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Tensile and Flexural Strength Properties of Surface-Modified Banana Fibre Epoxy Composites

BY

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DECLARATION

I Caren Jerono Kipchumba, hereby declare that this thesis is my original work. To the best of my knowledge, the work presented here has not been presented for a thesis in any other university.

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DEDICATION

This thesis work is dedicated to my loving mother, Florence, my dear husband, Justine and my adorable children, Terrance and Trevon, who have been a constant source of support and encouragement during the course of my research study.

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ABSTRACT

There is presently a rise in the research and development of composites reinforced using natural fibres because of an increase in environmental awareness driven by climate change concerns. This is because natural fibres are abundant, eco-friendly, cost effective and low in density. Additionally, they also have a high strength to weight ratio compared to synthetic and mineral fibres e.g. asbestos, Kevlar, and asbestos. Since natural fibres are low in density, they enable the production of composites with good mechanical properties and low mass per unit volume. Fibrous plants like bananas are abundant in tropical countries and are used as agricultural food crops. At the moment, banana fibres are a waste product and the only cost would be in its collection, grading and treating. Therefore, the fibres can be used for industrial applications such as making roofing tiles, furniture, seat cushions, interior panels of automobiles, and marine equipment (fishing nets and boats).

Despite there being numerous research published on the strengthening effect of different banana fibre surface modification methods, there are no known studies that have been carried out to compare alkalization and oxidative treatment of Giant Cavendish banana fibres.

This study represents the first species specific study that focused on examining and comparing the strength properties of untreated and surface-modified Giant Cavendish banana fibres. The banana fibres were mercerized using 0.06M Sodium Hydroxide (NaOH) and treated using 0.003M Potassium Permanganate ($KMnO_4$) solutions and the fibres' strength properties determined. The untreated and surface-modified fibres, in uniaxial alignment and varying volume fractions, were then used as reinforcement in a general purpose epoxy (glycidyl amine) resin matrix. Tensile and Flexural tests were then performed on the composites.

0.003M $KMnO_4$ treated banana fibres had the highest mean tensile strength of 209.32 MNm^{-2}, which translated to a 65.92% gain in tensile strength while the 0.06M NaOH treated

(mercerized) banana fibres had a mean tensile strength of 162.23 MNm^{-2}, which was a 28.60% gain in tensile strength compared to the untreated fibres respectively.

The 0.003M $KMnO_4$ treated banana fibre-reinforced epoxy resin recorded the greatest gain in tensile strength with a maximum tensile strength value of 7.42 MNm^{-2} at a fibre volume fraction of 5.40%. This in turn translated to a 470.77% gain in tensile strength compared to the unreinforced specimen. 0.06M NaOH treated banana fibre-reinforced epoxy resin on the other hand, recorded a maximum tensile strength value of 7.07 MNm^{-2} at an optimal fibre volume fraction of 5.50%. This translated to a 443.85% gain in tensile strength compared to the unreinforced epoxy specimens. The untreated banana fibre-reinforced epoxy resin had a maximum tensile strength value of 5.10 MNm^{-2} at an optimal fibre volume fraction of 3.30% compared to the unreinforced epoxy specimens.

Similarly, 0.003M $KMnO_4$ surface-modified banana fibre-reinforced epoxy resin recorded the greatest gain in flexural strength with a maximum modulus of rupture (MOR) of 14.15MNm^{-2} at a fibre volume fraction of 2.90%. This translated to a 256.42% increase in flexural strength compared to the unreinforced epoxy resin specimens. 0.06M NaOH treated banana fibre-reinforced epoxy resin had a maximum MOR of 9.83 MNm^{-2} at a fibre volume fraction of 2.80%. This in turn, translated to a 147.61% gain in flexural strength compared to the unreinforced specimens.

Untreated banana fibre reinforced epoxy resin had a maximum MOR value of 5.26 MNm^{-2} at a fibre volume fraction of 2%. This was a 32.49% gain in flexural strength compared to the neat epoxy specimens. These results were in agreement with the findings reported by Zin *et al.* [1] which showed that improved interfacial bond strength between surface-modified lignocellulosic fibres and polymeric matrices results in composites with better strength properties.

NOTATIONS

E	Young's Modulus
NaOH	Sodium Hydroxide
$KMnO_4$	Potassium Permanganate
%Vol.	Percentage volume
g	gram
ml	millilitres

ABBREVIATIONS

ANOVA	Analysis of variance
ASTM	American Society for Testing and Materials
BP	Benzoyl peroxide
BS	British Standard
CMC	Ceramic matrix composites
CDF	Cumulative Distribution Function
CI	Crystallinity index
DCP	Dicumyl peroxide
KARLO	Kenya Agriculture & Livestock Research Organization
LDPE	Low density polyethylene
MLDPE	Maleated low density polyethylene
MMC	Metal Matrix Composites
MOR	Modulus of Rupture
PF	Phenol formaldehyde
PMC	Polymer matrix composites
PP	Polypropylene
ROM	Rule of Mixtures
RPM	Revolutions per minute
SEM	Scanning electron microscope
SPI	Soy protein isolate
UoN	University of Nairobi
UTM	Universal Testing Machine

