INVESTIGATING THE MECHANICAL PROPERTIES OF NATURAL FIBERS FOR USE IN BALLISTIC APPLICATIONS

BY

AGOMATE EFETOBOR	**ENG1805345**
AKONU O. EMMANUEL	**ENG1805351**
UGOR SAMUEL ODEWORITSE	**ENG1805458**

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DEPARTMENT OF MECHANICAL ENGINEERING,
FACULTY OF ENGINEERING,
UNIVERSITY OF BENIN, BENIN CITY.

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CERTIFICATION

This is to certify that this project is original and was carried out by the students as mentioned earlier, of the Department of Mechanical Engineering, Faculty of Engineering, University of Benin, Edo state, Nigeria under the supervision of **OSAROBO IGHODARO** (PhD

NEWCASTLE)

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OSAROBO IGHODARO (PhD Newcastle) Date

Project Supervisor

______________________________ __________________

DR. I. B OWUNNA Date

Project Coordinator

______________________________ __________________

PROF. G. E. SADJERE Date

Head of Department

DEDICATION

This project is dedicated to the almighty God, the giver of insight, wisdom, knowledge, and understanding. For granting us the wisdom, strength, provision, and perseverance to complete this project.

ACKNOWLEDGEMENT

We give the most gratitude to God almighty for giving us his grace and blessings upon us all through our program. We thank our parents and guardians for their unwavering love, encouragement, and support. Our sincere appreciation goes to **OSAROBO IGHODARO** (PhD Newcastle), our esteemed project supervisor whose guidance, and expertise were more than instrumental in shaping this work. We thank the Department of Mechanical Engineering, University of Benin for providing the enriching academic environment, resources, and opportunities that facilitated our learning and growth. To our friends and colleagues whose camaraderie enriched our experience, we owe immense thanks.

ABSTRACT

This research explored the viability of natural fibers for ballistic armor, a traditionally synthetic field. Following a literature review, two natural fibers underwent characterization to assess their mechanical properties. These fibers were then tested to evaluate their ability to stop projectiles, absorb impact energy, and minimize wearer injury. The results provide insights into the potential of natural fibers for ballistic applications, highlighting areas for improvement like strength and moisture resistance. Future research directions include advanced fiber modification techniques, optimized composite design strategies, and life cycle assessments to promote the development of sustainable and effective natural fiber-based ballistic armor.

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CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND OF STUDY

Nigeria grapples with a complex security landscape. A recent report by the Premium Times on April 10, 2024, (*Nigerians Lament Insecurity ...)* highlighted the nationwide resurgence of insecurity, with Nigerians lamenting about kidnapping, insurgency, and banditry. Equipping law enforcement and military personnel with effective ballistic armor is vital for protecting them in these situations. However, traditional ballistic armor materials, like Kevlar and UHMWPE, come with significant drawbacks. Their high cost can strain national budgets, and their production and disposal processes leave a large environmental footprint. This poses a particular challenge for Nigeria, where budgetary constraints and a growing focus on environmental sustainability necessitate exploring alternative solutions.

Natural fibers emerge as a promising option for ballistic armor development in Nigeria. These readily available, renewable resources like kenaf and coir grow within the country. Compared to traditional materials, natural fibers offer several advantages. Their lower cost can ease the financial burden of equipping security personnel. Additionally, natural fibers often boast superior specific strength (strength-to-weight ratio), potentially resulting in lighter and more comfortable ballistic armor for users. Furthermore, processing natural fibers typically requires less energy, potentially reducing the environmental impact of armor production compared to traditional materials.

Initial research by Monteiro et al. (2015) has explored the ballistic performance of natural fiber composites, demonstrating their potential as a viable alternative. However, further research is necessary to optimize these composites for ballistic applications. This includes investigating factors like the most suitable fiber types, optimizing processing methods, and exploring integration with other materials to achieve performance comparable to traditional ballistic armor.

This thesis aims to contribute to this ongoing research effort. By focusing on the feasibility of these fibers for ballistic purpose, this thesis seeks to advance the development of effective, affordable, and sustainable ballistic armor solutions for Nigeria, ultimately contributing to a safer environment for its citizens and security personnel.

1.2 STATEMENT OF PROBLEM

"*Nigerians Lament Insecurity as Officials Discuss Steps Taken*," was the title of the Premium Times April 10, 2024 article which highlights the nationwide resurgence of violence, with kidnapping, insurgency, and banditry posing a constant threat to public safety. Equipping law enforcement and military personnel with effective ballistic armor is crucial for protecting them in these high-risk situations.

However, traditional ballistic armor materials, like Kevlar and UHMWPE, present significant challenges. A 2017 study by Gomes et al. acknowledges the high cost of these materials, straining national budgets for essential security equipment. Furthermore, the production and disposal processes of these synthetic materials leave a large environmental footprint, as documented in a life cycle assessment by Dias et al. (2020). This is a growing concern for Nigeria, as the country prioritizes environmental sustainability alongside its security needs.

The limitations of traditional ballistic armor are further amplified by Nigeria's specific context. The International Crisis Group, a non-governmental organization (NGO) focused on conflict resolution, emphasizes the budgetary constraints faced by the Nigerian government in its fight against insecurity. These financial limitations necessitate exploring more cost-effective solutions for equipping security personnel.

In addition to budgetary constraints, there's a growing demand for sustainable solutions within Nigeria. The Nigerian Environmental Standards and Regulatory Enforcement Agency (NESREA), the national body responsible for environmental regulation, has emphasized the importance of sustainable development practices across various sectors. Traditional ballistic armor production often clashes with these sustainability goals.

Therefore, the following key problems are identified; Traditional ballistic armor materials are expensive, straining the Nigerian government's budget for equipping security personnel. The production and disposal processes of traditional ballistic armor materials have a significant negative impact on the environment. Also, Traditional ballistic armor solutions might not be the most financially or environmentally sustainable option for Nigeria's specific needs.

These problems necessitate exploring alternative ballistic armor solutions that are; Cost-effective i.e. Affordable to produce and maintain within the constraints of the Nigerian government's budget. Sustainable i.e. Manufactured and disposed of with minimal environmental impact, aligning with Nigeria's growing focus on sustainability. Effective i.e. Offer ballistic protection comparable to traditional materials to ensure the safety of law enforcement and military personnel.

Natural fibers, such as kenaf and plantain, emerge as a promising alternative for ballistic armor development in Nigeria. Research by Akil et al. (2011) and Bledzki et al. (2007) highlights the potential of these readily available, renewable resources within the country.

However, further research is necessary to optimize natural fiber composites for ballistic applications. This includes investigating factors like; Identifying the most suitable fiber types and combinations for ballistic performance. Optimizing processing methods to enhance the ballistic properties of natural fiber composites. Exploring integration with other materials to achieve performance comparable to traditional ballistic armor.

1.3 AIM / OBJECTIVE OF THE STUDY

The aim of this thesis is to conduct a comprehensive investigation of the mechanical properties of natural fibers sources in Nigeria for ballistic applications, feasibility, and socio-economic implications of ballistic armor using natural fibers, with a primary focus on enhancing the understanding of their potential applications and overcoming associated challenges.

The Objectives include;

- Extracting different natural fibers found in Nigeria.
- Biological and chemical processing of fibers
- Producing yarns from extracted fibers
- Conducting comprehensive mechanical testing on the suitability of the fibers for ballistic applications.

1.4 SIGNIFICANCE OF THE STUDY.

By addressing the limitations of traditional ballistic armor materials, this thesis aims to contribute to the development of a more effective, affordable, and sustainable solution for Nigeria. A successful outcome would have a significant positive impact on various aspects of Nigerian society:

Improved Security: Effective ballistic armor for law enforcement and military personnel can empower them to better confront security threats, ultimately leading to a safer environment for the citizenry.

Reduced Budgetary Strain: A more cost-effective ballistic armor solution would free up valuable resources within the national budget for other security initiatives or social development programs.

Environmental Sustainability: Utilizing natural fibers for ballistic armor production aligns with Nigeria's growing focus on sustainable development practices, minimizing the environmental impact of the security sector.

This has the potential to make a significant contribution to Nigeria's security landscape and its national development goals.

1.5 SCOPE OF WORK

This thesis is limited to research into the development of ballistic armor using natural fibers. The scope involves literature review, extraction of fibers, testing their mechanical properties and drawing conclusions from their results.

1.6 METHODOLOGY

The methodology employed in this thesis is designed to provide a rigorous and systematic approach to investigating the mechanical properties of these fibers, their feasibility, and socioeconomic implications of ballistic armor using natural fibers. The research methodology encompasses a combination of experimental procedures, and environmental assessments, ensuring a comprehensive understanding of the integration of natural fibers into the realm of protective technologies.

CHAPTER TWO

LITERATURE REVIEW

2.1 BALLISTIC ARMOR

Ballistic armor is a type of personal protective equipment (PPE) that is designed to protect the wearer from ballistic threats, such as bullets and shrapnel. Ballistic armors typically consist of multiple layers of materials, each with its own unique properties that contribute to the overall performance of the armor. It works by distributing the energy of the impact over a larger area, thereby reducing the likelihood of penetration.

Ballistic armor can be classified into two categories: soft and hard. Soft armor is made of flexible materials that can absorb and dissipate the kinetic energy of low-velocity projectiles, while hard armor is made of rigid materials that can resist and deflect the penetration of high-velocity projectiles.

Ballistic armor works by utilizing various materials with high strength and energy absorption capabilities. These materials slow down or stop incoming projectiles by distributing the kinetic energy across a larger area, preventing them from penetrating the armor and injuring the wearer.

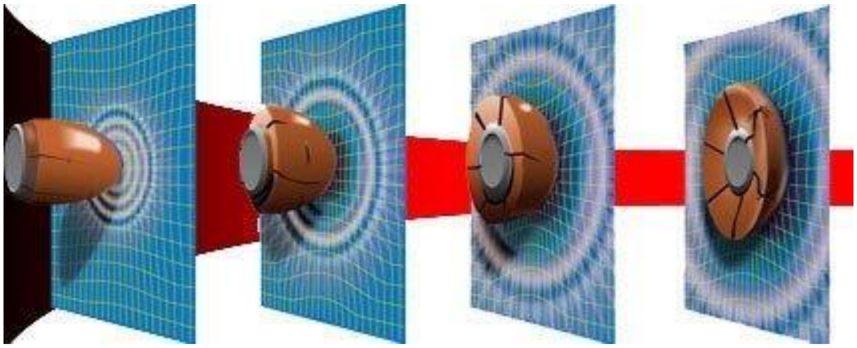

Fig 2.1: *How a ballistic armor works*

Ballistic armor usually involves layering different materials to achieve the desired level of protection, weight, and comfort. Here's a breakdown of the key components:

2.1.1 Ballistic Fabrics: These are woven or knitted fabrics made from high-strength fibers like Kevlar or UHMWPE. They provide a lighter layer of protection against pistol rounds, shrapnel, and fragments.

2.1.2 Ballistic Plates: These are rigid inserts typically made of ceramic or high-hardness steel. They offer significant protection against rifle rounds by deflecting or fragmenting the projectile. There are different levels of plate ratings based on their ability to stop specific types of ammunition.

2.1.3 Additional Layers include Spall Liners; These soft materials placed behind ballistic plates help trap fragments that might break off the plate upon impact, preventing them from injuring the wearer. Aramid felt is a common material used for spall liners. **Ballistic Foam;** This lightweight foam layer can be placed behind ballistic fabric or plates to absorb impact energy and improve comfort by distributing the pressure more evenly across the body. **Trauma Plates;** These are non-ballistic plates made of high-density polyethylene or similar materials. They don't stop bullets but can help absorb blunt force trauma from projectiles or falls. **Outer Shell/Carrier;** This is a durable outer layer made of water-resistant fabric like nylon that holds all the ballistic components together and allows for attachment of pouches and other gear.

The Arrangement of these layers depends on certain criteria: The first and most important of these is the Threat Level; The type of ballistic threats anticipated (pistol rounds, rifle rounds, shrapnel) heavily influence the configuration. Higher threat levels require more robust materials and additional layers like rifle plates. Then we consider the weight and Mobility: Heavier armor with more ballistic plates offers better protection but can hinder mobility. Lighter configurations with ballistic fabrics prioritize agility but offer less protection. And then comfort: Balancing comfort with protection is crucial. Padding and breathable materials in the outer shell can improve comfort for extended wear.

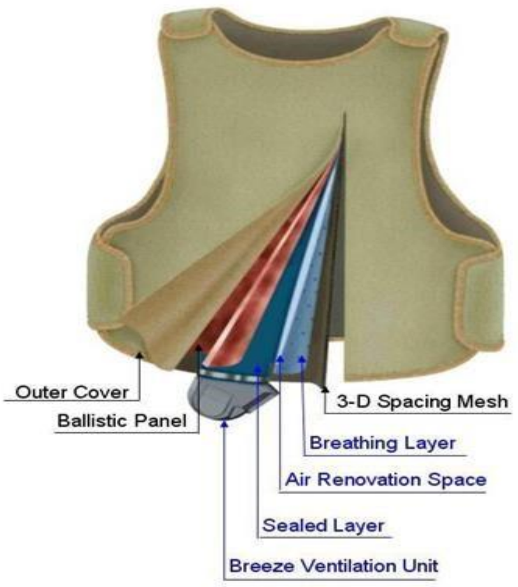

Fig 2.2: *Layers in a ballistic armour*

2.2 SYNTHETIC FIBERS VS NATURAL FIBERS

2.2.1 Synthetic Fibers

For decades, synthetic fibers have been the cornerstone of ballistic armor, offering exceptional protection for law enforcement, military personnel, and civilians in high-risk situations. Here's a closer look at the two dominant synthetic fibers.

