Addis Ababa University

Addis Ababa Institute of Technology

School of Graduate Studies

School Of Mechanical And Industrial Engineering

Investigation of Mechanical Characteristics of Woven Glass-Sisal Hybrid Composites

By:

Temkin Abdulkader Mehammud

Advisor: Dr. Mulugeta H.

A thesis submitted to the School of Mechanical and Industrial Engineering in partial fulfillment of the Degree of Master of Science in Mechanical Engineering (Mechanical Design)

December 2024

Addis Ababa Ethiopia

ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF MECHANICAL AND INDUSTRIAL ENGINEERING

DESIGN STREAM

MECHANICAL AND ENERGY ABSORPTION CHARACTERISTICS OF WOVEN GLASS-SISAL HYBRID COMPOSITES

Submitted by: TEMKIN ABDULKADER

Approved by the Board of Examiners:

Mulugeta Habtemariam (Ph.D.) ____________ ______

Advisor Date Signature

Araya Abera (Ph.D.) ____________

Internal Examiner Date Signature

Behailu Mamo ______

______

External Examiner Date Signature

Abdulkadir Aman (Ph.D.) ______

______

School Dean Date Signature

Declaration

I hereby declare that the work which is being presented in this thesis entitled "Mechanical and Energy Absorption Characteristics of Woven Glass-Sisal Hybrid Composites" is original work of my own, has not been presented for a degree of any other university and all the resource of materials used for this thesis have been duly acknowledged.

Temkin Abdulkader ____________________ _________________________

Signature Date

This is to certify that the above declaration made by the candidate is correct to the best of my knowledge.

Dr. Mulugeta H. ____________________ _________________________

Signature Date

ACKNOWLEDGEMENT

I would like to express my deepest gratitude to my advisor, Dr. Mulugeta H/Mariam, for his invaluable guidance, support, and patience throughout the research process. His mentorship was instrumental in the successful completion of this work.

I would also like to thank Mr. Yemanehbirhan Emiru, the research assistant and laboratory manager at the Central Laboratory of Addis Ababa Science and Technology University, for his continuous assistance during the experimental work. His help in managing the testing process and providing technical support was essential to this research.

My appreciation extends to the AAiT Mechanical Workshop, where I prepared my samples, for facilitating access to equipment and providing a conducive environment for the fabrication and testing of the composites.

Finally, I would like to thank those who encouraged me and showed me unwavering support throughout this journey.

ABSTRACT

Due to their ability to combine the advantages of both natural and synthetic fibers there has been a growing interest in hybrid fiber composites. These materials can improve mechanical properties while maintaining the benefits of natural fiber use. This research investigated the mechanical behavior and energy absorption characteristics of 2x2 twill woven sisal-glass hybrid epoxy composites focusing on interply and intraply configurations. Primarily the study aimed to evaluate the effect of hybrid configuration on tensile, compressive, shear, and quasi-static penetration properties compared to pure glass and sisal composites. Composites of pure sisal, pure glass, inteply, and intraply hybrid configurations were fabricated using a hand lay-up technique, with sisal fibers treated with 5% NaOH solution. A total of 80 samples, 5 for each test of each configuration, were tested following ASTM standards: D3039 for tensile, D695 for compressive, D3518 for shear, and D6264 for quasi-static penetration.

The pure glass composite exhibited the highest tensile strength (206.65 MPa) and compressive strength (181.82 MPa), while the pure sisal composite had the lowest values in both categories (55.89 MPa and 30.91 MPa, respectively). The intraply hybrid showed superior tensile (121.75 MPa) and compressive strength (92.76 MPa) compared to the interply configuration. Shear tests revealed a maximum shear strength of 22.12 MPa for the glass composite, with the intraply hybrid showing better performance (19.1 MPa) than the interply (17.2 MPa). In quasi-static penetration tests, the intraply hybrid absorbed the most energy (22.17 J) next to pure glass (26.97J), while the interply configuration absorbed slightly less (19.68 J) but exhibited higher punch shear strength (14.9 MPa) due to its layered structure.

These results demonstrated that hybridization, particularly in the intraply configuration, enhances energy absorption and mechanical performance compared to interply hybrid composites. The findings suggest that sisal-glass hybrid composites with intraply configuration could be suitable for lightweight structural applications where both strength and energy absorption are critical.

Key words: Interply Hybrid, Intraply Hybrid, 2X2 Twill Weave, Energy Absorption, Tensile Strength, compressive Strength, Shear Strength, Quasi-static Penetration, Punch shear strength

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

ASTM – American Society for Testing and Materials

CFRPC- Carbon Fiber Reinforced Polymer Composite

CMC- Ceramic Matix Composite

FRP – Fiber Reinforced Polymer

LCA – Life Cycle Assessment

MMC- Metal Matrix Composite

NaOH – Sodium Hydroxide

NFRPC- Natural Fiber Reinforced Polymer Composite

PMC – Polymer Matrix Composite

PSS – Punch Shear Strength

PMC- Polymer Matrix Composite

QSPT- Quasi-static Penetration Test

UTS- Ultimate Tensile Stress

CHAPTER ONE
INTRODUCTION

1.1. Background of the Study

The discovery of plastics by scientists marked the emergence of fiber-reinforced polymer composites (FRPC), which constitute strong networks of fibers as reinforcement and polymer matrix [1-3]. Composite materials are becoming increasingly popular in engineering and industrial applications due to their enhanced mechanical properties like strength, stiffness, and low-density owing to the addition of multiple distinct materials. Fiber reinforced polymer composites (FRPC), which are produced from either synthetic (e.g glass) or natural (e.g sisal) fibers, are one group of composites that have been extensively used due to their very high strength to weight ratio. FRPC has been widely used in various application areas [2, 4, 5]. They possess ease of production and unique flexibility in design capability [6].

Natural fibers are widely available, renewable, cost-effectiveness, biodegradable and have high specific properties [1, 7]. However, when used in structural applications its relatively low mechanical performance compared to synthetic fibers poses a challenge. Synthetic fibers on the other hand are used extensively as reinforcements for composites owing to their superior mechanical properties in numerous applications which require high strength and stiffness [1, 5, 8]. However, they are none recyclable, non-biodegradable, expensive to produce, and cause intense stress on the environment [1, 9].

One way of compensating for weaknesses of natural fiber is hybridizing with synthetic fibers into a single matrix [10]. The fibers can be arranged in various configurations, such as interply (alternating layers of different fiber types) or intraply (mixed fibers within the same layer) Hybrid composite materials can be prepared from two or more natural, synthetic fibers or with a mixing of both fibers [11]. Hybridization of natural fibers such as sisal with synthetic fibers like glass in hybrid composites benefits largely from the synergistic effect of the constituents and thereby an optimal and economical composite can be obtained through a compromise among environmental friendliness, material cost, and material properties [10, 12-14].

Hybrid composites reinforced with woven fabrics, while offering a balance of tensile strength, resistance to impact, and overall durability, are especially versatile. Among all the fabric types used in composite laminates, 2x2 twill fabrics are among the most common because of their superior drapeability and resistance to shear forces. This is because such a weave pattern permits more uniform distribution of stress, thereby producing better structural performance in laminated composites [15]. In the case of composite having natural fiber, the use of woven structures provides an opportunity to improve the interfacial bonding and stress distribution within the laminate [16]. Moreover, woven glass fibers introduction has been reported to reduce damage severity and make it more penetration resistant [17].

A range of tests are required to evaluate the mechanical performance of hybrid composites including tensile, compressive, in-plane shear, and quasi-static penetration tests. The tests provide critical insights into load-bearing capacity of the composite, stiffness, and failure mechanisms which are important to characterize the composite. Tensile and compressive tests are crucial for determining the strength and modulus of the composite, while in-plane shear tests evaluate the material's ability to resist intralaminar deformation and sliding force. The rest is essential for understanding the energy absorption and damage resistance of the composites.

Even though there are numerous studies conducted on hybrid composites, there are still gaps particularly regarding the comparative performance of hybrid with a configuration of intraply and interply hybridizations. In addition, there is a limited data on the quasi-static penetration and drop-weight impact behavior of these materials, which are crucial for assessing their potential in numerous applications.

This study addressed these gaps by evaluating the tensile, compressive, shear, and quasi-static penetration properties of 2x2 twill woven sisal, glass, and sisal-glass hybrid epoxy composites. The study made comparisons of mechanical properties and energy absorption of the laminates to determine the most effective material. The influence of hybridization on the mechanical properties and energy absorption of these materials is also insighted.

1.2. Statement of The Problem

Hybrid composites of natural fibers like sisal with synthetic fibers like glass have shown improvement in mechanical properties while addressing environmental issues. But the full potential of sisal-glass hybrid composites is yet to be explored. Limited studies have investigated how fiber architecture (2x2 twill weave pattern) affects the mechanical behavior (performance) and energy absorption of hybrid composites. Up to the understanding of the researcher the performance of intraply and interply hybrid fiber configuration under different loading conditions is not well understood.

Hybrid composites are known to improve some mechanical properties compared to natural fiber composites but there is no data on how sisal-glass hybrids with different hybrid configurations and fiber architectures perform under shear and quasi-static penetration. Understanding how these composites behave under such conditions is vital for their use in critical applications where materials are often subjected to a range of complex loads such as shear force and impact with a low velocity require both strength and energy absorption.

As far as the researcher's understanding the role of hybridization under different configurations and fiber arrangements in improving mechanical performance (properties) and energy absorption is not well characterized. Filling these gaps can provide valuable information on applying sisal-glass hybrid composites for lightweight, high-performance applications.

This research filled these gaps by experimentally investigating the tensile, compressive, shear, and quasi-static penetration of 2x2 twill woven glass-sisal hybrid epoxy composites. By comparing the performance of pure sisal, pure glass, and hybrid configurations, both interply and intraply, this study provided useful insights into improving the mechanical properties (performance) and energy absorption of hybrid composites for practical applications.

1.3. Objective of The Study

1.3.1. General Objective

The main objective of this study is to experimentally investigate the tensile, compressive, shear, and quasi-static penetration performances of interplay and intraply woven sisal/glass hybrid epoxy composite and evaluate their performance in comparison to pure glass-epoxy and pure sisal-epoxy composites.

1.3.2. Specific Objectives

Significantly, this study has the following specific objectives:

- To investigate the tensile strength, modulus, and elongation at break of 2x2 twill woven glass-epoxy, sisal-epoxy, and glass-sisal hybrid epoxy composites using tensile tests (ASTM D3039).
- To assess the compressive strength and deformation behavior of the composite laminates using compressive tests (ASTM D695).
- To evaluate the shear strength of the composite laminates using shear tests (ASTM D3518) for each configuration.
- To analyze the resistance of the composite laminates to localized damage and energy absorption through quasi-static penetration tests (ASTM D6264).

1.4. Significance of The Study

This study provides a valuable and deep understanding of the mechanical performance (properties) and energy absorption behavior of hybrid composites made from natural and synthetic fibers. Hybridization of sisal and glass fibers offers a promising solution to the challenges caused by the pure synthetic fiber composites. This study is significant in exploring the mechanical properties of sisal-glass hybrid composites, including tensile, compressive, shear, and quasi-static penetration behaviors, under different configurations.

This study provides a comparative analysis of inter-ply and intra-ply hybrid configurations with pure glass and sisal fiber composite. Through this, it fills the critical gaps in the previous studies and literature. The study contributes to the growing body of knowledge on natural fiber-reinforced composites by offering a deeper understanding of how hybridization and fiber arrangements influence the mechanical properties and energy absorption of the composites. Furthermore, this study supports efforts to promote sustainable material alternatives, potentially leading to increased sisal fiber utilization and economic benefits for agricultural communities engaged in sisal production.

1.5. Scope of the Study

The main focus of this research is investigation of tensile, compressive, shear, and quasi static penetration behavior of a 2x2 twill woven sisal/glass hybrid epoxy composite. The woven fabrics were prepared from a 5% NaOH solution treated sisal and E-glass fibers in 2x2 twill forms. The sisal fiber was treated with NaOH solution for four hours to improve the compatibility of the fiber with the epoxy matrix. The concentration selected based on prior literature demonstrating optimal surface modification without compromising fiber integrity.

The research focused on four composite laminates which were prepared in the form of pure sisal, pure glass, interply hybrid (SGSGSG stacking sequence) and intraply hybrid configuration. The composites were manufactured through the hand layup method using a fiber volume fraction of 40 wt%. A bidirectional 2×2 twill weave was selected because it is easier to work with and offers better shear stress distribution. The mechanical testing performed included: tensile (ASTM D3039), compressive (ASTM D695), in-plane shear (ASTM D3518), and quasi-static penetration (ASTM D6264). All were done under ASTM procedures, and also five replicates per configuration were done to ensure statistical reliability. Important factors were ultimate tensile strength (UTS), compressive strength, shear modulus, strain-at-failure, and energy absorption capacity.

1.6. Limitation of The Study

While this study gives us valuable insights into the mechanical and energy absorption properties of 2×2 twill woven sisal-glass hybrid epoxy composites, there are some theoretical, methodological, empirical and analytical limitations to acknowledge. Theoretically, the lack of a micromechanical model to explain stress transfer mechanisms between sisal and glass fibers limits understanding of load distribution in the hybrid architecture.

Methodologically, the hand lay-up process, although cheap, introduces variability in fiber alignment and resin distribution which may compromise interfacial bonding. The small sample size also limits statistical robustness as the researcher did not perform advanced analyses.

Empirically, the fiber volume fraction (40 wt%) and hybridization ratio (50:50 sisal-glass) were fixed, so the optimal fiber-to-matrix ratio or hybrid composition could not be explored. Microscopy was not used to characterize fiber-matrix interfaces or failure surfaces

1.7. Thesis Organization

This thesis is organized into five chapters, each covering a distinct aspect of the research process and findings:

Chapter One: Introduction: This chapter introduced the background of the study, including the significance of hybrid composites and the focus on sisal-glass woven fibers. It included the problem statement; research objectives; significance of the study; and scope of the research.

Chapter Two: Literature Review: This chapter presented a detailed review of the related literature on composite materials, natural fibers, hybrid composites, and factors affecting their mechanical properties; and previous studies on the energy absorption and mechanical properties of hybrid composites. Research gaps that this thesis aims to address are identified.

Chapter Three: Materials and Methods: This chapter describes the materials used in the study, including sisal and glass fibers, epoxy resin, and sodium hydroxide for chemical treatment. The preparation techniques for the hybrid composites and the experimental setup for the mechanical tests are also covered in this chapter.

Chapter Four: Results and Discussion: The findings of the tensile, compressive, shear, and quasi-static penetration tests of the composite laminates are presented and discussed. This chapter provides a comparative analysis of energy absorption and the mechanical properties of the different hybrid configurations.

Chapter Five: Conclusion and Recommendations: The final chapter summarizes the key findings of the study, offers conclusions based on the experimental results, and provides recommendations for possible future research and practical applications.

CHAPTER TWO

LITERATURE REVIEW

2.1. Fiber-Reinforced Polymer Composites

Fiber-reinforced polymer composites (FRPs) have emerged as among the most promising materials in various industries, including aerospace, automotive, construction, and sports. These composites combine the desirable properties of both the reinforcing fibers and the polymer matrix, resulting in a lightweight, strong, and durable material. The matrix, typically made of thermosetting or thermoplastic polymers, provides the bulk of the material's mechanical properties and bind the reinforcing fibers. [18].

The fibers in FRPC can either be synthetic or natural. Synthetic fibers have been used extensively as reinforcements for composites due to their exclusive mechanical properties in numerous applications which require high strength and stiffness [1, 5, 8]. Moreover, they are hydrophobic, compatible with polymer resins, and corrosion-resistant [10]. However, they cause intense stress on the environment and they are none recyclable, non-biodegradable, and expensive to produce [1, 9]. On the other hand, natural fibers are derived from plants, animals, and minerals [2, 19]. Kenaf, sisal, cane, banana, jute flax, coir, pulp, wood flour, pineapple leaf, and oil palm are the most common natural fibers used for the reinforcement of composite materials [20, 21].

Carbon fibers are widely used in high-performance applications because of their exceptional strength, stiffness, and low weight. On the other hand glass fibers are cost-effective and exhibit excellent corrosion resistance, which make them suitable for a range of applications [22]. Aramid fibers offer a unique combination of high strength, impact resistance, and flexibility. Natural fibers, like flax, hemp, and jute, are gaining popularity in environmentally friendly applications because of their renewable and biodegradable nature[23].

FRP composites offer several advantages over traditional materials such as steel, concrete, and wood [24]. One of the key benefits is their high strength-to-weight ratio, which allows for lightweight structures without compromising on structural integrity [25]. According to Chen, Baehr [25], carbon fiber polymer composites (CFRPC) exhibit a tensile strength up to 10 times higher than steel, while being approximately four times lighter. This exceptional strength-to-weight ratio makes FRP composites highly attractive for applications in aerospace, automotive, and sporting goods industries, where weight reduction is crucial for performance enhancement.

In addition to the impressive strength, FRP composites possess excellent corrosion resistance properties. Unlike traditional materials that may corrode or deteriorate when exposed to harsh environments, FRP composites are highly resistant to corrosion, making them to suit for applications in marine and offshore structures [26]. Alsayed, Al-Salloum [26] demonstrated that glass fiber-reinforced polymer (GFRP) composites exhibit exceptional resistance to both chemical and electrolytic corrosion, making them ideal choice for coastal infrastructure projects.

Furthermore, FRP composites offer design flexibility and customization options [6]. The orientation, type, and volume fraction of the fiber reinforcement can be tailored to meet specific mechanical requirements [27, 28]. By adjusting these parameters, engineers can optimize the mechanical properties of FRPCs to suit the intended application. Rezaei, Seyedhosseini [29] highlighted the ability of customizing the layup of carbon fiber-reinforced polymer laminates, allowing for the tailoring of stiffness and strength properties to achieve desired structural behavior.

Despite their numerous advantages, FRP composites also present challenges that need to be addressed. One of the primary concerns is their susceptibility to impact damage [30]. Safri, Sultan [30] discussed the impact characteristics of hybrid FRP composites and emphasized the need for advanced analysis techniques to accurately predict and mitigate damage caused by impacts. Furthermore, the expensiveness of FRP materials remains a significant hurdle for their widespread adoption in certain industries. However, ongoing research and development efforts are aimed at addressing these challenges and expanding the applications range for FRP composites.

The exceptional mechanical properties and versatility of fiber-reinforced polymer composites led to their extensive utilization in numerous industries. In aerospace, FRPs are used in aircraft structures, contributing to weight reduction and fuel efficiency [22]. For instance, the Boeing

787 Dreamliner extensively employs carbon fiber-reinforced composites, leading to a 20% reduction in fuel consumption compared to conventional aircraft [31].

In automotive applications, FRPs find use in body panels, chassis components, and interior parts. Composites used in automobiles improve crash safety, reduces vehicle weight, and enhances energy efficiency [32]. Luxury car manufacturers like BMW and McLaren have incorporated carbon fiber composites in their vehicles to achieve a perfect balance between performance, safety, and lightweight design.

The construction industry has also embraced FRPCs for infrastructure projects. FRPCs composites have been employed in bridges, reinforcement of concrete structures, and seismic retrofitting. The high strength and corrosion resistance of FRPs offer extended service life, reduced maintenance, and enhanced structural integrity in challenging environments [33].

Moreover, FRPCs have gained prominence in sports equipment, including tennis rackets, golf clubs, and bicycle frames. The lightweight nature of composites provides athletes with increased maneuverability and improved performance [34].

The manufacturing of FRPCs involves several processes, including fiber production, impregnation, lay-up, consolidation, and curing [18]. The fabrication technique according to Rajak, Pagar [18], depends on factors such as the type of fiber, desired mechanical properties, and component complexity.

2.2. Mechanical Properties of NFRPC

Mechanical performances of different NFRPC are performed by various researchers. The energy absorption of a material is measured by the energy amount that the material absorbed under load per a unit area. Betelie, Sinclair [35] investigated the tensile, flexural and impact strength of the sisal-reinforced epoxy composite. They investigated randomly oriented sisal fiber epoxy composites with different fiber weight fractions. Tensile tests showed that the 30% fiber content with (0°, 90°, 90°, 0°) orientation had the highest tensile strength of 85.5 MPa and modulus of 4.43 GPa. Fiber orientation plays a big role in tensile performance. Impact tests showed increase in impact strength with higher fiber content, peaking at 24.5 kJ/m² for 40% random oriented fibers. Results shows the effect of fiber content and alignment on mechanical properties, these composites can be used for automotive interior components. Another study

Maurya, Gupta [36] on the investigation of mechanical properties of randomly oriented 30wt% short sisal fiber composite, which is manufactured by hand lay-up method, reported that the energy absorption increase with the increase in fiber length.

Ratim, Bonnia [37] studied the effect of weaving pattern of kenaf fiber on the mechanical properties of kenaf epoxy composite processed by hand lay-up method. Specimens with mats, twill and plain weave and non-woven fiber structures were tested tensile and energy absorption test. Tensile tests according to ASTM D638 showed that the twill weave structure had the highest tensile strength due to its better interlacing which gave better crimp resistance and load distribution. The mat structure had lower tensile properties due to non crimped and randomly distributed fibers. The study shows that the arrangement of fibers affects the tensile behavior of natural fiber composites. From the energy absorption test results, twill weave pattern showed the highest impact property and there is no significant difference in impact resistance between mat and plain weaves. Similarly Masudur Rahman, Ruhul [38] conducted a comparative study on mechanical properties of plain, twill and basket weave structure of woven jute polypropylene composite. The composites were prepared employing compression molding technique with a constant fiber loading of 40wt%. According to the finding of the impact tests, which is executed according to DINEN ISO 179 standard, basket weave and plain weave jute polypropylene composites showed highest and energy absorption respectively.

A study by Venkatesan and Bhaskar [39] looked into the mechanical properties of abaca-sisal hybrid natural fiber composites using sisal and abaca fibers in an epoxy matrix. Tensile and shear tests were done according to ASTM standards to evaluate the mechanical performance. Results showed that 90° fiber orientation had the highest tensile strength due to optimal fiber alignment and effective load transfer and 0° orientation had the lowest tensile strength. 45° orientation had the highest shear strength due to interlocking between fibers and matrix which helps in better stress distribution. This study showed the effect of fiber orientation on tensile and shear properties of hybrid natural fiber composites.

A comprehensive analysis on the mechanical properties of twill, plain, herringbone weave jute fiber and intra-ply woven jute-banana fiber polyester composite was conducted by Rajesh, Singh [16]. The composite samples were prepared by employing compression molding technique. Tensile and impact tests as per ASTM standards showed that 4 layer jute basket weave composites had higher tensile strength (43.6 MPa) and impact resistance (250 J/m) than other configurations. The improved performance of basket weave composites is due to reduced crimp and efficient load distribution between fibers, herringbone weave had moderate improvement. Intra-ply hybridization with banana fibers further increased tensile properties but was slightly lower than jute basket composites. These results show the importance of fiber architecture and hybridization in natural fiber composites.

2.2.1. Sisal Fiber-Reinforced Polymer Composites

A sisal plant (Agave sisalana) is one of the species of flowering plants under the Agave genus which is native to South and North American tropical and sub-tropical areas [40]. It is a perennial plant that can produce 200-500 rosettes of sword-shaped succulent leaves within 6-9 years then its inflorescences [40-42]. The length of sisal pant leaves ranges from $1.5m$ to $2m$ with thorny edges.

Currently, the sisal plant is largely cultivated in South America, some parts of Asia, and East Africa, special in Brazil, Tanzania, Haiti, India, Indonesia, and Kenya [7, 9]. Sisal plants can grow on almost all soil types and in an arid hot climatic region that often is not suitable for other plants to grow [9, 40]. Its leaves are sandwich structures that contain coarse and hard fibers embedded longitudinally called sisal fibers [43]. According to the report of FAO [44], Ethiopia produced 700 tons of sisal fiber which is next to Tanzania, Kenya, South Africa, and Madagascar.

(A) (B)

Figure 0.1: (A) Sisal plant (B)sisal fiber

Each leaf of the sisal plant contains about $700 - 1400$ sisal fiber bundles, with an approximate length of $0.5 - 1.5m$ and a diameter of $200 - 400\ \mu m$ [9, 41-43]. The sisal fiber represents 4% of the leaf by weight, whereas 0.75% is the cuticle, 87.25% is water, and 8% is dry matter [9, 42].

Even though the amount of chemical composition varies depending on the age and place of growth, sisal fiber is composed of cellulose, lignin, wax, moisture, ash pentosan, and pectin. According to Akram Khan, Guru [45], sisal fiber is composed of wax about 0.9–1.2%, lignin 5-6%, holocellulose 77–85%, cellulose 65–73%, hemicellulose 9–11%, and moisture 9–11%, whereas Favaro, Ganzerli [46] indicated that sisal fiber contains 0.6%–1.1% ash, 7%–9% lignin, 21–24% hemicellulose and 43%–56% cellulose. On the other hand Drzal [47] reported that sisal fiber composed of cellulose around 66–78%, hemicellulose 10–14%, lignin 10–11%, pectin 10%, moisture 10–22%, and wax 2%.

Lignin and hemicellulose make a natural matrix that reinforces the cell wall containing spirally oriented cellulose [9]. Cellulose made crystalline microfibrils that look like slender rods and lignin is a phenolic compound that functions as a structural support plant material [48]. The presence of cellulose in sisal fiber gives the fiber a hydrophilic nature that makes it noncompatible with hydrophobic polymer resins [49]. To overcome this problem the fibers are modified with chemical treatments.

Owing to its lower density, biodegradability, cheaper availability, and higher specific strength, sisal fiber is suitable for composite reinforcement. It is also used for other applications such as twine, string, ropes, yarn, roofing tiles, mats, carpets, and some construction materials [41-43]. Its byproduct is fully biodegradable and it can be used as animal feeds, bio-energy, fertilizer, and ecological housing material [43].

Processing of sisal fiber for composites involves several stages to obtain fibers with desirable properties for use in composite materials. The process includes harvesting the sisal leaves, extraction of fibers, cleaning, drying, and sizing. These steps are crucial for enhancing the fiber's strength, reducing impurities, and improving its compatibility with the matrix material [50].

The first step in the processing of sisal fiber is the harvesting of sisal leaves. Sisal (Agave sisalana) is a plant that grows in arid regions and is primarily cultivated in Brazil, Tanzania, and Kenya. The leaves of the sisal plant contain the fibers that are used for various applications, including composites [51].

Once the sisal leaves are harvested, the next step is the extraction of fibers. The leaves are crushed and beaten to separate the long, fibrous strands from the non-fibrous material. The fiber extraction can be done manually or mechanically. Manual extraction involves a traditional method known as decortication, where the leaves are beaten with a mallet to loosen the fibers. Mechanical extraction methods, such as decorticating machines or mechanical decorticators, can also be used for higher efficiency and larger scale production [52].

After extraction, the sisal fibers go through a cleaning process to remove impurities such as dirt, dust, and other plant residues. This cleaning stage can involve washing the fiber with water for a cleaner fiber and sometimes chemicals to achieve more uniform fiber surface. Chemical treatments clean the fibers, and these treatments involve the use of various substances such as alkali, acetylation, silane, acrylation, benzoylation, malleated coupling agents, permanganate, isocyanates, and more. The purpose of treating the fibers with chemicals is to enhance the bond between the fiber surface and the polymer matrix. This treatment not only alters the fiber surface but also strengthens the fiber. As a result, the composites exhibited a reduced water absorption and improved mechanical properties [53].

Following cleaning, the fibers are dried to reduce their moisture content. Drying can be accomplished by various methods, including sun drying or using industrial drying equipment. It is important to ensure that the fibers are thoroughly dried to prevent the growth of mold and mildew during storage and transportation [52].

The final step in the processing of sisal fibers for composites is sizing. Sizing is the application of a protective coating or treatment on the fiber surface to enhance its compatibility with the matrix material in the composite. Sizing agents can improve the adhesion between the fiber and the matrix, leading to better mechanical properties of the composite material. Common sizing agents used for sisal fibers include silanes, epoxy resins, or other chemical treatments [54].

Sisal fiber reinforced polymer composites have shown great potential in the automotive sector, where lightweight and environmentally friendly materials are in high demand. These composites can be used for various applications such as interior components, door panels, seat backs, and trunk linings. The inherent strength and stiffness of sisal fibers contribute to improved impact resistance and reduced vibrations in the vehicle, leading to enhanced safety and comfort [55]. Additionally, the natural fibers' renewable and biodegradable characteristics align with the automotive industry's growing interest in sustainable materials [4].

In the construction sector, sisal fiber reinforced polymer composites are finding applications in structural elements, such as roofing sheets, wall panels, and partitions. These composites offer enhanced durability, thermal insulation, and resistance to weathering compared to traditional materials. Sisal composites have shown promising results in terms of their mechanical properties and potential for sustainable construction practices [56]. Additionally, their lightweight nature makes them suitable for use in earthquake-prone regions [49].