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CHAPTER 1: INTRODUCTION

1.1 Background Information: Banana Fibre

Banana fibre is a type of ligno-cellulosic fibre extracted from the pseudo-stem (stalk) of a banana plant through decortication. It is a member of the Musaceae family, and the genus Musa. It has attractive mechanical properties. As such, when compared to conventional materials like fibre glass, it gives better specific strength (strength to mass ratio) [2]. A Banana plant comprises of a clustered leaf stalk base which has a low density and a cylindrical cross-section typical of most plants as shown in figure 1.1. Following harvesting of the bananas, the fibre-rich stalk (also referred to as a 'pseudostem' or 'false stem') is considered waste and is either left to rot in the plantation, or chopped up and used as animal fodder. The fibre, if properly harvested from the pseudostem can be used in diverse industrial and non-industrial applications [3].

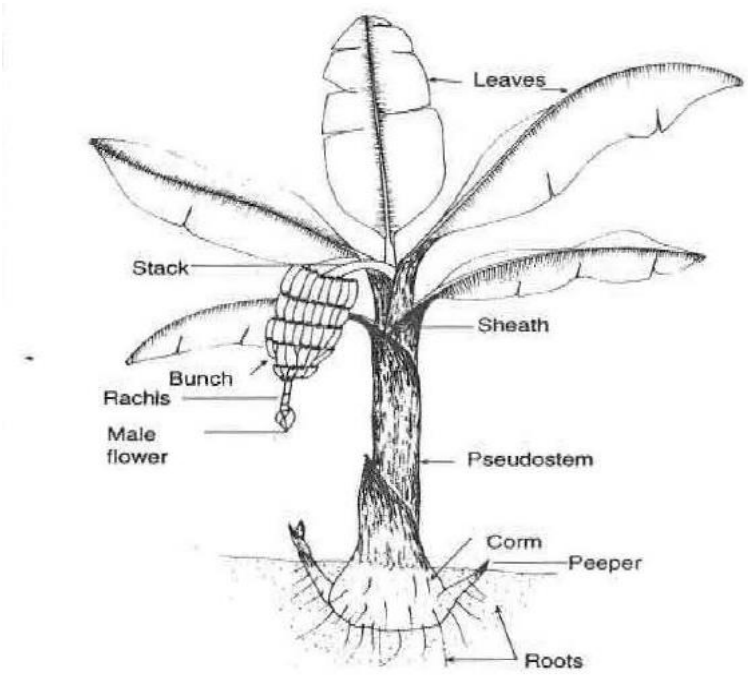

Figure 1. 1: Parts of a banana plant [4]

Banana production in Kenya has over the years changed from subsistence to a cash crop due to a rise in demand. Kenya is one of the world's leading countries with regards to banana production with an estimated annual production of 1.1 million metric tons. Other than its value as a food crop, sales from banana crop provide much-needed income in many Kenyan households. Additionally, there is a growing demand for bananas because of an increase in population as well as changing consumption lifestyle and habits [5].

1.2 Problem Statement

Banana fibres are biodegradable, affordable and have the potential of being used as a fibrous polymer reinforcement in resins such as epoxy resin, polyester resin and other thermoplastics. Like other lignocellulosic fibres, this can improve the abrasion resistance, stiffness and thermal stability of the resulting composite [6–8]. Surface impurities and a large number of hydroxyl units' make banana fibres unsuitable for reinforcing polymeric materials. In their natural state, the fibres have relatively smooth surfaces. This results in poor interfacial bonding because the hydrophilic fibres and hydrophobic resins are naturally incompatible.

On the banana fibre surface, waxy substances also present contribute to a large extent to the inefficient fibre to matrix bonding and insufficient surface wetting. In addition, banana fibres are the most absorbent of the lignocellulosic fibres, absorbing a lot of moisture, which leads to swelling and plasticizing, resulting in dimensional instability [9] when incorporated in a matrix. This limits the use of banana fibres as reinforcement in polymeric materials [6]. There is therefore a need to find a low cost banana fibre surface-modification method that improves the fibres strength properties and improves on the fibres compatibility with hydrophobic resins.

1.3 Objectives

1.3.1 Main Objective

To evaluate the effect of NaOH and $KMnO_4$ treatment of banana fibre on the tensile and flexural properties of banana fibre-reinforced epoxy (glycidyl amine) composites.

1.3.2 Specific Objectives

1. To determine the effect of varying the concentration of NaOH and $KMnO_4$ on the tensile properties of banana fibres.
2. To evaluate the tensile and flexural properties of mercerized (NaOH treated) surface-modified banana fibre-reinforced epoxy composites.
3. To evaluate the tensile and flexural properties of potassium permanganate ($KMnO_4$ treated) surface-modified banana fibre-reinforced epoxy composites.