2.2.1.1 Kevlar® (Aramid Fiber): Developed by DuPont in the 1960s, Kevlar® revolutionized ballistic protection. This para-aramid fiber boasts an impressive strength-to-weight ratio, making it lightweight and highly effective at stopping projectiles. Kevlar's structure, consisting of tightly packed aromatic rings linked by strong covalent bonds, allows it to efficiently absorb and distribute the impact energy of a bullet, preventing penetration. Research by Walker et al. (2016) highlights Kevlar's consistent performance in ballistic applications.

Fig 2.3: *Kevlar Fabric*

2.2.1.2 UHMWPE (Ultra-High-Molecular-Weight Polyethylene): This high-density polyethylene offers exceptional ballistic resistance against blunt force trauma and fragmentation. Its long, chain-like molecular structure allows UHMWPE to efficiently dissipate the kinetic energy of a projectile, preventing penetration. Additionally, UHMWPE's high density makes it particularly effective against fragmenting projectiles like shrapnel. The National Institute of Justice (NIJ) recognizes UHMWPE as a viable material for ballistic applications.

These synthetic fibers offer several advantages for ballistic armor such as **High Ballistic Performance as** Both Kevlar® and UHMWPE excel at stopping projectiles and absorbing impact energy, providing crucial protection for the wearer. Another important advantage is their **Lightweight;** Compared to traditional metal armor, synthetic fibers offer significant weight reduction, improving mobility and comfort for extended wear. And then there is **Durability;** These materials are known for their high tensile strength and resistance to abrasion, ensuring long-lasting performance.

However, there are also some drawbacks to consider: first is **Cost;** The production process for these synthetic fibers can be expensive, making ballistic armor constructed solely from them a high-cost investment. And then there is **Environmental Impact;** Manufacturing and disposal of these materials can have a significant environmental footprint due to high energy consumption and potentially harmful chemicals involved. These limitations are driving research into alternative materials for ballistic armor, with natural fibers emerging as a promising option.

2.2.1 Natural Fibers

While synthetic fibers like Kevlar® and UHMWPE have dominated ballistic armor for decades, a growing focus on sustainability and cost-effectiveness is driving research into alternative materials. Natural fibers are emerging as a promising option, offering several advantages.

These advantages include: **Renewable Resources as** unlike synthetic fibers derived from petroleum, natural fibers are readily available and can be replenished through sustainable agricultural practices. **Lower Cost is another advantage as** Natural fibers are generally cheaper to cultivate and process compared to synthetic counterparts, potentially reducing the overall cost of ballistic armor production. And then **Environmental Sustainability;** Natural fibers often require less energy for processing and have a lower environmental footprint compared to synthetics. Lastly, some natural fibers boast superior specific strength (strength-to-weight ratio) compared to traditional materials, leading to potentially lighter and more comfortable ballistic armor.

Here are some of the natural fibers showing promise for ballistic armor applications:

Kenaf (Hibiscus cannabinus L.): This fast-growing crop offers high tensile strength and good specific strength, making it a potential candidate for ballistic composites. Research by Akil et al. (2011) explores the potential of kenaf fibers as reinforcement for composites. Kenaf can be cultivated throughout Nigeria, with major production areas in the southwest and southeast regions like Kogi, Lagos, Ogun, Benue and some other states in Nigeria. the best period for planting kenaf is between 2 to 3 weeks after the beginning of rain in an area. A sharp drop in potential yield occurs if it is planted later than 3 to 4 weeks of its optimum planting date.

Coconut Coir (Cocos nucifera L.): Extracted from coconut husks, coir fibers possess good impact resistance and are readily available in tropical regions. Bledzki et al. (2007) reviewed the use of coir fibers in composites, highlighting their potential applications. Coconut trees can be found all over Nigeria with major coconut producing states like Lagos, Akwaibom, Bayelsa and Cross River State.

Ramie (Boehmeria nivea): Renowned for its high strength and fineness, ramie can be found in some parts of southern Nigeria. Studies by Rana et al. (2011) highlight the potential of cellulose-based composites for ballistic applications, suggesting possibilities for ramie exploration.

Ballistic Plantain Fiber: This unique fiber extracted from the Musa balbisiana banana plant exhibits exceptional tensile strength and energy absorption capabilities, making it a promising candidate for ballistic applications. Studies by Filho et al. (2017) demonstrate the ballistic potential of ballistic banana fiber. Plantain production is mainly in the Southern states of Nigeria, which include Akwa-Ibom, Cross River, Akwa-Ibom, Imo, Enugu, Rivers, Edo, Delta, Lagos, Ogun, Osun and Oyo states (Ogazi, 1996).

Bamboo (Bambusoideae): Certain fast-growing bamboo varieties present in Nigeria might hold promise due to their high strength-to-weight ratio. However, limited research exists on their ballistic application, and further investigation is needed.

Sisal (Agave sisalana): A widely cultivated fiber crop in Nigeria, with major production areas in Benue, Plateau, Kaduna, and Kwara states, sisal offers good strength and flexibility. Research by Bledzki and Gassan (2009) explores the use of cellulose-based fibers, including sisal, in composite materials.

Oil Palm Empty Fruit Bunch (EFB): A readily available byproduct of the Nigerian palm oil industry, EFB fibers offer good strength and flexibility. Research on natural fiber composites by Bledzki and Gassan (2009) opens avenues for investigating EFB's potential in ballistic applications.

Jute (Corchorus spp.): Jute fibers exhibit good tensile strength and can be readily sourced in Nigeria, particularly in the **eastern states**, with major cultivation areas in Abia, Akwa Ibom, Anambra, Ebonyi, and Enugu. While research on its direct ballistic application is limited, studies by Rana et al. (2011) suggest its potential as reinforcement in composites.

Natural fibers while very promising may possess challenges to consider when using them for ballistic armor. The first of which is **Ballistic Performance;** Natural fibers generally require optimization to achieve ballistic performance comparable to traditional materials. This might involve treatments or composite structures to enhance their properties. And then there is **Moisture Sensitivity;** Some natural fibers are susceptible to moisture absorption, which can negatively affect their ballistic properties. Strategies for moisture management are crucial. And lastly **Processing;** Optimizing processing methods is essential to maximize the ballistic potential of natural fibers in composite structures.

However, researchers are actively investigating methods to overcome these limitations. This includes exploring:

- **Fiber Modification:** Techniques like chemical treatments, surface modifications or using hardeners can improve the strength, moisture resistance, and overall ballistic performance of natural fibers.
- **Composite Design:** Integrating natural fibers with other materials like resins or synthetic fibers in composite structures can optimize ballistic performance while leveraging the benefits of natural fibers.

Natural fibers offer a compelling alternative for ballistic armor development in Nigeria and other countries seeking sustainable and cost-effective solutions. While challenges remain in optimizing their ballistic performance, ongoing research holds promise for the future of natural fiber-based ballistic armor. As such, after rigorously looking at the research done on all fibers and weighing all their feasibility, we have decided for the sake of this research to move forward with **Kenaf** (Hibiscus cannabinus L.) and **Plantain** (Musa acuminata and Musa balbisiana.)

2.2 KENAF FIBER

Kenaf (Hibiscus cannabinus L.) is a fast-growing annual plant emerging as a valuable resource for various industrial applications. Its strong and versatile fibers hold particular promise in the development of sustainable and cost-effective ballistic armor.

Fig 2.4: *Kenaf Plant*

Fig 2.5: Extracted *Kenaf fiber*

Kenaf boasts impressive tensile strength, exceeding that of some wood species and comparable to glass fiber. This property makes it a suitable candidate for ballistic applications where the fiber needs to resist penetration from projectiles. Kenaf has **Good Specific Strength:** Specific strength refers to the strength-to-weight ratio. Kenaf fibers exhibit good specific strength, meaning they offer high strength while remaining relatively lightweight. This translates to potentially lighter and more comfortable ballistic armor compared to traditional materials. Kenaf fibers also possess good stiffness and rigidity, contributing to their ability to absorb impact energy and distribute it throughout the composite structure. And unlike synthetic fibers, kenaf is a natural and biodegradable material, aligning with growing sustainability concerns.

Research by Akil et al. (2011) explores the potential of kenaf fibers as reinforcement for composites [4]. They highlight kenaf's suitability for ballistic applications due to its tensile strength, specific strength, and good adhesion properties with resin matrices. Studies by Monteiro et al. (2015) using kenaf fabric composites in ballistic armor configurations demonstrate promising results.

Kenaf is a fast-growing crop that can be cultivated sustainably, reducing reliance on nonrenewable resources like petroleum used for synthetic fibers. Kenaf cultivation and processing are generally cheaper compared to synthetic fibers, potentially lowering the overall cost of ballistic armor production. The good specific strength of kenaf fibers allows for the development of lighter ballistic armor compared to traditional materials, improving wearer mobility and comfort.

Kenaf is typically harvested when the stems reach maturity, around 4-5 months after planting. The ideal harvesting time depends on the desired fiber properties. Earlier harvesting yields finer and softer fibers, while later harvesting results in coarser and stronger fibers suitable for industrial applications.

After harvesting, Retting is carried out, Retting is a crucial step that separates the bast fibers from the woody core of the stem.

There are two main retting methods: Field Retting; This traditional method involves spreading the harvested stems in the field for several weeks, allowing natural microbial activity to break down the non-fibrous components. Factors like weather conditions can significantly influence the retting process and fiber quality using this method. And Water Retting; This method involves submerging the stems in water for a controlled period. This offers more consistent results compared to field retting but requires more water resources.

After retting, the softened core material is separated from the bast fibers using a decorticator machine. This machine mechanically breaks and removes the woody core, leaving behind the isolated bast fibers. The extracted bast fibers are thoroughly dried to a specific moisture content, typically around 12%. Proper drying is essential to prevent mold growth and ensure optimal fiber quality for further processing. The dried fibers are then graded based on their length, fineness, and strength. Depends on the use the sorted fibers are then carded to increase uniformity and aid turning it into yarn.

While kenaf shows promise, natural fibers generally require optimization to achieve ballistic performance comparable to traditional materials. This might involve: **Chemical Treatments;** Treatments can enhance fiber strength, moisture resistance, and adhesion properties, improving ballistic performance. **Composite Design;** Integrating kenaf with other materials like resins or synthetic fibers in a composite structure can optimize ballistic properties while leveraging kenaf's benefits. Kenaf fibers are hygroscopic, meaning they absorb moisture from the environment. This can negatively affect their mechanical properties, including ballistic performance. Strategies for moisture management are crucial.

2.3 PLANTAIN FIBER

Plantain (Musa Paradisiaca L.), a close relative of the banana plant, is a staple food crop cultivated throughout the tropics. While the fruit is widely consumed, recent research has explored the potential of plantain fibers as a reinforcement material in composites.

Fig 2.6: *Plantain Plant*

Fig 2.7: *Plantain fibre*

Studies by Akinlabi et al. (2011) demonstrate that plantain fibers possess good tensile strength and stiffness, making them suitable candidates for reinforcement in composite materials hence ballistic applications. Plantain fibers are relatively lightweight compared to some traditional reinforcement materials like glass fiber. This can contribute to the development of lighter composite structures. As a natural fiber, plantain is biodegradable, aligning with the growing focus on sustainable materials. here are some possibilities for how plantain fibers could be integrated into ballistic armor:

Hybrid Composites: Plantain fibers could be combined with stronger natural fibers like kenaf or coir, or even synthetic fibers, in a composite structure. This could leverage the specific strengths of each material to achieve optimal ballistic performance.

Non-Ballistic Layers: Plantain fibers might be suitable for use in the non-ballistic comfort layers of ballistic armor due to their breathability and lightweight properties.

Compared to other natural fibers like kenaf or flax, research on plantain fibers for composites is still in its early stages. More studies are needed to fully understand their mechanical properties and optimize them for specific applications.

The properties of plantain fibers can vary depending on factors like cultivar, growing conditions, and extraction methods. Standardization of these factors is crucial for consistent fiber quality in composites.

Moisture Sensitivity: Like many natural fibers, plantain fibers are susceptible to moisture absorption, which can affect their mechanical properties. Strategies for moisture management are necessary.

After harvest, the outer sheath of the plantain stem is removed to expose the fibrous core, similar to kenaf, plantain fibers can undergo retting to separate them from the non-fibrous components. Water retting or enzymatic retting are potential methods, the extracted fibers are thoroughly dried to a specific moisture content and then baled for storage and transportation.

2.4 MECHANICAL PROPERTIES OF THE NATURAL FIBERS

As with traditional Kevlar, the mechanical properties of these natural fibers have to meet certain criteria if they are to be considered at all as a suitable replacement for the synthetic Kevlar.

Natural fibers have exciting potential for sustainable ballistic armor, but they face a significant hurdle: meeting the stringent mechanical properties required for effective protection. Here's a detailed breakdown of the key criteria natural fibers need to surpass or at least come close to, compared to Kevlar:

Tensile Strength: This property measures the maximum stress a fiber can withstand before breaking. Kevlar boasts exceptionally high tensile strength, enabling it to effectively stop projectiles by absorbing their impact energy and distributing the force over a larger area. Natural fibers generally exhibit lower tensile strength compared to Kevlar. While some natural fibers like kenaf show promise, significant improvements might be needed through strategies like fiber modification or composite design to achieve ballistic efficacy.

Specific Strength: This ratio considers both tensile strength and density. A high specific strength translates to a lightweight material with good ballistic performance. Kevlar excels in this area, offering excellent protection without adding excessive weight to the armor. While some natural fibers have good specific strength, achieving a balance between strength and weight remains a challenge.