Sisal fiber reinforced polymer composites are also utilized in the manufacturing of consumer goods, such as furniture, household appliances, and sporting goods. These composites offer attractive aesthetics, improved strength, and environmental benefits compared to traditional materials [57]. For example, sisal composites can be used to create eco-friendly furniture with enhanced durability and a unique natural appearance [7]. The use of sisal fibers aligns with the increasing consumer demand for sustainable and biodegradable products [48].

2.3. Woven Fiber Composites

Woven fibers are composed of two sets of yarns, warp (lengthwise) and weft (crosswise), which are interlaced in various patterns such as plain, twill, and satin weaves [58]. Woven fabrics are constructed into 3D and 2D woven fabric forms. The 2D woven fabrics are made by interlacing two orthogonal sets of yarns of the weaving loom, warp; which is along the length of the weaving loom and weft runs across[59].

Woven fabric classified based on their interlacing patterns. The order of the mutual overlapping controls the type of weave form as shown in Figure 2.5. These directly influence the mechanical behavior of the composites. Plain weave fabrics offer higher stability but suffer from crimp-induced loss of mechanical properties, whereas twill and satin weaves exhibit lower crimp and better conformability to complex shapes [58]. However, woven fabrics inherently suffer from limitations such as yarn undulation, which can reduce their tensile strength. Techniques such as unidirectional weaving and biaxial reinforcement have been developed to address this issue [58, 60].

The mechanical performance of these composites is also highly influenced by the fiber type, yarn structure, and the matrix material used. According to [2]and Arumugam, Kandasamy [61], composites reinforced with woven natural fibers like jute, flax, and hemp have shown significant improvements in mechanical properties, including tensile strength, Young's modulus, and impact resistance.

Varying weave pattern, stacking sequence, and fiber crimp can optimize the mechanical performance of the woven fiber reinforced composites. Ahmed, Tariq [58] and Hasan, Horváth [62] reported that introduction of unidirectional and biaxial weaves has led to the improvement of in-plane shear and tensile properties, making them ideal for high-stress applications.

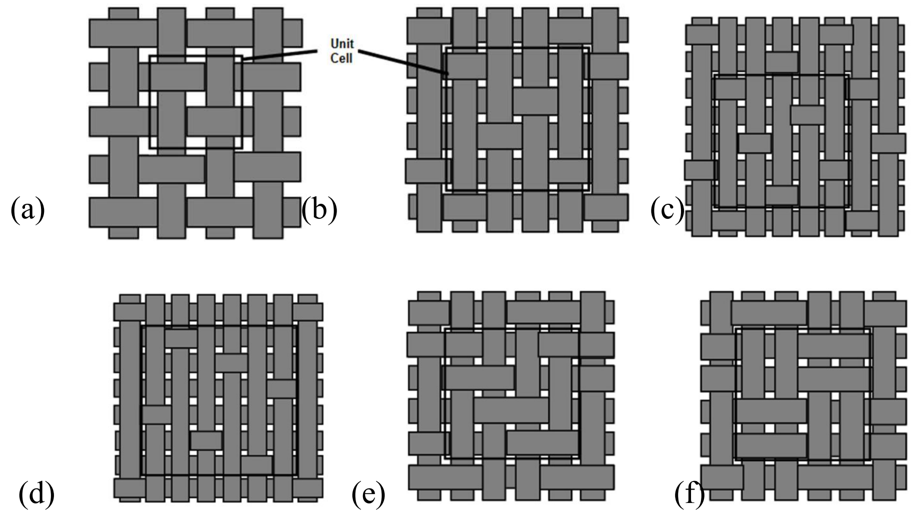


Figure 0.2: (a) plain weave (b) Cross-foot satin weave (c) Five harness satin weave (d) eight harness satin weave (e) 2x2 twill (f) 2x2 basket weave [63]

Woven fabric composites are used in a wide range of applications, from automotive parts and construction materials to aerospace components and ballistic armor. The choice of fabric type, weave pattern, and reinforcement method depends on the specific application requirements, such as load-bearing capacity, impact resistance, and thermal stability [60][62].

Woven flax and glass fiber composites have been utilized in automotive hoods, while woven jute and hemp composites have found applications in bio-based packaging and construction materials. These materials offer significant weight savings and environmental benefits compared to traditional materials like steel and aluminum [58, 62].

Among the different types of fiber reinforcements woven fibers are the most common due to their superior mechanical properties and ease of handling during composite manufacturing [60, 62]. Woven fiber composites offer an excellent balance of mechanical properties, such as high strength-to-weight ratio, good impact resistance, and directional strength, making them suitable for a wide range of applications [58].

2.4. Natural-Synthetic Hybrid Fiber Composites

Hybrid fiber composites are obtained by reinforcing a single matrix with multiple fiber types. The fiber can be a combination of different natural fibers, synthetic fibers, or synthetic and natural fibers. In a hybrid composite, the drawbacks of one fiber are complemented by the other constituent fiber and thereby a favorable balance in the performance of the composite can be achieved [64].

Hybridization can enhance the toughness, strength, and physical properties of the composite with a selection of a proper fiber type and ways of fiber combination [65]. Depending on the ways of constituent fibers combinations hybrid composites are categorized as interply, intraply, intermingled, selectively placed, and super hybrid composites [66]. In interply hybrid consisted of plies made of each constituent fiber stacked in an alternative sequence. Whereas, intraply hybrid composite consists of plies each made from a combination of constituent fibers [67]. Each ply of intermingled hybrid composite consists of randomly mixed constituent fibers. Selectively placed and super hybrid composites are constructed by pacing the reinforcement where additional strength is needed and by stacking metal composite plies in a certain stacking sequence respectively [66].

By incorporating synthetic fibers such as glass or carbon with natural fibers such as sisal or flax hybrid composites achieve higher tensile strength, impact resistance, and stiffness compared to purely natural fiber composites. Selver, Dalfi [68] showed that glass-natural fiber hybrid composites exhibited superior impact resistance and post-impact strength retention due to the synthetic fibers' ability to absorb and redistribute impact energy.

The inclusion of natural fibers in hybrid composites reduces the environmental impact associated with synthetic fibers. Natural fibers are renewable, biodegradable, and require less energy to produce. Neto, Queiroz [69] highlighted the growing interest in hybrid composites as a means to balance performance with sustainability, particularly in automotive and consumer products where environmental concerns are paramount.

Despite their numerous benefits, hybrid composites face several challenges that limit their widespread adoption in certain industries. Natural fibers are hydrophilic, meaning they absorb moisture from the environment, which can degrade the composite's mechanical properties over time. Hybridization with synthetic fibers can mitigate, but not completely eliminate this issue. Studies have shown that surface treatments and fiber modifications are essential to improve the durability of natural-synthetic fiber hybrids in humid environments[69].

Achieving strong interfacial bonding between natural and synthetic fibers in a composite matrix is critical for ensuring mechanical integrity. Differences in the chemical composition and surface properties of natural and synthetic fibers can lead to poor adhesion at the fiber-matrix interface, resulting in weak spots and premature failure under stress [70].

2.5. Factors Affecting the Mechanical Properties and Energy Absorption of Hybrid Composite

2.5.1. Effect of Fiber Stacking Sequence

Arpitha, Sanjay [71] performed an investigation of the hybridization effect of sisal/ glass epoxy composite five stacking sequences, i.e., a pure glass epoxy, two pure sisal epoxy (one with filler), two sisal/glass hybrid epoxy (GSSSG and GSGSG). The result of experimental investigations showed that the ultimate tensile strength of GSSSG and GSGSG are $108.224 MPa$ and $168.82 MPa$ respectively and the impact strength of GSSSG and GSGSG are $653.5\, J/m$ and $976.1\, J/m$ respectively. The impact strength of GSSSG is lower than GSGSG due to fiber pullout and poor adhesion of sisal with epoxy [71].

Santhanam, Dhanaraj [72] experimentally investigate the tensile, impact, water absorption, and flexural properties of banana/ glass hybrid epoxy. The researchers studied the effect of hybridization, stacking sequence, and chemical treatments on the mechanical properties of the composite. The composites consisting of woven mat banana and glass fibers were prepared by hand layup method with five different fiber sequences, BBBBB, GBBBG, BGBGB, BGGGB, GBGBG, and GGGGG. The finding of the investigation revealed that variations of stacking sequence have no significant effect on tensile and impact strength. GBBBG and GBGBG show improved water resistance and flexural strength largely. The glass fibers at the extreme layers serve as protective layers from the watery entry.

Das, Paul [10] conducted a study on the effect of fiber stacking sequence on the mechanical properties of non-woven mat jute/glass fiber hybrid polyester. The composites were prepared with seven different stacking sequences, JJJJJ, JG, JGJ, GJG, JGJG, JGJGJ, GJGJG, and GGGGG. The tensile, flexural, and impact tests were conducted as per ASTM D638-03, ISO 141205, and ASTM D6110-97 standards. The fibers stacking sequence was found to have a predominant effect on the mechanical properties. The composite with GJGJG fiber stacking sequence was revealed to have the highest mechanical properties compared to other hybrid composites. The tensile, impact, and flexural strength of this stacking sequence improved by 32.8%, 40%, and 29.99% than the pure jute composite.

2.5.2. The Effect of the way of Fiber Combination

Pegoretti, Fabbri [30] experimentally investigated the tensile and impact properties of the interply and intraply hybrid composites of polyester-based woven E-glass/polyvinyl alcohol hybrid composite. The symmetric interply hybrid composite showed better tensile performance, whereas intraply has higher impact resistance. Charpy impact test of interply and intraply hybrid carbon/Aramid epoxy composite revealed that the intraply hybrid had higher energy absorption [135]. But from the result of the impact test of aramid/polyethylene fiber, it was found that the impact energy absorbed by the interply hybrid is higher than intraply hybrid [139]. The research indicated that the energy absorption of interply hybrid is through deformation while polyethylene fiber deformation dominated the energy absorption of intraply hybrid.

Rajpurohit, Joannès [140] studied the hybridization effect of interply and intraply carbon/glass epoxy composite on tensile and compressive performance. The composites were prepared using the resin transfer molding method. From the experimental test interply and intraply hybrids showed a positive hybrid effect in tensile performance and only intraply hybrids showed a positive hybrid effect in compression. The investigation of mechanical and water absorption properties of woven banana/glass by Santhanam, Dhanaraj [141] found that due to the hybridization the tensile and impact strengths improved by 44.29% and 54% respectively. And water absorption decreased significantly.

Evaluation of tensile, impact and flexural properties of polyester-based sisal-jute-glass hybrid composite was done by Ramesh [142] through an experimental test. The five-layered hybrid composites, which consisted of glass fiber in the top, middle, and bottom layers and chopped sisal and jute fibers in the second and fourth layers, were prepared by hand layup process. The results of the tests revealed that incorporating glass fiber into sisal-jute fiber composite enhances the performance of the composite and it can be used as a substitute for glass fiber polymer composites. Another research by Arpitha, Sanjay [36] studied the effect of hybridization of filler-based woven sisal/glass hybrid epoxy composite. Hand layup and vacuum bagging methods were used to prepare the composite and tested with tensile, Izod-impact, and flexural tests. The results indicated that the increase in glass fiber content increases the tensile and impact performance and reduces the void content.

Several factors can influence the mechanical performance and energy absorption of hybrid composites material such as fiber stacking sequence [36], way of fiber mixing [140], fiber content, fiber weave architecture [11], and others.

2.5.3. The Effect of Fiber Weave Architecture

According to Kim and Sham [73] and Davies, Hitchings [74], in terms of damage tolerance and impact resistance of woven fiber composites are superior to unidirectional fiber composites. The type of weaving of the reinforcing fiber has a profound influence on the stress and strain behavior of the composite [75]. Yahaya, Sapuan [11] investigated the effect of fiber orientation kenaf/aramid hybrid epoxy composite. Woven, mat, and unidirectional fiber composites were prepared with the hand layup method for comparison. Compared to unidirectional and mat fiber the tensile strength of woven fiber composite is 20.78% and 43.55% higher respectively. The Charpy impact test revealed that the energy absorption capacity of woven fiber composite exceeds the mat and unidirectional fiber by 52.07% and 19.78% respectively.

Karahan and Karahan [76] studied the influence of weaving type and hybridization of woven carbon-aramid epoxy composite on the low-velocity impact response. Intraply hybrids of carbon in the warp and aramid in the fill direction are made in the form of Plain and 2x2 twill weave and unidirectional fiber. The stacking sequence and the fiber contents were kept constants for all samples. From the drop weight impact test results, it was found that the composite with a 2x2 twill weave has the highest impact energy absorption.

The effect of weaving type and fiber count on tensile, impact, and flexural strength interply hybrid woven kenaf/carbon epoxy hybrid composites is evaluated by Aisyah, Paridah [77]. The hybrid composites were prepared with the vacuum infusion method using plain and twill weave having 5x5 and 6x6 fiber count. The experimental result showed that the tensile and impact strength of the plain weave are higher than the satin weave.

Raja and Kumar [75] conducted an estimation of weave type on the tensile and compressive strength of jute/Kevlar intraply hybrid epoxy composite made through the vacuum resin transfer molding method. Plain, basket, twill, and satin weave fabrics were prepared jute in the warp and Kevlar in the fill direction. The tensile and compression tests were conducted according to ASTM D3039 and ASTM D6641 standards respectively. The tensile test result showed that twill weave has the highest and plain weave has the lowest strength. The percentage elongation of the composite increased from 6% to 30% from plain to twill weave. The satin weave is second place on tensile strength. The trend for compression strength is the same as the tensile strength

2.6. Previous Studies on Energy Absorption and Mechanical Properties of Hybrid Composite

Ferreira[1], Araújo [78] investigated the tensile properties of hybrid composites consisting of sisal and fiberglass in an epoxy matrix. The sisal fibers were treated with a 10% sodium bicarbonate solution to enhance fiber-matrix adhesion, which involved washing, drying, and immersion for five days. A layer of sisal fabric sandwiched between two layers of glass fabric in the hybrid composite. The results of the tensile test indicated that the hybrid composite performed better than the pure sisal fiber composite, with the hybrid composite achieving a maximum tensile strength of 44.85MPa compared to 25.76MPa for pure sisal fiber composite. Compared to tensile breaking stress (22.4MPa) and modulus of elasticity (2.27GPa) of the pure sisal fiber composite 74% and 86.4% improvement in the hybrid composite were observed. These findings demonstrated the effectiveness of hybridizing sisal fiberglass to improve the mechanical properties of natural fiber-based composites.

Kumaar, Kumar [79] examined the compressive properties of various compositions of hybrid sisal/glass fiber-reinforced epoxy composites. The composites were prepared using different compositions: SGSGS (20% sisal, 20% glass, 60% epoxy), EGEGE (30% glass, 70% epoxy), RSGS (30% random sisal, 10% glass, 60% epoxy), CSGS (30% continuous sisal, 10% glass, 60% epoxy), and GGG (40% glass, 60% epoxy). Hand layup method was employed to manufacture the composite laminates. The yield strength, compressive strength, and deflection percentage were determined from the compressive tests of the composite laminates. Among the samples, CSGS exhibited the highest compressive strength (915.5 kg/cm^2) and the lowest deflection (3.43%), followed by SGSGS with a compressive strength of 782.5 kg/cm^2 and deflection of 3.64%. The GGG exhibited a compressive strength of 577.8 kg/cm^2. Whereas RSGS sample showed a compressive strength of 198.2 kg/cm^2.

Arpitha, Sanjay [71] investigated the mechanical properties of woven fiber hybrid composite laminates made from sisal, glass, and epoxy resin, incorporating a silicon carbide filler. For the study laminates of pure glass fiber, pure sisal fiber, and hybrid combinations of sisal and glass, both with and without filler were made employing hand layup and vacuum bagging method. The results indicated that pure glass composites demonstrated superior tensile strength (186 MPa), and modulus of elasticity (1.2837 GPa) compared to pure sisal (33 MPa and 0.2014GPa). The hybrid composite laminates with alternating layering of sisal and glass show a tensile strength of 98.82 MPa and modulus of elasticity of 0.7216 GPa. Whereas the hybrid composite laminate having glass fiber only on the outer layer have 108.224MPa and 0.5322GPa.

Altaee and Mostafa [80] studied the mechanical Properties of Interply and Intraply Hybrid Laminates of Jute-Glass/Epoxy Composites. The composites were made by interply and intraply hybridization. The five layered pure glass (5G) and pure jute (5J) composite were made with 60wt% and 23wt% fiber content respectively. For interply configuration, three layering sequences were used: G3JG, GJGJG (9.66wt% jute and 36.34wt% glass) and 2GJ2G. For intraply configuration, two types of co-woven fabrics were made by replacing a single glass yarn with one or two jute yarns, designated as G1J1 (9.66wt% jute and 36.34wt% glass) and G1J2 respectively. The composite samples consisted of 5 layers of woven fabrics. Tensile tests were done according to ASTM D3039 standard, using a universal testing machine. The results showed that 5J the lowest UTS of 41.8MPa and 5G the highest of 360MPa. The interply hybrid composite with a configuration of GJGJG had 163MPa UTS. Among the intraply composites, G1J1 had tensile strength about 177MPa, that shows the effect of glass fiber placement and composition in improving tensile properties in hybrid composites.

Sharba, Leman [81]studied the tensile and compressive Properties of Woven Kenaf/Glass Sandwich Hybrid Composites studied the mechanical properties of hybrid composites made of woven kenaf and glass fibers in an unsaturated polyester resin matrix. The composites were prepared with different fiber fractions: 25wt% kenaf, 50wt% glass, 8.5wt% kenaf/30wt% glass (S1), 13wt% kenaf/24wt% glass (S2), 16.6wt% kenaf/19.5wt% glass (S3). The fibers were arranged in a sandwich structure, with 3 glass fiber layers on the outside and kenaf fibers in the core. Tensile and compressive tests were done according to ASTM D3039 and ASTM D3410 respectively. The results showed that the pure glass composite had the highest tensile strength of 211.5MPa and tensile modulus of 15.7GPa. S1, S2 and S3 had tensile strength of 121MPa, 95MPa and 83MPa respectively and pure kenaf composite had the lowest tensile strength of 41.5MPa. In compressive properties, the pure glass composite also showed the best performance with compressive strength of 185.3MPa and compressive modulus of 10.2GPa. S1, S2, S3 and pure kenaf composite had compressive strength of 89MPa, 87.8MPa, 83MPa, 77MPa respectively. These results showed that increasing the glass fiber content improved both tensile and compressive properties of the hybrid composites, glass fiber reinforcement is effective in improving the mechanical properties of natural fiber-based composites.

Kamesh, Gude [82] studied the mechanical properties of hybrid nanocomposites made from graphene filled sisal/glass fiber reinforced epoxy. The researchers used vacuum bag assisted hand lay-up method to fabricate the composites, using bidirectional woven sisal fibers and woven E-glass fabrics as reinforcement. The study investigated the effect of different weight percentages of graphene nanoplatelets (GNPs) (0%, 0.25%, 0.5%, 0.75%, 1%) in the polymer matrix. The fiber content was balanced at 50:50 volume fraction between sisal and glass fibers and GNPs were dispersed in the epoxy to improve the mechanical properties. Tensile testing as per ASTM standards showed that 1 wt% GNPs showed significant improvement in tensile strength and Young's modulus. The results showed that GNPs provided better load transfer between matrix and fibers, highest tensile strength and modulus was recorded at 1 wt% GNPs due to improved interfacial bonding and matrix reinforcement. Composite with pure sisal recorded to have a tensile strength of 28MPa. Pure glass composite and hybrid with alternating layer of sisal and glass composite with no GNP had 91MPa and 55Mpa tensile strength.

Sanjay and Yogesha [83]investigated the mechanical properties of hybrid composites made from jute, kenaf, and E-glass woven fabrics embedded in an epoxy matrix. The composite laminates were fabricated using a vacuum bagging method, with nine different laminate stacking sequences designed to evaluate the hybridization effects. Testing was done according to ASTM D638. Results showed that E-glass fiber composite (S1) had the highest tensile strength (332 MPa) and modulus (12.7 GPa) while pure jute (S2) and kenaf (S3) composites had much lower tensile performance. Hybrid laminates with both natural and E-glass fibers like jute-kenaf-glass (S9) had better tensile properties than single fiber composites with 129 MPa tensile strength and 5.9 GPa modulus. The study found that strategic hybridization and layering of natural and synthetic fibers has a big impact on the tensile behaviour of composite laminates, E-glass fiber plays a major role in improving mechanical strength.

Ramnath, Kokan [84]explored the mechanical properties of abaca–jute–glass fiber-reinforced epoxy composites, emphasizing the effects of hybridization. The study used abaca, jute, and E-glass woven roving as reinforcements within an epoxy matrix, fabricated using the hand lay-up method. The laminates were made with abaca and jute fibers in alternating layers, with E-glass layers on top and bottom for surface finish and strength. Fiber content was limited to 40% maximum. Tensile and double shear tests were done according to ASTM standards. Tensile test results showed that the abaca-jute-glass hybrid composite had higher tensile strength (57 MPa) than abaca or jute alone, due to good fiber-matrix interaction and hybrid layering. Double shear test results showed that the hybrid composite also had higher shear strength due to better interfacial adhesion and E-glass reinforcement. This study proves that strategic fiber hybridization is key to optimizing natural fiber composites.

Selmy, Elsesi [85]studied the in-plane shear of hybrid and non-hybrid glass fiber reinforced epoxy composites. Unidirectional (U) and random (R) glass fibers were used in an epoxy matrix with a total fiber volume fraction of 37%. The composites were made by hand lay-up and five different laminates were produced: [U]5 (non-hybrid), [R]5 (non-hybrid) and hybrid configurations [0.5R/U/U]S, [U/0.5R/U]S and [U/R/U/R/U]. Iosipescu shear tests according to ASTM D5379-93 were performed to measure in-plane shear strength (τxy) and shear modulus (Gxy). The results showed that the random fiber composite [R]5 had the highest in-plane shear strength (57.76 MPa) and far outperformed the unidirectional composite [U]5 (26.83 MPa).

Among the hybrid laminates, placing random fibers at the core ([U/U/0.5R]S) resulted in higher shear strength and modulus, showing the effect of fiber arrangement on shear performance. The results show that adding random fibers to unidirectional composites improves their in-plane shear properties, so hybridization is a good way to optimize the structure.

Muniyan, Suganya Priyadharshini [86] investigated the mechanical properties of zirconium carbide (ZrC) filler reinforced glass/banana hybrid fiber composites for structural applications. The materials used were woven E-glass fibers and bi-directional banana fibers with ZrC filler particles in epoxy matrix. The composite laminates were fabricated by compression molding under 35 bar at 120°C. The fiber arrangement was in a 7 layer sequence and the filler weight percentage was varied from 0 to 2 wt%. Tensile and compressive tests as per ASTM standards showed that the maximum tensile and compressive strength was achieved with 1.5 wt% ZrC filler with values of 85.3 MPa and 115.5 MPa respectively. The improvement in mechanical properties was due to the better interfacial bonding between matrix and fibers because of uniform distribution of ZrC particles. But at 2 wt% the strength decreased due to filler agglomeration which created stress concentration points and reduced the load transfer efficiency. This study shows the possibility of using ZrC fillers to improve the mechanical properties of natural fiber composites.

Erkendirci and Haque [87] studied the quasi-static penetration resistance of various glass fiber-reinforced thermoplastic composite systems. They used plain weave (PW) S-2 glass, E-glass and HDPE as materials, made into composite laminates via compression molding for the thermoplastic systems and vacuum-assisted resin transfer molding (VARTM) for the thermoset baseline (SC-15 epoxy). The fiber content varied with the number of layers, from 2 to 12, with the corresponding volume fractions measured according to ASTM standards. Quasi-static punch shear tests (QS-PST) were used to measure penetration resistance with different support span ratios to simulate various loading conditions. Results showed that PW S-2 glass/SC-15 composites had higher penetration resistance and energy dissipation than PW S-2 glass/HDPE and E-glass/HDPE composites. HDPE-based composites showed unique deformation mechanisms, including significant membrane tension-shear behavior, resulting in lower stiffness and energy dissipation than the baseline SC-15 epoxy system.

2.7. Summary of The Review and Research Potential

The literature reviews conducted so far revealed that weaving pattern of the fibers in the composite materials have predominant effect on the mechanical properties of the composite materials. Among the fiber weaving forms plain, 2x2 twill, and 2x2 satin weaves are easy to manufacture and have good mechanical performance.

Hybridization of natural fibers with synthetic fibers has a positive effect and improves the mechanical and physical properties of the composite. Moreover, the stacking sequence and ways of fiber combination (fiber configuration) also influence the performance of the hybrid composite. Interply and intraply hybridization have positive effects on the mechanical performance of the composite. In interply hybridization, stacking the natural and synthetic fibers in alternating sequence has positive effect on the mechanical properties of the composite than other sequences.

Few research has been conducted on the mechanical properties of 2X2 twill fiber weaving types. Some of them are investigated natural fiber composites and the rest were conducted on the intraply hybrid composites. But the researchers only took one woven fiber composite and compared it with unidirectional fiber composite.

Although previous studies indeed pointed out that hybrid composites have higher tensile and compressive strengths than natural fiber composites, comprehensive studies exploring the effects of fibers, their architecture, and arrangement (interply and intraply) on the complete range of mechanical properties for a variety of loading conditions are limited.

The interply and intraply hybridization strategies are also not well characterized, with very few comparisons in mechanical performance under differing testing conditions. Very little attention has been given to shear performance and quasi-static penetration.

To this end, this research experimentally investigated the influences of interplay and intraply hybridization on the mechanical properties and energy absorption of 2X2 twill hybrid sisal/glass epoxy composites. Tensile, compressive, shear, and quasi-static penetration tests were conducted to evaluate the mechanical performance and energy absorption of pure sisal, pure glass, interply hybrid, and intraply hybrid configuration composite laminates.

CHAPTER THREE
METERIALS AND METHODS

3.1. Material

For this research chemically treated sisal fiber, glass fiber, epoxy resin, and hardener are used for experimental investigation. Mold, mold releaser, weaving frame, roller, mixer, and other equipment are also used to assist in the preparation of the composite laminate.

3.1.1. Epoxy Resin

Epoxy is a thermosetting resin having a medium viscosity and light amber laminating resign. The basic mechanical and physical properties of a resin are primary concerns when used as a composite matrix. that is designed to offer the highest ultimate strength for a room temperature. Thermosetting resins such as epoxy, polyester, polyurethane, and phenolic are commonly used for composite materials for various applications [88]. Compared to other thermosets, epoxy resins have low toxicity, low shrinkage, less brittleness, good adhesion, and good electrical insulation [89-91]. They provide high strength, durability, chemical resistance, and chemical resistance to a composite [89, 90]. For this research Araldite LY 556 epoxy resin with hardner ARADUR 906 is used to make the matrix for the composite.

Table 3.1:Epoxy resin specifications

Product specification	**Value**
Base hardener ratio	100:95
Viscosity at 25 °C	$10000 - 12000\ mPa\ s$
Density at 25 °C	1.15 - 1.2 g/cm^3
Epoxide index	5.30 - 5.45

3.1.2. Hardener

Since epoxy is a viscous fluid, it needs to be solidified and cured to be used as a matrix and form the composite laminate. When epoxy and its hardener get mixed, a strong crosslink resin will be produced. When some of the crosslinks have formed, the system forms a gel and is said to be “gelled”. When most of the crosslinks have formed, the system forms a solid and is said to be “cured”. The catalyst initiates the chemical reaction of the epoxy resin and monomer ingredient from liquid to a solid state. Generally, the ratio of the epoxy resin and its hardener is specified by the manufacturer.

Figure 3: Epoxy resin and Hardner

3.1.3. Glass and sisal fiber

Glass fiber is a widely employed synthetic fiber having good moisture resistance and excellent mechanical properties. Compared to other synthetic fibers it is relatively cheaper. Most of the time it is used in the fabrication of structural composite material both hybrid and non-hybrid. It is formed from numerous filament arrangements. High tensile strength, excellent elastic capabilities, good thermal properties, strong electrical insulation, and the ability to resist compaction are the major characteristics of glass fibers Somaiah, Prasad [92].

Incorporating glass fiber into other fiber composites to form hybrid composites proved to give an acceptable performance with moderate cost. Many hybrid composites having glass and other materials like carbon, hemp, and jute fibers have been tested for their mechanical properties so far [56, 93]. For this study a woven E-glass was used for the reinforcement of the pure glass composite and together with sisal for the hybrid composite.

Sisal fiber is a vegetative fiber obtained from the sisal plant (*Agave Sisale*) by the extraction from the periphery of the leaf of the plant through mechanical decortication, retting, or scraping processes [9]. The sisal plant is cultivated in large quantities in South America, some parts of Asia, and East Africa, especially in Brazil, Tanzania, Haiti, India, Indonesia, and Kenya [7, 9].