1.4 Justification

Surface modification of natural fibres, including banana fibres, using various chemical treatments has been shown to reduce surface impurities, hydroxyl units and improve the dimensional stability of the treated fibres [6–8, 10].

Current research on the utilization of chemically modified banana fibre surfaces to reinforce epoxy composites have explored different species of bananas [8]. After analysing the properties and characteristics of Giant Cavendish banana species, this research focused on the use of Giant Cavendish with long stems of approximately 4-5 meters and harvested at nine (9) months.

A review done on alkali treatments' effect on sisal's mechanical and physical properties concluded that using an alkali treatment results in improved fibre-water resistance and mechanical properties [11]. Therefore, this study used NaOH and $KMnO_4$ to treat banana fibres

and determine its impact on the mechanical properties of composites reinforced in banana fibres.

1.5 Scope of the Study

This study focused on the static mechanical properties of untreated and treated (surface modified) banana fibres and their epoxy resin composites. The tensile test specimens were tested as per the BS 2782-3 standard on the Hounsfield tensometer (*Type W*). This test involved positioning the specimen in the tensile test machine and subjecting it to tension at specific loads until it breaks. This test was performed on (a) untreated banana fibres (b) treated banana fibres and (c) banana fibre-reinforced epoxy composites that have been reinforced with untreated and treated banana fibres.

The banana fibres were obtained from University of Nairobi's (UoN) College of Agriculture and Veterinary Sciences. Epoxy Resin was bought locally from reputable suppliers. During the study, banana stems of approximately 4-5m were harvested and then cut into 100 cm sections. The stalks of 100cm length were then stripped. The fibres were decorticated from the stalks using a 6-blade decorticator machine set at 2mm gap size and a rotating speed of 900 r.p.m.

The fibres were surface-modified using Sodium Hydroxide and Potassium Permanganate and their tensile strength properties determined. They were then (in their untreated and surface-modified states)) ultimately used in different fibre volume fractions as fibrous reinforcement in a 2:1 epoxy resin matrix.

57 beams each measuring 5 mm x 20 mm x 150 mm were tested for tensile strength, and 63 beams each measuring 10 mm x 20 mm x 300 mm were tested for flexural strength. The results were analysed using polynomial regression and optimal banana fibre volume fractions determined from the point of inflection of the regression curves.

1.6 Publications from the Study

From the findings of the current study, the following paper was published in Taylor & Francis' Journal of Natural Fibres (ISSN: 1544-046X), a peer-reviewed scientific journal listed in the SCImago Scopus® database (Elsevier B.V.):

Kipchumba J. Caren, Njoroge D. Kenneth & Munyasi M. David: **Strength Properties of Surface-Modified Giant Cavendish *(Musa acuminata)* Banana Fibers**. *Journal of Natural Fibers*, 2022, p. 1-14.

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CHAPTER 2: LITERATURE REVIEW

2.1 The Banana Plant

2.1.1 Types of Bananas Suitable for Decortication

The two major promising banana species for this research are the Giant Cavendish and a local plantain called Ng'ombe. The two would provide enough fibres of acceptable length (longer than sisal) as discussed below.

2.1.1.1 The Giant Cavendish

After analysing the many species of banana based on their properties and characteristics, the Great Cavendish is the most promising for this study. It has long stems of approximately 4-5 meters that generate fibres of similar length. It also takes 10-15 months to mature and make the stalks accessible. In between, some may be obtained from the constant pruning over the growth process.

2.1.1.2 Ng'ombe

This type of plantain species is mostly cultivated as a cooking banana. It is drought resistant, vigorous and has a predominant M balbisiana genetic characteristic. It is similar to the Giant Cavendish since its stem grows to an estimated height of 4-5metres. However, its fruit is green and takes around 15-24 months to mature.

2.1.2 Conditions for Optimal Growth

In East Africa, banana is widely cultivated as a food crop both for local consumption and for revenue generation through export. In Kenya, the crop is abundantly grown in many areas like Kerio Valley, Kakamega, Bungoma, Baringo, Kisii, Meru, Embu, Kirinyaga, Muranga, and the Coast Region. In Kitui, Machakos and Makueni, they are grown under irrigation where it has provided food and income for the locals.

The banana plant grows well under tropical conditions since it bears numerous leaves and very short roots. It requires humid atmospheres and soils and is able to thrive in areas where rainfall is more or less evenly distributed through the year. Lack of rainfall for more than 6 weeks is harmful to the plant. While prolonged drought is fatal to the banana plant, it cannot also withstand flooding, thus a warm humid climate is essential [12]. Additionally, the soil should be loose, properly drained, have moderate amounts of minerals and rich in humus. Table 2.1 is a summary of the required conditions for growth.

Table 2. 1: Optimal conditions for banana growth [12].