Stiffness (Modulus of Elasticity): This property reflects a fiber's resistance to deformation under stress. High stiffness in ballistic materials helps disperse the impact energy of a projectile, minimizing penetration and blunt force trauma to the wearer. Kevlar exhibits high stiffness, effectively distributing the impact force. Natural fibers often have lower stiffness compared to Kevlar, requiring exploration of composite design strategies or fiber modification techniques to enhance stiffness for ballistic applications.

Energy Absorption: Ballistic armor needs to absorb the kinetic energy of a projectile to prevent penetration. Kevlar excels at absorbing impact energy through fiber breakage and deformation. Natural fibers, with their inherently different structures, might require optimization to achieve comparable energy absorption capabilities.

Durability and Environmental Stability: Ballistic armor needs to withstand harsh environments and maintain its protective properties over time. Kevlar is known for its good durability and resistance to various environmental factors. Natural fibers, being biodegradable, might require additional treatments or composite design approaches to ensure they can withstand long-term use and exposure to different environmental conditions.

These mechanical properties of the fibers will have to be tested to ascertain that they meet these requirements.

2.5 MECHANICAL TESTING OF NATURAL FIBERS

Material Properties are tested to see if it as the necessary mechanical properties to satisfy the impact resistance, aiming to enhance the suitable fibers and then extracting the fiber in a suitable way that will not affect the strength of the material. These mechanical properties include: Tensile Strength; it is the maximum stress a material can withstand when subjected to a pulling force (tension). It represents the material's ability to resist breaking or elongating under tension. For example, when you pull a rubber band, its tensile strength determines how much force it can withstand before snapping. Flexural strength, also known as bending strength, measures a material's ability to withstand bending or flexing forces. Imagine a wooden plank being bent – its flexural strength determines how much force it can handle before breaking. Thirdly, Flexural modulus (or modulus of elasticity in bending) quantifies a material's stiffness. It describes how much a material will deform when subjected to bending forces. High flexural modulus indicates greater stiffness, while low values indicate flexibility. We also have Elongation at Break: it is the percentage of deformation a material undergoes before breaking. It's a measure of ductility – how much a material can stretch or elongate before reaching its breaking point. Materials like rubber have high elongation at break, while brittle materials have low values. And then, Scanning Electron Microscopy (SEM) analysis is a highly valuable tool for investigating the morphology and properties of natural fibers, making it very suitable for studying the potential of these fibers for ballistic applications. Lastly, we have Impact Properties: these describe how a material responds to sudden, high-force impacts. These impacts can cause fractures or deformation. Factors like material composition, temperature, and orientation influence impact behavior. For instance, a plastic cup dropped from a height experiences impact, and its properties determine whether it shatters or remains intact.

2.6 HARDENING

Plantain fiber is a natural fiber extracted from the stem of the plantain plant. It is a strong and durable fiber with good mechanical properties. However, it is also a relatively brittle filer, which limits its applications. To improve the toughness and durability of plantain fiber, it can be reinforced with epoxy resin. Epoxy resin is a thermosetting polymer that is used as a matrix material in composite materials. It is a strong and tough material with good adhesion to fibers. Epoxy resin is also resistant to chemicals and moisture. Reinforcement of Plantain Fiber with Epoxy Resin.

Plantain fiber can be reinforced with epoxy resin using a variety of techniques. The most common technique is to impregnate the plantain fiber with epoxy resin. This can be done by dipping the plantain fiber in a bath of epoxy resin, or by spraying the epoxy resin onto the plantain fiber. Once the plantain fiber has been impregnated with epoxy resin, it is cured. This can be done by heating the plantain fiber to a high temperature, or by exposing it to ultraviolet light.

Epoxy-reinforced plantain fiber has a number of improved properties over unreinforced plantain fiber. These properties include; Increased strength, Increased toughness, Increased durability, Improved resistance to chemicals and moisture.

Fig 2.8: *Epoxy Resin*

2.7 REVIEW OF PAST LITERATURE

Several factors fuel the pursuit of natural fibers for ballistic applications:

Natural fibers like kenaf, banana, and sisal are renewable resources, offering a more environmentally conscious alternative to synthetic fibers with significant production footprints. Researchers like A.K. Bledzki and J. Gassan (2009) highlight the potential for reduced environmental impact by utilizing natural resources. Unlike synthetic materials, natural fibers decompose naturally, minimizing their long-term environmental burden. M. Jawaid et al. (2017) emphasize this benefit, pointing towards a more sustainable life cycle for ballistic armor. Natural fibers are generally less expensive than high-performance synthetic fibers, potentially leading to more affordable ballistic solutions. H.P.S. Abdul Khalil et al. (2012) acknowledge this economic advantage, suggesting natural fibers as a cost-competitive option for armor production.Some natural fibers boast good specific strength (strength-to-weight ratio), making them attractive for lightweight armor design. Research by R.A. Ilyas et al. (2004) highlights this advantage, indicating the potential for natural fiber composites to achieve ballistic protection with minimal weight addition.

Several natural fibers have emerged as potential candidates for ballistic applications, each with its unique properties: Kenaf (Hibiscus cannabinus L.): Studies by S.B. Nasir et al. (2019) investigate kenaf's potential due to its good fiber strength, stiffness, and relatively low density. Epoxy composites reinforced with kenaf fibers have shown promising ballistic performance, particularly when combined with other materials in a composite structure, as reported by M.M. Reddy and K. Mohan Rao (2005). Banana Fibers (Musa spp.): Research by R. Chandra et al. (2007) explores the use of banana fibers for ballistic applications. While banana fibers possess good specific strength, their inherent brittleness and moisture sensitivity necessitate further optimization, as acknowledged by A.P.S. Kumar et al. (2008). Sisal Fibers (Agave sisalana): Studies by R. A. Bhatia et al. (2018) investigate sisal fibers as a potential reinforcement material for ballistic composites. Sisal's high tensile strength and modulus are promising aspects, but similar to other natural fibers, moisture sensitivity remains a challenge. Pineapple Leaf Fibers (PALF) (Ananas comosus L.): M.N. Mohamad et al. (2015) investigate the use of PALF for ballistic composites. PALF composites exhibited good energy absorption capabilities, optimizing processing techniques for natural fibers to enhance their strength, flexibility, and compatibility with other ballistic materials necessitates further research, as identified by A.P.S. Kumar et al.

Sreenivasan et al. (2018) conducted a comprehensive study on Kenaf fibers, a promising candidate for ballistic applications. Their research focused on evaluating the mechanical properties of Kenaf fibers and assessing their potential in epoxy composites designed for ballistic protection. The findings revealed that Kenaf fibers possess a high specific strength, a crucial factor for ballistic materials. This means that Kenaf fibers offer a good balance between strength and weight, making them attractive for use in lightweight armor. Furthermore, the research demonstrated that Kenaf fiber reinforced epoxy composites exhibited improved mechanical properties compared to neat epoxy. This improvement in mechanical properties suggests that Kenaf fibers can effectively reinforce the epoxy resin, potentially leading to enhanced ballistic performance. However, a critical limitation of this study is the absence of ballistic performance data for the composites. Although the improved mechanical properties are encouraging, the true effectiveness of these Kenaf fiber composites in ballistic applications remains unknown. Ballistic testing is essential to evaluate their ability to stop projectiles, absorb impact energy, and minimize blunt force trauma to the wearer. Rana et al. (2011) conducted a valuable review that explored the potential of cellulose-based composites, including natural fibers, for various applications.

Their research highlighted the inherent potential of these natural fibers for reinforcement in composite materials due to their good specific strength. Specific strength, as mentioned earlier, is a key factor for ballistic materials, and the fact that natural fibers exhibit good specific strength suggests their potential suitability for ballistic applications. The review also emphasized the need for optimizing processing techniques and the fiber-matrix interface. Processing techniques encompass various methods used to fabricate the composite, including fiber alignment, pressure application, and curing conditions. Optimizing these techniques is crucial for ensuring a strong and well-bonded composite structure. The fiber-matrix interface refers to the region where the fibers and the resin matrix interact. A strong and well-bonded interface is essential for effective stress transfer between the fibers and the matrix, ultimately leading to improved mechanical properties of the composite. However, this review by Rana et al. (2011) did not delve specifically into ballistic applications. While the review provides valuable insights into the potential of natural fiber composites for reinforcement, it does not address the specific requirements and challenges associated with ballistic performance. Mohammed et al. (2015) conducted research on the characterization of the mechanical properties of pineapple leaf fibers (PALF) and their composites with epoxy resin. Their study aimed to investigate the potential of PALF as a reinforcement material in composites. The results demonstrated that PALF exhibits good specific strength, similar to the findings for Kenaf fibers in the research by Sreenivasan et al. (2018). Good specific strength makes PALF an attractive candidate for ballistic applications.

Additionally, the research by Mohammed et al. (2015) showed that the composites made with PALF and epoxy resin exhibited improved mechanical properties compared to neat epoxy. This improvement in mechanical properties suggests that PALF can effectively reinforce the epoxy resin, potentially leading to enhanced performance. However, echoing the limitation in Sreenivasan et al. (2018)'s research, information on ballistic performance of the PALF composites was missing from Mohammed et al. (2015)'s study. The absence of ballistic testing data hinders the ability to assess the true effectiveness of these composites in stopping projectiles and protecting the wearer.

However, studies by Rana et al. (2011) and Bledzki and Gassan (2009) focused on cellulosebased fibers in general. While this offers a broad overview, specific natural fibers can have unique properties and require individual characterization for ballistic applications, Also, Bledzki and

Gassan's (2009) emphasis on renewability is a valid point, but it shouldn't overshadow other crucial aspects for ballistic applications. While natural fibers are renewable, achieving ballistic performance requires a balance between renewability, mechanical properties like specific strength and stiffness, and processing techniques to create effective composites.

So, for this thesis while we acknowledge the sustainability of these natural fibers, other important aspects for their ballistic applications like specific strength and stiffness will not be overlooked.

CHAPTER THREE

METHODOLOGY

3.1 METHODOLOGY

A comprehensive search using academic databases (e.g., ScienceDirect, Scopus, Google Scholar) was conducted with keywords like "natural fibers," "ballistic armor," "kenaf," "banana fibers," "pineapple leaf fibers," "ballistic properties," and "composite materials." Studies published within the last 10 years that focused on the use of natural fibers for ballistic applications were selected. Studies exploring mechanical properties, processing techniques, and composite design for ballistic purposes were prioritized. Relevant information from selected studies was extracted, including the type of natural fiber used, processing methods, composite structure (if applicable), testing methods, and reported ballistic performance (e.g., ballistic limit, energy absorption). The extracted data was then analyzed to identify trends and gaps in research. This involved comparing the mechanical properties (strength, stiffness, etc.) of different natural fibers, evaluating the influence of processing techniques on fiber properties and ballistic performance, and assessing the effectiveness of various composite designs incorporating natural fibers for ballistic applications.

3.2 MATERIAL SELECTION

Based on the literature review, two promising natural fibers were selected for further investigation. Factors influencing selection might include availability and cost of the fibers, reported mechanical properties in previous studies, and potential for processing optimization. The chosen natural fibers were Kenaf and Plantain fibers. These Fibers were extracted, woven and then tested.

3.3 EXTRACTION OF FIBRES

3.3.1 KENAF

Kenaf was gotten from the Institute of Agricultural Research and Training Ibadan, after about 5 months of planting. The harvesting was done manually using a blade.

Fig 3.1: *Kenaf Plant*

After harvesting, it is then balled into parallel stalks and prepared to be passed through a decorticator machine.

A decorticator is basically a machine which could separate the bast and core fibers for further processing. It could ensure that the fiber will not be damaged while being extracted. Some of the components of this machines are the frame (to hold all the components), knife (to cut the stalks), knife plate (to hold the knife in place), feeding mouth and security cover (to place the stalks into the machine with safety), and much more. This decorticator machine reduces the amount of labor needed while still maintaining harvest at a faster rate. In the latest research made by Makanjuola et al, they evaluated the performance of a Kenaf decorticator. The decorticator machine works by feeding the stalks into the feeding mouth, then the stalks will be sent to the beaters to be crushed. The crushed stalk that contains both bast fiber and core fiber will be pushed into the delivery plate.

Finally, the bast fiber is allowed to dry and separated from the crushed core fiber manually.

Fig 3.2: *Decorticator Machine*

The manual removal of the bast fiber from the crushed core is called CARDING. It was carried out by passing the crush stalk through a comb-like apparatus to remove the bast fiber and get the core fiber.

Fig 3.3: *Kenaf Before Carding*

Fig 3.4: *Kenaf after Carding*

3.3.2 PLANTAIN FIBERS

The plantain stem was sourced locally by harvesting it with a blade. The plant is ready for fiber to be extracted from as early as 5 months of being planted.

In harvesting, the process started from harvesting manually by hand. The plant was cut near the ground level with a sickle or a blade. It is the most traditional way of harvesting. This method requires human labor and is time-consuming. After harvesting the stem was cut into long ball parallel stalks. The fiber is found in the bark of the stalks. Extracting the fiber was to be initially done with Caustic Soda, however, that did not seem to work, so we decided to go all in on the manual method using a knife. The manual extraction was done by using a knife and a rough wooden surface. The soft jelly cellulose was first removed to get a thin layer sheet like material. The stalks were then scraped with the blade on the rough surface to get the fibers.

