding between the fibers and the resin, leading to fiber pull-out, cracking, and eventual fracture. Strengthening the bond between the fibers and resin would likely improve the material's mechanical properties and overall durability.

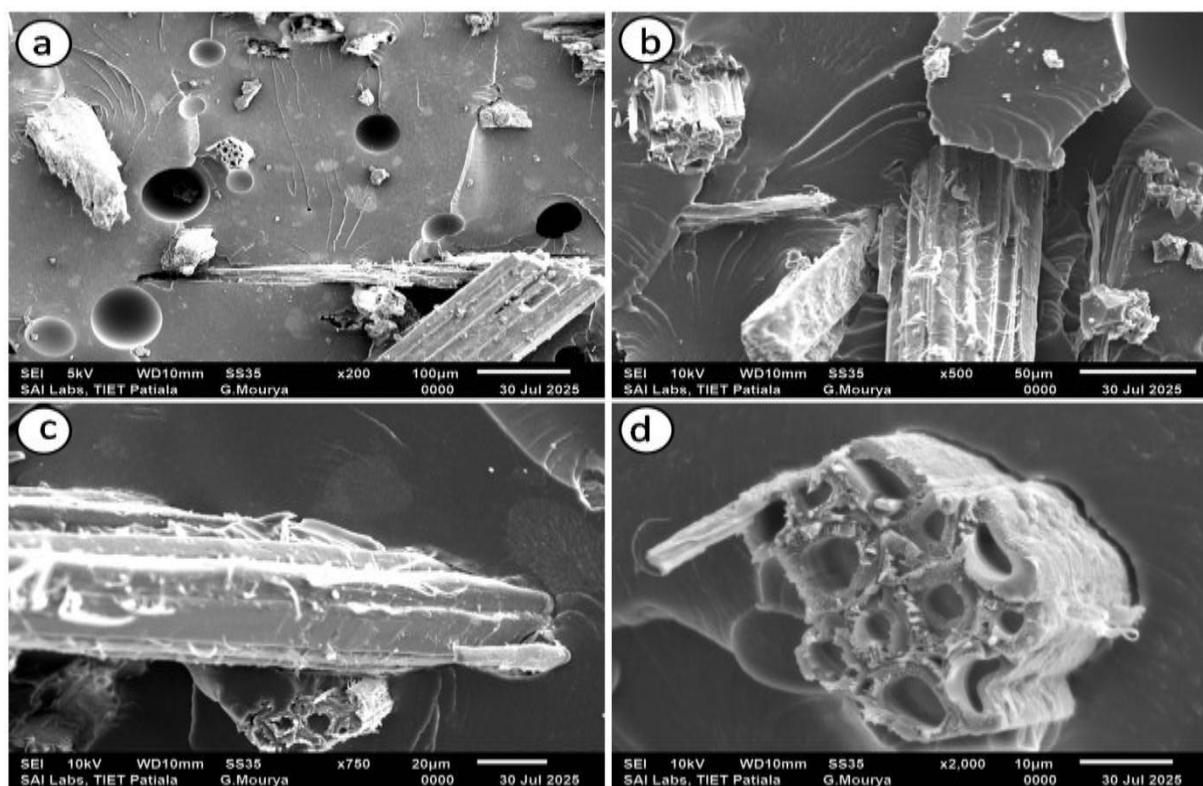


Figure 4.27 Fracture surfaces of jute reinforced polymer composite

4.2.4 Banana Fiber Reinforced Polymer Composite

The images above show the fracture characteristics of banana fiber-reinforced composite samples made with hardener HV 953 IN and resin AW 106 IN. Captured using scanning electron microscopy (SEM) at various magnifications, these images provide detailed insights into the material's fracture behavior and the interaction between the banana fibers and the resin matrix.

In image 4.28(a), at a magnification of 200x, the fractured surface reveals exposed banana fibers embedded in a rough resin matrix. There are noticeable voids and regions where the resin has failed to properly bond with the fibers, creating weak points that may cause the composite to fail under stress. In image 4.28(b), taken at a magnification of 500x, the fibers are more clearly visible, with some fibers showing signs of partial pull-out from the matrix. This suggests that the bond between the banana fibers and resin is not strong enough, leading to separation of the fibers when subjected to stress.