Condition	**Optimal Requirements**
Rainfall	1000mm to 2500 mm of annual rainfall. Optimal production requires 1400mm of evenly spread rainfall without prolonged drought.
Temperature	Warm to humid temperature required for optimal growth. 20 to 30^0C is the average temperature below which growth is hindered.
Altitude	Altitudes of 1800m above sea level recommended.
Soil	Can be grown in many different soils as long as they are well drained and fertile. Properly aerated soils are good during short periods of flooding. Light to medium drained loam soils are preferred while deep fertile soils high in humus should be selected. A pH of 5.5 to 6.5 is proposed for optimal growth.
Spacing	This depends on the banana variety, fertility of the soil and rainfall levels. For a five-year cycle, the following is recommended for fertile soil with enough rainfall:
	Short variety such as Dwarf Cavendish - 2.5m × 3m.
	Medium variety such as Williams - 3.0m × 4.0m
	Tall variety such as Poyo - 4.0m× 4.0m

Regardless of the conditions for growth, the banana plant can be cultivated in arid and semi-arid areas. For example, in Kwale County, Zai Pits are used to grow the Giant Cavendish banana species. After cultivation, the whole tree is removed and chopped up for use as farm animal feeds while the rest is left to rot and provide humus to the soil. It is at this point that the extraction of the banana fibres for use as reinforcement comes in handy at minimal cost.

2.2 Fibre-Reinforced Composites

A composite can be defined as a material comprising of two (or more) distinct phases that possesses qualities that are distinct from each of its constituent phases [13, 14]. It is formed by mixing two or more components together that are chemically or physically dissimilar by physical or chemical means to obtain a new material [13, 15].

It has a matrix (continuous component) and fillers (discontinuous or discrete component) as shown in figure 2.1. Inside the composite, both the matrix and the fillers form one component. The reinforced material is the matrix, which also binds the fillers while the filler is the composite component that bears the load [16].

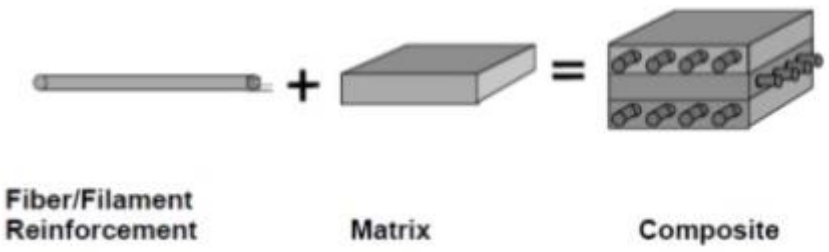

Figure 2. 1: General representation of a fibre-reinforced composite [15].

Composites are generally categorized as particle reinforced composites (PRC), metal matrix composites *(MMC)*, ceramic matrix composites (CMC) or fibre reinforced composites (FRC). Within FRC, the fibrous reinforcement can be long, continuous and unidirectional, or short, discontinuous and randomly distributed within the composite. In this research, continuous unidirectional banana fibres were used as reinforcement in an epoxy matrix.

2.2.1 Stress Distribution in Continuous Fibre Reinforced Composites

In the mathematical model of the stress distribution in a continuous fibre reinforced composites an assumption is made that before cracking, the fibrous reinforcement is bonded to the matrix such that, there is equal strain in both the fibres and the matrix such that:

$$\varepsilon_f = \varepsilon_m = \varepsilon_c \text{…….....…..(2.1)}$$

where ε_f, ε_m and ε_c are the strains in the fibre, matrix and composite respectively.

Since both the matrix and the fibres are assumed to be elastic, the stress in the fibre can be calculated as:

$$\sigma_f = E_f \varepsilon_f = E_f \varepsilon_c \text{ ……....(2.2)}$$

And the stress in the matrix can be calculated as:

$$\sigma_m = E_m \varepsilon_m = E_m \varepsilon_c \text{……(2.3)}$$

where σ_f and σ_m are the stresses in the fibre and matrix respectively while E_f and E_m are the Young's Moduli for the fibre and matrix respectively. The load is also shared by the matrix and the fibrous reinforcement such that if P_c is the load on the composite, then:

$$P_c = P_f + P_m \text{……...…….(2.4)}$$

where P_f and P_m are the loads borne by the fibrous reinforcement and the matrix respectively. Using the relationship Force = Stress x Area, equation 2.4 can be rewritten as:

$$\sigma_c A_c = \sigma_f A_f + \sigma_m A_m \text{…….……(2.5)}$$

which is the same as:

$$\sigma_c = \sigma_f \frac{A_f}{A_c} + \sigma_m \frac{A_m}{A_c} \text{……..……(2.6)}$$

where;

σ_c – average tensile stress in the composite

A_f – cross-sectional area of the fibres

A_m – cross-sectional area of the matrix

A_c – cross-sectional area of the composite

Due to the practical challenges of accurately measuring A_f and A_m, fibre volume fraction is used instead. This is based on the relationship:

$$V_f = \frac{A_f}{A_c}\ and\ V_m = \left(1 - V_f\right) = \frac{A_m}{A_c} \text{.....(2.7)}$$

where V_f and V_m are the fibre and matrix volume fractions respectively. Making this substitution, equation 2.6 becomes:

$$\sigma_c = \sigma_f V_f + \sigma_m V_m = \sigma_f V_f + \sigma_m (1 - V_f) \text{..... (2.8)}$$