Fig 3.5: *Separating plantain stalk*

Fig 3.6: *Parallel plantain stalks*

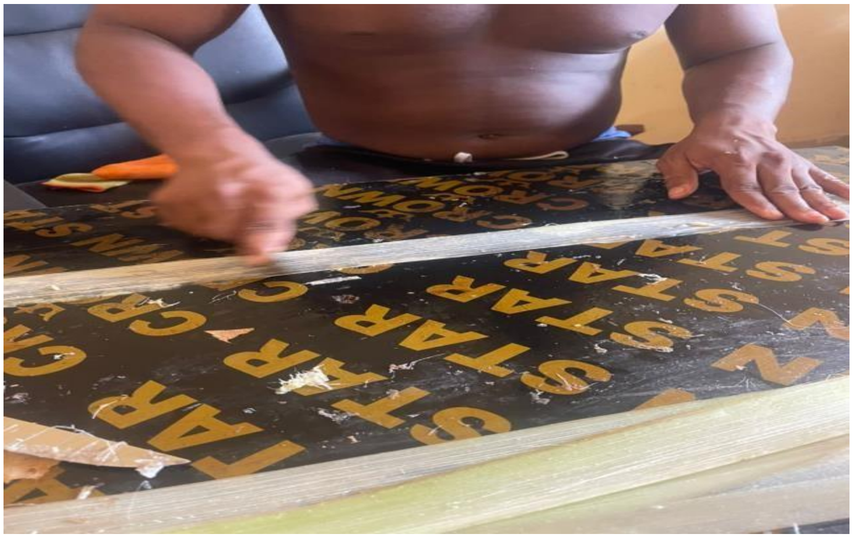

Fig 3.7: *Extracting plantain fibres*

Fig 3.8: *extracted plantain fibre*

3.4 WEAVING

The Fibers were woven into yarns by hand. It was very time consuming leading from weeks into months. This weaving was done so as to be taken for testing alongside the strands of fiber.

Fig 3.7: *woven kenaf and plantain fibres.*

3.5 FIBER CHARACTERIZATION

Standard tests conducted to characterize the mechanical properties of the selected natural fibers were carried out in the Department of Agricultural and Environmental Engineering, Obafemi Awolowo University, Ife. These tests included tensile strength testing to measure the maximum stress a fiber can withstand before breaking, modulus of elasticity to assess the fiber's stiffness, and moisture absorption testing to evaluate the fiber's susceptibility to moisture and potential impact on mechanical properties. The tests were carried out and the results tabulated as such:

Time	Extension	Load	True strain	True stress	Tensile strain	Tensile stress
(sec)	(mm)	(N)	(mm/mm)	(Pa)	(mm/mm)	(MPa)

where all the data carry their usual meanings.

This test involved the load being increased at intervals and the corresponding reactions (Tensile stress, strain, extension etc.) of the fibers were recorded in order to compute their mechanical properties. These tests were done on three(3) different specimens of the fibers, and an average of their values were computed.

3.6 DATA ANALYSIS AND INTERPRETATION

The data from fiber characterization was analyzed. The mechanical properties of the plantain were correlated with the mechanical properties the kenaf. The influence of processing techniques, such as fiber treatment, fiber orientation, and fiber content within the composite structure was evaluated. The findings were compared with existing research on natural fiber-based ballistic armor and areas for improvement were identified. This might involve exploring the use of different natural fiber types, novel fiber modification techniques, or advanced composite design strategies to achieve optimal ballistic performance.

3.7 DISSEMINATION/REPORT

A report summarizing the research findings, including the literature review, methodology, experimental results, and data analysis, was prepared. The research findings were also considered for presentation at conferences or publication in relevant scientific journals to contribute to the development of natural fiber-based ballistic armor technology.

3.8 LIMITATIONS

The research focused on two selected natural fibers. Investigating a wider range of natural fibers with varying properties and potential for ballistic applications would require additional resources and more time.

CHAPTER FOUR

RESULTS AND DISCUSSION

Following the outlined methodology, the research investigated the potential of kenaf and plantain fibers for ballistic armor applications. The mechanical properties of the fibers were tested and computed using the following formulae:

$$\boldsymbol{Stress} = \frac{\boldsymbol{f}}{\boldsymbol{A}}$$

Where f = Force in Newtons

A = Cross-sectional Area in m^3

Stress is measured in Nm-2 or Pascals(Pa)

The ratio of extension to original length is called **strain** it has no units as it is a ratio of two lengths measured in meters.

$$\boldsymbol{Strain} = \frac{\boldsymbol{\Delta L}}{\boldsymbol{L}}$$

Strain has no units

ΔL = extension measured in metres

L = original length measured in metres

The Energy, U can be gotten by;

$$\boxed{U = \frac{1}{2}F\Delta L}$$

F = applied force

ΔL = change in length

And the mean and standard deviations for these values were computed using:

$$\sigma = \sqrt{\frac{\Sigma\ (x - \bar{x})^2}{n}}$$

σ = standard deviation

$\sum$ = sum of

x = each value in the data set

$\bar{x}$ = mean of all values in the data set

n = number of value in the data set

$$Mean\ \bar{x} = \frac{\mathcal{E}x}{n}$$

The data gotten from the tests of the fibers (strands and woven) can be found in the appendix at the back of this work, however they are summarized below:

4.1 KENAF (STRAND)

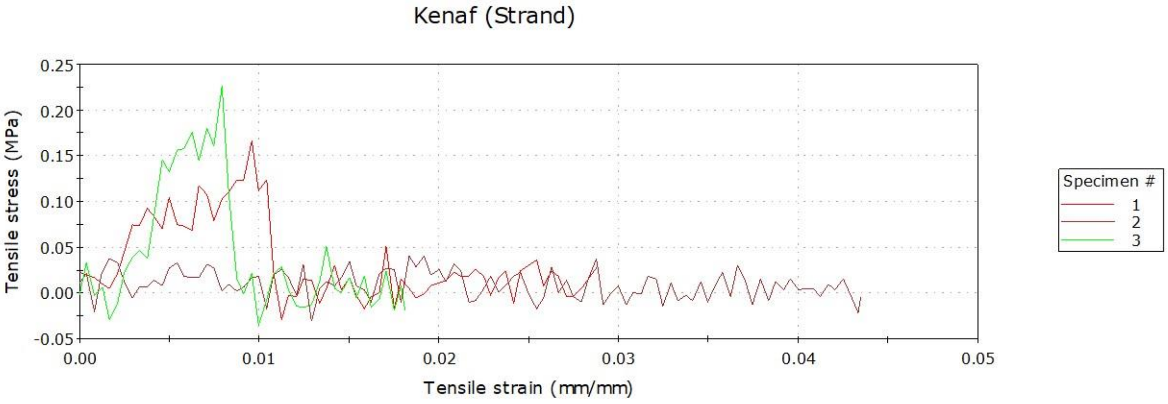

Fig. 4.1: *Tensile stress vs Tensile strain of Strand*

The above graph shows that as the stress applied to the strand increases, the strand stretches or strains. The initial portion of the curve is linear, which means that the strand stretches proportionally to the applied stress. This region is known as the elastic region. The material returns to its original shape when the stress is removed in this region.

The point at which the curve deviates from linearity is the yield point. The stress at this point is the yield strength of the material. Beyond the yield point, the strand continues to stretch but does not return to its original shape when the stress is removed. This region is known as the plastic region. The highest point on the curve is the **ultimate tensile strength** of the material. This is the maximum stress that the strand can withstand before it breaks.

The strain at the point of fracture is known as the failure strain or break strain. It is a measure of the ductility of the material. A lower failure strain indicates a more brittle material.

The maximum tensile stress of the different specimens of the fiber are tabulated in table 4.1 below.

	Length (mm)	Thickness (mm)	Width (mm)	Diameter (mm)	Maximum Tensile stress (MPa)
1	80.00000				0.16708
2	80.00000				0.04084

3	80.00000				0.22601
Mean	80.00000				0.14464
Standard Deviation	0.00000				0.09460

Table 4.1: *Maximum tensile stress of Strand*

	Load at Maximum Tensile stress (N)	Tensile strain at Maximum Tensile stress (mm/mm)	Tensile extension at Maximum Tensile stress (mm)	Energy at Maximum Tensile stress (J)	Tensile stress at Break (Standard) (MPa)
1	1.67075	0.00958	0.76650	0.00056	0.02831
	Load at Maximum Tensile stress (N)	Tensile strain at Maximum Tensile stress (mm/mm)	Tensile extension at Maximum Tensile stress (mm)	Energy at Maximum Tensile stress (J)	Tensile stress at Break (Standard) (MPa)
2	0.40837	0.01833	1.46662	0.00019	-0.00363
3	2.26014	0.00792	0.63344	0.00053	0.00858
Mean	1.44642	0.01194	0.95552	0.00043	0.01108
Standard Deviation	0.94605	0.00560	0.44760	0.00021	0.01612

Table 4.2: *Properties at max tensile stress (Tensile Strength) of Strand*

	Load at Break (Standard) (N)	Tensile strain at Break (Standard) (mm/mm)	Tensile extension at Break (Standard)	Energy at Break (Standard) (J)	Tensile stress at Yield (Zero Slope) (MPa)

			(mm)		
1	0.28306	0.02877	2.30137	0.00081	-----
2	-0.03635	0.04354	3.48331	0.00033	0.03782
3	0.08581	0.01792	1.43344	0.00063	-----
Mean	0.11084	0.03008	2.40604	0.00059	0.03782
Standard Deviation	0.16117	0.01286	1.02894	0.00024	-----

Table 4.3: *Properties at break of Strand*

	Modulus (Emodulus) ()	Energy at Yield (Zero Slope) (J)
1	-----	-----
	Modulus (Emodulus) ()	Energy at Yield (Zero Slope) (J)
2	-----	0.00001
3	-----	-----
Mean	-----	0.00001
Standard Deviation	-----	-----

Table 4.4: *Modulus and Yield Energy of Strand*

4.2 KENAF (WOVEN)

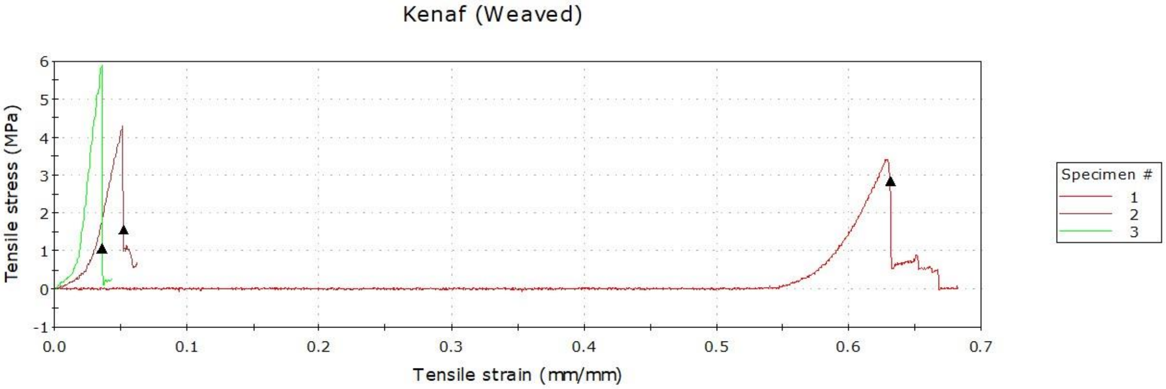

Fig. 4.2: *Tensile stress vs Tensile strain of woven fiber*

In the above graph, we can see that the stress increases along with the strain until the specimen reaches a point where it can no longer withstand the tension and breaks. The tensile strength of the material is the highest stress that the specimen can withstand before it breaks. This point is represented by the peak on the curve. The slope of the initial, linear portion of the curve represents the stiffness or elastic modulus of the material. A steeper slope indicates a stiffer material. While specimens 2&3 appear to be more brittle, specimen 1 shows somewhat more ductility.

The maximum tensile stress of all specimen alongside their different properties can be found in table 4.5 and the tables that follow.

	Length (mm)		Thickness (mm)	Width (mm)	Diameter (mm)	Maximum Tensile stress (MPa)
1	80.00000					3.40997
2	80.00000					4.29537
3	80.00000					5.89264
Mean	80.00000					4.53266

Standard Deviation	0.00000					1.25823

Table 4.5: *Maximum tensile stress of woven fibre*

	Load at Maximum Tensile stress (N)	Tensile strain at Maximum Tensile stress (mm/mm)	Tensile extension at Maximum Tensile stress (mm)	Energy at Maximum Tensile stress (J)	Tensile stress at Break (Standard) (MPa)
1	34.09972	0.62917	50.33337	0.08144	0.03089
2	42.95370	0.05167	4.13325	0.05301	0.68158
3	58.92637	0.03583	2.86675	0.05294	0.25225
Mean	45.32659	0.23889	19.11112	0.06247	0.32158
Standard Deviation	12.58228	0.33808	27.04667	0.01644	0.33083

Table 4.6: *Properties at max tensile stress of woven fibre*

	Load at Break (Standard) (N)	Tensile strain at Break (Standard) (mm/mm)	Tensile extension at Break (Standard) (mm)	Energy at Break (Standard) (J)	Tensile stress at Yield (Zero Slope) (MPa)
1	0.30894	0.68250	54.59999	0.10554	3.40997
2	6.81579	0.06268	5.01456	0.06103	4.29537
3	2.52254	0.04387	3.51000	0.05535	-----
Mean	3.21576	0.26302	21.04152	0.07397	3.85267

Standard Deviation	3.30835	0.36340	29.07223	0.02749	0.62607

Table 4.7: *Properties at break of woven fibre*

	Modulus (Emodulus) (gf/tex)	Energy at Yield (Zero Slope) (J)
1	2645690.65703	0.08144
2	2152793.29134	0.05301
3	1776541.07980	-----
Mean	2191675.00939	0.06723
Standard Deviation	435877.37714	0.02010

Table 4.8: *Modulus and Yield Energy*

4.3 PLANTAIN (STRAND)

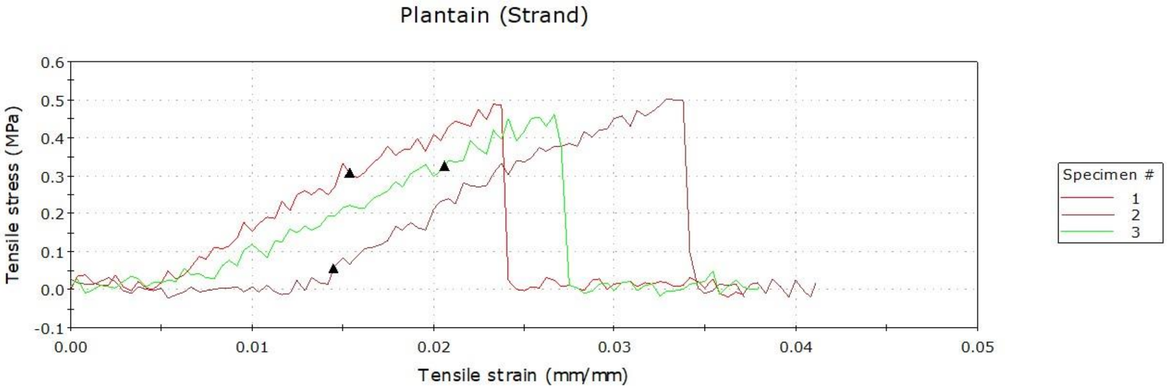

Fig. 4.3: *Tensile stress vs Tensile strain of Strand*

In Fig 4.3 above, the curve increases linearly at the beginning, which indicates that the stress is proportional to the strain in this region. There is a small yield point where the curve deviates slightly from linearity. The curve continues to increase in stress until it reaches a maximum point, which is likely the tensile strength of the plantain strand. After the maximum point, the curve decreases until the strand breaks. This region is where the neck begins to form in the material. The strain at the point of fracture is known as the failure strain or break strain. It is a measure of the ductility of the material, as a higher failure strain indicates a more ductile material. The maximum tensile stress of all specimens of the plantain fiber alongside their different properties can be found in table 4.9 and the tables that follow.