Image 4.28(c), captured at a magnification of 750x, shows further details of the interaction between the fibers and resin. Larger voids and cracks are visible around the fibers, indicating

that the resin matrix has not provided adequate support. These cracks are likely a result of poor adhesion between the resin and fibers, which leads to matrix failure and compromises the composite's strength. Finally, in image 4.28(d), at the highest magnification of 2,000x, individual banana fibers are shown to have broken or fractured, with surrounding resin displaying localized cracking. These fractures indicate that both the fibers and matrix have failed, with the weak bonding between the resin and the banana fibers being a key factor in the material's overall weakness.

In conclusion, these SEM images show that the banana fiber-reinforced composite made with hardener HV 953 IN and resin AW 106 IN exhibits weak bonding between the fibers and the resin. This weak bond leads to fiber pull-out, matrix cracking, and eventual fiber fracture. Strengthening the interfacial bonding between the fibers and resin could significantly improve the composite's overall mechanical properties and durability.

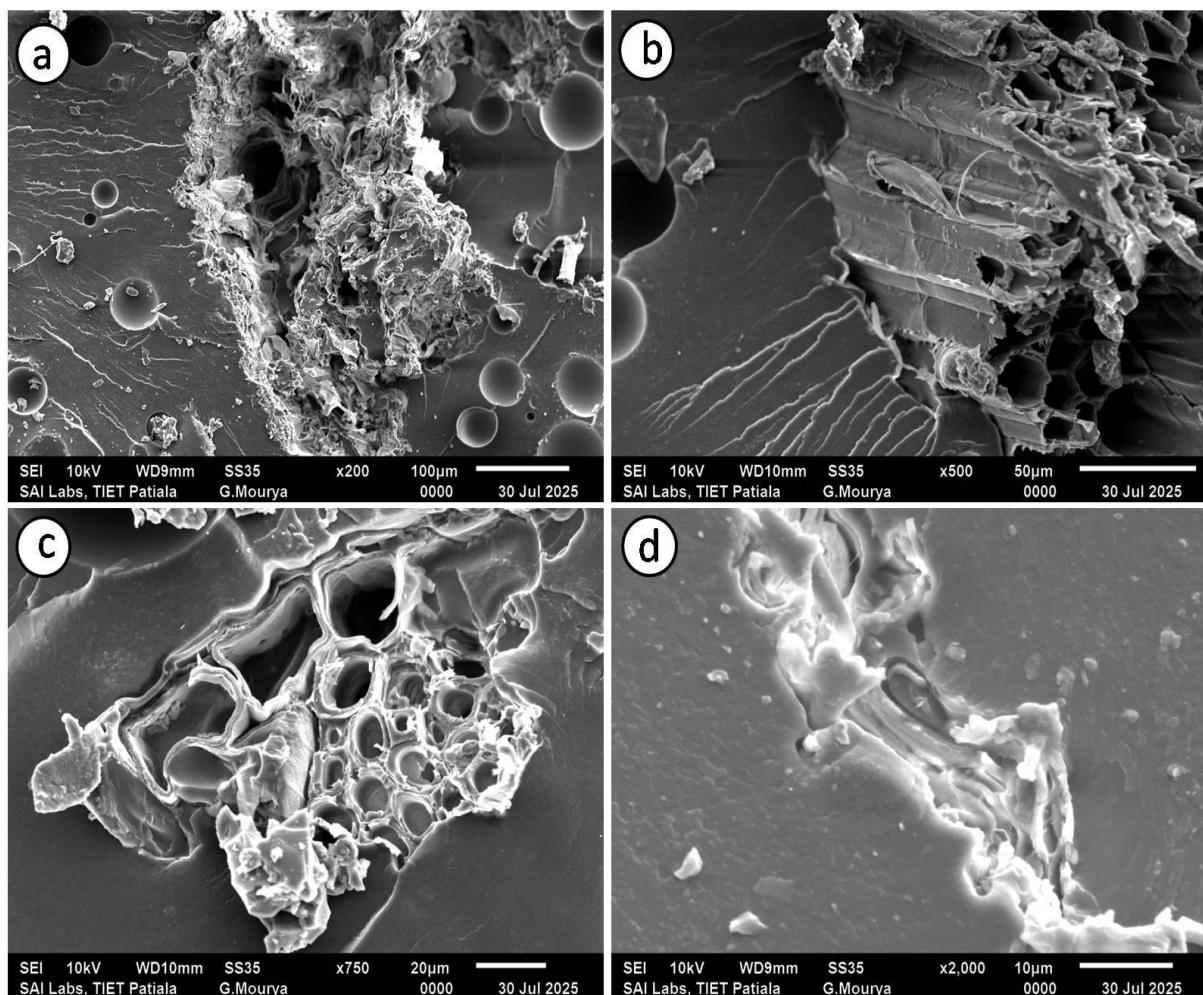


Figure 4.28 Fracture surfaces of banana fiber reinforced polymer composite

4.2.5 Abaca Reinforced Polymer Composite

The images above display the fracture characteristics of abaca fiber-reinforced composite samples made with hardener HV 953 IN and resin AW 106 IN. These images, captured using scanning electron microscopy (SEM) at various magnifications, provide detailed insights into the material's fracture behavior and the interaction between the abaca fibers and resin matrix.