By dividing equation 2.8 by ε_c and using equations 2.2 and 2.3, equation 2.8 becomes:

$$E_c = E_f V_f + E_m V_m = E_f V_f + E_m\left(1 - V_f\right) = E_m + V_f\left(E_f - E_m\right) \text{...(2.9)}$$

Equation 2.9 is referred to as the Rule of Mixtures (ROM) and it shows that the Young's Modulus of a unidirectional, continuous fibre-reinforced composite lies somewhere in between the Modulus of the fibrous reinforcement and the Modulus of the matrix. For effective reinforcement, $E_f >> E_m$.

2.3 Banana Fibre Properties and Applications

The banana plant, like most plant-based natural fibres have a very complicated structure made of a lumen and a cell wall also known as the central channel (shown in Figure 2.2). The banana cell wall has three parts: secondary wall, primary wall and middle lamella. The secondary wall has three segments namely external wall, middle wall and internal wall. The primary wall has a disorganized cellulose matrix comprised of lignin, pectin and hemicellulose while the middle lamella is responsible for mechanical behaviour [17]. On the other hand, the lumen enables water transportation.

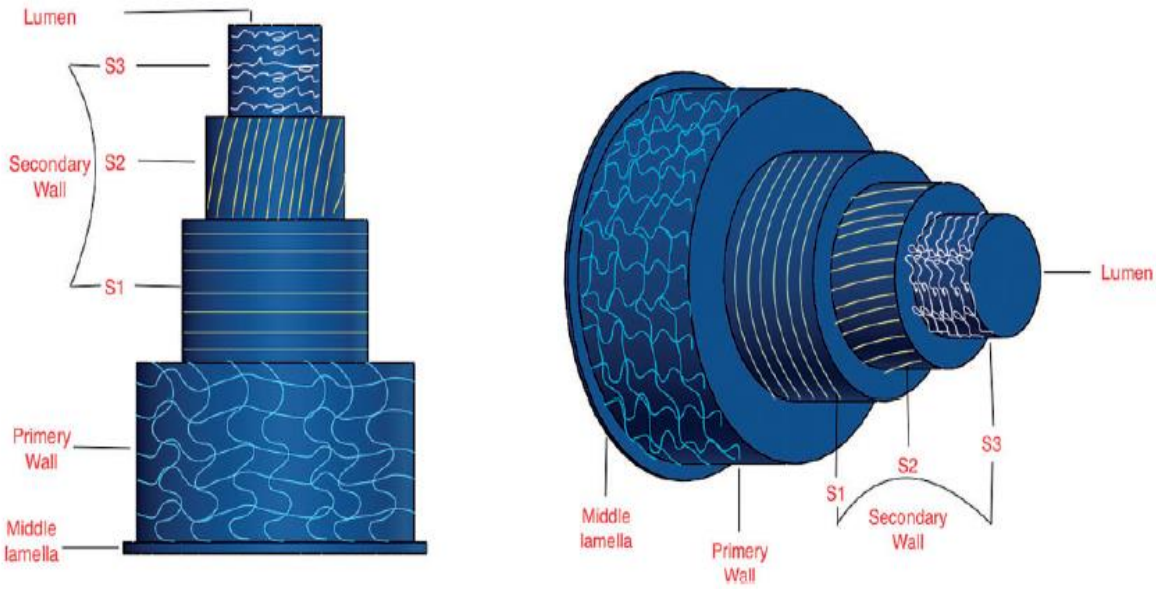

Figure 2. 2: A banana fibre structure [17]

The chemical constituents of banana fibres are listed in Table 2.2. The mechanical and physical properties of banana fibres are governed by the percentage of chemical constituents in the fibres. The structure of banana fibre comprises of a cellulose microfibril network, which is the reinforcing agent while lignin/hemicellulose/pectin (noncellulosic) constituents act as the matrix phase [18]. The cellulose microfibril (key structural part of the banana fibre) is connected to the hemicellulose constituents by hydrogen bonding.

Table 2. 2: Plant fibres chemical composition [17]

Natural fiber	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Pectin (%)	Waxes (%)
Flax	70.5	16.5	2.5	0.9	–
Hemp	81	20	4	0.9	0.8
Henequen	60	28	8	–	0.5
Coir	46	0.3	45	4	–
Bamboo	34.5	20.5	26	–	–
Abca	62.5	21	12	0.8	3.0
Alfa	45.4	38.5	14.9	–	2.0
Bagasse	37	21	22	10	–
Banana	62.4	12.5	7.5	4	–
Cotton	89	4	0.75	6	0.6
Curaua	73.6	5	7.5	–	–
Jute	67	16	9	0.2	0.4
Kenaf	53.5	21	17	2	–
Kapok	13.16	–	–	–	–
Isora	74	–	23	–	1.09
Sisal	60	11.5	8	1.2	–
Pineapple	80.5	17.5	8.3	4	–
Ramie	72	14	0.8	1.95	–
Piassava	28.6	25.8	45	–	–

Table 2.3 shows the morphological (physical) properties of some natural fibres. The fibre lengths given in the table are the typical lengths at which the fibres are used as discontionus fibre reinforcement in cementitious matrices [19]. The strength to weight ratio of banana fibres has an inverse relationship with its density while the mechanical properties have a direct relationship with the aspect ratio and volume fraction; this makes the fibre density a critical physical property. A larger area of exposure of fibres to the matrix phase is achievable with a higher aspect ratio and volume fraction [20].