According to Betelie, Sinclair [35], the sisal plant also grows abundantly in Ethiopia and it provided an economic advantage by supporting industries manufacturing sisal fiber composites. Its good specific strength, flexibility, low durability, ability to stretch, chemical affinity, acid resistance, good stiffness, good impact resistance properties, and easy availability makes sisal fiber a good choice for reinforcement of polymer composite [36, 88, 94, 95].

(A) (B)

Figure 4: (A) Glass fiber and (B) Sisal fiber

3.1.4. Sodium Hydroxide

Natural fibers have poor adhesion with polymer resin. Due to this manufacturing natural fiber-reinforced composite faces challenges. Natural fibers are hydrophilic whereas polymers are hydrophobic. This significantly affects the composite by causing premature aging due to degradation and loss of strength. Treating the natural fibers with Alkali eliminates hemicellulose and lignin, which are responsible for this problem, from natural fiber thereby increasing the cellulose content and fibrillation [96]. For this research 5% NaOH solution was used to treat the sisal fiber. The distilled water was used to make the NaOH solution.

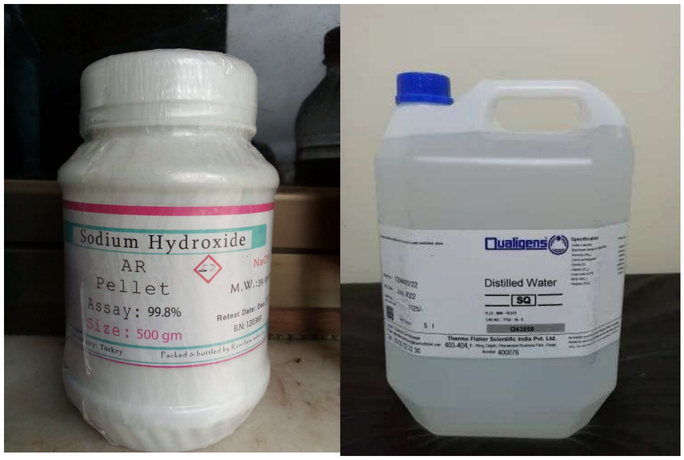


Figure 5: NaOH and distilled water

3.1.5. Distilled water

Distilled water is used to remove excess touches of the alkali treatment on the sisal fiber. A normal wash was applied to perform this.

3.2. Experimental Method

3.2.1. Preparation of Sisal Fiber

3.2.1.1. Sisal Fiber Extraction

Sisal fiber preparation involves collecting matured sisal plant leaves, extraction of fibers, treating the extracted fibers with alkali, and washing it with distilled water. The sisal plant leaves were collected from southern Ethiopia where it is abundantly available. After the sisal leaves were collected exposed to sun to make the extraction easier.

There are many techniques of natural fiber extraction from machine extraction and chemical extraction to mechanical extraction methods. For this research a mechanical method was used to extract the fiber from the collected sisal plant leaves. The extracted fiber then left to dry exposed to sun.

Figure 6: Cutting of sisal leaf.

Figure 7: manual Fiber extraction

Figure 8: Extracted sisal fiber.

3.2.1.2. Fiber treatment

Chemical treatment of natural fibers has emerged as an integral part of developing fiber-reinforced composite materials. Due to their hydrophilic nature, natural fibers find difficulty in their direct use in polymer composites. This character results in poor bonding with hydrophobic polymer matrices. Thus, the mechanical strength and durability of the resulting composites become limited. To overcome these issues, chemical treatments like sodium hydroxide (NaOH) treatment, acetylation, and gamma radiation are applied to enhance fiber-matrix adhesion, remove impurities, and modify the fiber surface, making the fibers more suitable for high-performance composites [97].

Natural fibers are rich in lignin, hemicellulose, and other impurities that interfere with their ability to form strong bonds with polymer matrices. The removal of these impurities through chemical treatments largely enhances the performance of fiber-reinforced polymer composites. Adugna Ayalew and Fenta Wodag [98] reported that NaOH treatment is one of the most common and effective chemical treatments for sisal fibers, primarily because of its ability to improve fiber-matrix adhesion by cleaning the fiber surface and increasing surface roughness

NaOH treatment also reduces water absorption and enhances the composite's durability in humid environments, thereby improving the hydrophobicity of the fibers. This makes NaOH-treated fibers particularly suitable for outdoor and high-moisture applications. In comparison to other chemical treatments, NaOH treatment is cost-effective and yields high-performance results. Treatments such as acetylation and gamma radiation tend to be more expensive and complex. Acetylation, for example, involves grafting acetyl groups onto the cellulose structure of the fiber, reducing water absorption and improving the fiber's durability. However, its mechanical benefits are not as pronounced as those seen with NaOH treatment[99].

Bichang'a, Wambua [100] and Srisuwan, Prasoetsopha [101] investigated the effect of chemical treatment on mechanical properties of hand lay-up manufactured woven sisal epoxy composite. In the first research the effect of NaOH is studied whereas the second research studied the effect of alkalization and salinization. The result of Bichang'a, Wambua [100] indicated that, the impact strength of 4% NaOH treated composite is 28.67% higher than the untreated one. Srisuwan, Prasoetsopha [101] used 4wt% NaOH and 2wt% γ-glycidoxyl trimethoxysilane solutions for fiber treatment, pure epoxy and epoxy blended with grafted depolymerized natural rubber. The finding revealed that the blended epoxy composite has 163% higher impact strength of neat one and composite with salinized sisal fiber has higher impact strength than alkalized sisal fiber. A similar study by Prasad, Gowda [102] reported that untreated coir fiber polyester composite yield higher impact strength than the one treated with 5% NaOH.

The duration of the treatment and optimal concentration of NaOH chemical are serious factors to get the best results. Studies suggest that NaOH concentrations between 2% and 5% are the most effective for sisal fibers. A study by Moraes, Sierakowski [103] demonstrated that a 5% NaOH solution applied for an hour gave the optimal balance between fiber surface cleaning and mechanical performance improvement without degrading the fibers. The study also reported that higher concentrations or longer treatment durations can damage the fiber structure, reducing the overall strength of the composite.

In another study, sisal fibers treated with NaOH concentrations of 2%, 6%, and 10% were compared, with a soaking time of 24 to 72 hours. It was found that a 6% NaOH solution with a soaking time of 48 hours provided the best combination of tensile and bending strength for sisal fiber-polyester composites [98]. Prolonged exposure to higher concentrations of NaOH lead to excessive removal of lignin and hemicellulose, and made the fiber weak.

Since natural fibers are hydrophilic, they will not easily bind with polymer matrices. Therefore, the surface of the fibers should be modified with chemical treatment to enhance the interfacial adhesion of sisal fiber with the epoxy resin.

After the extracted sisal fiber dried enough it was treated with 5% NaOH solution. The fiber soaked into the solution for 10 hours in door at room temperature inside a sealed container. After the soaking was done, it was washed using distilled water to remove the traces of NaOH. Lastly, the fibers dried-up for about 48 hours at room temperature using sunlight.

3.2.2. Determination of mass of fiber and matrix

Fiber and matrix volume fraction

For a given volume of the fiber (v_f) and matrix (v_m) the total mass of the composite (v_c) is given by:

$$v_c = v_f + v_m \qquad 3.1$$

The volume fraction of the fiber:

$$V_f = \frac{v_f}{v_c} \qquad 3.2$$

The mass fraction of the matrix:

$$V_m = \frac{v_m}{v_c} \qquad 3.3$$

The sum of the mass fractions is

$$V_f + V_m = 1 \qquad 3.4$$

Fiber and matrix weight fraction

For a given mass of the fiber (w_f) and matrix (w_m) the total mass of the composite (w_c) is given by:

$$w_c = w_f + w_m \qquad 3.5$$

The mass fraction of the fiber:

$$W_f = \frac{w_f}{w_c} \qquad 3.6$$

The mass fraction of the matrix:

$$W_m = \frac{w_m}{w_c} \qquad 3.7$$

The sum of the mass fractions is

$$W_f + \quad W_m = 1 \qquad 3.8$$

From a definition of density of a material:

$$w = \rho v \qquad 3.9$$

Where, w is mass, ρ is density, and v is volume of the material

Equation (3.6) and (3.7) can be rewritten in in terms of mass and volume fraction as

$$W_f = \frac{\rho_f}{\rho_c} V_f \text{ and } \quad W_m = \frac{\rho_m}{\rho_c} V_m \qquad 3.10$$

Or in terms of individual constituent

$$W_f = \frac{\frac{\rho_f}{\rho_m}}{\frac{\rho_f}{\rho_m} V_f + V_m} V_f \qquad \text{and} \quad W_m = \frac{1}{\frac{\rho_f}{\rho_m}(1 - V_m) + V_m} V_m \qquad 3.11$$

Density

From Equation (3.8) the density of a composite can be calculated as:

$$\rho_c v_c = \rho_f v_f + \rho_m v_m \qquad 3.12$$

The de[104]nsity of the composite is:

$$\rho_c = \rho_f V_f + \rho_m V_m \qquad 3.13$$

In terms of weight fractions of the fiber and the matrix:

$$\frac{1}{\rho_c} = \frac{W_f}{\rho_f} + \frac{W_m}{\rho_m} \qquad 3.14$$

Calculation of the mass of epoxy resin and sisal and glass fibers

A thorough review of recent literatures showed that several studies [104-108] conducted on hybrid composite found 40wt % to have best overall performance. For this study therefore a 40% fiber by weight was chosen for all composite laminates, i.e. pure glass, pure sisal, and hybrid composites.

The mold prepared to fabricate the composite laminate have the dimensions of $40\ cm\ X 20\ cm$. According to the ASTM standards for the tests the composite laminate should have a thickness of $5mm$. Therefore, the volume of the composite laminate is $400mm\ X\ 200mm\ X\ 5mm$.

The densities of the fibers were determined following the Standard Test Method for Density of High-Modulus Fibers (ASTM D3800). The test is effective in measuring the density of synthetic fiber like glass and carbon. During the test the fiber, which has a known mass, was immersed in water, then the volume of water displaced by the fiber was measured. For this study the test was used to determine the density of both glass and sisal fibers. The fibers were prepared as milled powder to reduce the void between strands of fibers.

Using ASTM D3800 standard testing the average density of glass and sisal fibers found to be $2.57\ g/cm^3$ and $1.4\ g/cm^3$ respectively. The density of sisal fibers has estimated ranging from 1.30 to $1.60\ g/cm^3$ [9, 109, 110].

The density of E-glass fibers ranges between $2.55\ g/cm^3$ and $2.617\ g/cm^3$. This variation can be attributed to different manufacturing conditions and specific applications [111-113]. The density of the glass found through test is acceptable in reference to prior literature.

Using the weight fraction of the fiber (40wt%) and the epoxy (60wt%), and the density of sisal fiber ($1.4G/cm^3$), glass fiber ($2.57g/cm^3$), and epoxy resin ($1.17\ g/cm^3$)

Given Data:

Density of sisal fiber (ρ_s): 1.4 g/cm^3

Density of glass fiber (ρ_g): 2.57 g/cm^3

Density of epoxy matrix (ρ_m): 1.17 g/cm^3

Total volume of the composite (v_cl): 400 cm^3

Mass of sisal fiber = Mass of glass fiber: $w_s = w_g$

A) Pure Sisal-Epoxy Composite

From Equation (3.1) and (3.7)

$v_c = v_f + v_m = 400\ cm^3$ and

$w_c = w_f + w_m$

From the weight fraction condition

$$w_s = 0.4w_c$$

$$w_m = 0.6w_c$$

Relationship between mass and volume

$$w_s = \rho_s v_s = 1.4 * v_s$$

$$w_m = \rho_m v_m = 1.17 * v_m = 1.17(400 - v_s)$$

$$w_c = 1.4v_s + 1.17(400 - v_s)$$

From equation (3.14):

$$\frac{1}{\rho_c} = \frac{W_s}{\rho_s} + \frac{W_m}{\rho_m} = \frac{0.4}{1.4} + \frac{0.6}{1.17}$$

$$\rho_c = 1.252\ g/cm^3$$

Mass of composite is $w_c = 500\ g$

The volume of sisal fiber is then 139.13 cm^3

The mass of the sisal fiber is 194.78 g

And the mass of the epoxy resin 305.2 g

B) Pure Glass-Epoxy Composite

Employing similar procedure

Density of the composite is 1.495 g

Mass of composite is $w_c = 598.38\ g$

The volume of glass fiber is then $92.86\ cm^3$

The mass of the glass fiber is$238.65\ g$

And the mass of the epoxy resin $359\ g$

C) Sisal-glass hybrid composite

The weight fraction of both fibers are equal, i.e. $W_s = W_g = 20\%$

Mass of glass and sisal are:

$$w_s = 0.2w\_c$$

And $w_g = 0.2w\_c$

Volume of glass, sisal and epoxy are

$$v_g = \frac{0.2w_c}{2.57}$$

$$w_s = 0.2w_c/1.4$$

$$w_m = 0.6w_c/1.17$$

The total volume of the composite

$$v_c = v_g + v_s + v_m$$

Mass of composite:

$$w_c = v_c\left(\frac{W_g}{\rho_g} + \frac{W_s}{\rho_s} + \frac{W_m}{\rho_m}\right)^{-1}$$

$$w_c = 545.33\ g$$

Density of the composite is $1.363\ g$

Mass of composite is $w_c = 545.33\ g$

The mass of glass fiber is then $109\ g$

The mass of the sisal fiber is $109\ g$

And the mass of the epoxy resin $327.2\ g$

3.3. Preparation of Mold and Weaving Frame

The mold with a dimension of $40cm\ X\ 20cm$ was prepared and used for the fabrication and compression of the composite laminate. To weave the fibers a wooden frame was prepared. The frame was nailed with small nails to assist the weaving of the fibers. The frame was made with a dimension of $40cm X\ 40cm$.

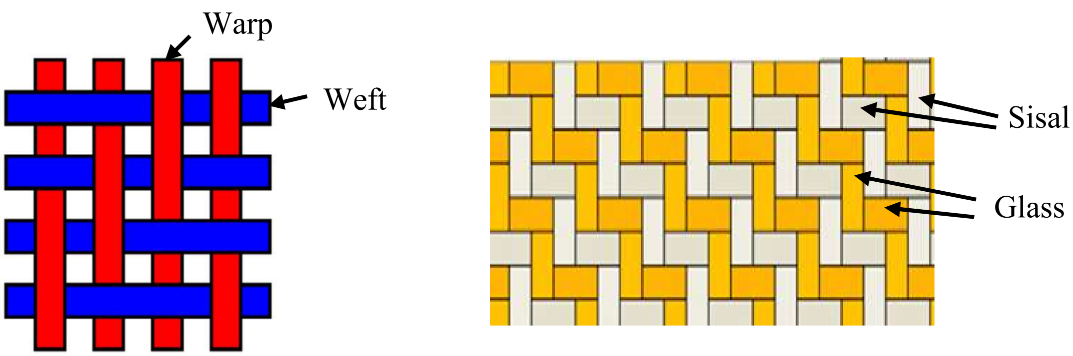
(A) (B)

Figure 9: (A) Box mold for composite (B) Wooden frame for fiber weaving

3.3.1. Woven Fabric Preparation

After the sisal fiber is dried enough it was prepared for the weaving process. For this research, woven fabrics were prepared in the form of 2x2 twill weave. Both sisal and glass fibers woven fabrics were made in each ply individually for pure sisal, pure glass and interplay hybrid composite. Whereas the woven fabrics for the intraply hybrid composite laminate were made by weaving sisal and glass fiber in the same ply arranged one after the other. The weaving process was done by hand using weaving frame.

Figure 10: Weaving process of fibers



(A) (B)

Figure 11: Weaving architecture of (A) pure sisal and pure glass ply and (B) intraply hybrid ply

The above figure depicted that, for pure sisal, pure glass plies are prepared by weaving the respective constituents in both weft and warp direction. These woven plies can also be used to fabricate interply hybrid composite. On the other hand, intraply hybrid plies are made by weaving both glass and sial fibers in the same ply. The waving is done by arranging glass and sial fibers in weft and warp direction alternatively.

3.4. Composite Laminate Design

For this research, three distinct types of composite laminates were prepared, pure sisal epoxy, pure glass epoxy, and interply hybrid sisal/glass epoxy and intraply hybrid sisal/glass epoxy composites. Each of the three composites have six layers. The interply hybrid composite have sisal and glass fiber layers stacked in an alternative fashion, SGSGSG. Including pure fiber and hybrid fiber composites there are four composite laminates, formed from 2x2 twill weave fabrics.

There are various techniques to manufacture composite laminate. For this study, hand layup method was be used. The hand lay-up technique of fabrication is an ISO standard recommendation. Moreover, using this technique, fibers reinforced composites are fabricated with an epoxy matrix [114]. Many authors who investigated fiber-reinforced epoxy composite materials used the hand layup method to fabricate the specimen.

Hand lay-up is one of the oldest and simplest manufacturing methods for FRPMCs. It involves manually placing individual layers of fibers in a mold and applying resin by hand. The process is cost-effective and versatile, allowing the large and complex geometries production. However, it is labor-intensive, time-consuming, and can result in inconsistent fiber orientations [115]. The main steps involved in hand layup are as follows [116]:

a. **Cutting**: Reinforcement fibers, such as fiberglass or carbon fabric, are cut into appropriate sizes and shapes.
b. **Resin Application**: A liquid resin, like epoxy or polyester, is applied to the mold using brushes or rollers.
c. **Fiber Placement**: The cut fibers are manually placed onto the resin-coated mold, layer by layer, ensuring proper orientation and coverage.
d. **Consolidation**: Pressure is applied to the layup using tools, such as rollers or squeegees, to remove air and ensure good contact between the fibers and resin.
e. **Curing:** The layup is allowed to be cured in an oven or at room temperature, depending on the resin system used.

f. **Trimming and Finishing**: Once cured, the excess material is trimmed, and any necessary finishing operations are performed to achieve the final shape and surface quality.

All the composite laminates were prepared following ASTM D5687/ D5687M – 20 standards. It provides guidelines to facilitate the proper preparation of composite laminates and test specimens from fiber-reinforced organic matrix composite prepreg.

In the hand layup process, resins are impregnated by hand into fibers which are in the form of woven fabrics. Rollers or brushes are used to accomplish this, with the increasing use of nip-roller type impregnators for forcing resin into the fabrics utilizing rotating rollers and a bath of resin.

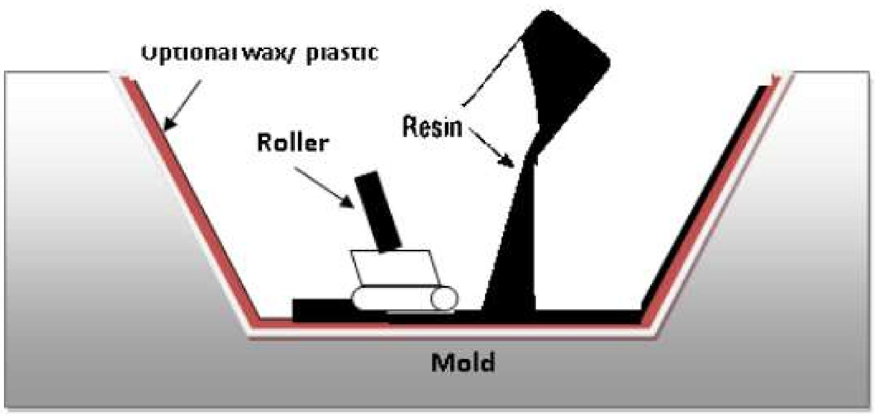


Figure 3.12: Hand layup technique of composite laminate preparation

In hand lay-up specimen fabrication, curing is an important process. One way to accomplish it is by applying a pressure on the mold to squeeze and remove excess resin and air gaps formed by the hydraulic press and leaving the laminate to cure under standard atmospheric conditions.

Figure 13: Composite laminate fabrication

Figure 14: Fabricated composite laminates: interply hybrid, pure glass, intraply hybrid, and pure sisal composite laminate (from left to right)

3.4.1. Test Specimen cutting

Specimen cutting process was a crucial part of preparing the composite materials for testing mechanical properties. Ensuring precise and accurate cuts was essential to maintain the integrity of the material and get reliable data from the tests. For this study, four types of composite laminates were produced. These are 2x2 twill woven sisal epoxy, 2x2 twill woven glass epoxy, 2x2 twill woven interply hybrid, and 2x2 twill woven intraply hybrid composites. For each specimen the corresponding ASTM standards were followed. The cutting process required great care to avoid damaging the composite material's fibers and matrix.

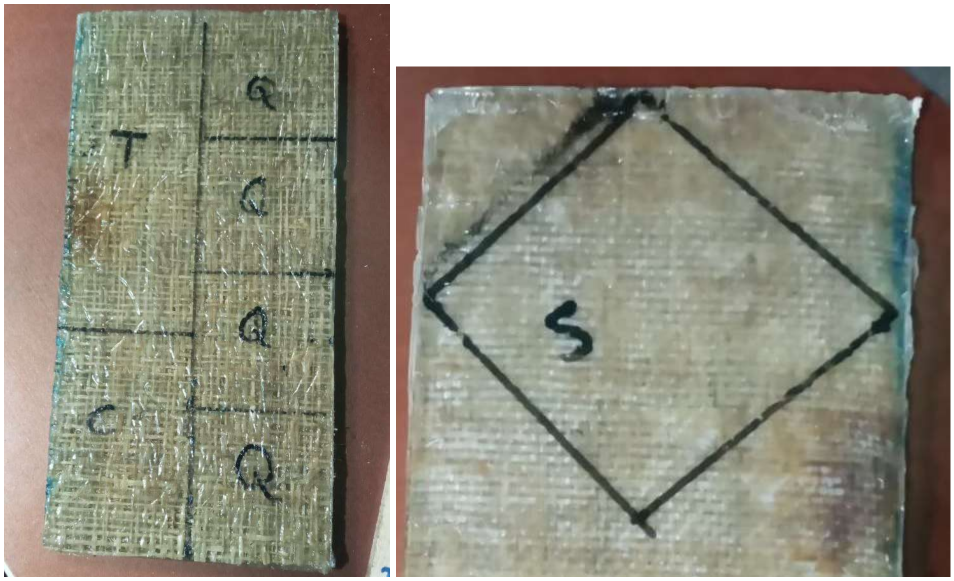


Figure 15: Composite laminate prepared for cutting

For the tensile test, specimens were cut following the guidelines of ASTM D3039/D3039M-17. It specifies the dimensions and preparation for testing the tensile properties of composite materials. Each specimen was cut to 250 mm in length and 25 mm in width, with the thickness of 5 mm.

Compressive test specimens were prepared according to ASTM D695 standard. It provides guidelines for determining the compressive properties. The specimens were cut to 25 mm in length, 25 mm in width, and their thickness 5 mm. For even distribution of the compressive load during testing the surfaces of the specimens were polished.

ASTM D3518/D3518M-18 standard was followed to cut the shear specimens. It focuses on determining the in-plane shear response of composite materials. Specimens were cut with a length of 250 mm, and a width of 25 mm. their thickness is the same as the tensile and compressive specimens.

The specimens were cut in a way that the fibers oriented as ±45° relative to the longitudinal and the loading direction. This orientation is important for producing shear stress in the fibers and matrix during testing. Special care was taken to mark and cut the laminate with this fiber orientation in mind.

A

B

C

Figure 16: Cut specimen for (A) Tensile test, (B) Compressive test, and (B) Shear test

The quasi-static penetration test specimens were cut as per ASTM D6264/D6264M-17 standards. The test requires square composite plates that are subject to a concentrated force at the center. This test helps measure the material’s resistance to indentation.

The specimens for this test were cut with the dimensions of 150 mm × 150 mm square plates with a thickness of 5 mm. These dimensions allowed for enough surface area to distribute the force from the indenter.

After cutting, the center of each specimen was precisely marked to ensure that the force during testing would be applied exactly at the center. Eight holes were drilled out from each specimen so that the test fixture could hold it firmly.

A 

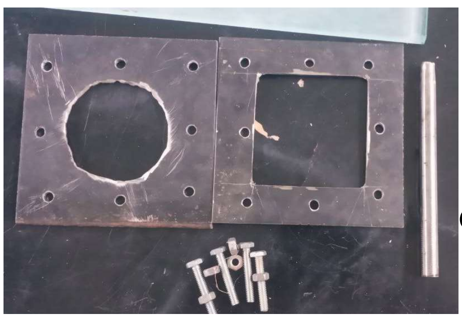
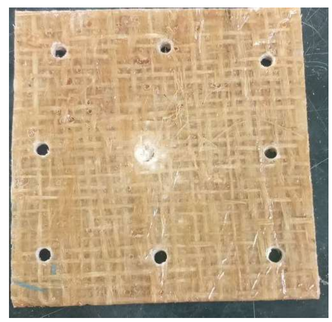
B  C 

Figure 17: Quasi static penetration test (A) Cut specimen, (B) Fixture, and (C) Drilled specimen

3.5. Experimental Setup and processes

In this research, four experimental tests were conducted: tensile, compressive, shear and quasi static penetration tests. Each of the tests and sample preparation for each test performed as per their respective ASTM test standards. In addition to the interplay and intralpy hybrid composites, samples prepared for pure sisal and glass fiber composite for the sake of comparison.

All the tests were performed using universal testing machine at Addis Ababa Scinece and Technology University. The machine has the following specifications:

Table 2: Specifications of a universal testing machine used for the test

Model	WDW-100S
Max. test load	100kN
Accuracy	±0.5%
Effective measuring range	0.2%-100% of Full capacity
Speed range	0.001-1000mm/min
Accuracy	±0.5%
Resolution	0.006um
Power	4KW

3.5.1. Tensile Test

Tensile testing is essential to evaluate the strength and stiffness of materials under uniaxial tensile loading. The tensile properties tell how well the material can withstand tensile forces without failure.

The main purpose of this test in this study is to determine the tensile strength of the composite laminates made of 2X2 twill woven glass and sisal fibers and interplay and intraply hybrid sisal/glass fibers. The test was conducted as per ASTM D3039 standard. The ASTM D3039/D3039M-17 standard specifies the method for determining the tensile strength, modulus, and elongation of fiber reinforced polymer composites. As per the standard 5 specimens were prepared for each composite type .

The tests were conducted with a universal testing machine (UTM) specified in the above table and depicted in the figure below. The specimens were mounted in the machine grips, with a gauge length of 150 mm marked for strain measurement. The tests were carried out at a constant crosshead speed of 2 mm/min.

A B

Figure 18: A) Universal testing machine and B) tensile test setup

3.5.2. Compressive Testing

Compressive testing determines the capacity of materials to resist crushing forces. The compressive tests for this study were done by subjecting the composite specimens to axial compression loading applied based on the ASTM D695 standard. ASTM D695 is a standard developed for determining the compressive properties of rigid plastics, including both unreinforced and reinforced composites with high moduli. The 2x2 twill woven sisal-glass hybrid epoxy composite falls under the category of reinforced polymer composites, the characteristics of the epoxy matrix makes the composite a rigid plastic. The hybrid nature of this composite, combining both natural (sisal) and synthetic (glass) fibers, results in a material with potentially high modulus and significant load-bearing capacity, which ASTM D695 can evaluate.

In-plane, the twill weave structure tends to provide relatively isotropic properties because of the balanced and symmetrical distribution of fibers. These essential characteristics of the twill fabric make the mechanical properties along the principal direction of the composite the same. So, there is no need to do the compressive test in multiple directions.

ASTM D695 offers flexibility regarding specimen geometry as well as accommodating thin materials through specific specimen preparation guidelines. Given the hybrid nature of the composite in this study this flexibility is crucial for ensuring that specimens are representative of the typical form of the material. Proper specimen preparation is essential to minimize stress concentration and ensure uniform load distribution during testing. The ASTM D695 standard provides clear guidelines for such preparation, which is particularly important for woven composites to prevent premature failure due to edge defects or misalignment.

The procedure outlined in this standard allows for the determination of fundamental compressive properties such as compressive strength and modulus of elasticity which are essential for understanding performance of the material under compressive loading. For the test five specimens were taken for each composite type to ensure repeatability.

Compression tests were performed using a UTM equipped with a compressive load cell. Specimens were placed between the platens and compressive load was applied at a constant cross-head speed of 1.5 mm/min to ensure even distribution of force along the specimen axis. The gauge length of the composite material is 25 mm. Load and displacement were monitored continuously throughout each test. Compressive strength and modulus were determined from the stress-strain curve.