In image 4.29(a), at a magnification of 200x, the fractured surface reveals exposed abaca fibers surrounded by rough, fragmented resin areas, along with visible voids. These voids suggest incomplete bonding between the resin and fibers, which may lead to weak spots within the composite material. Image 4.29(b), taken at 500x magnification, shows a closer look at the fracture, with some fibers appearing to be partially pulled out of the resin matrix. This indicates that the bond between the abaca fibers and the resin is insufficient to maintain structural integrity under stress.

In image 4.29(c), at 750x magnification, the interaction between the fibers and the resin matrix becomes more apparent, with larger voids and cracks visible around the fibers. These signs of matrix failure suggest that the resin did not fully support the fibers, leading to localized fracture and weakness in the composite. Finally, image 4.29(d), at the highest magnification of 2,200x, shows the individual fibers in greater detail. These fibers exhibit breakage and the surrounding resin matrix shows signs of cracking. This indicates that the failure is not only due to poor bonding but also involves the mechanical failure of the fibers and matrix under stress.

In conclusion, the SEM images highlight that the composite material made with abaca fibers, HV 953 IN hardener, and AW 106 IN resin exhibits weak interfacial bonding between the fibers and the resin. This weak bonding leads to fiber pull-out, matrix cracking, and eventual fiber breakage, limiting the material's overall strength. Improving the adhesion between the fibers and the resin would likely enhance the mechanical performance and durability of the composite.