Table 2. 3: Natural fibres physical properties [17]

Name of the fiber	Diameter (μ)	Length (mm)	Density (kg/mm^3)	Moisture gain (%)
Abca	18.2	4.9	1500	14
Alfa	–	–	890	–
Bagasse	20	1.7	900	–
Banana	–	2.9	1325	–
Bamboo	25	2	1500	–
Coir	17.5	1.25	1250	13
Cotton	14.5	42	1550	8.59
Curaua	–	–	1400	–
Flax	20	31.75	1450	12
Hemp	19.9	11.2	1200	–
Isora	–	–	1200	1.2
Jute	18.4	2.55	1400	17
Kapok	25	20	384	10.9
Kenaf	19.8	2.35	1300	17
Piassava	–	–	1400	–
Pineapple	50	–	1540	–
Ramie	31.55	160	1550	8.5
Sisal	21	2.5	1400	14

This research focused on how the tensile and flexural properties of banana fibres and resulting banana fibre-reinforced composites are influenced by chemical surface treatments of the fibres. The elimination of noncellulosic constituents (lignin, pectin, hemicellulose and waxes) affects the mechanical properties of banana fibres. The reason is that, noncellulosic constituents available on the surface of the fibres restrict surface (interfacial) bonding between the matrix phase and reinforcing phase [21]. The interfacial bonding and crystallinity index (CI) of banana fibres determine its mechanical properties. Hence, surface treatments, interfacial bonding, and CI or crystallinity of cellulose was crucial to consider in this research.

Since the mechanical properties of banana fibre composites are determined by the mechanical properties of the banana fibres, it is important to be conversant with these properties. The mechanical properties of banana fibres are shown in Table 2.4. The natural

fibres possess specific strength values that are comparable or sometimes even better than synthetic fibres.

Table 2. 4: Natural fibres mechanical properties [17]

Natural fibre	Tensile Strength (MPa)	Specific Tensile Strength (MPa/(Kg/m^3))	Young's Modulus (GPa)	Specific Young's Modulus (MPa/(Kg/m^3))	Failure Strain (%)
Abca	12	-	41	-	3.4
Alfa	350	-	22	-	5.8
Bagasse	290	-	17	-	-
Banana	721.5	534.5	29	22	2
Bamboo	575	383	27	18	-
Coir	140.5	122	6	5.2	27.5
Cotton	500	323	8	5.25	7
Curaua	825	-	9	-	7.5
Flax	700	482.5	60	41	2.3
Hemp	530	360	45	30.5	3
Isora	550	-	-	-	5.5
Jute	325	230	37.5	26.5	2.5
Kapok	93.3	300	4	12.9	1.2
Kenaf	743	-	41	-	-
Piassava	138.5	-	2.83	-	5
Pineapple	1020	708.5	71	49.5	0.8
Ramie	925	590	23	15	3.7
Sisal	460	317.5	15.5	-	-

2.3.1 Strength Properties of Banana Fibre

Recently, composites reinforced in banana fibres have generated a lot of interest because of their diverse application in passenger cars under-floor protection [22] [23]. Mechanical properties of banana fibre were examined by Kulkarni *et al.* [24]. They established that banana fibre failure under tension is caused by fracture of microfibrils that is due to cell wall tearing. The potential of Jamaican banana, bagasse fibres and coconut coir in composites were assessed by Justiz-smith *et al.* [25]. They carried out tests using samples from the fibres to determine their moisture absorption, water content, tensile strength, ash content, carbon content and also carried out compound chemical analysis. The results revealed that while

coconut had the highest lignin content, banana fibre gave the highest cellulose, carbon content, and the highest tensile strength.

Further research on cement and polymer composites reinforced using banana fibres were carried out by Venkateshwaran and Elayaperumal [26] based on its structure, mechanical and physical properties. They noted that its low elongation at yield, low density and high tensile strength of banana fibre made it a good choice for utilization in sectors such as construction and equipment.