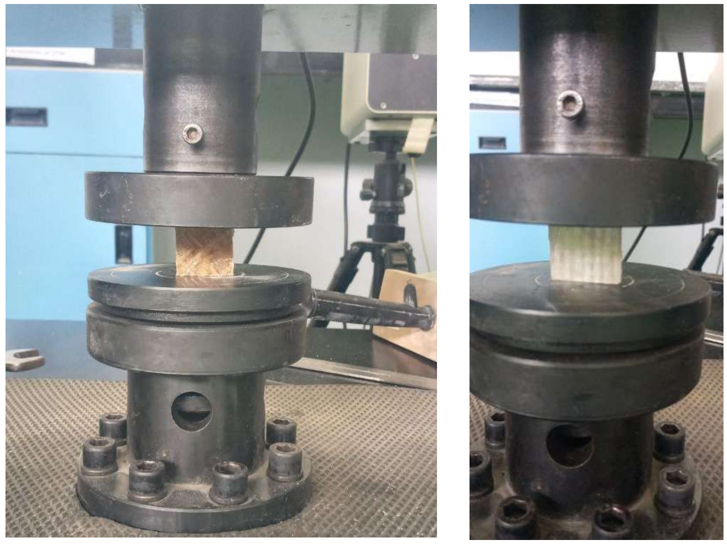


Figure 19: Compressive test setup

3.5.3. Shear testing

Shear testing assesses the resistance of composites to internal sliding forces. The internal sliding force is a key factor determining the performance of a material under torsional, bending or shear loading. The ASTM D3518/D3518M-18 standard describes the procedure for determining the in-plane shear response of fiber-reinforced composites using a ±45° laminate. This test helps to investigate the ability of the laminate to resist shear loads.

The shear tests were conducted using a universal testing machine. The shear load was applied through tensile loading of the ±45° laminate. The rate of loading was set at 2 mm/min as per the standard. The guage length for the testing specimen was 150 mm. as with the other tests 5 specimen per laminate type were tested to ensure repeatability.

Load and strain were measured continuously throughout the test. Shear stress and strain were calculated, and the shear modulus and ultimate shear strength were determined from the data.

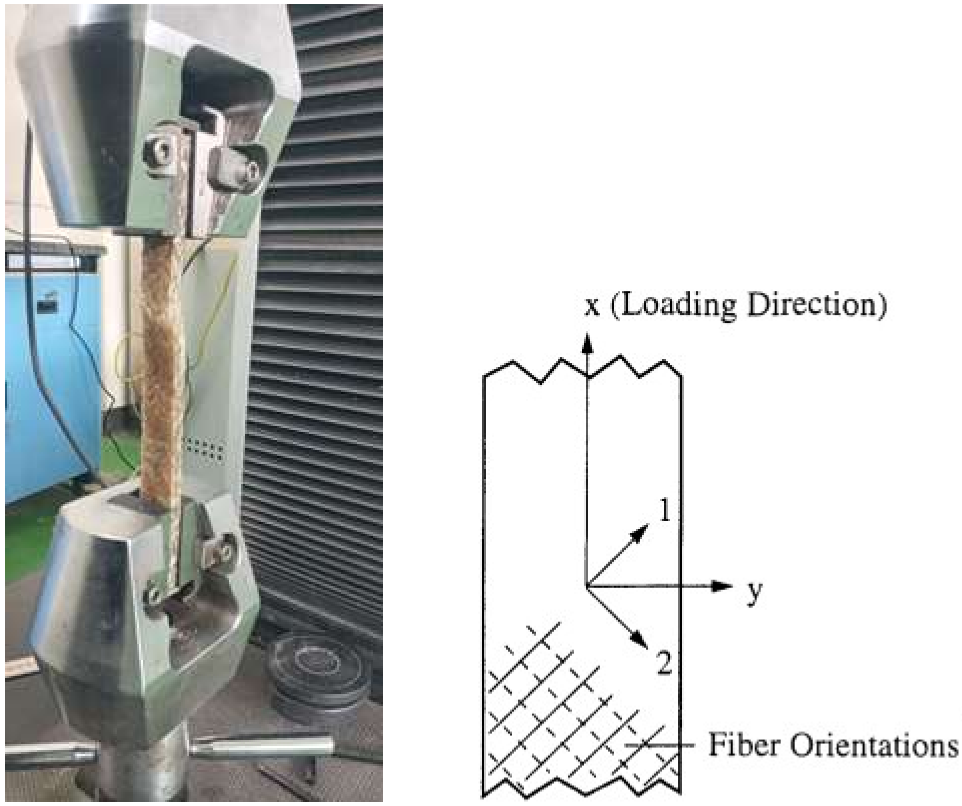


Figure 20: Shear test setup

3.5.4. Quasi-static penetration test

Quasi-static penetration testing evaluates the resistance of a material to localized loading, which is very important for assessing impact damage resistance in composite structures. The quasi-static penetration test, as described in ASTM D6264/D6264M-17, is used to assess the damage resistance of fiber-reinforced polymer matrix composites to penetration under a gradually applied compressive force. The primary purpose is to simulate and evaluate how the material behaves when subjected to slow penetrating loads.

To conduct the test a support fixture was required. Support fixture with a dimension of 200mm in length and 200 mm in width and an edge supported configuration was used for the testing setup shown in the figure below. A 13 mm diameter rod with hemispherical tip was used as an indenter to test the penetration of the specimen.

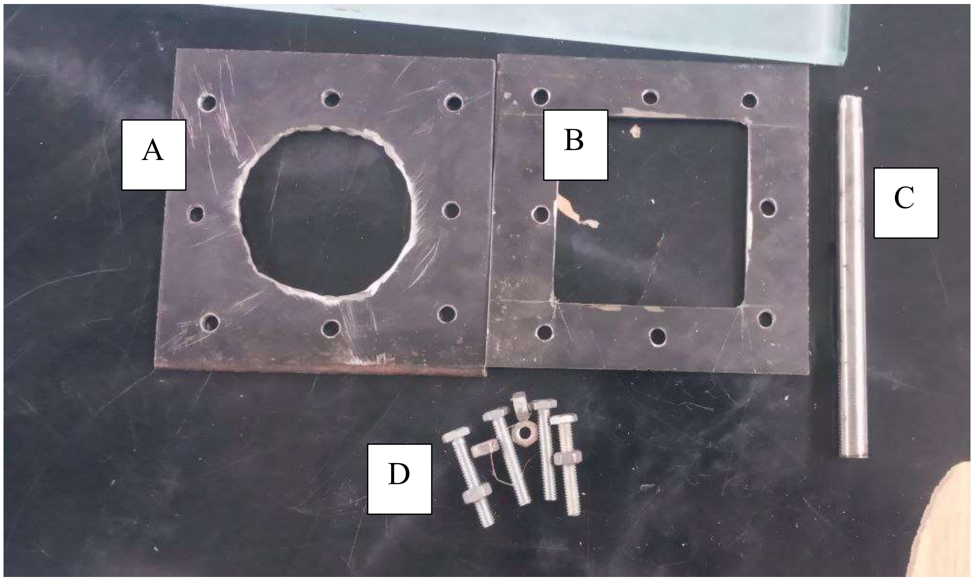


Figure 21: quasi static penetration test fixture (A) Lower support, (B) Upper support, (C) indenter rod, and (D) 11M bolts

Before testing the specimens were sandwiched between the upper and lower support steel plates. The upper support was used as a clamp to hold the specimens firmly. A rectangular hole with a dimension greater than the testing region was cut out to let the indenter pass through and not to interfere with the tests. The lower support has a circular opening at its center with a diameter of 122 mm as per the standard. 11M bolts were used to tightly hold the specimens between the supports.

A universal testing machine was used to perform the tests. The specimen in the support fixture was placed on the top of a hollow bottom fixture of the machine. The indenter was positioned at the center of the specimen as shown in the figure below and a displacement-controlled crosshead speed of 1.25 mm/min was used since the setup was the edge-supported configuration.

Figure 22: Quasi-static penetration test setup

3.5.5. Determination of Mechanical Properties

Tensile Properties

During the tensile testing the specimen was subjected to a longitudinal uniaxial loading. This load is perpendicular to the cross section of the specimen (width X thickness).

Tensile stress is calculated using the applied load and the cross-sectional area of the specimen. The tensile stress at any required data point is given by:

$$\sigma_i = P_i/A \qquad 3.15$$

The ultimate tensile strength, which is the maximum stress that the material can withstand before failure, can be calculated as:

$$\sigma_{ULT} = P_{max}/A \qquad 3.16$$

The young's modulus of elasticity, which expresses the stiffness of a material can be calculated as:

$$E = \frac{\sigma}{\epsilon} \qquad 3.17$$

Strain at failure (ϵ) express the maximum strain of the material at failure of the material. Can either be expressed as a ratio of elongation (δ) to the original gauge length of the material or the percentage of elongation to the original length of the material (L_o)

$$\epsilon = \frac{\delta}{L_o} \qquad 3.18$$

$$\epsilon = \frac{\delta}{L_o} * 100\% \qquad 3.19$$

Compressive Properties

During the compressive testing the specimen was subjected to a compressive longitudinal uniaxial loading. This load is perpendicular to the cross section of the specimen (width X thickness).

Compressive stress is calculated using the applied load and the cross-sectional area of the specimen. The compressive stress at any required data point is given by:

$$\sigma_i = P_i/A \qquad 3.20$$

The ultimate compressive strength, which is the maximum stress that the material can withstand before failure, can be calculated as:

$$\sigma_{ULT} = P_{max}/A \qquad 3.21$$

The young's modulus of elasticity, which expresses the stiffness of a material can be calculated as:

$$E = \frac{\sigma}{\epsilon} \qquad 3.22$$

Strain at failure (ϵ) express the maximum strain of the material at failure of the material. Can either be expressed as a ratio of elongation (δ) to the original gauge length of the material or the percentage of elongation to the original length of the material (L_o)

$$\epsilon = \frac{\delta}{L_o} \qquad 3.23$$

$$\epsilon = \frac{\delta}{L_o} * 100\% \qquad 3.24$$

In-Plane Shear Properties

During the in-plane shear testing the specimen having $\pm 45^0$ fiber orientation is subjected to uniaxial tensile loading. This load is perpendicular to the cross section of the specimen (width X thickness).

The ultimate in-plane shear stress (τ_{12}) is given by

$$\tau_{12} = \frac{P_{max}}{2A} \qquad 3.25$$

Where:P_{max}: maximum load at or below 5 % shear strain

A: cross sectional area of the specimen

The shear modulus of elasticity (G_{12}), which expresses the stiffness of a material can be calculated as:

$$G_{12} = \frac{\tau_{12}}{\gamma_{12}} \qquad 3.26$$

Quasi static penetration test

From the quasi static penetration test the energy absorption capacity and punch shear were determined. For the test a steel rod with hemispherical tip with 13mm diameter was used as an indenter and a support plate having a hole of diameter 122mm was also used.

The tests were done to evaluate the maximum penetrating force (P) and to determine the punch shear strength (PSS) of the composite laminates. The punch shear strength value corresponds to the maximum penetrating force counteracting the deformation of the material due to the indenter pressure, and thus its resistance of faillure, and is calculated as:

$$PSS = \frac{P}{\pi D\_p H_c} \qquad 3.27$$

Where: P – maximum punching force,

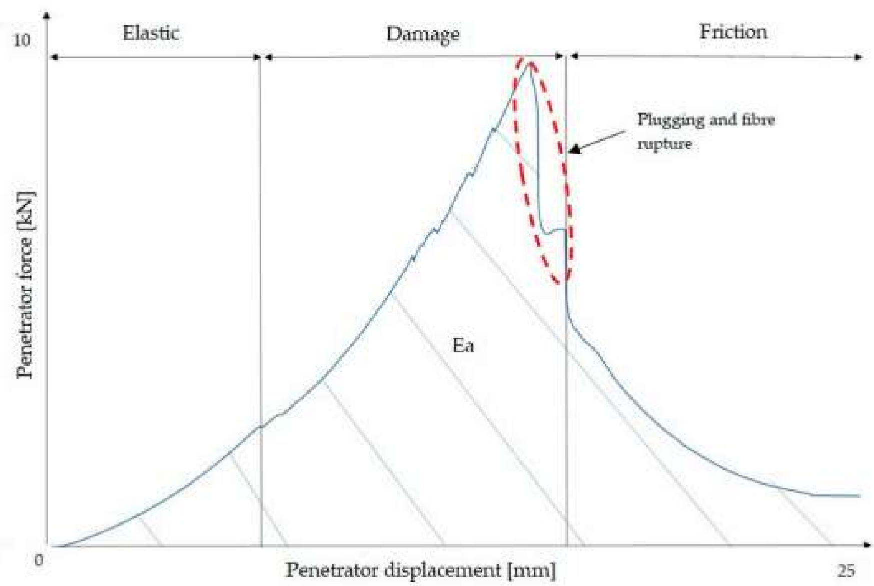
Dp – punch diameter,(13 mm)

Hc – sample thickness. (5mm)

The quasi-static energy absorption of the composite laminates was determined based on the area under the force vs displacement graphs. A typical load -displacement graph of a quasi static penetration test looks like the one shown in Figure 26. The energy absorbed by the composite laminate is the mechanical work done on it during the test, which is the integral of the force over the indenter displacement. Mathematically:

$$Energy\ absorbed = \int F(x)\,dx \qquad 3.28$$

Where: F(x) is the load at displacement x and x is the indenter displacement.



Source [117]

Figure 23: different regions under load- displacement curve of the test

Since the load displacement graphs are complex, the energy absorbed during the quasi static penetration test was determined by trapezoidal integration. Under this method the area under the curve was approximated using numerical integration techniques as:

$$Energy\ absorbed = \sum_{i=1}^{n} \frac{F_i + F_{i+1}}{2} * \Delta x$$

Where: F_i and F_{i+1} are successive load values, and Δx the displacement interval between them

CHAPTER FOUR

RESULT AND DISCUSSION

This section discussed the results of the experimental tests of the mechanical performance and energy absorption capacity for the four composite laminates: 2x2 twill woven pure sisal, pure glass, interply hybrid sisal-glass, and intra-ply hybrid sisal-glass epoxy composite. Their corresponding ASTM standards were followed to conduct the tensile, compressive, shear, and quasi-static penetration tests. Mechanical properties such as ultimate tensile strength, compressive strength, shear modulus, and energy absorption were evaluated from the test results.

Each set of results is presented alongside a discussion of the behavior of the composites, including comparisons with relevant literature and failure mechanisms briefly.

4.1. Tensile Test Results

This section the key mechanical properties are analyzed including ultimate tensile strength (UTS), strain at failure, and tensile modulus from the results of the tensile tests conducted on 2x2 twill woven sisal-glass interply hybrid, 2x2 twill woven sisal-glass intraply hybrid, 2x2 twill woven pure glass, and 2x2 twill woven pure sisal.

The figures below depict the behavior of the composite laminates during uniaxial tensile loading. The pure sisal composite laminate in the first section of the curve experience relatively low gradient, which indicates the quick deformation for a small change of the lad relative to others. The pure glass composite laminate curve has relatively stepper curve before it reaches its ultimate. This indicates that it has relatively larger stiffness than the rest.

The ultimate tensile strength (UTS) results revealed a distinct hierarchy in the tensile performance of the composite laminates. The pure glass composite laminate exhibited the highest UTS of 206.65 MPa. Whereas pure sisal composite laminate had the lowest UTS of 58.89 MPa due to the lower tensile capacity of natural sisal fibers. The UTS of the intraply hybrid composite laminate was slightly higher than the interply hybrid composite, i.e. 124.45 and 119.03 MPa respectively. This suggests that the intraply configuration allows for effective load distribution across the fiber layers. But the presence of the weaker sisal fibers reduces the overall tensile strength compared to pure glass.

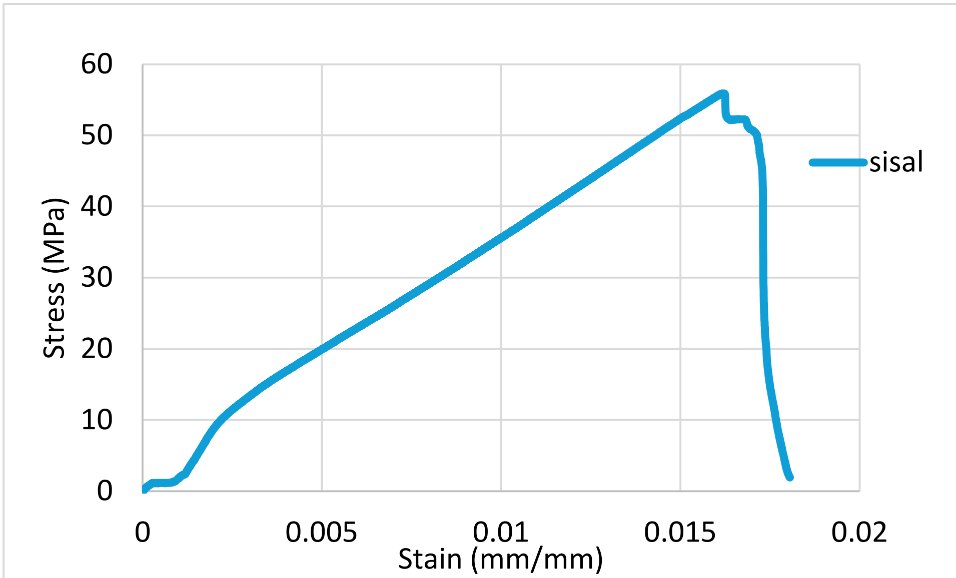


Figure 24: Average Stress-Strain curve of 2 x2 twill woven pure sisal epoxy composite

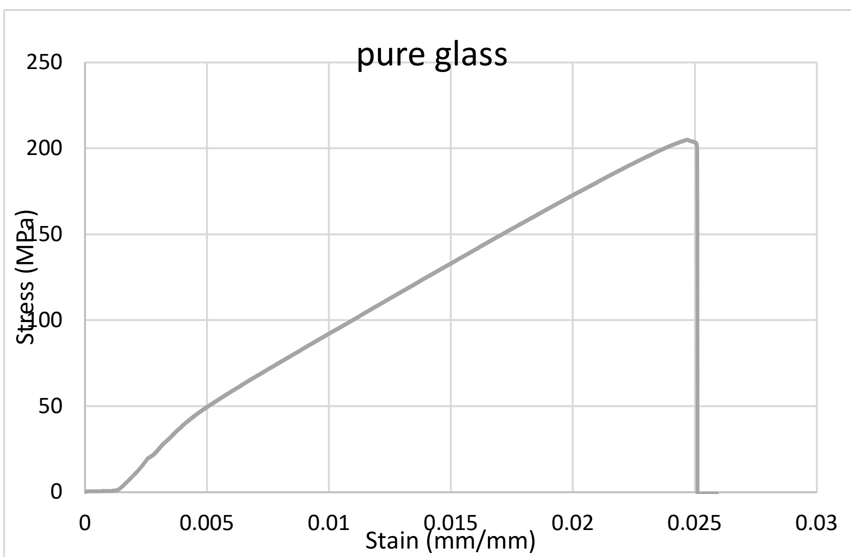


Figure 25: Average Stress-Strain curve of 2 x2 twill woven pure glass epoxy composite

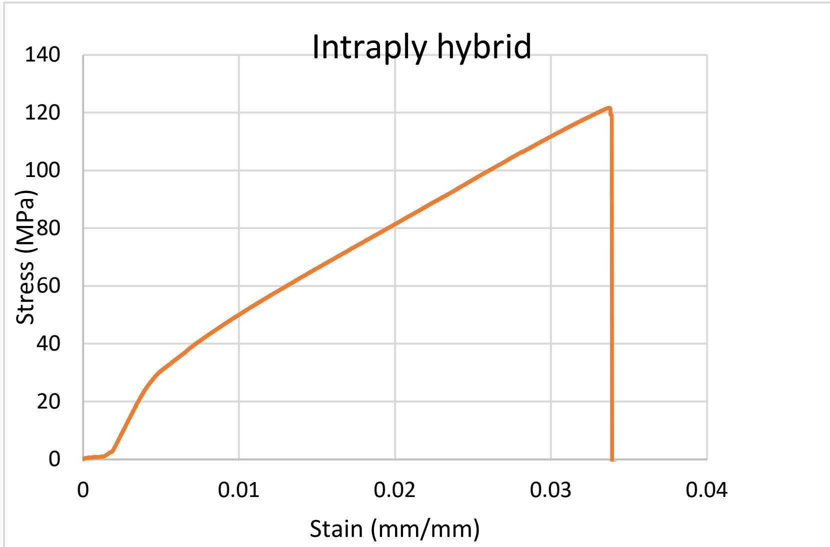


Figure 26: Average Stress-Strain curve of 2 x2 twill woven intraply hybrid glass- sisal epoxy composite specimens

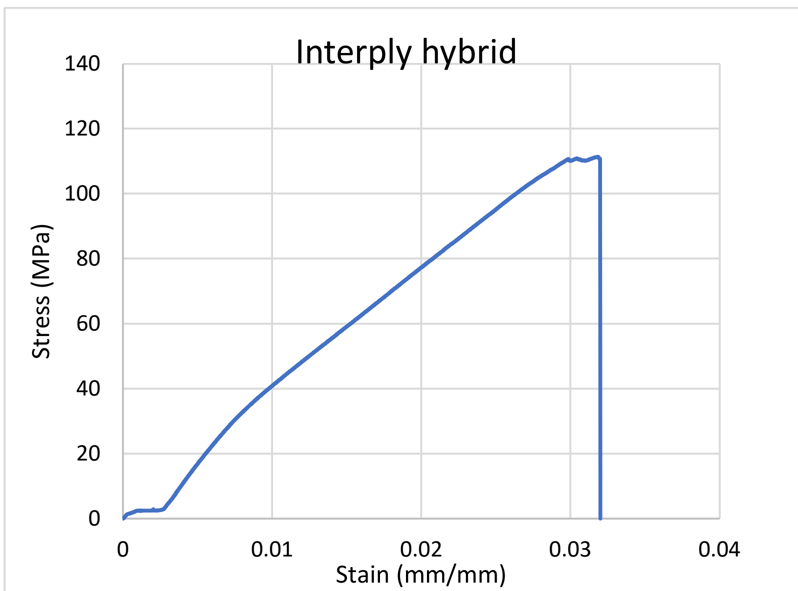


Figure 27: Average Stress-Strain curve of 2 x2 twill woven interply hybrid glass- sisal epoxy composite

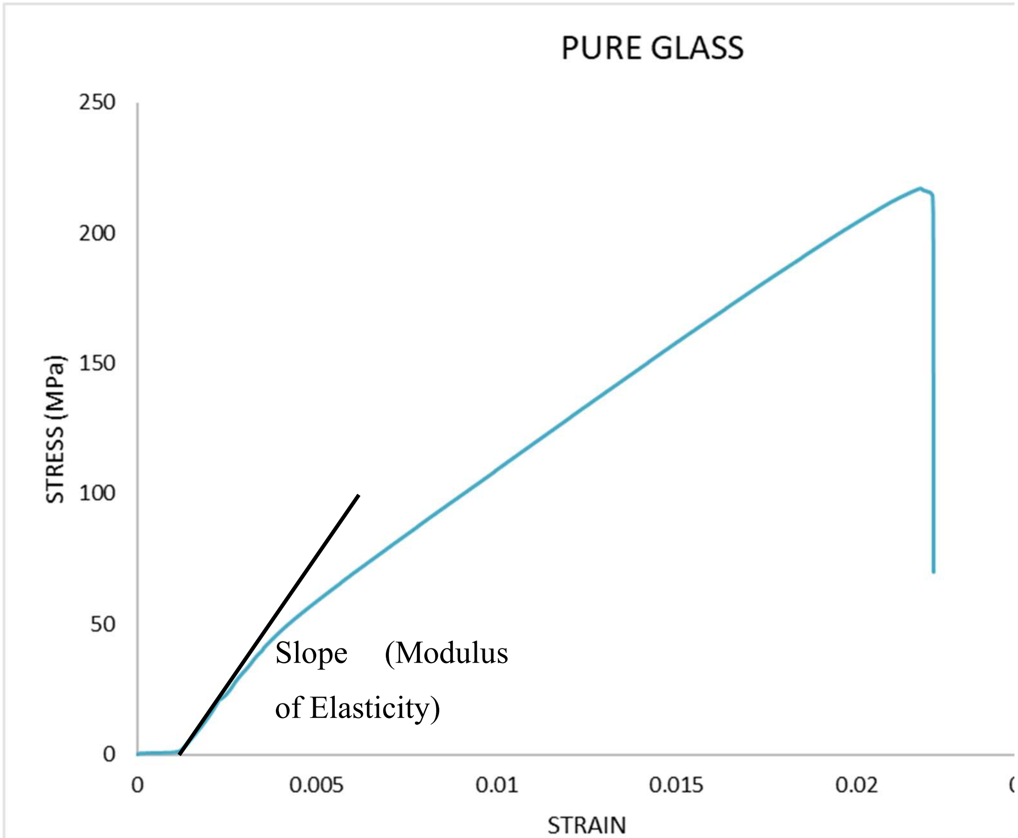


Figure 28: Modulus of Elasticity (slope) of stress strain graph of tensile test

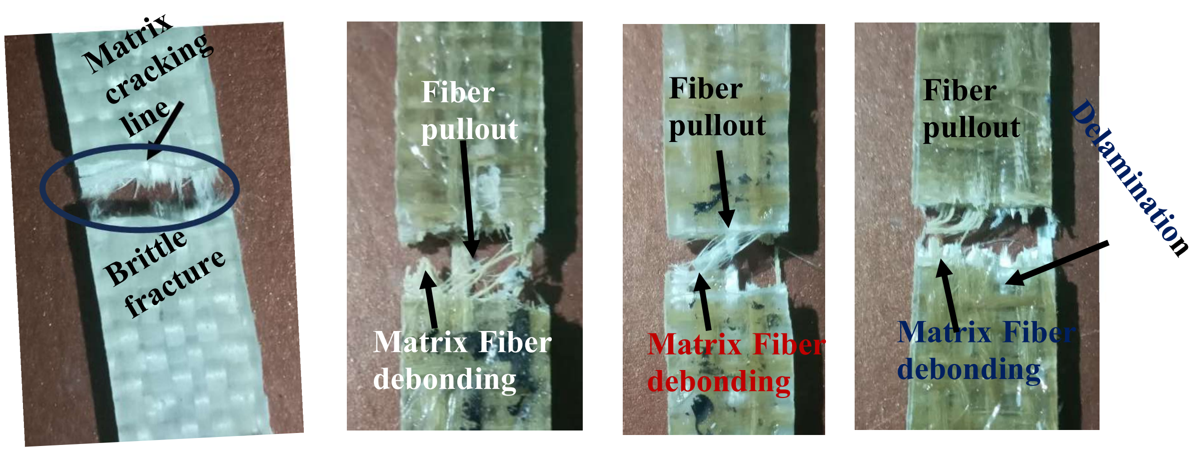
The tensile modulus of the composite laminates followed a similar trend to the UTS. Pure glass composite has the highest modulus of 11.87 GPa. This reflects its stiffness and resistance to deformation under tensile loads. The pure sisal composite showed the lowest tensile modulus, i.e. 4.3GPa. This is indicative of its more flexible nature. The hybrid composites offered an intermediate modulus, suggesting that the combination of sisal and glass fibers provides a balance between stiffness and flexibility, 7.09 GPa for intraply hybrid composite and 5.94GPa for interply hybrid composite.

From the stress-strain graphs it can be seen that the pure glass, intraply hybrid, and interply hybrid composite abruptly rupture after they reach the ultimate tensile stress (UTS). This happened due to the presence of glass fiber in the composite in the hybrid and pure glass epoxy composite. Even though they are known for their stiffness, glass fibers tend to be more brittle, breaking at lower strains. The ductile behavior of the sisal fiber on the other hand, made the pure sisal composite show a different behavior.

Table 3: Tensile properties of composite laminates

Laminate	Ultimate Tensile Strength (MPa)	Tensile Modulus (GPa)
Sisal-Glass Interply Hybrid	119.03	5.94
Sisal-Glass Intraply Hybrid	124.46	7.9
Pure Glass	206.65	11.87
Pure Sisal	206.65	4.3

For the test result it can be deduced that strength of pure sisal epoxy composite increased by 65.87 MPa for intraply and by 55.47 MPa hybridization of sisal with glass. But due to the hybridization the glass with sisal the tensile strength decreased by 83.29 MPa and 93.69 MPa for intraply and interplay hybridization. The intraply hybrid configuration and pure sisal both excel in terms of flexibility. On the other hand, the pure glass and interply hybrid configurations offer ductility.