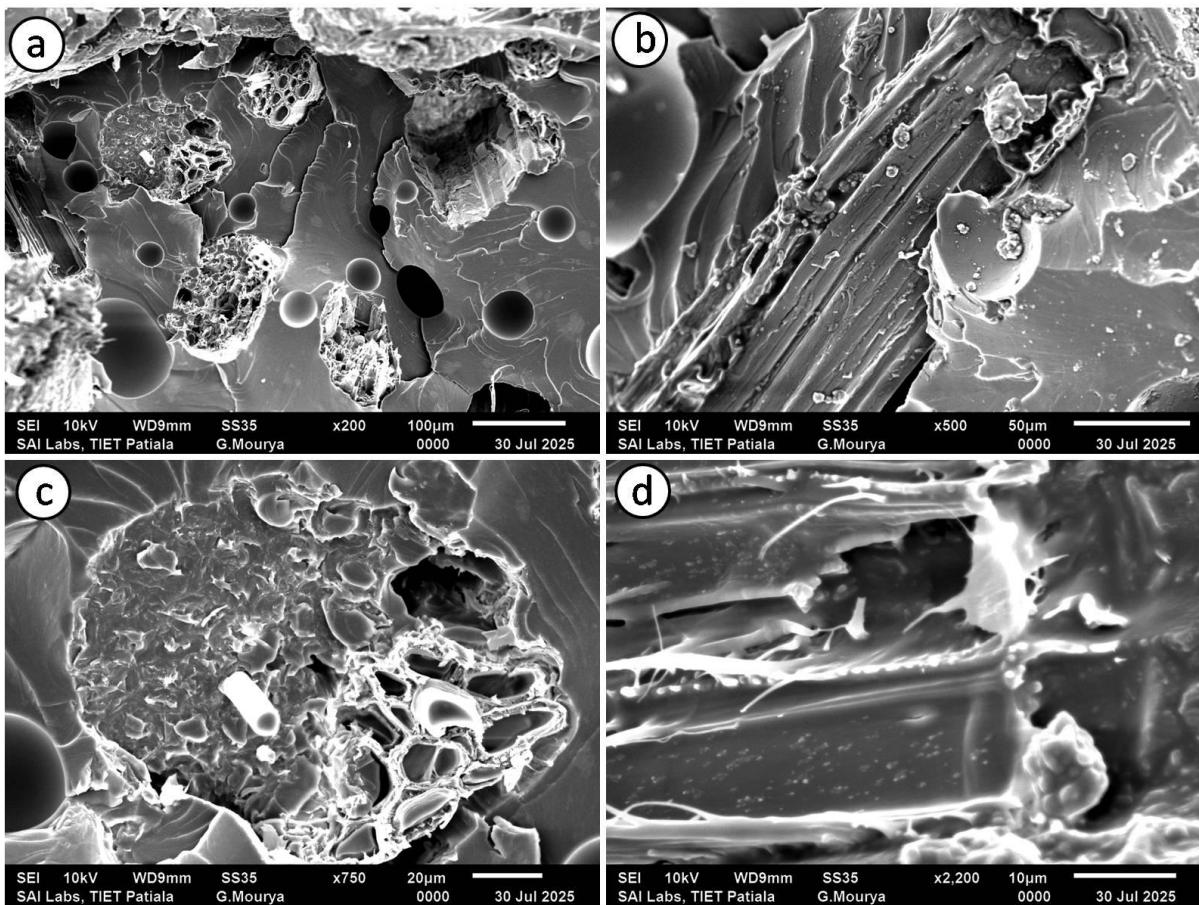


Figure 4.29 Fracture surfaces of abaca reinforced polymer composite

4.2.6 Hemp Reinforced Polymer Composite

The images above show the fracture characteristics of hemp fiber-reinforced composite samples made with hardener HV 953 IN and resin AW 106 IN. These images, captured using scanning electron microscopy (SEM) at different magnifications, reveal valuable insights into the material's fracture behavior and the interaction between the hemp fibers and resin matrix.

In image 4.30(a), taken at a magnification of 200x, the fractured surface shows exposed hemp fibers within the resin matrix, with visible voids and rough areas around the fibers. These voids suggest incomplete bonding between the resin and fibers, leading to potential weak points within the composite. In image 4.30(b), at 500x magnification, the fibers appear more clearly, with some fibers partially pulled out of the matrix. This indicates that the resin did not sufficiently bond with the hemp fibers, allowing them to detach under stress, a common failure mode in fiber-reinforced composites.

In image 4.30(c), at 750x magnification, further details of the fiber-matrix interaction are visible. The resin matrix shows signs of cracking and void formation around the fibers, indicating that the material experienced localized failure. This suggests that the bonding between the resin and fibers was not strong enough to prevent the formation of cracks, which could reduce the composite's overall strength. Finally, in image 4.30(d), at the highest magnification of 2,000x, the individual hemp fibers are shown to have fractured, with the surrounding resin matrix displaying localized cracking. This fracture behavior points to the weakness in the fiber-matrix interface, where poor bonding contributed to both fiber and resin failure.

Overall, these SEM images reveal that the hemp fiber-reinforced composite made with HV 953 IN hardener and AW 106 IN resin exhibits weak bonding between the hemp fibers and the resin, leading to fiber pull-out, matrix cracking, and fiber fracture. Improving the interfacial bonding between the fibers and resin could significantly enhance the mechanical properties and durability of the composite.