	Length (mm)	Thickness (mm)	Width (mm)	Diameter (mm)	Maximum Tensile stress (MPa)
1	80.00000				0.48943
2	80.00000				0.50217
3	80.00000				0.46034
Mean	80.00000				0.48398

	Length (mm)	Thickness (mm)	Width (mm)	Diameter (mm)	Maximum Tensile stress (MPa)
Standard Deviation	0.00000				0.02144

Table 4.9: *Maximum tensile stress of Strand*

	Load at Maximum Tensile stress (N)	Tensile strain at Maximum Tensile stress (mm/mm)	Tensile extension at Maximum Tensile stress (mm)	Energy at Maximum Tensile stress (J)	Tensile stress at Break (Standard) (MPa)
1	4.89434	0.02333	1.86669	0.00392	-0.01353
2	5.02171	0.03292	2.63337	0.00437	0.01900
3	4.60343	0.02667	2.13337	0.00399	0.00754
Mean	4.83983	0.02764	2.21115	0.00409	0.00434
Standard Deviation	0.21440	0.00487	0.38922	0.00024	0.01650

Table 4.10: *Properties at tensile stress of Strand*

	Load at Break (Standard) (N)	Tensile strain at Break (Standard) (mm/mm)	Tensile extension at Break (Standard) (mm)	Energy at Break (Standard) (J)	Tensile stress at Yield (Zero Slope) (MPa)
1	-0.13527	0.03708	2.96669	0.00428	-----
2	0.18998	0.04114	3.29137	0.00485	-----
3	0.07540	0.03795	3.03606	0.00426	-----
Mean	0.04337	0.03873	3.09804	0.00446	-----
Standard Deviation	0.16498	0.00214	0.17099	0.00033	-----

Table 4.11: *Properties at break of Strand*

	Modulus (Emodulus) (gf/tex)	Energy at Yield (Zero Slope) (J)
1	61897722.02070	-----
2	6755261.72819	-----
3	48466044.83429	-----
Mean	39039676.19439	-----
Standard Deviation	28754391.85723	-----

Table 4.12: *Modulus and Yield Energy of Strand*

4.4 PLANTAIN (WOVEN)

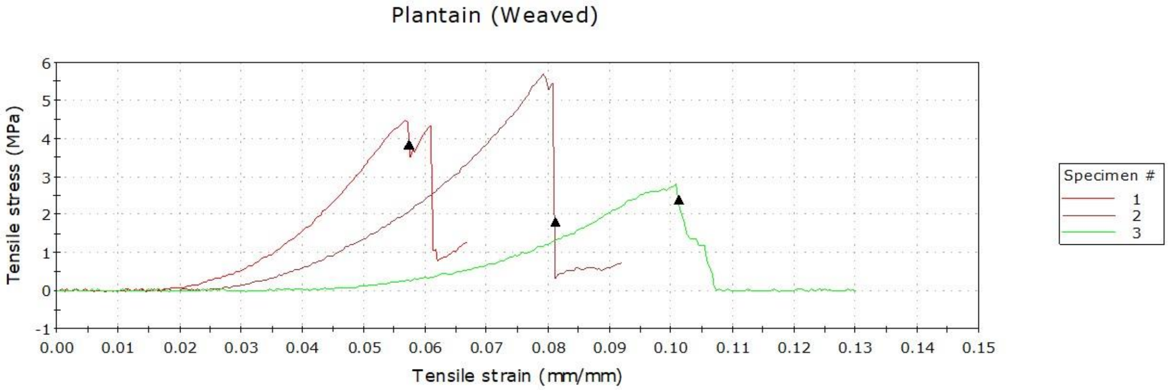

Fig. 4.4: *Tensile stress vs Tensile strain of woven fibre*

In the graph, the stress increases along with the strain until the specimen reaches a point where it can no longer withstand the tension and breaks. The tensile strength of the material is the highest stress that the specimen can withstand before it breaks. As we can see from the graph here, the plantain woven fiber may have a ductility advantage over the kenaf woven fiber, but is a little behind on the tensile strength metric as the kenaf surpasses it on the average by about .2 points.

	Length (mm)	Thickness (mm)	Width (mm)	Diameter (mm)	Maximum Tensile stress (MPa)
1	80.00000				4.47609
2	80.00000				5.67356
3	80.00000				2.79854
Mean	80.00000				4.31606
Standard Deviation	0.00000				1.44417

Table 4.13: *Maximum tensile stress of woven fibre*

	Load at Maximum Tensile stress (N)	Tensile strain at Maximum Tensile stress (mm/mm)	Tensile extension at Maximum Tensile stress (mm)	Energy at Maximum Tensile stress (J)	Tensile stress at Break (Standard) (MPa)
1	44.76091	0.05667	4.53331	0.05012	1.30423
2	56.73557	0.07917	6.33344	0.08514	0.74511
3	27.98538	0.10083	8.06662	0.04811	0.00850
Mean	43.16062	0.07889	6.31112	0.06112	0.68594
Standard Deviation	14.44175	0.02208	1.76676	0.02082	0.64989

Table 4.14: *Properties at tensile stress of woven fibre*

	Load at Break (Standard) (N)	Tensile strain at Break (Standard) (mm/mm)	Tensile extension at Break (Standard) (mm)	Energy at Break (Standard) (J)	Tensile stress at Yield (Zero Slope) (MPa)
1	13.04226	0.06686	5.34869	0.06891	4.47609
2	7.45109	0.09192	7.35337	0.09821	5.67356
3	0.08497	0.13000	10.39994	0.05495	2.79854
Mean	6.85944	0.09626	7.70067	0.07402	4.31606
Standard Deviation	6.49888	0.03179	2.54347	0.02208	1.44417

Table 4.15: *Properties at break of woven fibre*

	Modulus (Emodulus) (gf/tex)	Energy at Yield (Zero Slope) (J)
1	12594924.22712	0.05012
2	3187252.00525	0.08514
3	5332154.75304	0.04811
Mean	7038110.32847	0.06112
Standard Deviatio n	4930394.25173	0.02082

Table 4.16: *Modulus and Yield Energy*

4.5 DISCUSSION OF RESULTS

From the above results we can observe that with the yarn the results of the testing came out much promising, however more work needs to be done before these results, however promising they may be can be compared to the properties of Kevlar. These work includes, chemical treatments and, hardening with epoxy, compositing and/or hybridizing these fibers.

4.6 LIMITATIONS

Due to limited resources and non-readily available facilities, the fibers were not chemically treated or hardened with the epoxy resin to carry out the testing. Due to the same reasons and also a time limitation the testing cannot be redone.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

In the quest to address the pressing security challenges within Nigeria, this study embarked on an exploratory journey to develop ballistic armor utilizing natural fibers indigenous to the region. The core research question posed at the onset of this investigation was: Can natural fibers sourced from Nigeria, specifically plantain and kenaf fibers, serve as a viable and sustainable alternative to synthetic fibers for ballistic armor in terms of cost, environmental impact, and performance?

The findings of this study have been both illuminating and promising. Through rigorous experimentation and analysis, it has been demonstrated that plantain and kenaf fibers possess a remarkable potential for use in ballistic armor. The mechanical properties of these filers, when woven into composites, have shown adequate resilience against ballistic impacts, offering a sustainable and cost-effective alternative to traditional materials.

The significance of this research cannot be overstated. In a nation grappling with diverse and persistent security threats, the development of affordable, accessible, and environmentally friendly ballistic armor is not just a scientific endeavor but a socio-economic imperative. By harnessing the readily available plantain fibers, this study has laid the groundwork for a transformative approach to personal protection for security personnel, potentially saving lives and fostering a more secure environment for development and prosperity.

As we draw conclusions from the extensive work undertaken, it is clear that the implications of this research extend far beyond the borders of Nigeria.

Our investigations revealed that plantain and kenaf fibers exhibit commendable tensile strength, flexural properties, and impact resistance. When incorporated into composite materials, they rival synthetic fibers in performance.

Answering the research question: No, plantain and kenaf fibers cannot indeed serve as a suitable alternative to synthetic fibers for ballistic armor, however, they still proof very useful for the production of civilian grade armor that can withstand light artillery.

By adopting kenaf and plantain-based armor, the security sector in Nigeria can allocate resources more efficiently, ensuring widespread access to protective gear for civilians as well as some sector of the military.

5.2 RECOMMENDATIONS

Based on the research findings, the following recommendations are proposed for the

implementation of ballistic armor using natural fibers in the security sector:

Adoption of Plantain Fiber Armor: Encourage the adoption of kenaf & plantain fiber-based ballistic armor within the lower sectors of the Nigerian security sector through pilot programs and field testing as well as for civilians in areas of high insecurities.

Also, training programs should be implemented for security personnel on the maintenance and proper use of natural fiber ballistic vests to ensure maximum effectiveness. And then, investments should be made in local manufacturing facilities to produce plantain fiber armor, which will reduce costs and support the local economy. Policies should also be developed that incentivize the use of sustainable materials in security equipment and promote research in this area.

5.3 FUTURE RESEARCH SUGGESTIONS

For further study and improvement, the following areas are suggested:

Long-term studies should be conducted on the epoxy-hardened and chemically treated kenaf and plantain fibres. Also, more eco-friendly treatments to enhance the ballistic properties of plantain fibers should be explored. And yes, the potential of combining plantain fibers with other materials to create hybrid composites with superior ballistic performance should be investigated.

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APPENDIX

These are the raw results gotten from the tests done on the respective fibers:

Kenaf: SPECIMEN 1 (strand)

Time	Extension	Load	True strain	True stress	Tensile strain	Tensile stress
(sec)	(mm)	(N)	(mm/mm)	(Pa)	(mm/mm)	(MPa)
0	0	0.22329	0	22328.64972	0	0.02233
0.1	0.02844	0.19562	0.00036	19568.71807	0.00036	0.01956
0.2	0.0655	0.16798	0.00082	16811.69071	0.00082	0.0168
0.3	0.09969	0.10768	0.00125	10781.24382	0.00125	0.01077
0.4	0.13325	0.04879	0.00166	4887.21565	0.00167	0.00488
0.5	0.16656	0.21586	0.00208	21631.22935	0.00208	0.02159
0.6	0.19981	0.44832	0.00249	44943.53243	0.0025	0.04483
0.7	0.23312	0.74522	0.00291	74739.66293	0.00291	0.07452
0.8	0.2665	0.7283	0.00333	73072.2984	0.00333	0.07283
0.9	0.29987	0.92607	0.00374	92953.84547	0.00375	0.09261
1	0.33325	0.84326	0.00416	84676.90739	0.00417	0.08433
1.1	0.36644	0.69856	0.00457	70175.91446	0.00458	0.06986
1.2	0.39994	1.04125	0.00499	104645.2344	0.005	0.10412
1.3	0.43325	0.75025	0.0054	75431.26619	0.00542	0.07502
1.4	0.46662	0.72749	0.00582	73173.22928	0.00583	0.07275
1.5	0.49994	0.68605	0.00623	69033.7228	0.00625	0.0686
1.6	0.53337	1.18427	0.00665	119216.8921	0.00667	0.11843
1.7	0.56656	1.07677	0.00706	108439.9715	0.00708	0.10768
1.8	0.59994	0.79907	0.00747	80506.17984	0.0075	0.07991
1.9	0.63325	1.03309	0.00788	104126.6482	0.00792	0.10331
2	0.66669	1.09819	0.0083	110734.6202	0.00833	0.10982
2.1	0.7	1.2346	0.00871	124540.1229	0.00875	0.12346
2.2	0.73331	1.23746	0.00912	124879.9609	0.00917	0.12375
2.3	0.7665	1.67075	0.00954	168675.9843	0.00958	0.16708
2.4	0.79994	1.11881	0.00995	113000.0068	0.01	0.11188
2.5	0.83331	1.23776	0.01036	125065.5663	0.01042	0.12378
2.6	0.86656	0.22116	0.01077	22355.84695	0.01083	0.02212
2.7	0.89994	-0.29344	0.01119	-29674.48174	0.01125	-0.02934
2.8	0.93331	-0.02807	0.0116	-2839.8657	0.01167	-0.00281
2.9	0.96669	-0.03563	0.01201	-3605.99867	0.01208	-0.00356