A B C D

Figure 29: Failure mode of (A) pure glass, (B) pure sisal, (C) intraply hybrid, and (D) interply hybrid composite laminates

Failure mechanisms during tensile testing varied across the composite configuration. Figure 31 depicted the failure modes of all the composite laminates. As depicted in figure 31 (A) pure glass epoxy composite primarily experienced a brittle failure, with fiber breakage and matrix cracking dominating the failure process. It showed almost no sign of fiber pullout which is most probably due to the strong adhesion between glass fiber and the epoxy matrix. However, pure sisal epoxy composite (Figure 31 (B)) showed a more ductile failure, with fiber pull-out and matrix fiber occurring before complete fracture. In addition, delamination between layers was noticed. The intraply hybrid composites displayed a combination of failure modes. As shown in Figure 31(C) it experienced extensive sisal fiber pullout, fiber matrix debonding. With interplay hybrid composite in addition to fiber pullout and fiber matrix debonding delamination occurred between the sisal and glass layers as shown in Figure 31(D). Intraply hybrid showed a better fiber interaction and less severe delamination.

4.2. Compressive Test Result

The results of the compressive tests revealed a similar trend to the tensile results. Pure glass epoxy composite laminate outperformed the other laminates in terms of compressive strength. The pure sisal epoxy composite laminate exhibited the lowest compressive strength. Pure glass and pure sisal composite laminate respectively had 181.82 MPa and 30.91 MPa. Among the hybrid composites the intraply configuration provided a moderate compressive strength performing better than the sisal composite but slightly below the glass composite. The interply and intraply hybrid composites had compressive strengths of 59.97 MPa and 92.76 MPa, respectively.

The figures from Figure 32 to Figure 35 showed the stress strain of each composite laminate. From each figure the slope of the first linear part of the graph indicates the stiffness of the material, i.e. modulus of elasticity. The modulus of elasticity was highest for the glass epoxy composite at 42.855 GPa. The sisal epoxy composite had the lowest modulus of 2.43 GPa. Whereas the interply and intraply hybrids had moduli of 3.16 GPa and 9.51 GPa, respectively.

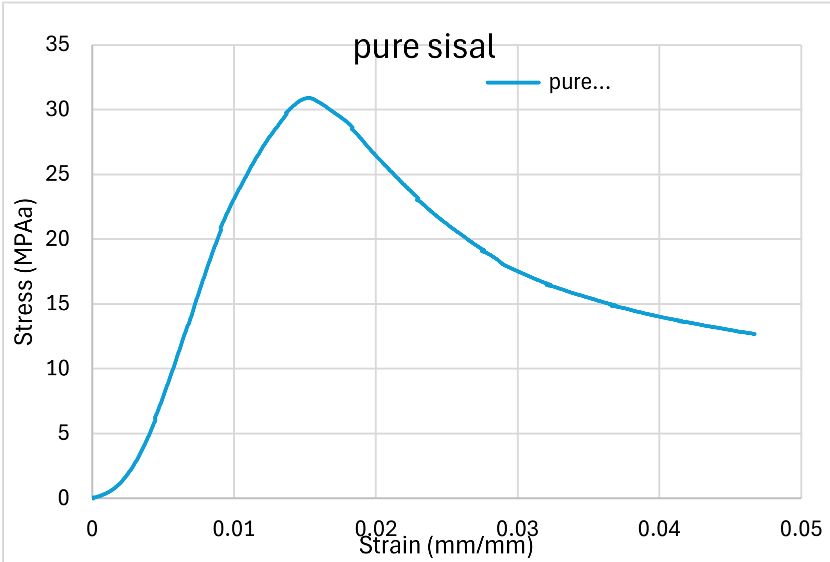


Figure 30: Average Stress-Strain curve of 2 x2 twill woven sisal epoxy composite

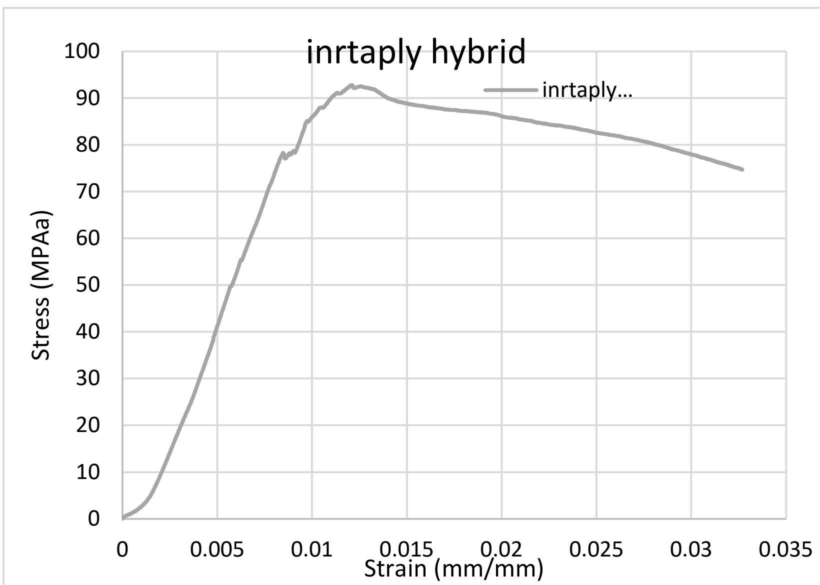


Figure 31: Average Stress-Strain curve of 2 x2 twill woven intraply hybrid glass- sisal epoxy composite

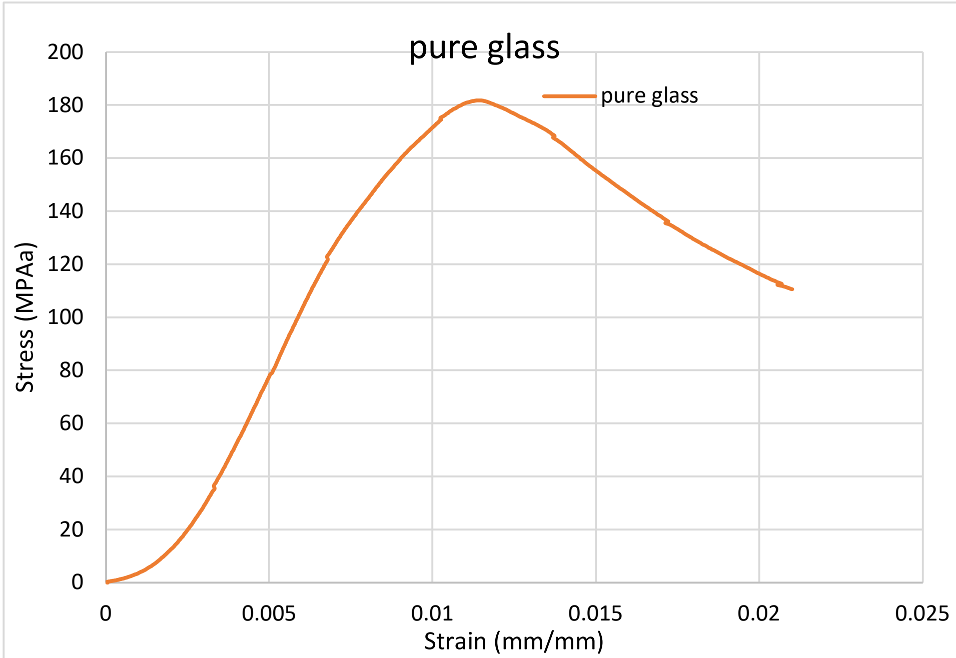


Figure 32: Average Stress-Strain curve of 2 x2 twill woven glass epoxy composite

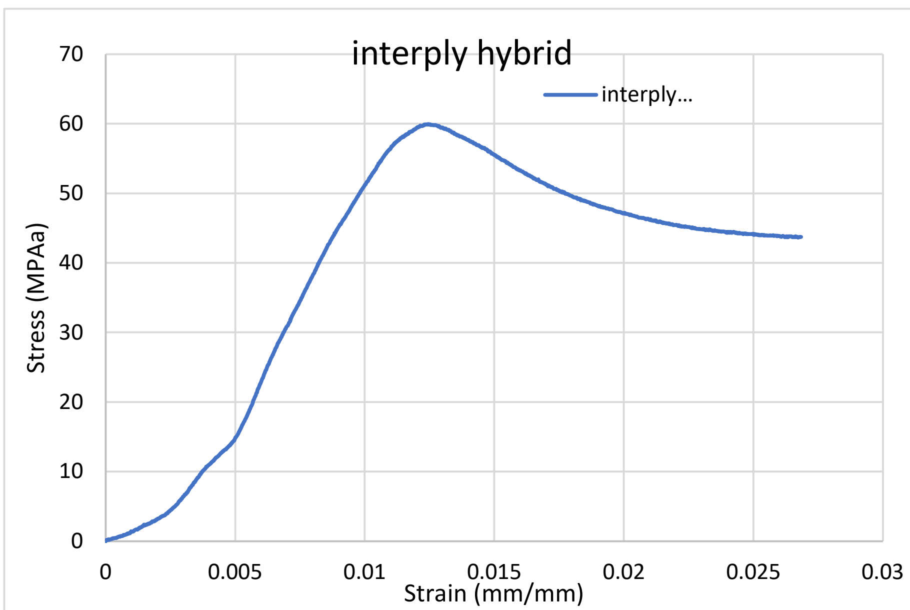


Figure 33: Average Stress-Strain curve of 2 x2 twill woven interply hybrid glass- sisal epoxy composite

The strain at failure for the glass epoxy composite was 0.021. This indicated a relatively low strain tolerance compared to the sisal epoxy composite, which had a strain at failure of 0.0467. The interply and intraply hybrid composites showed strains at failure of 0.0268 and 0.033, respectively. The strain at failure of the hybrid composites were relatively larger than the pure glass composite laminate because of the presence of sisal fiber.

A B C D

Figure 34: compressive test specimen cross section (A) pure sisal, (B) interply hybrid, (C) intraply hybrid, and (D) pure glass composite

The failure modes in compressive testing varied across the composites. The failure modes include fiber buckling, kinking, and matrix cracking, with distinct differences depending on the reinforcement type. From Figure 36 it can be seen that glass fiber composites displayed more brittle fractures, whereas sisal and hybrid composites exhibited more gradual failure. The pure glass composite laminate failed through matrix cracking and fiber crushing. Whereas pure sisal composite laminate experienced fiber kinking and matrix crushing. The hybrid composites demonstrated a combination of these failure modes. Delamination was observed between the fiber layers of the interply hybrid, while intraply hybrid showed fewer delamination issues. This is due to a better load distribution in the intraply hybrid.

The presence of glass fiber significantly enhances the compressive performance of the composite laminates as it can be seen on the results. Due to the natural limitations of sisal fibers in handling compressive load pure sisal laminates demonstrated the lowest compressive strength and modulus. The hybrid laminates, particularly the intraply configuration, performed better than the pure sisal composite. This suggested that this hybrid configuration led to better load-sharing during compression. The higher strength and modulus of intraply laminate compared to the interply configuration suggest that a more integrated distribution of glass and sisal fibers results in improved compressive behavior, as the stiffness of the glass helps to mitigate local buckling of the sisal fibers.

Figure 32 showed that pure sisal laminates undergo more deformation before failure. This comes at the cost of lower overall strength. The hybrid laminates, particularly the intraply configuration, showed a balanced performance with moderate strain at failure and improved strength, suggesting an effective combination of the ductility of sisal and the stiffness of glass fibers. This balance is advantageous for applications requiring both strength and some degree of flexibility.

4.3. In-plane Shear Test Result

The maximum shear stress was determined using the shear load at 5% shear strain point. As shown in figure 38 the maximum shear stress of the composite laminates is marked with vertical broken line. From the result revealed in the figure, the glass epoxy composite had the highest ultimate shear strength of 22.12 MPa, consistent with the strong shear resistance of glass fibers. The sisal epoxy composite exhibited a lower shear strength of 14.97MPa, as expected, while the hybrid composites displayed intermediate shear strength values. The intraply hybrid composite is slightly higher than the interplay hybrid composite, i.e. 19.1 MPa and 17.2 MPa.

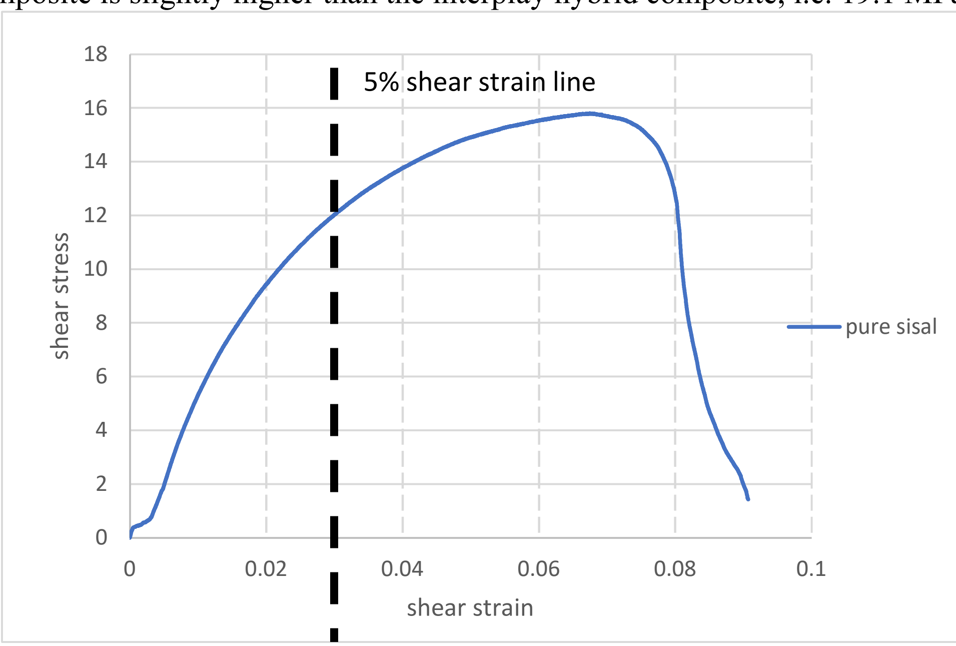


Figure 35: Average Stress-Strain curve of 2 x2 twill woven pure sisal epoxy composite of shear test

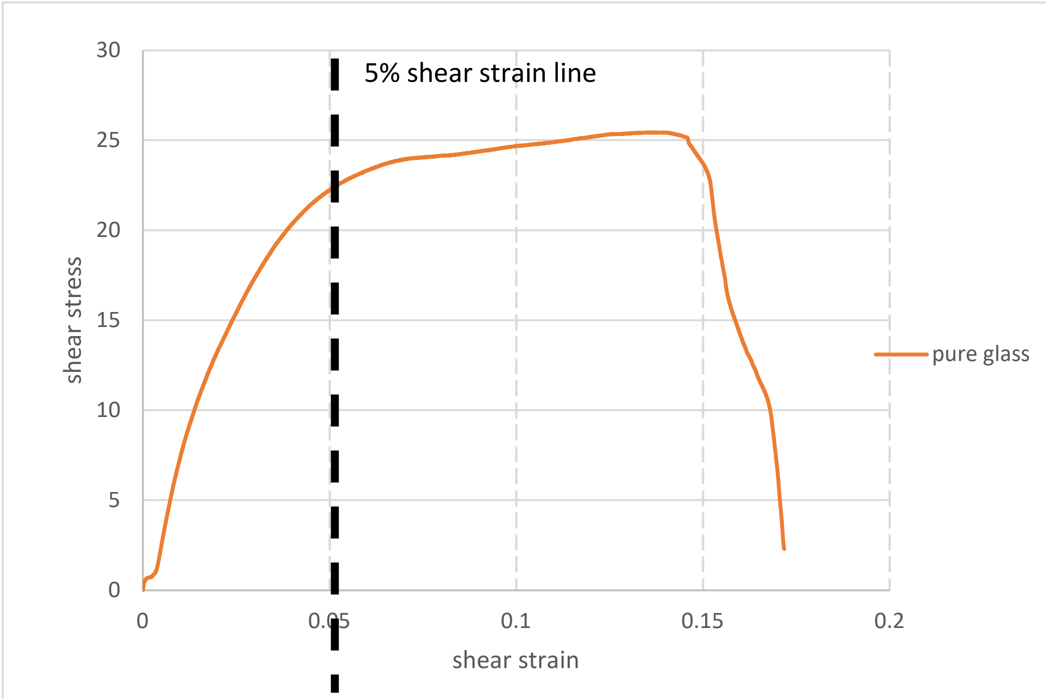


Figure 36: Average Stress-Strain curve of 2 x2 twill woven pure Glass epoxy composite of shear test

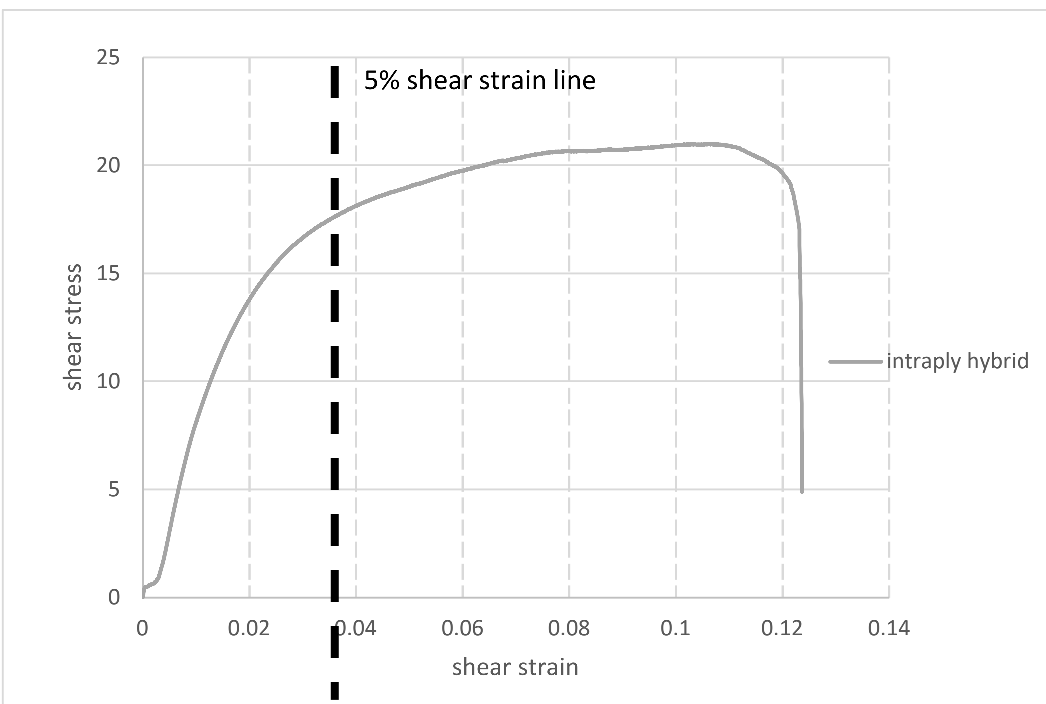


Figure 37: Average Stress-Strain curve of 2 x2 twill woven intraply hybrid epoxy composite of shear test

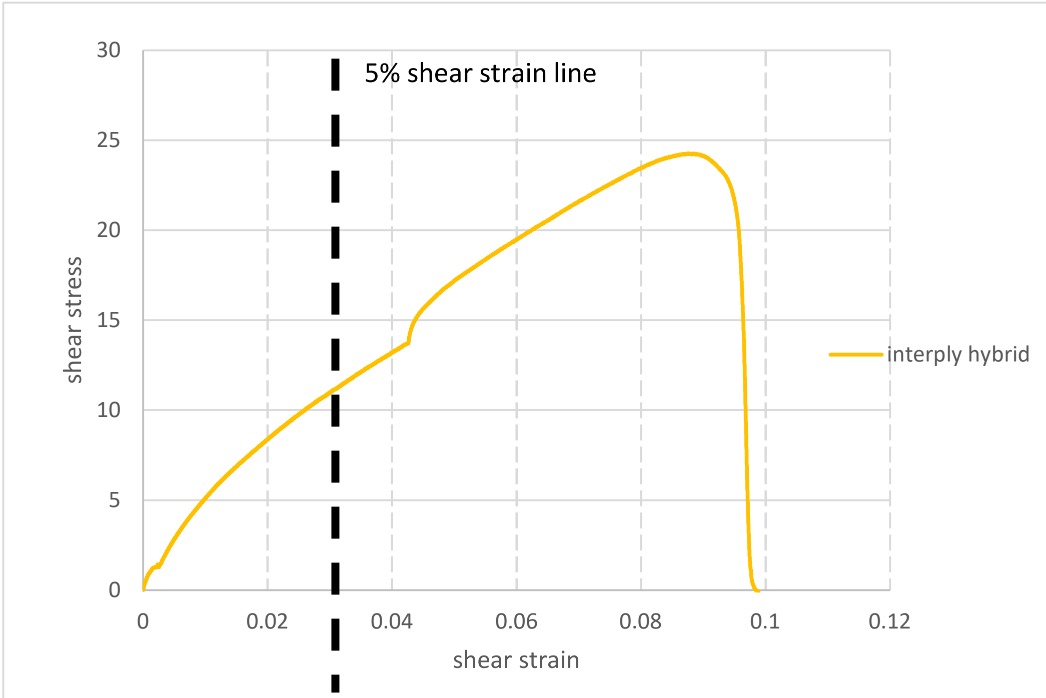


Figure 38: Average Stress-Strain curve of 2 x2 twill woven interply hybrid epoxy composite of shear test

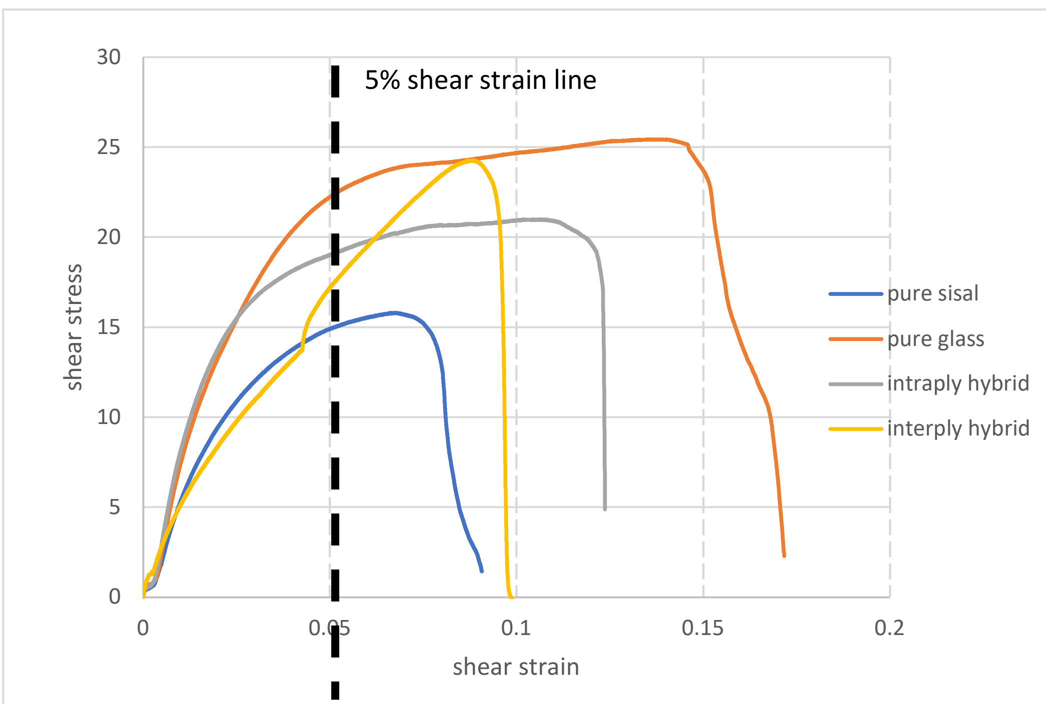
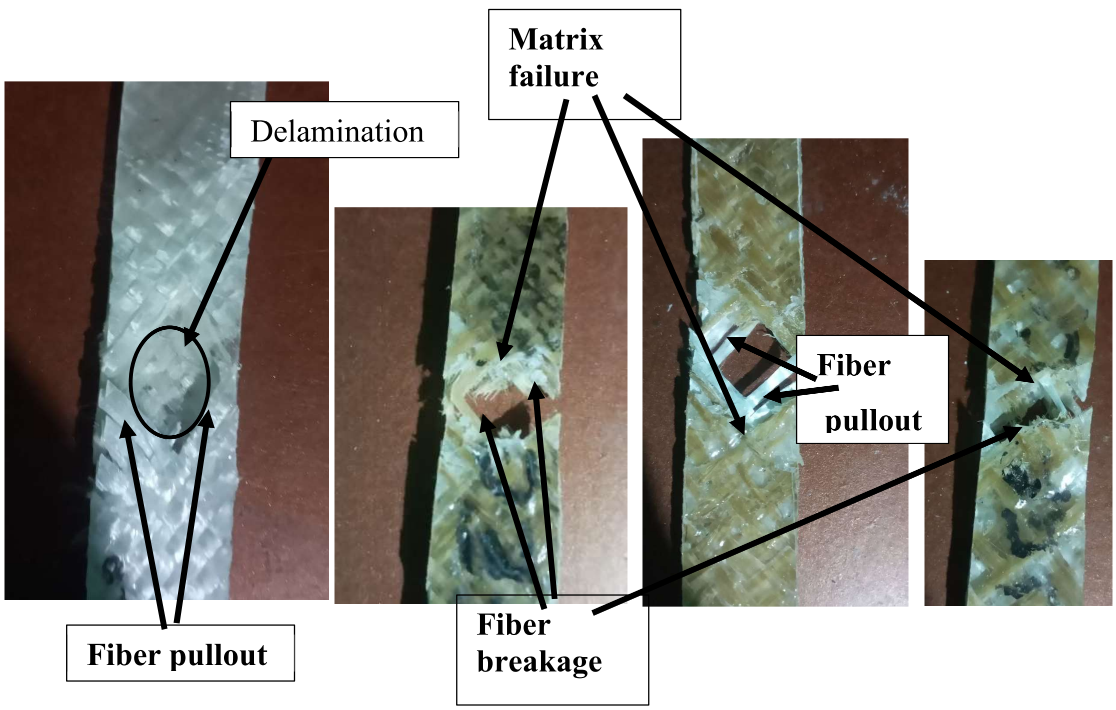


Figure 39: Combined stress stain curve of all composite laminates

The shear modulus results reflected the material's resistance to deformation under shear stress. The glass epoxy composite exhibited the highest shear modulus of 6.18GPa, while the sisal epoxy composite had the lowest 2.14Gpa. The hybrid composites once again provided intermediate shear modulus values intraply (3.91 GPa) slightly higher than interply hybrid (3.26Mpa), suggesting a good compromise between stiffness and flexibility.

Fiber matrix interaction is a major factor for the failure mechanisms observed in the shear tests. Figure 43 depicted that the glass epoxy composite failed primarily through delamination, fiber pullout and matrix cracking, while the sisal and intraply hybrid epoxy composite experienced fiber breaking and matrix failure. The interply hybrid composites showed mixed failure modes, with less severe delamination compared to the pure glass composite.



(A) (B) (C) (D)

Figure 40: Shear tested specimens (A) Glass, (B) Sisal, (C) Interply hybrid, and (D) Intraply hybrid composite

4.4. Quasi static penetration test.

The quasi-static penetration resistance was measured to assess the energy absorption capabilities of each laminate. The energy absorption values calculated from the area under the load-displacement curves for each laminate. The result indicated that the pure glass epoxy composite had the total absorbed energy of 26.969J. This inherent strength and stiffness of glass fibers was responsible for the highest energy absorption. The pure sisal composite laminate had the lowest total absorbed energy of 15.758 J. The interply and intraply hybrid composites laminates had higher energy absorption than pure sisal composites, with the intraply hybrid demonstrated better total energy absorption than the interply configuration, i.e. 22.174 J and 19.676J respectively. The intraply hybrid offered more effective load distribution and gradual failure mechanisms, allowing it to absorb more energy. This highlighted the advantage of hybridization, particularly in the intraply configuration, in enhancing energy absorption.

The energy absorption up to maximum load, which is how much energy the composite can absorb before it reaches its peak load showed the same trend. The pure glass composite absorbed 18.531 J, followed by the interply hybrid 15.671 J, intraply hybrid 12.558 J and pure sisal composite 7.973 J. These results confirm that glass fibers provide more energy absorption before failure. The interply hybrid absorbed more energy up to maximum load than the intraply hybrid, probably because of the alternating layers of sisal and glass fibers in the interply structure which allows better resistance to localized stress before peak load. The lower energy absorption in intraply hybrids may be due to the more distributed fiber arrangement which while good for gradual failure and overall toughness may result to lower energy absorption up to maximum load.

Peak load of the composite laminates is the maximum load the laminates can withstand before failure. The pure glass composite had the highest peak load of 4.188KN, followed by the interply hybrid 3.043 KN, intraply hybrid 2.726KN and pure sisal 1.829KN. The higher peak load of the pure glass composite indicates that glass fibers are better in resisting penetration. Interply hybrid had better peak load than intraply hybrid although intraply hybrid had more balanced performance between strength and energy absorption. The slight reduction in peak load in intraply hybrid may be due to more uniform fiber distribution which leads to more gradual failure mechanism that sacrifices peak strength for toughness.