Several studies have been carried out to predict a number of mechanical properties such as flexural and tensile of banana fibres in their natural state and banana fibre-reinforced polymers. The results indicated that banana fibres exhibited high mechanical properties [20, 24]. Rao and Rao [27] carried out a comparative research to analyse the stress and strain of banana fibres. The tensile test done as per ASTM-D 3379-75 standard showed that stress and fibre strain were directly proportional with banana attaining a stress value of 560MPa at 3.5% strain. They additionally forecasted using stress-strain plots that banana fibres were stiffer and stronger than sisal fibres

In addition, Geethamma *et al.* [28] approximated banana fibre tensile strength and elastic modulus and found it to vary between 525-755 MPa and 7-21 GPa respectively. They also found that at break, banana fibre had a percentage elongation of between 1.0 -3.5% while its diameter varied between 0.08-0.25mm. Currently, there are no studies on record that have been done on to determine the strength properties of Giant Cavendish banana fibres. Most studies have focused on the Giant Cavendish banana disease vulnerability and susceptibility [29–32], the fruits nutritional value [33–35], the Giant Cavendish banana plant antimicrobial properties [36, 37] and the plant fibres potential in pulp production [38–41]. The current study

thus represents the first species specific study on the strength properties of AAA cultivar (Giant Cavendish) banana fibres.

2.3.2 Natural Fibres Application

Sanjay *et al.* [42] reviewed the applications of natural plant fibres and its composites. They concluded that natural plant fibre composites for use in diverse applications is an emerging area in material science. Natural fibres are gradually substituting ceramic and metal-based applications in industries including automotive, marine, aerospace, and electronic. They possess attractive specific properties, however, they have a wide variation in individual properties, which can be solved by improving processes used to produce natural fibres and their composites [43].

Additionally, Prasad *et al.* [44] studied and optimised natural fibres (Ramie, Pineapple and Sisal) reinforced in epoxy to fabricate a mud guard component for a two-wheeler automobile. They selected the best combination of the natural fibres for use in fabricating the mud guard through hand layup method.

A review on natural fibres and their application areas based on new developments in bio-composites done by Gurunathan *et al.* [45] found out that single fibre properties are a firm base for the generation of fresh and sustainable uses for natural fibre composites in the 21st century "green" materials setting. They concluded that bio-composites have gained attention in polymer science with applications varying from building to automobile sectors.

Also, a review by Satyanarayana *et al.* [46] discussed how the automobile industry uses natural fibre composites to make headrests, seat shells, door panels, armrests and instrument panels. They suggested that there was a need for the recognition of research and development done in developing countries where natural fibres are abundantly available. They concluded

that there is a rise in the range of applications as a result of development of naturally viable products based on natural resources for both matrices and reinforcements.

The growing benefits of these biodegradable materials is supported by the rising number of published articles in the last decade, including reviews and patents (figure 2.3). Elvers *et al.* [47] carried out bibliographic analyses of biodegradable polymers with regards to information patented to precisely describe the present research areas and forecast trends in future development.

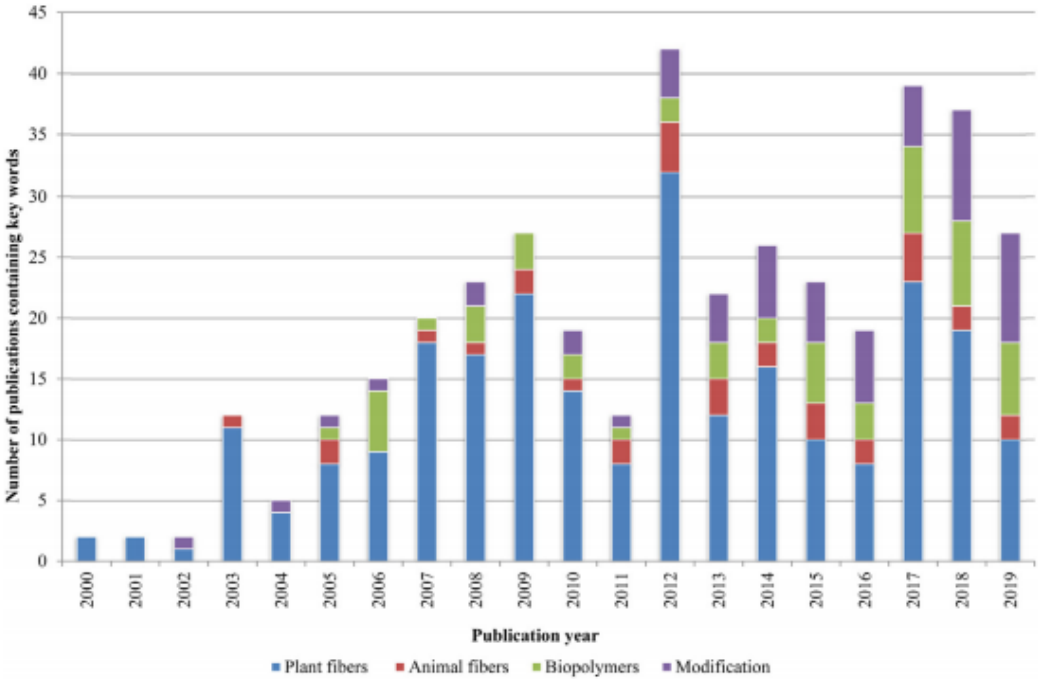

Figure 2. 3: Year 2000 to 2019 total number of articles published on plant fibres, animal fibres, biopolymers and their modifications [48]