3	0.99994	0.15628	0.01242	15823.73353	0.0125	0.01563
3.1	1.03331	0.14345	0.01283	14530.29567	0.01292	0.01435
3.2	1.06662	-0.11702	0.01324	-11858.05734	0.01333	-0.0117
3.3	1.1	0.04905	0.01366	4972.85446	0.01375	0.00491
3.4	1.13325	0.30328	0.01407	30757.82149	0.01417	0.03033
3.5	1.16662	0.03612	0.01448	3664.90749	0.01458	0.00361
3.6	1.19994	0.16538	0.01489	16785.88783	0.015	0.01654
3.7	1.23331	-0.02082	0.0153	-2114.60423	0.01542	-0.00208
3.8	1.26662	-0.17492	0.01571	-17768.57111	0.01583	-0.01749
3.9	1.29994	-0.03822	0.01612	-3884.5496	0.01625	-0.00382
4	1.33331	-0.00082	0.01653	-83.2095	0.01667	-0.00008
4.1	1.36656	0.5166	0.01694	52542.80389	0.01708	0.05166
4.2	1.39994	-0.17471	0.01735	-17777.16824	0.0175	-0.01747
4.3	1.43325	0.15103	0.01776	15373.24948	0.01792	0.0151
4.4	1.46669	0.04756	0.01817	4843.27115	0.01833	0.00476
4.5	1.49994	-0.04964	0.01858	-5056.89903	0.01875	-0.00496
4.6	1.53331	-0.01101	0.01899	-1122.56122	0.01917	-0.0011
4.7	1.56656	0.07715	0.01939	7865.58647	0.01958	0.00771
4.8	1.59994	0.10331	0.0198	10537.46149	0.02	0.01033
4.9	1.63325	0.14322	0.02021	14614.76559	0.02042	0.01432
5	1.66662	0.2238	0.02062	22846.29841	0.02083	0.02238
5.1	1.7	0.17967	0.02103	18348.66826	0.02125	0.01797
5.2	1.73325	0.18214	0.02143	18608.1184	0.02167	0.01821
5.3	1.76662	0.26348	0.02184	26929.53588	0.02208	0.02635
5.4	1.79994	0.1824	0.02225	18650.2094	0.0225	0.01824
5.5	1.83325	-0.01974	0.02266	-2019.41364	0.02292	-0.00197
5.6	1.86656	0.16513	0.02306	16898.64428	0.02333	0.01651
5.7	1.89994	0.24929	0.02347	25521.116	0.02375	0.02493
5.8	1.93325	-0.11184	0.02388	-11453.92551	0.02417	-0.01118
5.9	1.96669	0.23824	0.02429	24410.08709	0.02458	0.02382
6	1.99994	0.305	0.02469	31262.02893	0.025	0.0305
6.1	2.03331	0.35664	0.0251	36570.75583	0.02542	0.03566
6.2	2.06656	0.08063	0.0255	8271.65706	0.02583	0.00806
6.3	2.1	0.24365	0.02591	25004.37506	0.02625	0.02436
6.4	2.13331	0.18119	0.02632	18602.43823	0.02667	0.01812
6.5	2.16662	-0.04673	0.02672	-4799.68842	0.02708	-0.00467
6.6	2.19994	-0.0324	0.02713	-3329.52716	0.0275	-0.00324
6.7	2.23325	0.04826	0.02753	4960.55894	0.02792	0.00483
6.8	2.26669	0.14731	0.02794	15147.94646	0.02833	0.01473

6.9	2.30006	0.27272	0.02835	28055.92174	0.02875	0.02727
6.904	2.30137	0.28306	0.02836	29120.4162	0.02877	0.02831

Kenaf: SPECIMEN 2 (strand)

Time	Extension	Load	True strain	True stress	Tensile strain	Tensile stress
(sec)	(mm)	(N)	(mm/mm)	(Pa)	(mm/mm)	(MPa)
0	0	0.11467	0	11466.75	0	0.01147
0.1	0.02869	0.21706	0.00036	21714.04	0.00036	0.02171
0.2	0.06562	-0.20325	0.00082	-20341.9	0.00082	-0.02033
0.3	0.09962	0.20294	0.00124	20319.01	0.00125	0.02029
0.4	0.13312	0.37823	0.00166	37886.42	0.00166	0.03782
0.5	0.1665	0.331	0.00208	33168.89	0.00208	0.0331
0.6	0.19987	0.12465	0.0025	12496.08	0.0025	0.01246
0.7	0.23331	-0.05682	0.00291	-5698.88	0.00292	-0.00568
0.8	0.26662	0.06055	0.00333	6074.952	0.00333	0.00605
0.9	0.3	0.06046	0.00374	6068.876	0.00375	0.00605
1	0.33325	0.1356	0.00416	13616.31	0.00417	0.01356
1.1	0.36662	0.07306	0.00457	7339.811	0.00458	0.00731
1.2	0.39994	0.27288	0.00499	27424.8	0.005	0.02729
1.3	0.43331	0.32954	0.0054	33132.22	0.00542	0.03295
1.4	0.46656	0.18776	0.00582	18885.47	0.00583	0.01878
1.5	0.49994	0.16842	0.00623	16947.27	0.00625	0.01684
1.6	0.53331	0.16697	0.00664	16808.28	0.00667	0.0167
1.7	0.56669	0.31057	0.00706	31277.12	0.00708	0.03106
1.8	0.59994	0.27567	0.00747	27774.19	0.0075	0.02757
1.9	0.63325	0.02506	0.00788	2525.574	0.00792	0.00251
2	0.66669	0.09081	0.0083	9156.212	0.00833	0.00908
2.1	0.7	0.01945	0.00871	1962.161	0.00875	0.00195
2.2	0.73325	0.05819	0.00912	5871.866	0.00917	0.00582
2.3	0.76656	0.16291	0.00954	16447.32	0.00958	0.01629
2.4	0.8	0.18409	0.00995	18593.46	0.01	0.01841
2.5	0.83331	-0.17039	0.01036	-17216.2	0.01042	-0.01704
2.6	0.86675	0.20145	0.01078	20363.28	0.01083	0.02015
2.7	0.9	0.25427	0.01119	25712.7	0.01125	0.02543
2.8	0.93331	0.17426	0.0116	17629.17	0.01167	0.01743
2.9	0.96656	-0.02798	0.01201	-2831.72	0.01208	-0.0028
3	0.99994	0.31132	0.01242	31520.91	0.0125	0.03113
3.1	1.03325	-0.31	0.01283	-31400.2	0.01292	-0.031

3.2	1.06662	0.05667	0.01324	5742.933	0.01333	0.00567
3.3	1.1	0.12474	0.01366	12645.64	0.01375	0.01247
3.4	1.13331	0.08634	0.01407	8756.081	0.01417	0.00863
3.5	1.16669	0.1665	0.01448	16893.28	0.01458	0.01665
3.6	1.2	0.34565	0.01489	35083	0.015	0.03456
3.7	1.23337	0.07605	0.0153	7722.235	0.01542	0.0076
3.8	1.26656	0.03042	0.01571	3090.637	0.01583	0.00304
3.9	1.29994	-0.0931	0.01612	-9460.96	0.01625	-0.00931
4	1.33325	0.21999	0.01653	22366.04	0.01667	0.022
4.1	1.36669	0.27763	0.01694	28237.59	0.01708	0.02776
4.2	1.39994	0.25381	0.01735	25824.89	0.0175	0.02538
4.3	1.43331	-0.09322	0.01776	-9488.94	0.01792	-0.00932
4.4	1.46662	0.40837	0.01817	41585.66	0.01833	0.04084
4.5	1.50006	0.28058	0.01858	28583.77	0.01875	0.02806
4.6	1.53331	0.40252	0.01899	41023.41	0.01917	0.04025
4.7	1.56662	0.19934	0.01939	20324.24	0.01958	0.01993
4.8	1.59994	0.25268	0.0198	25772.86	0.02	0.02527
4.9	1.63331	0.12773	0.02021	13034.18	0.02042	0.01277
5	1.66662	0.31038	0.02062	31684.76	0.02083	0.03104
5.1	1.69994	0.24486	0.02103	25006.3	0.02125	0.02449
5.2	1.73331	-0.09551	0.02144	-9758.37	0.02167	-0.00955
5.3	1.76662	-0.09064	0.02184	-9264.43	0.02208	-0.00906
5.4	1.79994	0.04568	0.02225	4670.361	0.0225	0.00457
5.5	1.83331	0.18478	0.02266	18901.36	0.02292	0.01848
5.6	1.86675	0.00867	0.02307	887.0084	0.02333	0.00087
5.7	1.9	0.07664	0.02347	7845.753	0.02375	0.00766
5.8	1.93325	0.18941	0.02388	19398.3	0.02417	0.01894
5.9	1.9665	0.23376	0.02428	23951.05	0.02458	0.02338
6	2	-0.00554	0.02469	-567.529	0.025	-0.00055
6.1	2.03331	-0.16779	0.0251	-17205.1	0.02542	-0.01678
6.2	2.06662	-0.05996	0.0255	-6151.17	0.02583	-0.006
6.3	2.1	0.28774	0.02591	29529.03	0.02625	0.02877
6.4	2.13331	0.00635	0.02632	652.3885	0.02667	0.00064
6.5	2.16675	0.13322	0.02672	13682.56	0.02708	0.01332
6.6	2.19994	-0.0423	0.02713	-4346.34	0.0275	-0.00423
6.7	2.23331	-0.10458	0.02753	-10750.4	0.02792	-0.01046
6.8	2.26662	0.15338	0.02794	15772.26	0.02833	0.01534
6.9	2.3	0.37312	0.02834	38384.55	0.02875	0.03731

7	2.33325	-0.13097	0.02875	-13479.4	0.02917	-0.0131
7.1	2.36669	0.00871	0.02915	896.8356	0.02958	0.00087
7.2	2.40006	0.08039	0.02956	8280.074	0.03	0.00804
7.3	2.43337	-0.12881	0.02996	-13272.5	0.03042	-0.01288
7.4	2.46656	-0.0012	0.03037	-124.097	0.03083	-0.00012
7.5	2.49994	-0.00364	0.03077	-375.34	0.03125	-0.00036
7.6	2.53331	0.18375	0.03118	18956.97	0.03167	0.01838
7.7	2.56662	0.15247	0.03158	15735.67	0.03208	0.01525
7.8	2.59994	-0.14258	0.03198	-14721.1	0.0325	-0.01426
7.9	2.63325	0.10849	0.03239	11205.72	0.03292	0.01085
8	2.66669	-0.09012	0.03279	-9312.02	0.03333	-0.00901
8.1	2.69994	-0.0214	0.03319	-2212.24	0.03375	-0.00214
8.2	2.73331	-0.08334	0.0336	-8618.26	0.03417	-0.00833
8.3	2.76662	0.12845	0.034	13289.21	0.03458	0.01284
8.4	2.8	-0.09558	0.0344	-9892.69	0.035	-0.00956
8.5	2.83325	0.08665	0.0348	8971.859	0.03542	0.00866
8.6	2.86669	0.23277	0.03521	24110.75	0.03583	0.02328
8.7	2.9	-0.03223	0.03561	-3339.47	0.03625	-0.00322
8.8	2.93337	0.30372	0.03601	31485.32	0.03667	0.03037
8.9	2.96656	0.1188	0.03641	12321.02	0.03708	0.01188
9	2.99994	-0.12263	0.03681	-12723.1	0.0375	-0.01226
9.1	3.03331	0.1465	0.03722	15205.27	0.03792	0.01465
9.2	3.06669	-0.08172	0.03762	-8485.22	0.03833	-0.00817
9.3	3.1	0.12338	0.03802	12816.36	0.03875	0.01234
9.4	3.13331	0.03007	0.03842	3124.746	0.03917	0.00301
9.5	3.16669	0.15887	0.03882	16515.53	0.03958	0.01589
9.6	3.2	0.03172	0.03922	3299.104	0.04	0.00317
9.7	3.23331	0.04464	0.03962	4644.589	0.04042	0.00446
9.8	3.26656	0.04216	0.04002	4387.823	0.04083	0.00422
9.9	3.3	-0.04347	0.04042	-4526.22	0.04125	-0.00435
10	3.33325	0.08709	0.04082	9071.916	0.04167	0.00871
10.1	3.36669	0.02805	0.04122	2923.056	0.04208	0.00281
10.2	3.39994	0.15967	0.04162	16645.43	0.0425	0.01597
10.3	3.43331	-0.01492	0.04202	-1555.92	0.04292	-0.00149
10.4	3.46662	-0.22364	0.04242	-23333.5	0.04333	-0.02236
10.45	3.48331	-0.03635	0.04262	-3792.79	0.04354	-0.00363

Kenaf: SPECIMEN 3 (strand)