These values indicate how much each laminate can withstand penetration force and absorb energy. Intraply hybrids with more integrated fibers absorbed more energy than interply hybrid, means better stress distribution and fiber interaction.

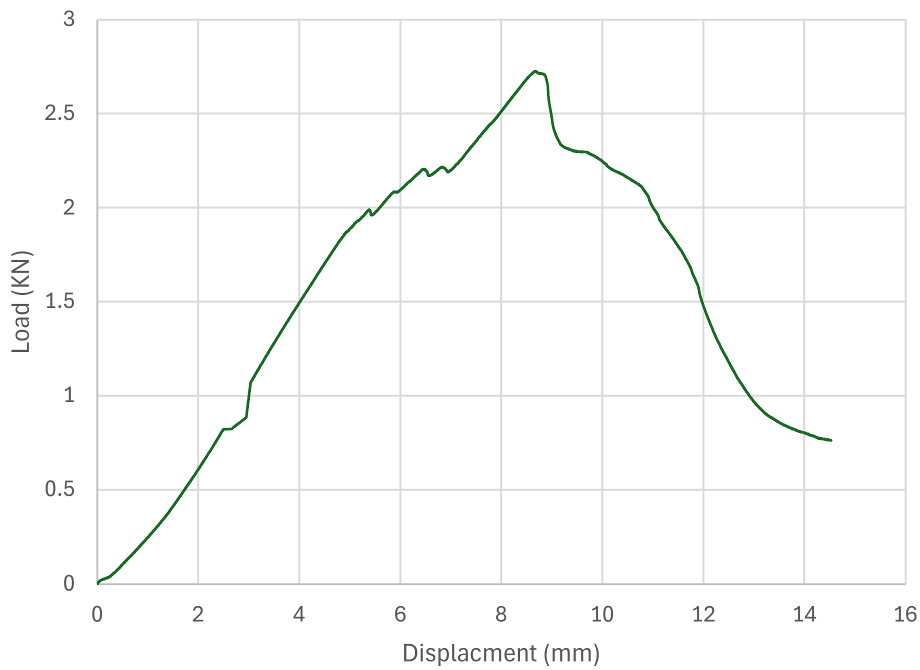


Figure 41: Average Load- Displacement graph of QSPT result of interply hybrid composite

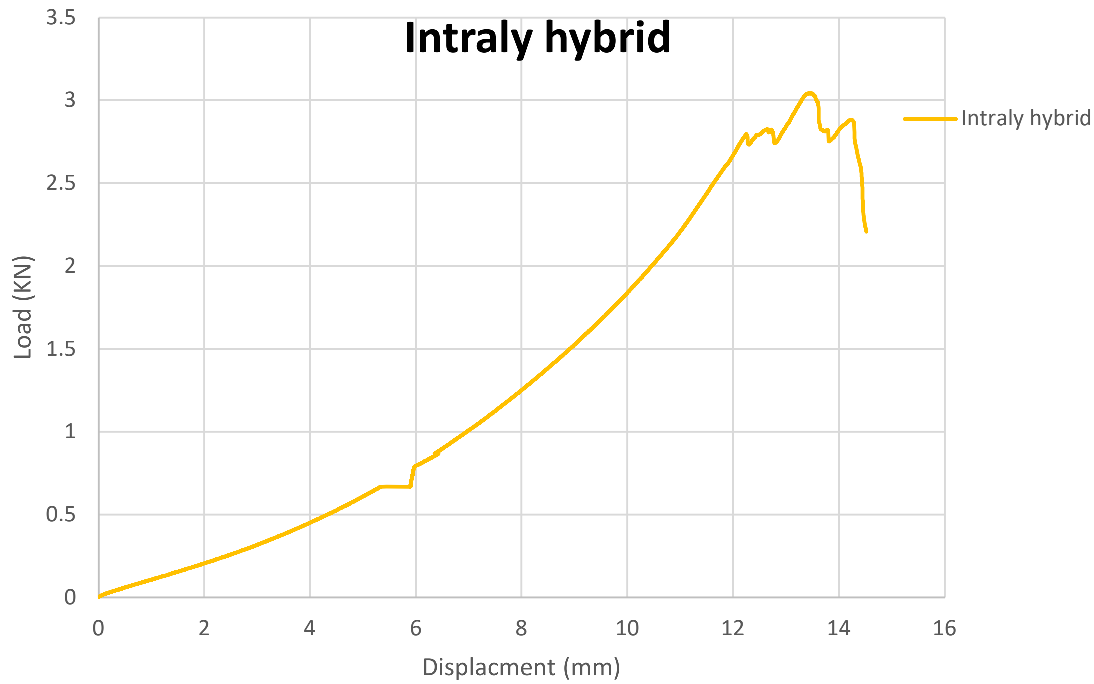


Figure 42: Load- Displacement graph of QSPT result of intraply hybrid composite

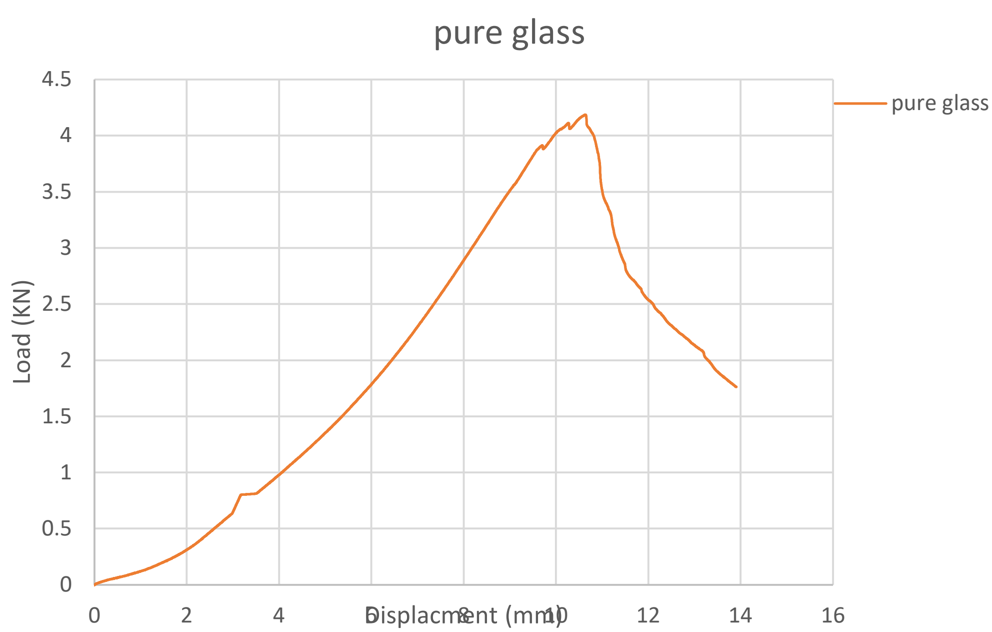


Figure 43: Load-displacement graph of QSPT result of pure glass composite

Figure 44: Load-Displacement graphs of QSPT result of pure sisal composite

In a quasi-static penetration test of fiber-reinforced polymer composites, the load-displacement graph typically exhibits three distinct regions: elastic, damage, and friction regions as depicted in Figure 26. Each region reflects different material responses to the applied load during the penetration process.

In the first region the composite laminates behave elastically, and the laminates experienced an elastic bending. It signifies the initial loading behavior and indicates the material's stiffness and elastic limit. As the load increases beyond the elastic limit, the material enters the damage region. In this region internal damage mechanisms (such as micro-cracking, fiber-matrix debonding, and matrix cracking) begin to occur, and the graph peaks multiple times, which can correspond to the rupture of subsequent reinforcement fibers or destruction of matrix layers, or delamination. The region indicates how well the composite can withstand further loading before catastrophic failure.

The load may level off or even decrease slightly as the punch penetrates the material in the friction region. This behavior is often due to the interaction between the punch and the damaged material. This region highlights the effect of surface interaction and material deformation, showing how friction can influence penetration behavior. Understanding this region can provide insights into the failure mechanisms of composites underload and the potential for energy absorption beyond material failure.

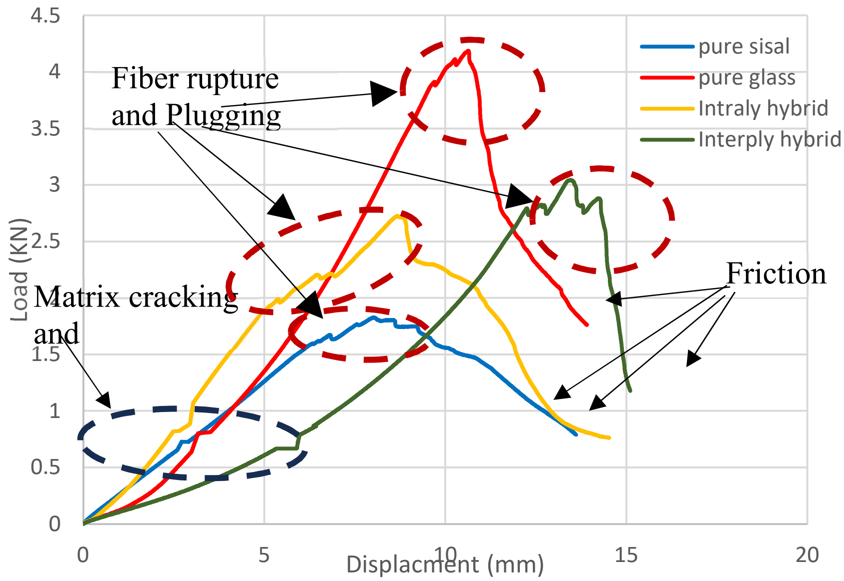


Figure 45: Failure stages of all the composite laminates

Table 4: The total energy absorbed, peak load, and punch shear strength (PSS) of composite laminate

Parameters	Composite laminates			
	Pure glass	Pure sisal	Interply hybrid	Intraply hybrid
Total energy absorbed (J)	26.969	15.758	19.676	22.174
Energy absorbed up to peak load (J)	18.531	7.973	15.671	12.558
Peak load (KN)	4.188	1.829	3.043	2.726
PSS (MPa)	20.508	8.957	14.902	13.35

Even though the laminates have the same three stages of destruction, the shape differences in the load-displacement graphs were observed. This characterizes the quasi-static penetration behavior of the composite laminates. As depicted in figure 45, the course of penetration curve of pure sisal composite laminate has relatively flatter curve, with lack of a clear peak load. Intraply hybrid composite laminate followed nearly similar course as the pure sisal composite laminate but have a noticeable peak. Whereas, due to the presence of glass fabric layers, pure glass and interplay hybrid composite laminates follow relatively the same pattern experiencing a noticeable peak followed by sudden drop of load after formation of plug, except glass has higher peak.

In order for a full interpretation and understanding of the quasi-static penetration resistance of the composite laminates, taking the thickness of the laminates into consideration is necessary. Determination of penetration resistance taking the thickness of laminates can be done by calculating the punch shear strength (PSS) of the laminates as stated in equation 3.27.

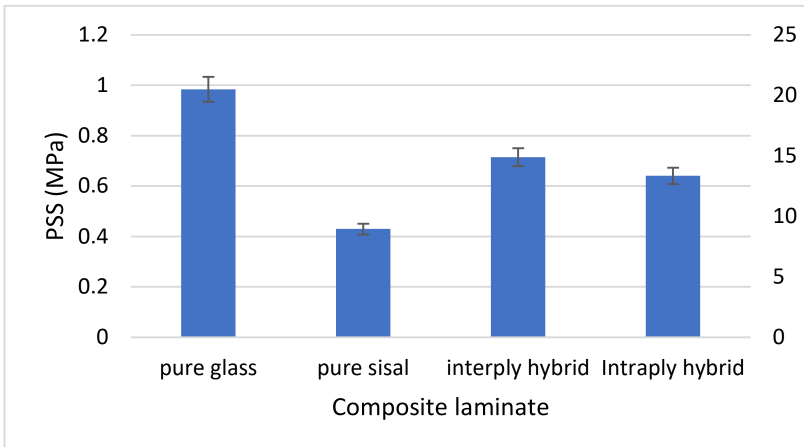
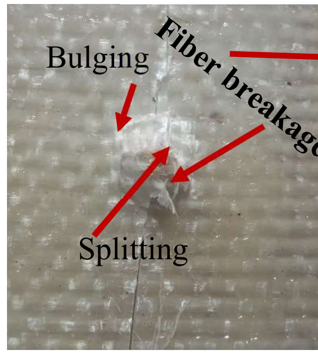
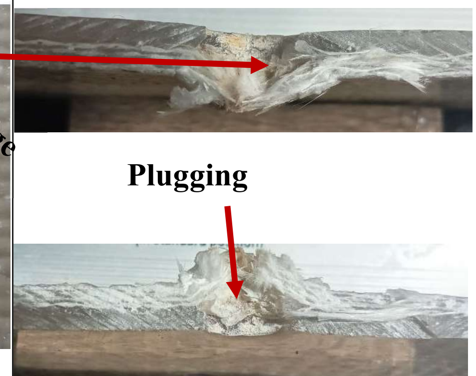
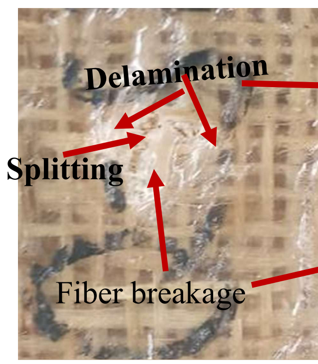
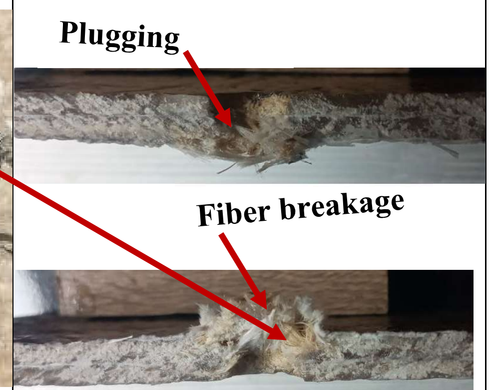


Figure 46: PSS of composite laminates

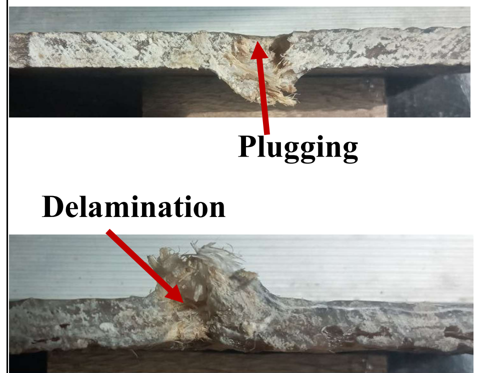
From the result of calculating the punch shear strength, pure glass fiber composite laminates showed the highest resistance of puncture of 20.508MPa. Pure sisal composite laminate, on the other hand, has the lowest puncture resistance of 8.957MPa. Interply hybrid composite once again showed slightly higher punch shear strength of 14.902MPa. This is due to the presence of separate glass and sisal fabric layers. Intraply hybrid composite laminate

The ability of glass fiber to resist shear forces under localized loading led to the highest PSS in the pure glass composite. Whereas the lower mechanical properties of pure sisal composite resulted in the lowest PSS. The interply hybrid configuration demonstrated better shear resistance than the intraply hybrid. Although the latter still outperformed the pure sisal laminate. The more integrated fiber arrangement intraply hybrid resulted in improved stress distribution during penetration, even if it did not reach the same shear resistance as the interply configuration.

Table 5: Front back, back part, and cross-sectional part of the quasi-static penetration test samples

	Front part	Back part	Cross section
Pure glass			
Pure sisal			
Interply hybrid			

Intraply hybrid



The failure modes varied along with the different configurations of composite laminates. The glass epoxy composite exhibited the highest peak load but showed a relatively brittle failure, indicating limited energy absorption post-peak. The sisal epoxy composite, while having a lower peak load, displayed significant energy absorption through mechanisms like fiber pull-out and delamination, which are typical of natural fiber composites. The hybrid laminates provided a balance between strength and energy absorption, with the intraply configuration performing better due to the improved interaction between the glass and sisal fibers. The increased penetration energy in the sisal epoxy composite suggests that the natural fibers contribute significantly to energy dissipation, resulting in a more ductile failure mechanism

Overall, the results of the quasi-static penetration test indicate that while the pure glass composite offers the best performance in terms of peak load, PSS, and energy absorption, hybridization of sisal and glass fibers provides a beneficial balance between strength and toughness. The intraply hybrid composite stands out for its superior energy absorption and balanced performance, making it more suitable for applications requiring both impact resistance and toughness. On the other hand, the interply hybrid composite demonstrates higher peak load and shear strength, which may be advantageous for applications prioritizing structural strength. These results suggest the potential of sisal/glass hybrid composites as a promising material for impact-resistant and load-bearing applications, with the choice of configuration (interply or intraply) depending on the specific performance requirements.

4.5. Comparison of Results of This Study and Other Literature

Table 6 below depicts the mechanical properties and energy absorption of different composites including this study. The studies were done on the hybrid of different natural and synthetic fiber composites. Since the natural fibers possess different properties in different parts of the world, their mechanical performance (properties) and energy absorption capacities can widely vary depending on the location, their content in the composite, method of fabrication, and way of combination of the fibers. Even though there are some difference between the values of results of energy absorption and mechanical properties composite, mostly due to the forementioned reason, the results of this study agree with the previous literature . Our results featuring 30wt% sisal fiber reinforced composites, represent materials and a manufacturing method that are viable for Ethiopia

Table 6: Comparison of Results of This Study and Other Literature

Fiber and matrix	composition	orientation	Test		Ref.
Pure Sisal epoxy	40wt%	Twill weave	Tensile 55.89Mpa	Modulus 4.3GPa	Current work
			Compressive 30.9MPa	2.4 GPa	
			Shear 14.97MPA	2.14 GPa	
			QSPT 15.75J	Peak load 1.8KN	
Pure glass epoxy	40wt%	Twill weave	Tensile 205.89Mpa	Modulus 11.89GPa	Current work
			Compressive 181.8MPa	42.85GPa	
			Shear 22.12MPa	26.18GPa	
			QSPT 26.97J	Peak load 4.18KN	
Intraply hybrid of sisal/glass epoxy	Sisal 20wt% Glass	Twill weave	Tensile 121.7Mpa	Modulus 7.9GPa	

	20wt%		Compressive 92.76MPa	9.51 GPa	Current work
			Shear 19.1MPa	3.91 GPa	
			QSPT 22.17J	Peak load 2.7KN	
Interply hybrid of sisal/glass epoxy	Sisal 20wt% Glass 20wt%	Twill weave	Tensile 119.03Mpa	Modulus 5.94GPa	Current work
			Compressive 59.97MPa	3.16 GPa	
			Shear 17.2MPa	3.26 GPa	
			QSPT 19.68J	Peak load 3.04KN	
Pure sisal epoxy	Sisal 19.1 wt%	Plain weave	Tensile 25.76Mpa	Modulus 2.7GPa	[78]
Interply glass/sisal epoxy (GSG)	Glass 25wt% Sisal 19.1 wt%	Plain weave	Tensile 44.85Mpa	Modulus 3.7GPa	
Pure glass epoxy	Glass 40wt%	continuous	Compressive 57.78Mpa	Modulus 5.7GPa	[79]
Interply glass/sisal epoxy (SGSGS)	Glass 20wt% Sisal 20wt%	unidirectional	Compressive 7.82Mpa	Modulus 2.91GPa	
Pure glass epoxy	Glass 37wt%	woven	Tensile 186Mpa	Modulus 1.28GPa	[71]
Pure sisal epoxy	27wt%	Woven	Tensile 33MPa	Modulus 0.2014GPa	
Interply glass/sisal epoxy (GSSSG)	Glass 19.6wt% Sisal 12.2wt%	Woven	Tensile 98.82Mpa	Modulus 0.72GPa	
Interply glass/sisal epoxy (GSGSG)	Glass 26.15wt% Sisal 7.28wt%	Woven	Tensile 108.22Mpa	Modulus 0.52GPa	

Pure glass epoxy (5G)	Glass 60wt%	woven	Tensile 360Mpa	Modulus 8.9GPa	[80]
Pure jute epoxy(5J)	23wt%	Woven	Tensile 41.8MPa	Modulus 3.15GPa	
Interplyglass/jute epoxy (GJGJG)	Jute 9.66wt% Glass 36.3wt%	Woven	Tensile 163Mpa	Modulus 5.1GPa	
Intraply glass/jute epoxy	Jute 9.66wt% Glass 36.3wt%	Woven	Tensile 174Mpa	Modulus 5.2GPa	
Pure glass epoxy	Glass 50wt%	woven	Tensile 211.5Mpa	Modulus 15.7GPa	[81]
Pure kenaf epoxy	25wt%	Woven	Tensile 41.5MPa	Modulus 6GPa	
			Compressive 77MPa	11.72GPa	
Interply glass/kenaf epoxy	Jute 16.6wt% Glass 19.5wt%	Woven	Tensile 83Mpa	Modulus 3.7GPa	
			Compressive 80MPa	11.6GPa	
			Compressive 185MPa	10.2GPa	
Pure Jute epoxy	Jute 40wt%	woven	Tensile 52.55Mpa	Modulus 1.2GPa	[84]
			In plane Shear 9.3MPa	0.67GPa	
Jute/glass hybrid epoxy	Jute 20wt% Glass 20wt%	Woven	Tensile 146.5MPa	Modulus 2.5GPa	
			In plane Shear 71.1MPa	1.2GPa	
Pure glass epoxy	Glass 37wt%	unidirectional	Shear 26.8Mpa	Modulus 3.8GPa	[85]
		Random	Shear 57.76MPa	Modulus 3.15GPa	

Pure Glass epoxy	Glass 69wt%	woven	QSPT 20.5J	Peak load 2.4KN	[84]
Intraply flax/glass hybrid epoxy	52wt%	Woven	QSPT 20J	Peak load 1.6KN	
Interply flax/glass hybrid epoxy	55wt%	Woven	QSPT 19J	Peak load 1.8KN	

UNIT FIVE

CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

This study has investigated the mechanical properties and energy absorption of 2x2 twill woven sisal/glass hybrid epoxy composites in interply and intraply hybrid configurations. It looked into the behavior of these composites under tensile, compressive, shear and quasi-static penetration loading. From the result of the experiment the following conclusions are drawn:

- Intraply hybrid composite outperformed interply hybrid in tensile strength, i.e. 121.75MPa & 11.36MPa. It showed a balance of glass fiber strength and sisal flexibility with much better tensile performance than pure sisal composite. But both hybrid configurations are outperformed by pure glass composite, 206.65MPa. This means hybridization especially in intraply configuration allows better load distribution between the fibers
- In compression, the pure glass composite showed the highest compressive strength of181.82MPa. Pure sisal composite was the weakest (30.91MPa), but the hybrid composites were in the middle again. Intraply was 54.7% better than interply hybrid composite (59.97MPa), likely due to more effective load sharing between fibers, reducing fiber buckling and matrix cracking.
- In-plane shear testing showed that pure glass composites were the strongest shear resistant of 22.12MPa, pure sisal composite was the weakest with 14.97 MPa. Hybrid composites were better than pure sisal, intraply was 11.04% better than interply hybrid composite (17.2MPa). Fiber-matrix bonding and woven architecture helped the hybrid laminates.
- The quasi-static penetration test results showed that the pure glass had the highest peak load of 4.19 KN, total energy absorption of 26.97 J, energy absorbed up to peak load of 18.53 J, and punch shear strength of 20.51 MPa. Pure sisal had the lowest in all parameters. The hybrid composites were in between, the intraply hybrid had higher total energy absorption (22.17 J) than interply hybrid (19.68J), while interply hybrid had

higher peak load of 3.04 KN and punch shear strength of 14.9MPa than intraply hybrid composite (2.7 KN &13.33 MPa).

5.2. Recommendations

Based on the findings of this study, several practical recommendations can be made regarding the potential applications and further development of 2x2 twill woven sisal/glass hybrid epoxy composites:

- Intraply hybrid composites have balance between energy absorption and mechanical strength so are ideal for applications where impact resistance and light weight are key such as automotive (bumpers, door panels) and sports (helmets, protective gear).
- Interply hybrid composites with their high load bearing and shear strength are better suited for structural applications in construction where materials need to withstand compressive and shear forces. Examples are wall panels, flooring systems and light weight support structures.
- Since sisal is eco friendly, hybrid composites with high natural fiber content can be used in green design projects, green buildings and eco friendly consumer products where both environmental and performance are key.

5.3. Future Work

This study conducted experimental investigation of tensile, compressive, and shear performance, and energy absorption of a 2X2 twill woven sisal glass hybrid epoxy composite, focusing on interply and intraply hybrid. Through this the study investigated the effect of hybrid configurations of the fabrics on the mechanical and energy absorption performance of the composites. The following are the possible study areas as an extension of this study.

- Fiber Volume Fraction Optimization: More research is needed to optimize the fiber volume fraction of sisal and glass fibers in hybrid composites. Varying the natural to synthetic fiber ratio will help to fine tune the mechanical properties and energy absorption for specific application requirements.

- Dynamic Impact: Future work should focus on dynamic impact, especially high-speed impact to simulate real life scenarios like vehicle crash or ballistic impact. This will give a better understanding of the composite's energy absorption and failure mechanisms.
- Other Weave Architectures: Investigation of other weave patterns like satin or basket weaves to see if the mechanical properties can improve and tailor the composites to specific applications.
- Hybridization with Other Natural Fibers: Hybridizing glass fibers with other natural fibers like jute, hemp or flax will give insight into how different natural fibers affect the mechanical performance and sustainability of the composite.
- Environmental Testing and Durability: Long term durability testing including testing under extreme environmental conditions (e.g. high humidity, UV exposure, thermal cycling) is necessary to see how the material ages and weathers. How the material performs over time in these conditions is critical for outdoor and structural applications.

REFERENCE

1. Vigneshwaran, S., et al., *Recent advancement in the natural fiber polymer composites: A comprehensive review.* Journal of Cleaner Production, 2020. **277**: p. 124109.
2. Aisyah, H., et al., *A comprehensive review on advanced sustainable woven natural fiber polymer composites.* Polymers, 2021. **13**(3): p. 471.
3. Gudayu, A.D., et al., *Sisal fiber reinforced polyethylene terephthalate composites; Fabrication, characterization and possible application.* Polymers and Polymer Composites, 2022. **30**: p. 09673911221103317.
4. Senthilkumar, K., et al., *Mechanical properties evaluation of sisal fiber reinforced polymer composites: A review.* Construction and Building Materials, 2018. **174**: p. 713-729.
5. Mishra, V. and S. Biswas, *Physical and mechanical properties of bi-directional jute fiber epoxy composites.* Procedia engineering, 2013. **51**: p. 561-566.
6. Satapathy, A., et al., *Processing and characterization of jute-epoxy composites reinforced with SiC derived from rice husk.* Journal of Reinforced Plastics and Composites, 2010. **29**(18): p. 2869-2878.
7. Fiore, V., et al., *A new eco-friendly chemical treatment of natural fibers: Effect of sodium bicarbonate on properties of sisal fiber and its epoxy composites.* Composites Part B: Engineering, 2016. **85**: p. 150-160.
8. Ahmed, M.M., et al., *Enhancement of impact toughness and damage behaviour of natural fiber reinforced composites and their hybrids through novel improvement techniques: A critical review.* Composite Structures, 2021. **259**: p. 113496.
9. Naveen, J., et al., *Mechanical and physical properties of sisal and hybrid sisal fiber-reinforced polymer composites*, in *Mechanical and physical testing of biocomposites, fiber-reinforced composites and hybrid composites*. 2019, Elsevier. p. 427-440.
10. Das, S.C., et al., *Effect of stacking sequence on the performance of hybrid natural/synthetic fiber reinforced polymer composite laminates.* Composite Structures, 2021. **276**: p. 114525.
11. Yahaya, R., et al., *Effect of fiber orientations on the mechanical properties of kenaf–aramid hybrid composites for spall-liner application.* Defence Technology, 2016. **12**(1): p. 52-58.
12. John, K. and S.V. Naidu, *Tensile properties of unsaturated polyester-based sisal fiber–glass fiber hybrid composites.* Journal of Reinforced Plastics and Composites, 2004. **23**(17): p. 1815-1819.
13. Ismail, S.O., E. Akpan, and H.N. Dhakal, *Review on natural plant fibers and their hybrid composites for structural applications: Recent trends and future perspectives.* Composites Part C: Open Access, 2022: p. 100322.

14. Shamsuyeva, M., O. Hansen, and H.-J. Endres, *Review on hybrid carbon/flax composites and their properties.* International Journal of Polymer Science, 2019. **2019**.