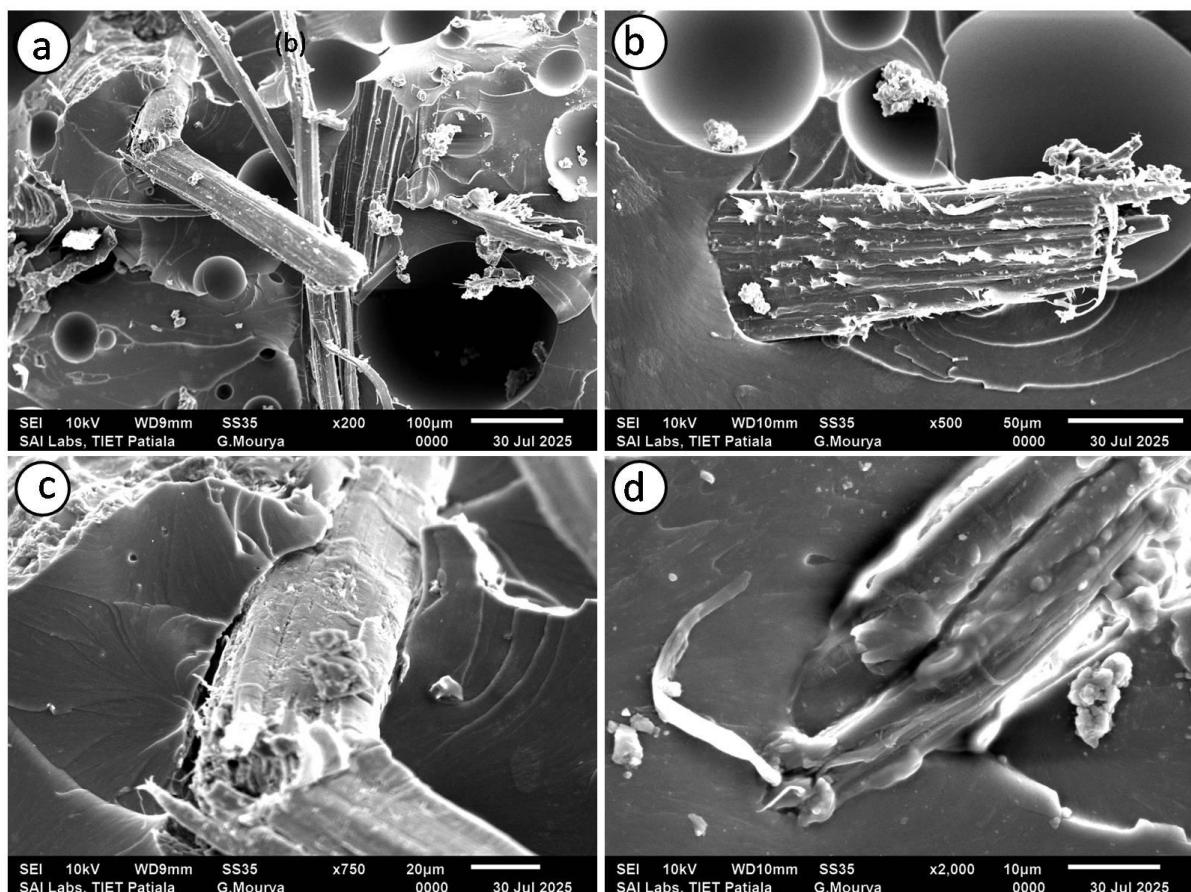


Figure 4.30 Fracture surfaces of hemp reinforced polymer composite

5.1 Conclusion

5.1.1 Resin Hardener Polymer

The data indicates that the ratio of 10:8 results in the highest strength value, demonstrating the optimal combination of resin and hardener for achieving maximum strength. As the ratio decreases from 10:8 to 10:9.5, the strength values generally decrease as well, suggesting that higher proportions of resin relative to hardener lead to a stronger composite. This trend highlights the importance of the resin-harder ratio in determining the mechanical properties of the material, with a balanced ratio leading to the best performance. Overall, the results suggest that carefully selecting the resin-to-hardener ratio is critical in optimizing the strength of polymer composites.

5.1.2 Rice Straw Reinforced Polymer Composite

It is evident that the composite's strength increases as the amount of rice straw increases up to 12% by weight, where the strength reaches its highest value of around 50 MPa. Beyond this point, as the rice straw content continues to rise, the strength values sharply decline, particularly after 20% weight, indicating that excessive rice straw content leads to a decrease in the composite's mechanical strength. The decrease in strength at higher rice straw content may be attributed to poor bonding between the rice straw and the resin matrix, resulting in weaker interfaces and reduced overall material integrity. These findings suggest that there is an optimal rice straw content around 12% by weight for achieving the best performance in terms of strength, while higher amounts reduce the composite's effectiveness.

5.1.3 Jute Reinforced Polymer Composite

The results show that the strength increases steadily as the jute content rises, peaking at 12.5% and 15% by weight, where the strength remains consistently high, close to 50 MPa. However, at higher concentrations of jute, specifically at 20%, the strength significantly drops, indicating that excessive jute content leads to a decrease in the composite's strength. This decline could be due to poor interaction between the jute fibers and the resin matrix at higher loadings, resulting in weak points that fail under stress. These findings suggest that an optimal jute content exists around 12.5% to 15% by weight for achieving the highest strength in the

composite, with further increases in jute content negatively impacting the material's performance.