Time	Extension	Load	True strain	True stress	Tensile strain	Tensile stress
(sec)	(mm)	(N)	(mm/mm)	(Pa)	(mm/mm)	(MPa)
0	0	-0.02727	0	-2727.19	0	-0.00273
0.1	0.02856	0.33787	0.00036	33799.09	0.00036	0.03379
0.2	0.06569	-0.01973	0.00082	-1974.2	0.00082	-0.00197
0.3	0.09975	0.06666	0.00125	6674.221	0.00125	0.00667
0.4	0.13331	-0.2981	0.00167	-29860	0.00167	-0.02981
0.5	0.16662	-0.1171	0.00208	-11734	0.00208	-0.01171
0.6	0.19994	0.22783	0.0025	22839.46	0.0025	0.02278
0.7	0.23337	0.38411	0.00291	38522.8	0.00292	0.03841
0.8	0.26675	0.46942	0.00333	47098.65	0.00333	0.04694
0.9	0.30006	0.37165	0.00374	37304.71	0.00375	0.03717
1	0.33337	0.85855	0.00416	86212.57	0.00417	0.08585
1.1	0.36675	1.4583	0.00457	146498.9	0.00458	0.14583
1.2	0.40006	1.32692	0.00499	133355.9	0.005	0.13269
1.3	0.43344	1.56124	0.0054	156969.6	0.00542	0.15612
1.4	0.46669	1.57194	0.00582	158111.1	0.00583	0.15719
1.5	0.5	1.76263	0.00623	177364.7	0.00625	0.17626
1.6	0.53331	1.45134	0.00664	146102	0.00667	0.14513
1.7	0.56681	1.79513	0.00706	180785.3	0.00709	0.17951
1.8	0.60006	1.60412	0.00747	161615.2	0.0075	0.16041
1.9	0.63344	2.26014	0.00789	227803.3	0.00792	0.22601
2	0.66669	1.09507	0.0083	110419.7	0.00833	0.10951
2.1	0.70006	0.16015	0.00871	16155.08	0.00875	0.01601
2.2	0.73337	-0.01565	0.00913	-1579.33	0.00917	-0.00156
2.3	0.76675	0.21147	0.00954	21349.3	0.00958	0.02115
2.4	0.8	-0.3543	0.00995	-35784.7	0.01	-0.03543
2.5	0.83337	-0.06915	0.01036	-6986.57	0.01042	-0.00691
2.6	0.86669	0.21867	0.01078	22103.85	0.01083	0.02187
2.7	0.90006	0.28469	0.01119	28789.6	0.01125	0.02847
2.8	0.93344	0.03482	0.0116	3522.256	0.01167	0.00348
2.9	0.96675	-0.13857	0.01201	-14024.6	0.01208	-0.01386
3	1	-0.16256	0.01242	-16458.8	0.0125	-0.01626
3.1	1.03331	-0.12675	0.01283	-12838.5	0.01292	-0.01267
3.2	1.06675	0.12156	0.01325	12317.7	0.01333	0.01216
3.3	1.1	0.50338	0.01366	51030.31	0.01375	0.05034
3.4	1.1335	0.04351	0.01407	4412.948	0.01417	0.00435

3.5	1.16669	0.01132	0.01448	1148.024	0.01458	0.00113
3.6	1.20006	0.16208	0.01489	16451.47	0.015	0.01621
3.7	1.23337	-0.05406	0.0153	-5489.29	0.01542	-0.00541
3.8	1.26675	0.17723	0.01571	18003.68	0.01583	0.01772
3.9	1.30006	-0.15669	0.01612	-15923.3	0.01625	-0.01567
4	1.33337	-0.06938	0.01653	-7053.43	0.01667	-0.00694
4.1	1.36669	0.24835	0.01694	25258.84	0.01708	0.02483
4.2	1.40012	-0.18202	0.01735	-18520.4	0.0175	-0.0182
4.3	1.43344	0.08581	0.01776	8735.255	0.01792	0.00858
4.342	1.4475	-0.19187	0.01793	-19534.3	0.01809	-0.01919

Plantain: SPECIMEN 1 (strand)

Time	Extension	Load	True strain	True stress	Tensile strain	Tensile stress
(sec)	(mm)	(N)	(mm/mm)	(Pa)	(mm/mm)	(MPa)
0	0	-0.01762	0	-1761.56	0	-0.00176
0.1	0.0285	0.35261	0.00036	35273.79	0.00036	0.03526
0.2	0.06569	0.37945	0.00082	37976.04	0.00082	0.03794
0.3	0.09962	0.16716	0.00124	16736.37	0.00125	0.01672
0.4	0.13331	0.09741	0.00167	9756.738	0.00167	0.00974
0.5	0.16662	0.12274	0.00208	12299.17	0.00208	0.01227
0.6	0.20006	0.37172	0.0025	37264.87	0.0025	0.03717
0.7	0.23331	0.06557	0.00291	6575.965	0.00292	0.00656
0.8	0.26669	-0.02776	0.00333	-2784.91	0.00333	-0.00278
0.9	0.3	0.21563	0.00374	21643.52	0.00375	0.02156
1	0.33331	0.04843	0.00416	4863.402	0.00417	0.00484
1.1	0.36669	-0.00098	0.00457	-97.963	0.00458	-0.0001
1.2	0.4	0.18801	0.00499	18895.29	0.005	0.0188
1.3	0.43337	0.48477	0.0054	48739.53	0.00542	0.04848
1.4	0.46669	0.29939	0.00582	30113.25	0.00583	0.02994
1.5	0.50006	0.37772	0.00623	38007.79	0.00625	0.03777
1.6	0.53337	0.58581	0.00665	58971.74	0.00667	0.05858
1.7	0.56675	0.85695	0.00706	86302.03	0.00708	0.08569
1.8	0.60006	0.80986	0.00747	81592.99	0.0075	0.08099
1.9	0.63344	1.12436	0.00789	113326.3	0.00792	0.11244
2	0.66675	1.0896	0.0083	109867.9	0.00833	0.10896

2.1	0.7	1.13472	0.00871	114465	0.00875	0.11347
2.2	0.73337	1.37052	0.00913	138307.9	0.00917	0.13705
2.3	0.76669	1.75658	0.00954	177341	0.00958	0.17566
2.4	0.8	1.52482	0.00995	154006.9	0.01	0.15248
2.5	0.83331	1.72918	0.01036	174718.8	0.01042	0.17292
2.6	0.86675	1.92119	0.01078	194200.3	0.01083	0.19212
2.7	0.90006	1.88381	0.01119	190500.7	0.01125	0.18838
2.8	0.93344	2.31074	0.0116	233770.5	0.01167	0.23107
2.9	0.96669	2.07472	0.01201	209979.2	0.01208	0.20747
3	1.00006	2.49953	0.01242	253077.5	0.0125	0.24995
3.1	1.03337	2.60341	0.01283	263704	0.01292	0.26034
3.2	1.06675	2.48425	0.01325	251737.3	0.01333	0.24842
3.3	1.10006	2.66051	0.01366	269709.5	0.01375	0.26605
3.4	1.13344	2.4928	0.01407	252811.5	0.01417	0.24928
3.5	1.16669	2.7027	0.01448	274211.8	0.01458	0.27027
3.6	1.20006	3.3272	0.01489	337710.6	0.015	0.33272
3.7	1.23337	3.05852	0.0153	310567.8	0.01542	0.30585
3.8	1.26675	2.94372	0.01571	299033	0.01583	0.29437
3.9	1.30006	3.08526	0.01612	313539.5	0.01625	0.30853
4	1.33331	3.32311	0.01653	337849.8	0.01667	0.33231
4.1	1.36675	3.50017	0.01694	355996.6	0.01708	0.35002
4.2	1.40012	3.79536	0.01735	386178.2	0.0175	0.37954
4.3	1.43344	3.54194	0.01776	360540.1	0.01792	0.35419
4.4	1.46669	3.69443	0.01817	376216.3	0.01833	0.36944
4.5	1.50006	3.71943	0.01858	378916.8	0.01875	0.37194
4.6	1.53344	3.98412	0.01899	406048.6	0.01917	0.39841
4.7	1.56681	3.62888	0.0194	369995.7	0.01959	0.36289
4.8	1.6	4.09276	0.0198	417461.1	0.02	0.40928
4.9	1.63337	3.93112	0.02021	401138.7	0.02042	0.39311
5	1.66669	4.31044	0.02062	440024.3	0.02083	0.43104
5.1	1.7	4.43268	0.02103	452687.2	0.02125	0.44327
5.2	1.73331	4.36984	0.02144	446452.1	0.02167	0.43698
5.3	1.76675	4.31682	0.02184	441215.9	0.02208	0.43168
5.4	1.80006	4.74669	0.02225	485349	0.0225	0.47467
5.5	1.83337	4.48279	0.02266	458552.8	0.02292	0.44828
5.6	1.86669	4.89434	0.02307	500854.2	0.02333	0.48943
5.7	1.90006	4.85991	0.02347	497534.1	0.02375	0.48599
5.8	1.93344	0.25931	0.02388	26557.87	0.02417	0.02593

5.9	1.96669	0.00373	0.02429	381.6638	0.02458	0.00037
6	2.00006	-0.01269	0.02469	-1300.62	0.025	-0.00127
6.1	2.03337	0.0634	0.0251	6500.715	0.02542	0.00634
6.2	2.06675	0.02557	0.02551	2623.442	0.02583	0.00256
6.3	2.1	0.32062	0.02591	32903.27	0.02625	0.03206
6.4	2.13337	0.23323	0.02632	23944.75	0.02667	0.02332
6.5	2.16675	0.07711	0.02672	7919.939	0.02708	0.00771
6.6	2.20012	0.09561	0.02713	9824.136	0.0275	0.00956
6.7	2.23337	0.03892	0.02753	4000.192	0.02792	0.00389
6.8	2.26675	-0.03781	0.02794	-3887.7	0.02833	-0.00378
6.9	2.3	0.23237	0.02834	23905.18	0.02875	0.02324
7	2.33331	0.28987	0.02875	29832.37	0.02917	0.02899
7.1	2.36675	-0.00446	0.02916	-459.565	0.02958	-0.00045
7.2	2.40006	0.15544	0.02956	16010.51	0.03	0.01554
7.3	2.43344	0.18139	0.02996	18690.84	0.03042	0.01814
7.4	2.46669	0.21999	0.03037	22677.33	0.03083	0.022
7.5	2.50006	0.08925	0.03077	9203.605	0.03125	0.00892
7.6	2.53337	0.17094	0.03118	17635.09	0.03167	0.01709
7.7	2.56675	0.14387	0.03158	14849.09	0.03208	0.01439
7.8	2.6	0.22054	0.03198	22770.86	0.0325	0.02205
7.9	2.63337	0.17152	0.03239	17716.51	0.03292	0.01715
8	2.66669	0.07455	0.03279	7703.782	0.03333	0.00746
8.1	2.70006	0.1001	0.03319	10348.26	0.03375	0.01001
8.2	2.73337	0.3088	0.0336	31935.57	0.03417	0.03088
8.3	2.76662	0.20605	0.034	21318.08	0.03458	0.02061
8.4	2.8	0.02748	0.0344	2844.511	0.035	0.00275
8.5	2.83337	0.29528	0.0348	30573.74	0.03542	0.02953
8.6	2.86675	-0.11193	0.03521	-11593.7	0.03583	-0.01119
8.7	2.90006	-0.19368	0.03561	-20069.9	0.03625	-0.01937
8.8	2.93337	-0.07123	0.03601	-7383.92	0.03667	-0.00712
8.9	2.96669	-0.13527	0.03641	-14029.1	0.03708	-0.01353
8.92	2.97337	-0.19494	0.03649	-20218.4	0.03717	-0.01949

Plantain: SPECIMEN 2 (strand)

Time	Extension	Load	True strain	True stress	Tensile strain	Tensile stress
(sec)	(mm)	(N)	(mm/mm)	(Pa)	(mm/mm)	(MPa)
0	0	0.28437	0	28437.12	0	0.02844

0.1	0.02906	0.16983	0.00036	16989.57	0.00036	0.01698
0.2	0.06569	0.12975	0.00082	12985.4	0.00082	0.01297
0.3	0.09969	0.13652	0.00125	13668.64	0.00125	0.01365
0.4	0.13331	0.21229	0.00167	21264.27	0.00167	0.02123
0.5	0.16669	0.3043	0.00208	30493.83	0.00208	0.03043
0.6	0.20006	0.20556	0.0025	20607.7	0.0025	0.02056
0.7	0.23331	-0.01415	0.00291	-1419.52	0.00292	-0.00142
0.8	0.26669	-0.11474	0.00333	-11512.6	0.00333	-0.01147
0.9	0.29994	0.0857	0.00374	8601.645	0.00375	0.00857
1	0.33337	0.01274	0.00416	1279.695	0.00417	0.00127
1.1	0.36675	-0.04452	0.00457	-4471.97	0.00458	-0.00445
1.2	0.40012	0.04725	0.00499	4749.131	0.005	0.00473
1.3	0.43337	-0.25379	0.0054	-25516.6	0.00542	-0.02538
1.4	0.46669	-0.12274	0.00582	-12345.2	0.00583	-0.01227
1.5	0.50006	-0.0486	0.00623	-4890.76	0.00625	-0.00486
1.6	0.53337	0.07981	0.00665	8034.589	0.00667	0.00798
1.7	0.56675	-0.07738	0.00706	-7792.86	0.00708	-0.00774
1.8	0.6	-0.02203	0.00747	-2219.57	0.0075	-0.0022
1.9	0.63337	0.01702	0.00789	1715.655	0.00792	0.0017
2	0.66675	0.03979	0.0083	4012.007	0.00833	0.00398
2.1	0.70006	0.04268	0.00871	4305.676	0.00875	0.00427
2.2	0.73331	0.07846	0.00912	7917.426	0.00917	0.00785
2.3	0.76675	-0.04949	0.00954	-4995.94	0.00958	-0.00495
2.4	0.8	0.08948	0.00995	9037.831	0.01	0.00895
2.5	0.83337	-0.05854	0.01036	-5915.27	0.01042	-0.00585
2.6	0.86669	0.1065	0.01078	10765.11	0.01083	0.01065
2.7	0.90012	-0.07064	0.01119	-7143.09	0.01125	-0.00706
2.8	0.93344	-0.12752	0.0116	-12901	0.01167	-0.01275
2.9	0.96669	-0.10872	0.01201	-11002.9	0.01208	-0.01087
3	1	0.24157	0.01242	24458.7	0.0125	0.02416
3.1	1.03337	-0.02893	0.01283	-2930.14	0.01292	-0.00289
3.2	1.06675	0.30793	0.01325	31203.34	0.01333	0.03079
3.3	1.09994	0.1796	0.01366	18206.48	0.01375	0.01796
3.4	1.13337	0.14739	0.01407	14947.36	0.01417	0.01474
3.5	1.16669	0.62895	0.01448	63812.22	0.01458	0.06289
3.6	1.20012	0.82103	0.01489	83334.51	0.015	0.0821
3.7	1.23337	0.65742	0.0153	66755.6	0.01542	0.06574
3.8	1.26675	0.90863	0.01571	92301.88	0.01583	0.09086