15. Maier, R. and A.-C. Mandoc, *Investigation on layer hybridization of glass/carbon fiber woven reinforced composites subjected to low-speed impact.* Journal of Composites Science, 2023. **7**(2): p. 83.

16. Rajesh, M., S.P. Singh, and J. Pitchaimani, *Mechanical behavior of woven natural fiber fabric composites: Effect of weaving architecture, intra-ply hybridization and stacking sequence of fabrics.* Journal of Industrial Textiles, 2018. **47**(5): p. 938-959.

17. Md Shah, A.U., M.T. Hameed Sultan, and S.N.A. Safri, *Experimental evaluation of low velocity impact properties and damage progression on bamboo/glass hybrid composites subjected to different impact energy levels.* Polymers, 2020. **12**(6): p. 1288.

18. Rajak, D.K., et al., *Fiber-reinforced polymer composites: Manufacturing, properties, and applications.* Polymers, 2019. **11**(10): p. 1667.

19. Parbin, S., et al., *Mechanical properties of natural fiber reinforced epoxy composites: A review.* Procedia Computer Science, 2019. **152**: p. 375-379.

20. Rashdi, A., et al., *Combined Effects of Water Absorption Due to Water Immersion, Soil Buried and Natural Weather on Mechanical Properties Of Kenaf Fiber Unsaturated Polyester Composites (KFUPC).* International Journal of Mechanical and Materials Engineering, 2010. **5**(1): p. 11-17.

21. Kumar, A. and A. Srivastava, *Preparation and mechanical properties of jute fiber reinforced epoxy composites.* Industrial Engineering & Management, 2017. **6**(234): p. 2169-0316.1000234.

22. Soutis, C., *Carbon fiber reinforced plastics in aircraft construction.* Materials Science and Engineering: A, 2005. **412**(1-2): p. 171-176.

23. Akter, M., M.H. Uddin, and H.R. Anik, *Plant fiber-reinforced polymer composites: a review on modification, fabrication, properties, and applications.* Polymer Bulletin, 2023: p. 1-85.

24. GangaRao, H., *Infrastructure applications of fiber-reinforced polymer composites*, in *Applied Plastics Engineering Handbook*. 2017, Elsevier. p. 675-695.

25. Chen, A.Y., et al., *Carbon-fiber reinforced polymer composites: A comparison of manufacturing methods on mechanical properties.* International Journal of Lightweight Materials and Manufacture, 2021. **4**(4): p. 468-479.

26. Alsayed, S., et al., *Performance of glass fiber reinforced polymer bars under elevated temperatures.* Composites Part B: Engineering, 2012. **43**(5): p. 2265-2271.

27. Rajesh, M. and J. Pitchaimani, *Mechanical properties of natural fiber braided yarn woven composite: comparison with conventional yarn woven composite.* Journal of Bionic Engineering, 2017. **14**(1): p. 141-150.

28. Joseph, P., K. Joseph, and S. Thomas, *Effect of processing variables on the mechanical properties of sisal-fiber-reinforced polypropylene composites.* Composites science and Technology, 1999. **59**(11): p. 1625-1640.

29. Rezaei, F., et al., *Customized carbon fiber-reinforced polymer laminates for orthotropic plates using a variable-angle tow placement strategy.* Composites Part B: Engineering, 2018. **151**: p. 242-253.

30. Safri, S.N.A., et al., *Impact behaviour of hybrid composites for structural applications: A review.* Composites Part B: Engineering, 2018. **133**: p. 112-121.

31. Belarbi, A., M. Dawood, and B. Acun, *Sustainability of fiber-reinforced polymers (FRPs) as a construction material*, in *Sustainability of construction materials*. 2016, Elsevier. p. 521-538.

32. Ahmad, H., et al. *A review of carbon fiber materials in automotive industry*. in *IOP Conference Series: Materials Science and Engineering*. 2020. IOP Publishing.

33. Fang, H., et al., *Connections and structural applications of fiber reinforced polymer composites for civil infrastructure in aggressive environments.* Composites Part B: Engineering, 2019. **164**: p. 129-143.

34. Kaufmann, J., *New Materials for sports equipment made of anisotropic fiber-reinforced plastics with stiffness related coupling effect.* Procedia engineering, 2015. **112**: p. 140-145.

35. Betelie, A.A., et al., *Mechanical properties of sisal-epoxy composites as functions of fiber-to-epoxy ratio.* AIMS Materials Science, 2019. **6**(6): p. 985-996.

36. Maurya, H.O., et al., *Study on the mechanical properties of epoxy composite using short sisal fiber.* Materials Today: Proceedings, 2015. **2**(4-5): p. 1347-1355.

37. Ratim, S., N. Bonnia, and S. Surip. *The effect of woven and non-woven fiber structure on mechanical properties polyester composite reinforced kenaf*. in *AIP Conference Proceedings 2nd*. 2012. American Institute of Physics.

38. Masudur Rahman, A., A. Ruhul, and S. Alimuzzaman, *Effect of Weave Structure and Yarn Density on Mechanical Attributes of Jute Fabric Reinforced Polypropylene Composites.* Journal of Textile Science & Engineering, 2018. **8**(1).

39. Venkatesan, K. and G.B. Bhaskar, *Evaluation and Comparison of Mechanical Properties of Natural Fiber Abaca-sisal Composite.* Fibers and Polymers, 2020. **21**(7): p. 1523-1534.

40. Asfaw, K.G., *Investigation of the reasons for the unique growth and development of agave species (Agave sisalana and Agave americana) crop plants at the southern, central, north western and eastern parts of Tigray, Ethiopia.* Current Research Journal of Biological Sciences, 2011. **3**(4): p. 273-281.

41. Puttegowda, M., et al., *Potential of natural/synthetic hybrid composites for aerospace applications*, in *Sustainable composites for aerospace applications*. 2018, Elsevier. p. 315-351.

42. Li, Y., Y.-W. Mai, and L. Ye, *Sisal fiber and its composites: a review of recent developments.* Composites science and technology, 2000. **60**(11): p. 2037-2055.

43. Ekundayo, G. and S. Adejuyigbe, *Reviewing the development of natural fiber polymer composite: a case study of sisal and jute.* American Journal of Mechanical and Materials Engineering, 2019. **3**(1): p. 1.

44. FAO, *Jute, kenaf, sisal, abaca, coir and allied fibers Statistical bulletin 2021*, in *Jute, kenaf, sisal, abaca, coir and allied fibers Statistical bulletin*. 2022, FAO: Rome.

45. Akram Khan, M., et al., *Characterisation studies and impact of chemical treatment on mechanical properties of sisal fiber.* Composite Interfaces, 2011. **18**(6): p. 527-541.

46. Favaro, S., et al., *Chemical, morphological and mechanical analysis of sisal fiber-reinforced recycled high-density polyethylene composites.* Express Polymer Letters, 2010. **4**(8).

47. Drzal, L.T., *Natural fibers, biopolymers, and biocomposites*. 2005: CRC press.

48. Saxena, M., et al., *Sisal fiber based polymer composites and their applications*, in *Cellulose fibers: Bio-and nano-polymer composites*. 2011, Springer. p. 589-659.

49. Ibrahim, I.D., et al., *Mechanical properties of sisal fiber-reinforced polymer composites: a review.* Composite Interfaces, 2016. **23**(1): p. 15-36.

50. Rong, M.Z., et al., *The effect of fiber treatment on the mechanical properties of unidirectional sisal-reinforced epoxy composites.* Composites Science and technology, 2001. **61**(10): p. 1437-1447.

51. Prasad, M.G., et al., *Investigation of mechanical properties of sisal fiber reinforced polymer composites.* Advanced Journal of Graduate Research, 2017. **1**(1): p. 40-48.

52. Mohanty, A.K., M. Misra, and L.T. Drzal, *Natural fibers, biopolymers, and biocomposites*. 2005: CRC press.

53. Li, X., L.G. Tabil, and S. Panigrahi, *Chemical treatments of natural fiber for use in natural fiber-reinforced composites: a review.* Journal of Polymers and the Environment, 2007. **15**: p. 25-33.

54. Gassan, J. and A.K. Bledzki, *Possibilities for improving the mechanical properties of jute/epoxy composites by alkali treatment of fibers.* Composites Science and Technology, 1999. **59**(9): p. 1303-1309.

55. Holbery, J. and D. Houston, *Natural-fiber-reinforced polymer composites in automotive applications.* Jom, 2006. **58**(11): p. 80-86.

56. Rana, R., S. Rana, and R. Purohit, *Characterization of properties of epoxy sisal/glass fiber reinforced hybrid composite.* Materials Today: Proceedings, 2017. **4**(4): p. 5445-5451.

57. Azman, M., et al., *Natural fiber reinforced composite material for product design: A short review.* Polymers, 2021. **13**(12): p. 1917.

58. Ahmed, U., et al., *Comparison of mechanical behavior of biaxial, unidirectional and standard woven fabric reinforced composites.* Fibers and Polymers, 2020. **21**: p. 1308-1315.

59. Yaakob, M.Y., *A Review on Potential of Development New Weave Pattern Design using Glass Fiber and Kenaf Fiber for Intraply Composite.* International Journal of Integrated Engineering, 2015. **7**(2).

60. Chowdhury, I.R. and J. Summerscales, *Woven Fabrics for Composite Reinforcement: A Review.* Journal of Composites Science, 2024. **8**.

61. Arumugam, S., et al., *A Review on the Effect of Fabric Reinforcement on Strength Enhancement of Natural Fiber Composites.* 2022.

62. Hasan, K.F., P.G. Horváth, and T. Alpár, *Potential fabric-reinforced composites: a comprehensive review.* Journal of Materials Science, 2021. **56**(26): p. 14381-14415.

63. Cox, B.N. and G. Flanagan, *Handbook of analytical methods for textile composites*. 1997.

64. Jawaid, M. and H.A. Khalil, *Cellulosic/synthetic fiber reinforced polymer hybrid composites: A review.* Carbohydrate polymers, 2011. **86**(1): p. 1-18.

65. Arjun, K., S. de Barros, and S. Budhe, *Theoretical determination of elastic and flexural modulus for inter-ply and intra-ply hybrid composite material.* Composite Structures, 2022. **281**: p. 114971.

66. Pegoretti, A., et al., *Intraply and interply hybrid composites based on E-glass and poly (vinyl alcohol) woven fabrics: tensile and impact properties.* Polymer International, 2004. **53**(9): p. 1290-1297.

67. Uzay, Ç., D. Acer, and N. Geren, *Impact strength of interply and intraply hybrid laminates based on carbon-aramid/epoxy composites.* European Mechanical Science, 2019. **3**(1): p. 1-5.

68. Selver, E., H. Dalfi, and Z. Yousaf, *Investigation of the impact and post-impact behaviour of glass and glass/natural fiber hybrid composites made with various stacking sequences: Experimental and theoretical analysis.* Journal of Industrial Textiles, 2022. **51**(8): p. 1264-1294.

69. Neto, J., et al., *A review of recent advances in hybrid natural fiber reinforced polymer composites.* Journal of Renewable Materials, 2022. **10**(3): p. 561.

70. Attia, M.A., et al., *Hybrid composite laminates reinforced with flax-basalt-glass woven fabrics for lightweight load bearing structures.* Journal of Industrial Textiles, 2022. **51**(3_suppl): p. 4622S-4664S.

71. Arpitha, G., et al., *Hybridization effect of sisal/glass/epoxy/filler based woven fabric reinforced composites.* Experimental Techniques, 2017. **41**(6): p. 577-584.

72. Santhanam, V., et al., *Experimental investigation on the mechanical properties of woven hybrid fiber reinforced epoxy composite.* Materials Today: Proceedings, 2021. **37**: p. 1850-1853.

73. Kim, J.-K. and M.-L. Sham, *Impact and delamination failure of woven-fabric composites.* Composites Science and Technology, 2000. **60**(5): p. 745-761.

74. Davies, G., D. Hitchings, and G. Zhou, *Impact damage and residual strengths of woven fabric glass/polyester laminates.* Composites Part A: Applied Science and Manufacturing, 1996. **27**(12): p. 1147-1156.

75. Raja, N. and K. Kumar. *Estimation of Tensile and Compression Properties of 2D Woven Jute and Kevlar Hybrid Laminate*. in *IOP Conference Series: Materials Science and Engineering*. 2020. IOP Publishing.

76. Karahan, M. and N. Karahan, *Effect of weaving structure and hybridization on the low-velocity impact behavior of woven carbon-epoxy composites.* Fibers & Textiles in Eastern Europe, 2014.

77. Aisyah, H., et al., *Effects of fabric counts and weave designs on the properties of laminated woven kenaf/carbon fiber reinforced epoxy hybrid composites.* Polymers, 2018. **10**(12): p. 1320.

78. Ferreira[1], C.R., et al., *Mechanical properties of sisal/fiberglass reinforced composites.* 2020.

79. Kumaar, R.K., et al., *Investigation of material properties of natural and synthetic fiber hybrid composite material.* AIP Conference Proceedings, 2022. **2446**(1).

80. Altaee, M.A. and N.H. Mostafa, *Mechanical properties of interply and intraply hybrid laminates based on jute-glass/epoxy composites.* Journal of Engineering and Applied Science, 2023. **70**(1): p. 121.

81. Sharba, M.J., et al., *Tensile and Compressive Properties of Woven Kenaf/Glass Sandwich Hybrid Composites.* International Journal of Polymer Science, 2016. **2016**(1): p. 1235048.

82. Kamesh, B., et al., *Investigation of the mechanical, absorption, flammability and swelling properties of graphene filled sisal/glass fiber reinforced polymer hybrid nanocomposites.* Cogent Engineering, 2024. **11**(1): p. 2342433.

83. Sanjay, M. and B. Yogesha, *Studies on hybridization effect of jute/kenaf/E-glass woven fabric epoxy composites for potential applications: Effect of laminate stacking sequences.* Journal of Industrial Textiles, 2018. **47**(7): p. 1830-1848.

84. Ramnath, B.V., et al., *Evaluation of mechanical properties of abaca–jute–glass fiber reinforced epoxy composite.* Materials & Design, 2013. **51**: p. 357-366.

85. Selmy, A., et al., *In-plane shear properties of unidirectional glass fiber (U)/random glass fiber (R)/epoxy hybrid and non-hybrid composites.* Composites Part B: Engineering, 2012. **43**(2): p. 431-438.

86. Muniyan, V., et al., *Comprehensive glass/banana fiber characterization with zirconium carbide filler-reinforced hybrid composites for lightweight structural applications.* Engineering Research Express, 2024.

87. Erkendirci, Ö.F. and B.Z.G. Haque, *Quasi-static penetration resistance behavior of glass fiber reinforced thermoplastic composites.* Composites Part B: Engineering, 2012. **43**(8): p. 3391-3405.

88. Keya, K.N., et al., *Natural fiber reinforced polymer composites: history, types, advantages and applications.* Materials Engineering Research, 2019. **1**(2): p. 69-85.

89. Jin, F.-L., X. Li, and S.-J. Park, *Synthesis and application of epoxy resins: A review.* Journal of Industrial and Engineering Chemistry, 2015. **29**: p. 1-11.

90. Manjula, P., et al. *Fabrication and properties testing of sisal fiber reinforced epoxy composites with random orientation*. in *AIP Conference Proceedings*. 2020. AIP Publishing LLC.

91. Mullins, M., D. Liu, and H.-J. Sue, *Mechanical properties of thermosets*, in *Thermosets*. 2018, Elsevier. p. 35-68.

92. Somaiah, A., B.A. Prasad, and N.K. Nath, *A comprehensive review: Characterization of glass fiber reinforced polymer composites with fillers from a Thermo-mechanical perspective.* Materials Today: Proceedings, 2022.

93. Aslan, M., M. Tufan, and T. Küçükömeroğlu, *Tribological and mechanical performance of sisal-filled waste carbon and glass fiber hybrid composites.* Composites Part B: Engineering, 2018. **140**: p. 241-249.

94. Mughal, M.M., et al., *Effect of silanized sisal fiber on thermo-mechanical properties of reinforced epoxy composites.* Journal of Composite Materials, 2020. **54**(15): p. 2037-2050.

95. Srisuwan, S. and P. Chumsamrong. *Effects of weave type and fiber content on physical properties of sisal fiber/epoxy composites*. in *Advanced Materials Research*. 2010. Trans Tech Publ.

96. Sreekumar, P., et al., *Effect of fiber surface modification on the mechanical and water absorption characteristics of sisal/polyester composites fabricated by resin transfer molding.* Composites Part A: Applied Science and Manufacturing, 2009. **40**(11): p. 1777-1784.

97. Yadav, D., et al. *Effect of concentration of NaOH treatment on mechanical properties of epoxy/sisal fiber composites*. in *IOP Conference Series: Materials Science and Engineering*. 2021. IOP Publishing.

98. Adugna Ayalew, A. and A. Fenta Wodag, *Characterization of chemically treated sisal fiber/polyester composites.* Journal of Engineering, 2022. **2022**(1): p. 8583213.

99. Dorneles de Castro, B., et al., *Influence of gamma radiation treatment on the mechanical properties of sisal fibers to use into composite materials.* Fibers and Polymers, 2020. **21**: p. 1816-1823.

100. Bichang'a, D.O., P.M. Wambua, and E.N. Oyondi, *Effect of alkali treatment on mechanical properties of sisal woven fabric reinforced epoxy composites.* American Journal of Engineering Research, 2017. **6**(6): p. 4.

101. Srisuwan, S., et al., *The effects of alkalized and silanized woven sisal fibers on mechanical properties of natural rubber modified epoxy resin.* Energy Procedia, 2014. **56**: p. 19-25.

102. Prasad, G.E., B.K. Gowda, and R. Velmurugan, *A study on impact strength characteristics of coir polyester composites.* Procedia Engineering, 2017. **173**: p. 771-777.

103. Moraes, A., et al., *Sodium borohydride as a protective agent for the alkaline treatment of sisal fibers for polymer composites.* Composite Interfaces, 2011. **18**(5): p. 407-418.

104. Ollivia, S., A. Juwono, and S. Roseno. *Tensile properties and deflection temperature of polypropylene/Sumberejo kenaf fiber composites with fiber content variation*. in *IOP Conference Series: Materials Science and Engineering*. 2017. IOP Publishing.

105. Atmakuri, A., et al., *Analysis of mechanical and wettability properties of natural fiber-reinforced epoxy hybrid composites.* Polymers, 2020. **12**(12): p. 2827.

106. Ramasamy, S., et al., *Study on effect of fiber loading natural Coccinia grandis fiber epoxy composite.* Journal of Natural Fibers, 2022. **19**(14): p. 7542-7552.

107. Vijayakumar, S. and K. Palanikumar, *Evaluation on mechanical properties of randomly oriented Caryota fiber reinforced polymer composites.* Journal of Materials Research and Technology, 2020. **9**(4): p. 7915-7925.

108. Hu, R. and J.-K. Lim, *Fabrication and mechanical properties of completely biodegradable hemp fiber reinforced polylactic acid composites.* Journal of Composite Materials, 2007. **41**(13): p. 1655-1669.

109. Kassegn, E., et al., *Experimental Study on Single Fiber Tensile Properties of Sisal Fibers Using a Digital Image Correlation Method as a Strain Measurement.* Journal of Natural Fibers, 2024. **21**(1): p. 2325557.

110. Lau, K.-t., et al., *Properties of natural fiber composites for structural engineering applications.* Composites Part B: Engineering, 2018. **136**: p. 222-233.

111. Maciel, N.d.O.R., et al., *Comparative tensile strength analysis between epoxy composites reinforced with curaua fiber and glass fiber.* Journal of materials research and technology, 2018. **7**(4): p. 561-565.

112. Verma, D., *Development and Characterization of Al-E Glass Fiber Composites*. 2015.

113. Rude, T., L. Strait Jr, and L. Ruhala, *Measurement of fiber density by helium pycnometry.* Journal of composite materials, 2000. **34**(22): p. 1948-1958.

114. Saravana Kumar, M., et al., *Optimization of machining parameter in drilling of coir-bagasse natural fiber reinforced polymer composites.* International journal of scientific & technology research, 2020. **9**(1): p. 4250-55.

115. Mallick, P.K., *Fiber-reinforced composites: materials, manufacturing, and design*. 2007: CRC press.

116. Elkington, M., et al., *Hand layup: understanding the manual process.* Advanced manufacturing: polymer & composites science, 2015. **1**(3): p. 138-151.

117. Pach, J., N. Frączek, and J. Kaczmar, *The effects of hybridisation of composites consisting of aramid, carbon, and hemp fibers in a quasi-static penetration test.* Materials, 2020. **13**(20): p. 4686.

APPENDIX

Appendix A: Tensile test

For the tensile testing five specimens were tested for each composite laminate configurations, i.e. pure sisal, pure glass, interply and intraply hybrid composite laminates. The following figures reveal the results of the tensile stress and strain of each specimen of each composite configuration.

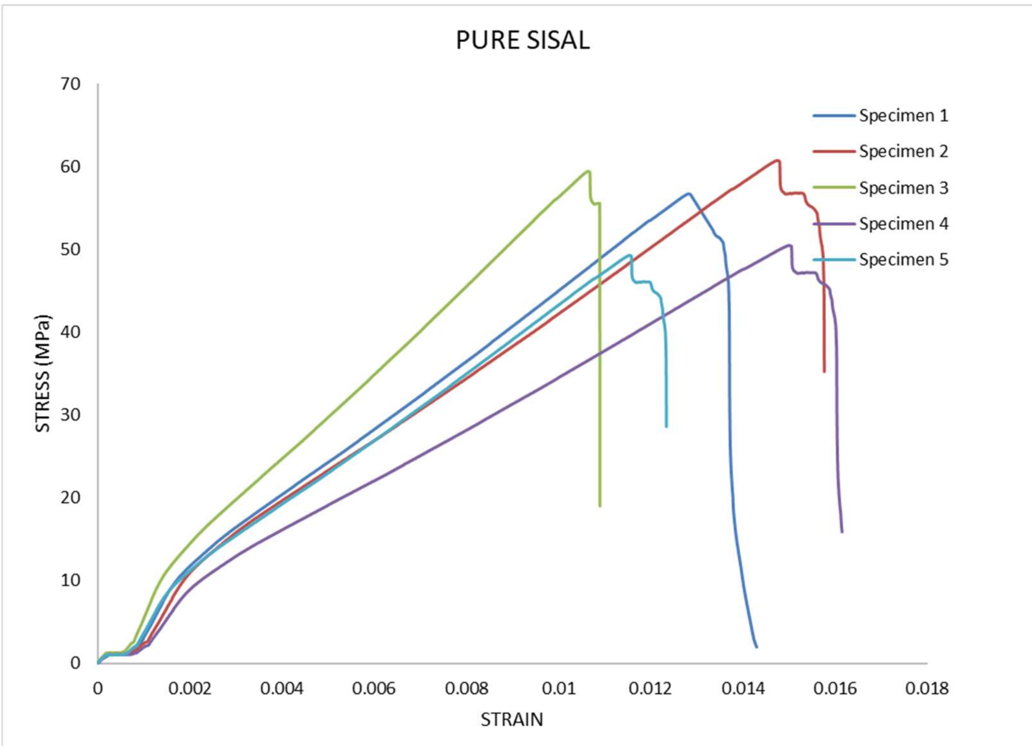


Figure 47: Stress-Strain curve of 2 x2 twill woven pure sisal epoxy composite

Table 7: UTS, elastic modulus, and strain at failure of 2 x2 twill woven pure sisal epoxy composite

Specimen	UTS (MPa)	Elastic Modulus (GPa)	Strain at failure
1	56.65	4.11	0.0143
2	60.69	4.13	0.016
3	59.34	4.22	0.015.
4	50.4	3.95	0.0165
5	49.9	4.1	0.0125

Due to the big difference from other the result of specimen four and five were rejected and the averages were calculated using the results of the three specimens.

The following figure shows the stress-strain of pure glass composite laminate.

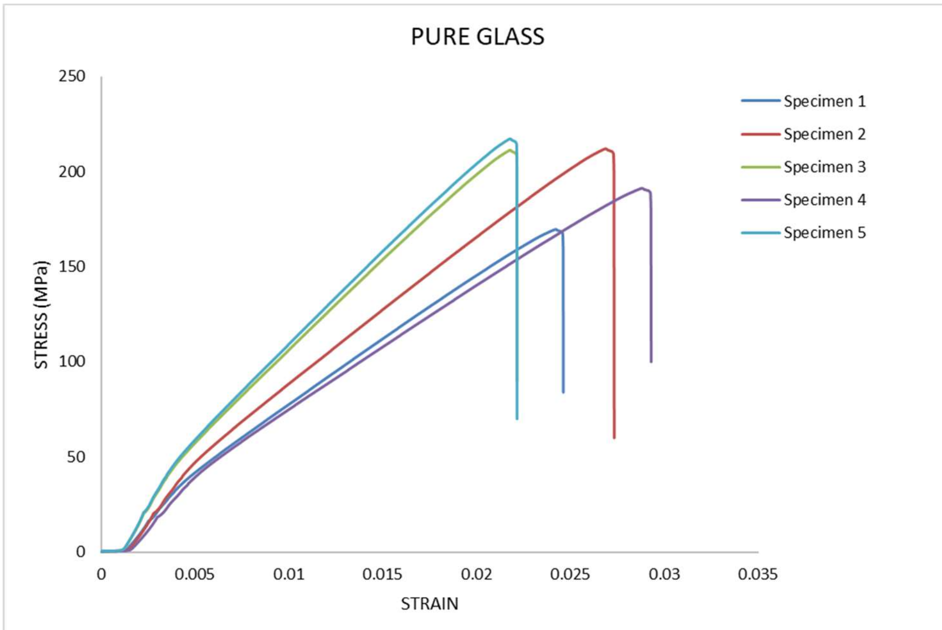


Figure 48: Stress-Strain curve of 2 x2 twill woven pure glass epoxy composite

Table 8: UTS, modulus, and stain at failure of 2 x2 twill woven pure glass epoxy composite

Specimen	UTS (MPa)	Elastic Modulus (GPa)	Strain at failure
1	215.09	12.7	0.023
2	210.7	11.31	0.027
3	211.17	12.3	0.023
4	189.68	11.57	0.03
5	168.14	10.95	0.025

Since the difference between the result of the fifth specimen and the others is large, it is excluded from part of the calculation of the average results.