5.1.4 Banana Fiber Reinforced Polymer Composite

The results show that as the banana fiber content increases, the strength generally rises, reaching its peak at 12% by weight, where the composite demonstrates the highest strength of nearly 90 MPa. Between 2% and 12%, there is a steady increase in strength, indicating that banana fibers effectively reinforce the polymer matrix up to a certain limit. However, after 12%, the strength values start to level off and then decrease significantly beyond 20%. At higher banana fiber contents, particularly at 30%, the strength drops sharply, suggesting that excessive fiber loading may disrupt the matrix structure or create weak points, thus reducing the overall strength of the composite. These findings highlight that an optimal banana fiber content exists around 12% by weight for maximum strength, and further increases beyond this point can lead to diminishing returns in terms of the composite's mechanical performance.

5.1.5 Abaca Reinforced Polymer Composite

The strength values increase as the fiber content rises, with a notable peak at 10% by weight, where the composite reaches the highest strength of over 100 MPa. Between 2% and 10%, the material exhibits a steady increase in strength, suggesting that the abaca fibers significantly enhance the mechanical properties of the composite. However, beyond 10%, the strength starts to plateau and then declines sharply at higher fiber content, especially at 20% and beyond. This drop in strength at higher fiber concentrations could indicate that excess fiber loading leads to poor fiber-matrix bonding or causes structural inconsistencies, ultimately reducing the composite's overall strength. The results suggest that the optimal fiber content for achieving the best mechanical performance is around 10%, beyond which further increases in fiber content negatively impact the material's strength.

5.1.6 Hemp Reinforced Polymer Composite

The results demonstrate that as the hemp content increases, the composite's strength generally rises, with a notable peak at 20% hemp content. At this point, the strength reaches its highest value of approximately 70 MPa. Beyond 20%, the strength starts to decrease, particularly at 30%, where the material shows a sharp drop in strength. This decline could indicate that excessive hemp fiber content disrupts the fiber-matrix bonding or causes structural inconsistencies, reducing the composite's overall strength. The data suggests that hemp content

of around 20% provides the best balance between reinforcement and material integrity, offering the highest mechanical performance, while higher fiber content leads to diminishing returns.

5.2 Future Work

Future work on natural fiber reinforced composites (NFRCs) that use powdered fibers from jute, banana, rice straw, abaca, and hemp holds significant potential for improving the performance and sustainability of polymer materials. The use of powdered natural fibers as fillers in composites could help enhance mechanical properties such as tensile strength, impact resistance, and thermal stability. One critical aspect of future research is the effective dispersion of these powdered fibers within the polymer matrix. Achieving uniform distribution is crucial for consistent composite performance, and exploring advanced processing techniques such as extrusion, melt compounding, or even 3D printing could optimize fiber integration.

Additionally, improving the bond between the natural fibers and the polymer matrix is essential for maximizing the composite's strength and durability. Research into fiber surface treatments like chemical modifications or plasma treatment could improve this bond, preventing issues like fiber pull-out and enhancing the overall mechanical properties.

The development of hybrid fiber composites using different natural fibers could also be an area of exploration. Combining powders from fibers like jute and banana, or rice straw and hemp, may create materials that offer a balance of strength, flexibility, and toughness, catering to specific application requirements such as in the automotive or construction industries. Such hybrid materials could take full advantage of the unique properties of each fiber, resulting in composites with enhanced overall performance.

In addition to mechanical improvements, future research should focus on the sustainability aspect of natural fiber composites. The integration of biodegradable matrices or eco-friendly resins could lead to completely sustainable composites that are both strong and environmentally friendly. Investigating ways to improve the recycling process and the end-of-life management of these composites will be important for reducing their environmental impact.

Another area of future work is the enhancement of the thermal properties of these composites. Different natural fibers will likely affect the heat resistance and fire-retardant qualities of the composites in unique ways, and identifying how to improve these properties could open up new applications for these materials in heat-sensitive industries.

Finally, scaling up production processes is essential for the widespread application of powdered natural fiber composites. Transitioning from laboratory-scale research to large-scale manufacturing will require solving challenges related to cost-effectiveness, consistency in quality, and feasibility for industrial use. As processing techniques advance, these composites could find commercial applications in fields like packaging, automotive, and construction.

In summary, the future of natural fiber reinforced composites, particularly those incorporating powdered fibers from materials like jute, banana, rice straw, abaca, and hemp, offers exciting possibilities. With continued research focused on improving processing methods, fiber-matrix bonding, hybrid systems, and sustainability, these materials have the potential to become an integral part of the next generation of eco-friendly, high-performance composites.

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