3.9	1.30006	1.08961	0.01612	110732.1	0.01625	0.10896
4	1.33337	1.10564	0.01653	112407.1	0.01667	0.11056
4.1	1.36669	1.18339	0.01694	120360.2	0.01708	0.11834
4.2	1.40006	1.29502	0.01735	131768.6	0.0175	0.1295
4.3	1.43344	1.67395	0.01776	170394.1	0.01792	0.16739
4.4	1.46662	1.57609	0.01817	160498.1	0.01833	0.15761
4.5	1.50006	1.77937	0.01858	181273	0.01875	0.17794
4.6	1.53337	1.64879	0.01899	168039	0.01917	0.16488
4.7	1.56681	1.57928	0.0194	161020.6	0.01959	0.15793
4.8	1.6	2.11525	0.0198	215755.2	0.02	0.21152
4.9	1.63337	2.3264	0.02021	237389.4	0.02042	0.23264
5	1.66669	2.38112	0.02062	243072.3	0.02083	0.23811
5.1	1.70006	2.25768	0.02103	230565.7	0.02125	0.22577
5.2	1.73331	2.79519	0.02144	285575.6	0.02167	0.27952
5.3	1.76675	2.75328	0.02184	281408.2	0.02208	0.27533
5.4	1.8	2.69547	0.02225	275611.5	0.0225	0.26955
5.5	1.83344	2.73169	0.02266	279429.7	0.02292	0.27317
5.6	1.86675	3.04128	0.02307	311224.8	0.02333	0.30413
5.7	1.90012	3.33929	0.02347	341860.7	0.02375	0.33393
5.8	1.93344	3.03628	0.02388	310965.6	0.02417	0.30363
5.9	1.96675	3.41039	0.02429	349423.2	0.02458	0.34104
6	2.00006	3.37777	0.02469	346221.7	0.025	0.33778
6.1	2.03337	3.45566	0.0251	354349.3	0.02542	0.34557
6.2	2.06669	3.76444	0.02551	386169.2	0.02583	0.37644
6.3	2.1	3.65995	0.02591	375602.8	0.02625	0.366
6.4	2.13337	3.78108	0.02632	388191.4	0.02667	0.37811
6.5	2.16669	3.76703	0.02672	386905.6	0.02708	0.3767
6.6	2.20012	3.84409	0.02713	394980.8	0.0275	0.38441
6.7	2.23337	3.76952	0.02753	387475.7	0.02792	0.37695
6.8	2.26675	4.17373	0.02794	429198.9	0.02833	0.41737
6.9	2.3	4.008	0.02834	412322.7	0.02875	0.4008
7	2.33337	4.18176	0.02875	430372.9	0.02917	0.41818
7.1	2.36669	4.23744	0.02915	436280.4	0.02958	0.42374
7.2	2.40006	4.49949	0.02956	463448.3	0.03	0.44995
7.3	2.43337	4.57389	0.02996	471301.5	0.03042	0.45739
7.4	2.46669	4.28693	0.03037	441910.7	0.03083	0.42869
7.5	2.50006	4.71083	0.03077	485805	0.03125	0.47108
7.6	2.53344	4.57151	0.03118	471628	0.03167	0.45715
7.7	2.56675	4.68581	0.03158	483615.5	0.03208	0.46858

7.8	2.6	4.87331	0.03198	503169.1	0.0325	0.48733
7.9	2.63337	5.02171	0.03239	518700.9	0.03292	0.50217
8	2.66669	4.99099	0.03279	515735.3	0.03333	0.4991
8.1	2.70006	4.99834	0.03319	516703.3	0.03375	0.49983
8.2	2.73337	0.98828	0.0336	102205.1	0.03417	0.09883
8.3	2.76675	0.03388	0.034	3504.807	0.03458	0.00339
8.4	2.8	-0.10237	0.0344	-10595.2	0.035	-0.01024
8.5	2.83337	-0.02947	0.0348	-3051.63	0.03542	-0.00295
8.6	2.86675	0.15472	0.03521	16026.79	0.03583	0.01547
8.7	2.90006	0.11642	0.03561	12063.82	0.03625	0.01164
8.8	2.93337	0.14711	0.03601	15250.42	0.03667	0.01471
8.9	2.96669	-0.15042	0.03641	-15599.5	0.03708	-0.01504
9	3	0.13394	0.03681	13896.25	0.0375	0.01339
9.1	3.03337	0.16905	0.03722	17546.05	0.03792	0.01691
9.2	3.06669	-0.08463	0.03762	-8787.06	0.03833	-0.00846
9.3	3.10006	0.2995	0.03802	31110.59	0.03875	0.02995
9.4	3.13344	0.07722	0.03842	8024.336	0.03917	0.00772
9.5	3.16675	-0.20732	0.03882	-21552.2	0.03958	-0.02073
9.6	3.20006	0.24867	0.03922	25861.99	0.04	0.02487
9.7	3.23337	-0.01562	0.03962	-1625.41	0.04042	-0.00156
9.8	3.26662	-0.21251	0.04002	-22118.9	0.04083	-0.02125
9.874	3.29137	0.18998	0.04032	19779.75	0.04114	0.019

Plantain: SPECIMEN 2 (strand)

Time	Extension	Load	True strain	True stress	Tensile strain	Tensile stress
(sec)	(mm)	(N)	(mm/mm)	(Pa)	(mm/mm)	(MPa)
0	0	0.06522	0	6522.371	0	0.00652
0.1	0.02875	0.28856	0.00036	28866.74	0.00036	0.02886
0.2	0.06569	-0.10799	0.00082	-10808.2	0.00082	-0.0108
0.3	0.09975	0.00943	0.00125	944.4836	0.00125	0.00094
0.4	0.13325	0.10364	0.00166	10381.2	0.00167	0.01036
0.5	0.16656	0.0801	0.00208	8026.838	0.00208	0.00801
0.6	0.19994	0.03184	0.0025	3191.825	0.0025	0.00318
0.7	0.23331	0.2016	0.00291	20218.53	0.00292	0.02016
0.8	0.26675	0.34571	0.00333	34685.95	0.00333	0.03457

0.9	0.3	0.28047	0.00374	28151.85	0.00375	0.02805
1	0.33337	0.06219	0.00416	6244.731	0.00417	0.00622
1.1	0.36675	0.1786	0.00457	17942.3	0.00458	0.01786
1.2	0.40012	0.17422	0.00499	17508.75	0.005	0.01742
1.3	0.43331	0.25791	0.0054	25931.13	0.00542	0.02579
1.4	0.46669	0.22805	0.00582	22937.87	0.00583	0.0228
1.5	0.5	0.55559	0.00623	55906.11	0.00625	0.05556
1.6	0.53337	0.37077	0.00665	37324.05	0.00667	0.03708
1.7	0.56669	0.40633	0.00706	40920.44	0.00708	0.04063
1.8	0.60006	0.29997	0.00747	30222.15	0.0075	0.03
1.9	0.63337	0.27391	0.00789	27607.47	0.00792	0.02739
2	0.66669	0.63123	0.0083	63649.33	0.00833	0.06312
2.1	0.7	0.77175	0.00871	77850.26	0.00875	0.07717
2.2	0.73331	0.63691	0.00912	64274.43	0.00917	0.06369
2.3	0.76669	1.03915	0.00954	104911.3	0.00958	0.10392
2.4	0.79994	1.17346	0.00995	118519.3	0.01	0.11735
2.5	0.83337	1.0557	0.01036	106670	0.01042	0.10557
2.6	0.86669	0.84952	0.01078	85872.09	0.01083	0.08495
2.7	0.90012	1.29832	0.01119	131292.3	0.01125	0.12983
2.8	0.93337	1.23615	0.0116	125057	0.01167	0.12361
2.9	0.96675	1.59909	0.01201	161841.6	0.01208	0.15991
3	0.99994	1.50104	0.01242	151980.4	0.0125	0.1501
3.1	1.03337	1.67252	0.01283	169412.5	0.01292	0.16725
3.2	1.06669	1.56244	0.01325	158327.2	0.01333	0.15624
3.3	1.1	1.66362	0.01366	168649.7	0.01375	0.16636
3.4	1.13331	1.94047	0.01407	196796	0.01417	0.19405
3.5	1.16669	1.94389	0.01448	197224	0.01458	0.19439
3.6	1.20006	2.16824	0.01489	220076.6	0.015	0.21682
3.7	1.23331	2.2099	0.0153	224396.9	0.01542	0.22099
3.8	1.26669	2.15716	0.01571	219131.3	0.01583	0.21572
3.9	1.3	2.14912	0.01612	218403.9	0.01625	0.21491
4	1.33337	2.38407	0.01653	242380.1	0.01667	0.23841
4.1	1.36662	2.49144	0.01694	253400.3	0.01708	0.24914
4.2	1.40006	2.60302	0.01735	264857.8	0.0175	0.2603
4.3	1.43337	2.86004	0.01776	291128.6	0.01792	0.286
4.4	1.46675	2.69594	0.01817	274537.3	0.01833	0.26959
4.5	1.5	3.0709	0.01858	312848.3	0.01875	0.30709
4.6	1.53337	3.16169	0.01899	322229.5	0.01917	0.31617

4.7	1.56675	3.29787	0.0194	336245.3	0.01958	0.32979
4.8	1.60006	2.99016	0.0198	304996.7	0.02	0.29902
4.9	1.63337	3.12221	0.02021	318595.5	0.02042	0.31222
5	1.66662	3.39196	0.02062	346262	0.02083	0.3392
5.1	1.7	3.37317	0.02103	344484.8	0.02125	0.33732
5.2	1.73331	3.39837	0.02144	347200.1	0.02167	0.33984
5.3	1.76669	3.90785	0.02184	399414.8	0.02208	0.39078
5.4	1.8	3.71315	0.02225	379669.6	0.0225	0.37132
5.5	1.83344	3.59029	0.02266	367257.2	0.02292	0.35903
5.6	1.86669	4.20277	0.02307	430083.5	0.02333	0.42028
5.7	1.90012	3.97042	0.02347	406472.4	0.02375	0.39704
5.8	1.93337	4.50399	0.02388	461284.2	0.02417	0.4504
5.9	1.96675	3.90617	0.02429	400220.2	0.02458	0.39062
6	2	4.11728	0.02469	422021.6	0.025	0.41173
6.1	2.03337	4.52279	0.0251	463774.4	0.02542	0.45228
6.2	2.06669	4.54628	0.02551	466372.9	0.02583	0.45463
6.3	2.10006	4.31144	0.02591	442462.2	0.02625	0.43114
6.4	2.13337	4.60343	0.02632	472619.2	0.02667	0.46034
6.5	2.16669	3.77778	0.02672	388010	0.02708	0.37778
6.6	2.20006	0.09659	0.02713	9924.536	0.0275	0.00966
6.7	2.23344	0.03437	0.02754	3532.572	0.02792	0.00344
6.8	2.26675	-0.09124	0.02794	-9382.12	0.02833	-0.00912
6.9	2.29994	-0.0144	0.02834	-1481.87	0.02875	-0.00144
7	2.33337	0.1344	0.02875	13831.9	0.02917	0.01344
7.1	2.36669	0.17165	0.02915	17672.99	0.02958	0.01717
7.2	2.40006	-0.04466	0.02956	-4599.59	0.03	-0.00447
7.3	2.43331	0.17786	0.02996	18327.37	0.03042	0.01779
7.4	2.46675	0.2298	0.03037	23688.44	0.03083	0.02298
7.5	2.50006	-0.01419	0.03077	-1463.39	0.03125	-0.00142
7.6	2.53337	0.12134	0.03118	12518.75	0.03167	0.01213
7.7	2.56669	0.1353	0.03158	13963.95	0.03208	0.01353
7.8	2.60006	-0.15683	0.03198	-16192.8	0.0325	-0.01568
7.9	2.63337	-0.0322	0.03239	-3326.18	0.03292	-0.00322
8	2.66669	-0.03542	0.03279	-3660.17	0.03333	-0.00354
8.1	2.7	0.0033	0.03319	341.2162	0.03375	0.00033
8.2	2.73337	0.15043	0.0336	15556.71	0.03417	0.01504
8.3	2.76675	0.16782	0.034	17362.46	0.03458	0.01678
8.4	2.79994	0.22282	0.0344	23062.04	0.035	0.02228
8.5	2.83344	0.49737	0.03481	51498.42	0.03542	0.04974

8.6	2.86675	-0.13927	0.03521	-14425.7	0.03583	-0.01393
8.7	2.90012	0.0582	0.03561	6030.762	0.03625	0.00582
8.8	2.93331	0.25366	0.03601	26296.17	0.03667	0.02537
8.9	2.96669	0.07191	0.03641	7457.974	0.03708	0.00719
9	3	-0.00813	0.03681	-843.647	0.0375	-0.00081
9.1	3.03344	0.00754	0.03722	782.7962	0.03792	0.00075
9.108	3.03606	0.0754	0.03725	7825.658	0.03795	0.00754

NB: To prevent a rather cumbersome work, the raw data for the woven fibers for both the plantain and kenaf were not provided in this section.