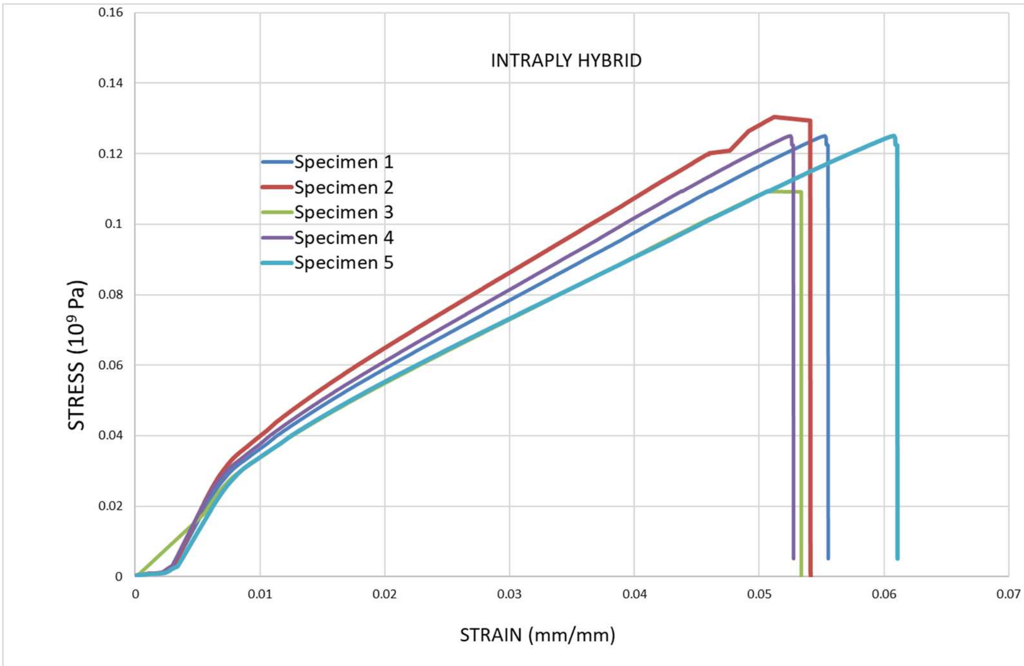


Figure 49: Stress-Strain curve of 2 x2 twill woven intraply hybrid glass- sisal epoxy composite specimens

Table 9: UTS, modulus, and stain at failure of 2 x2 twill woven intraply hybrid composite

Specimen	UTS (MPa)	Elastic Modulus (GPa)	Strain at failure
1	123.7	7.96	0.023
2	129.3	7.75	0.027
3	115.25	6.4	0.023
4	122.12	7.87	0.03
5	122.7	7.94	0.025

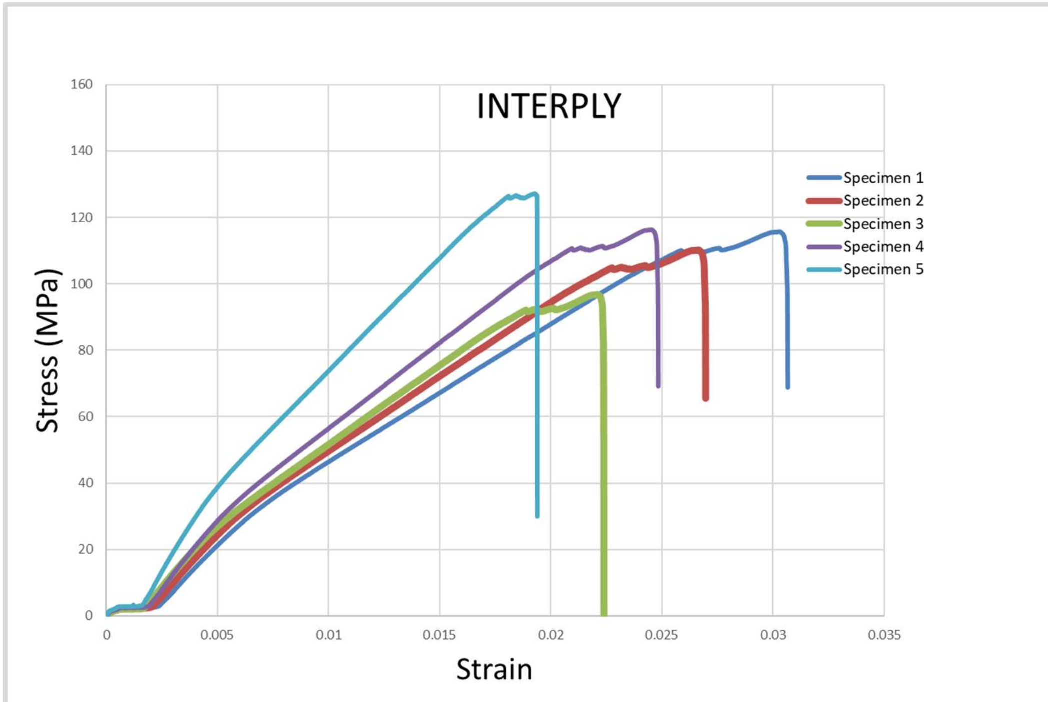


Figure 50. Stress-Strain curve of 2 x2 twill woven interply hybrid glass- sisal epoxy composite

Table 10 UTS, modulus, and stain at failure of 2 x2 twill woven interply hybrid composite

Specimen	UTS (MPa)	Elastic Modulus (GPa)	Strain at failure
1	123.7	5.84	0.018
2	115.4	5.6	0.027
3	99.26	6.4	0.023
4	118.74	5.92	0.03
5	118.27	5.86	0.032

Appendix B: Compressive Test

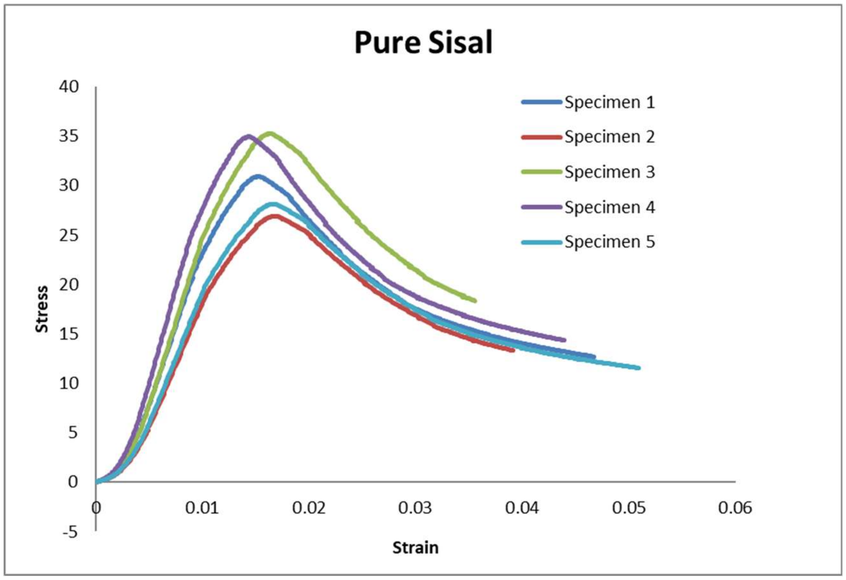


Figure 51. Compressive Stress-Strain curve of 2 x2 twill woven sisal epoxy composite

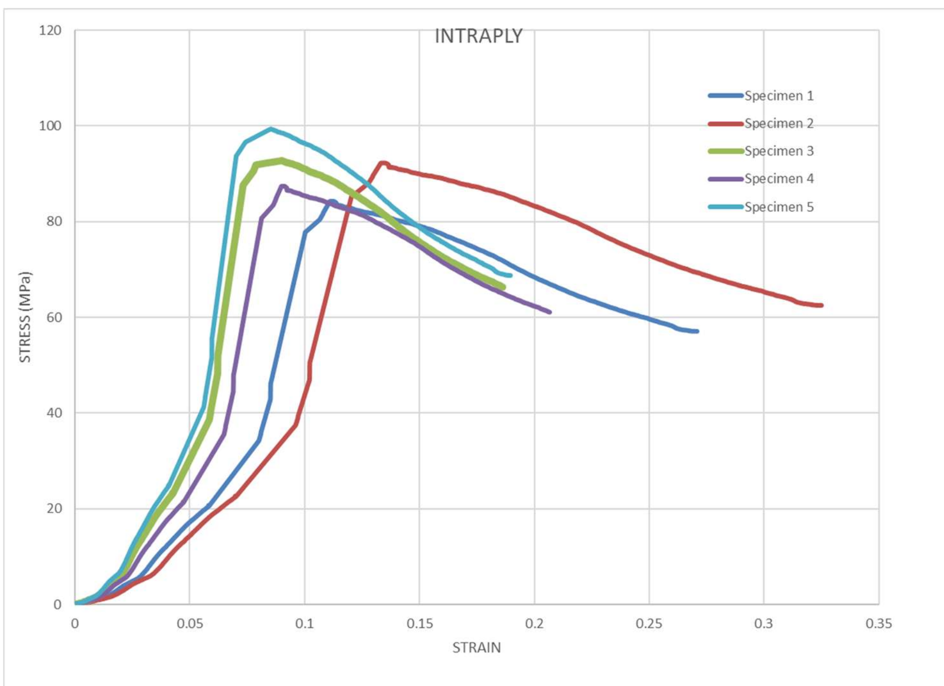


Figure 52. compressive Stress-Strain curve of 2 x2 twill woven intraply hybrid glass- sisal epoxy composite

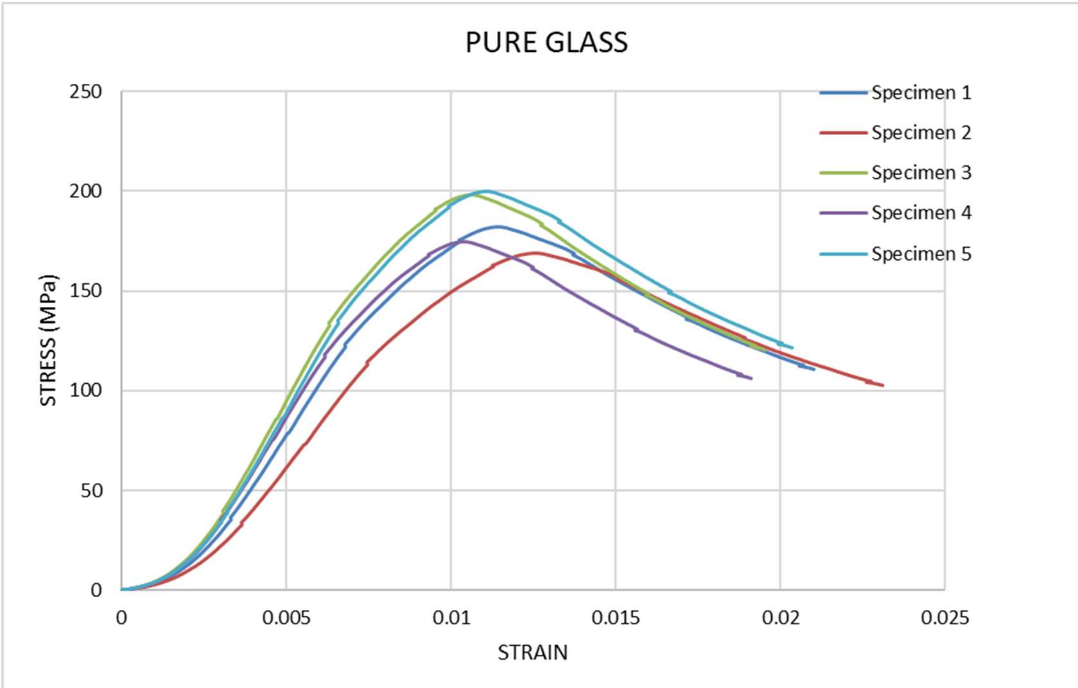


Figure 53 Compressive. Stress-Strain curve of 2 x2 twill woven glass epoxy composite

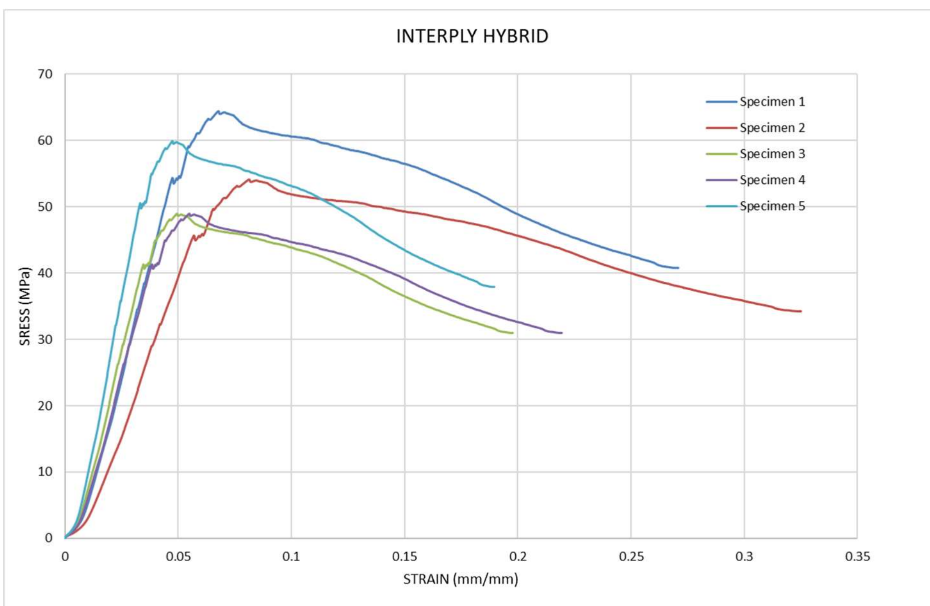


Figure 54. Compressive Stress-Strain curve of 2 x2 twill woven interply hybrid glass- sisal epoxy composite

Appendix C: In-Plane Shear Test

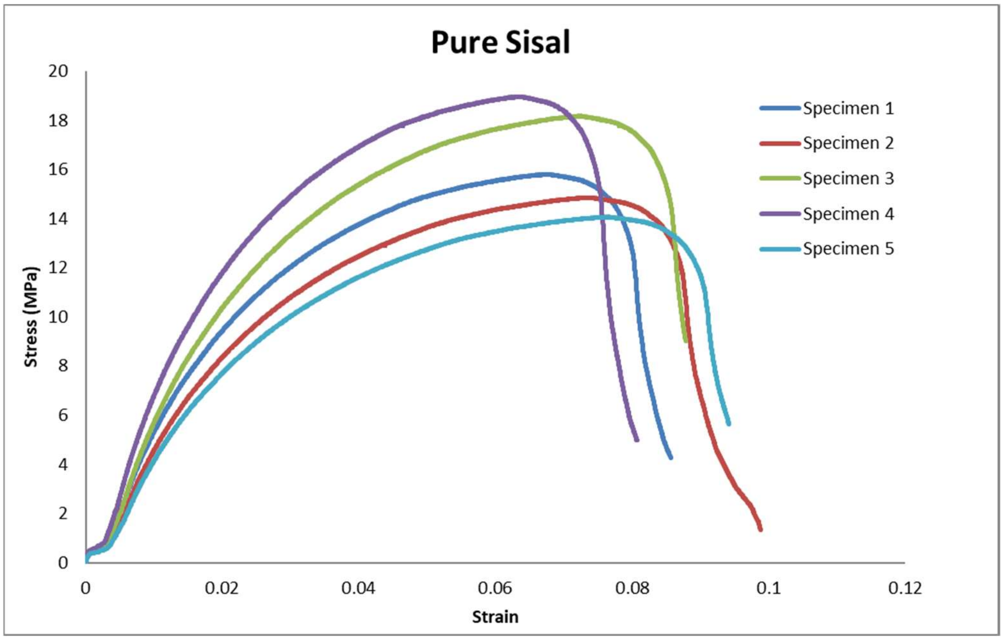


Figure 55.In-plane shear Stress-Strain curve of 2 x2 twill woven pure sisal epoxy composite of shear test

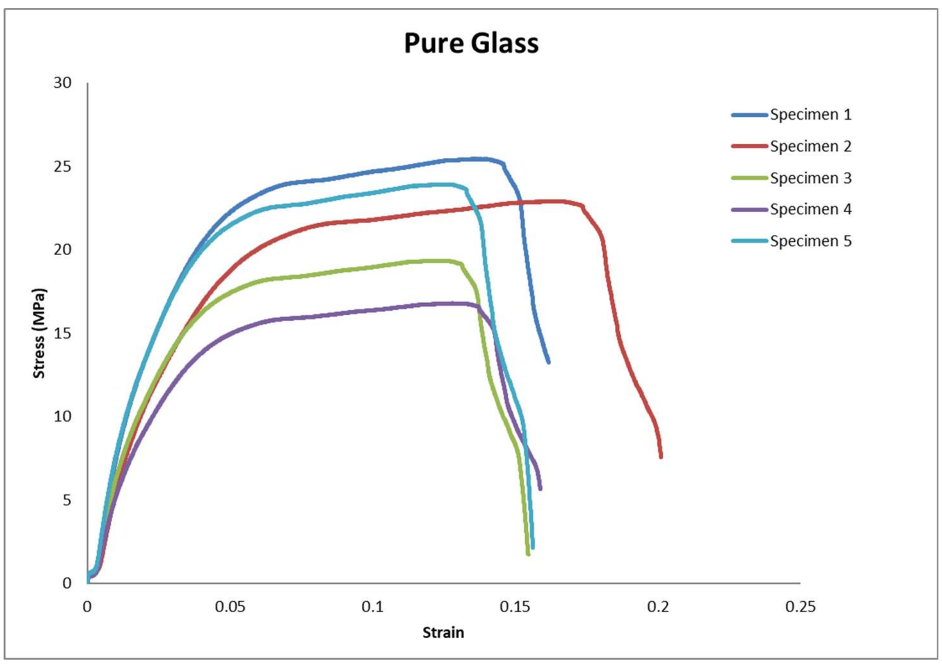


Figure 56. Stress-Strain curve of 2 x2 twill woven pure Glass epoxy composite of shear test

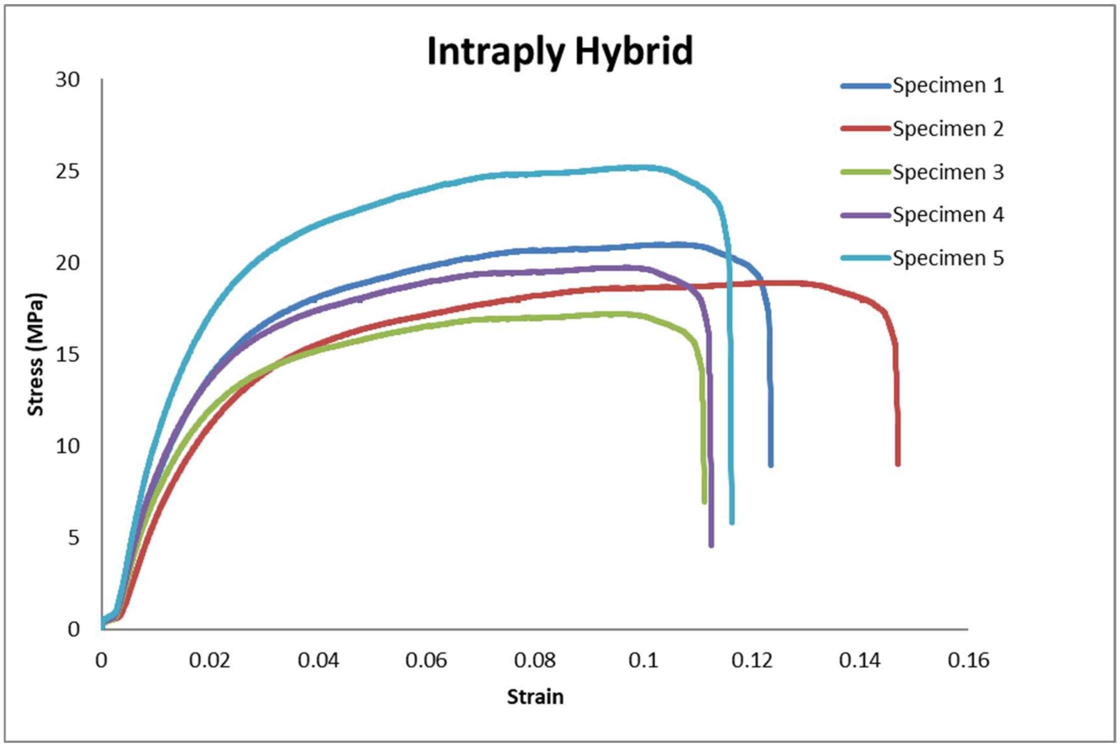


Figure 57. Stress-Strain curve of 2 x2 twill woven interply hybrid epoxy composite of shear test

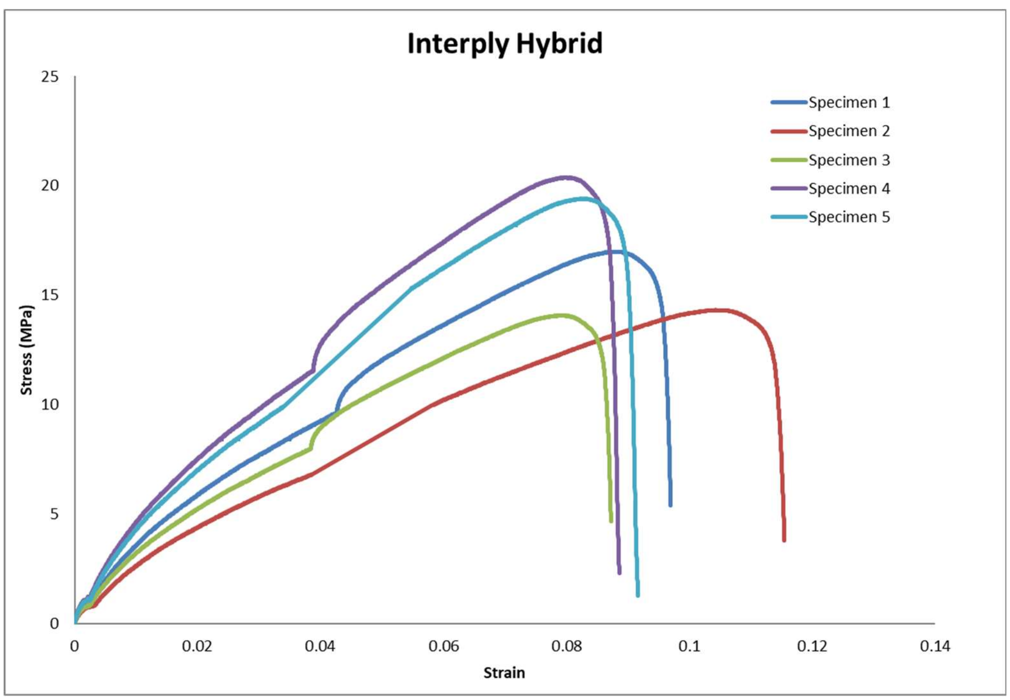


Figure 58. Stress-Strain curve of 2 x2 twill woven intraply hybrid epoxy composite of shear test

Appendix D: Quasi static penetration test

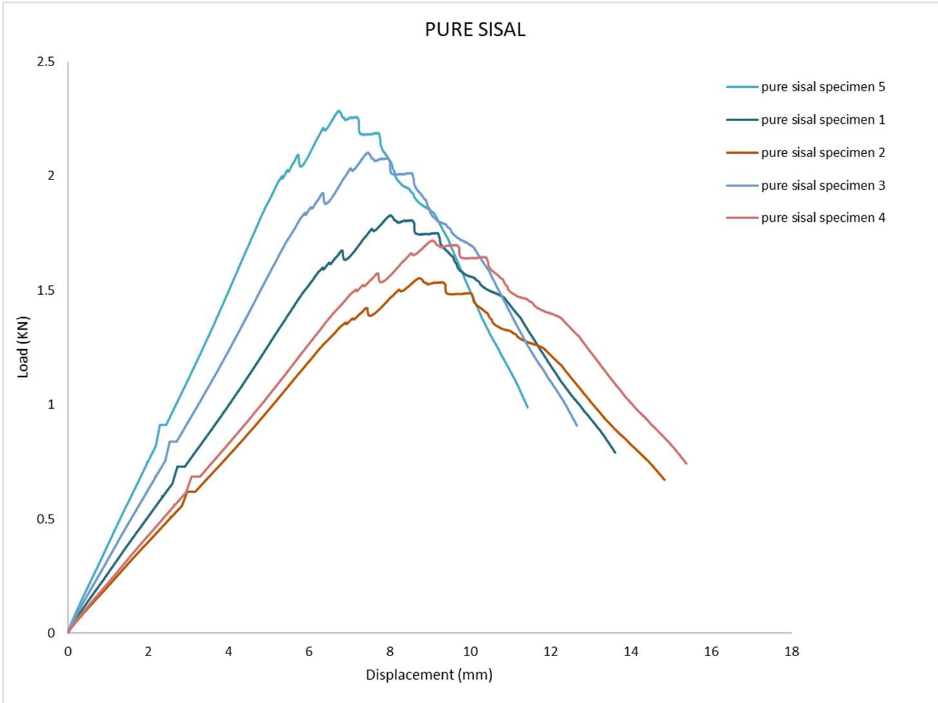


Figure 59. Load-Displacement graphs of QSPT result of pure sisal composite

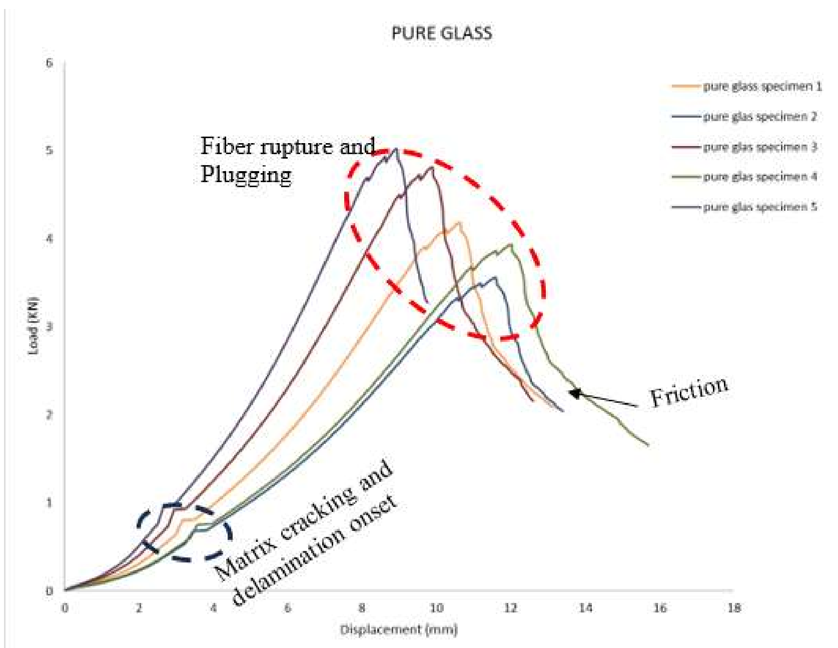


Figure 60. Load-displacement graph of QSPT result of pure glass composite

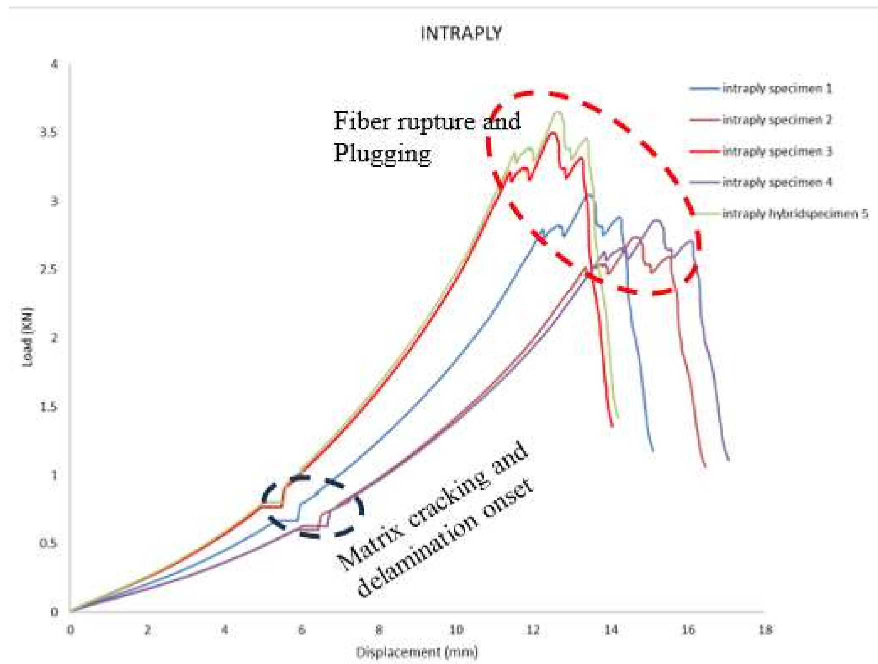


Figure 61. Load- Displacement graph of QSPT result of intraply hybrid composite

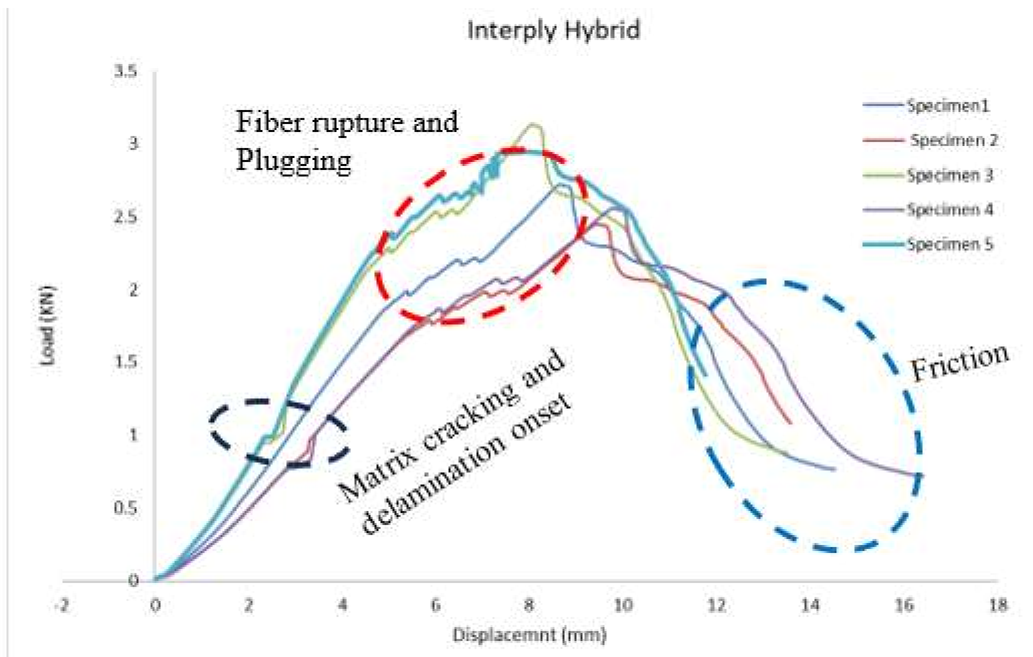


Figure 62. Load- Displacement graph of QSPT result of interply hybrid composite