2.4 Effect of Chemical Treatment of Banana Fibre on its Morphology, Crystallinity and Mechanical Properties

The strength of the bond between the fibre and the polymer matrix influences the degree of the reinforcement of fibre inside the composite. However, high moisture absorption by the fibre is as result of the pendant hydroxyl and polar groups present in the fibre causes weak

interfacial bonds connecting to the hydrophobic polymer matrix. Hence, for more desirable mechanical properties to be achieved, it is essential to generate hydrophobic fibres using relevant chemical treatments. Such treatments reduce fibre hydrophilic behavior by minimizing moisture absorption. Therefore, to acquire greater performance of the resulting composite, fibre surface modification is necessary [49].

2.4.1 Alkalization

Banana fibres are treated chemically using Sodium hydroxide (NaOH) to remove lignin, pectin, natural oils and waxy substances that cover fibre cell wall outer surface [5]. Cleaning and bleaching of plant fibre surfaces are normally done using NaOH. By swelling through alkalization (also known as mercerization), the delicate structure of native cellulose I is modified to cellulose II. Cellulose I refers to naturally occurring cellulose, which exists in parallel strands without hydrogen bonding inter-sheet whereas cellulose II exists in non-parallel strands with hydrogen bonding inter-sheet [50]. NaOH and cellulose reaction is shown in Equation (2.10) and Figure 2.4 respectively.

$$\text{Cell-OH} + \text{NaOH} \rightarrow \text{Cell-O}^{-}\text{Na}^{+} + \text{H}_2\text{O} + [\text{Surface impurities}] \ldots\ldots..(2.10)$$

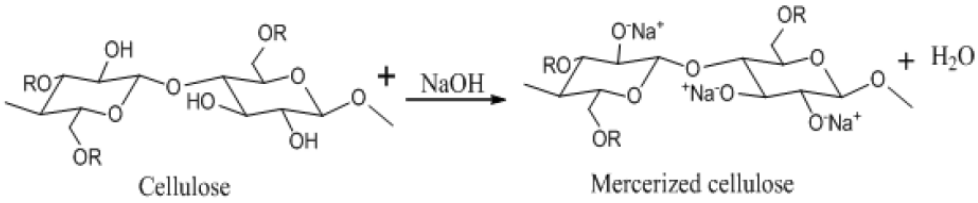

Figure 2. 4: Cellulose fibre reaction with NaOH [6]

It is crucial to note that during fibrillation, alkalization depolymerizes the molecular structure of native cellulose I as shown in figure 2.5 (a) resulting in crystallites of short lengths as shown in figure 2.5(b). In fibrillation, delamination of the cell wall occurs leading to

microscopically hairy appearance of fibre surface. This increases the effective surface area available for contacting a matrix since the composite fibre is broken down into smaller pieces.

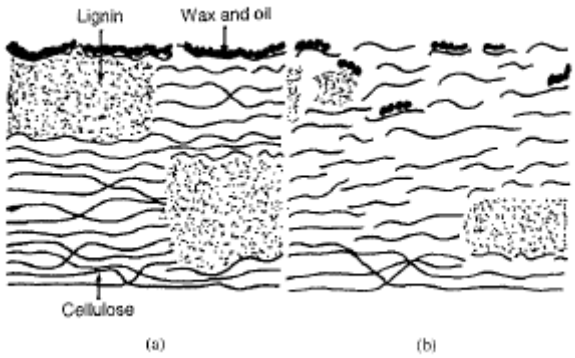

Figure 2. 5: Distinctive structure of (a) untreated and (b) alkalized cellulosic fibre [6]

After alkalization, Mwaikambo and Ansell [6] found that the surface topography of sisal, jute and hemp became rougher than before the treatment. Spectrographs from SEM of sisal, jute and hemp show that separate cells have been bound together by weak intermolecular bonds rich in lignin. This shows that plant fibre alkalization alters the crystallographic structure and surface topography of the fibre. This means, elimination of surface impurities through mercerization enhances fibre-matrix adhesion because it facilitates the bonding reaction and consequently mechanical interlocking. Caution however must be taken when choosing the concentration of NaOH for alkalization since some fibres at given concentrations of NaOH have decreased thermal resistance [8]. Treatment via alkalization is considered to be the cheapest and most environmentally friendly chemical fibre surface-modification method [51, 52]. This makes it an affordable and cost effective fibre surface-modification technique for the treatment of Giant Cavendish banana fibres in the current study.

2.4.2 Peroxide Treatment

Peroxide belongs to a group of chemical compounds with a structure R-O-O-R and a divalent ion O-O. Decomposition takes place easily in organic peroxides thus forming free

radicals (RO-) that react with the hydrogen part of the cellulosic fibre and matrix as shown in figure 2.6 [53]. Fahim and Chand [54] outlined the reaction between peroxide-initiated free radical and polyethylene as shown in equations 2.11 to 2.14.

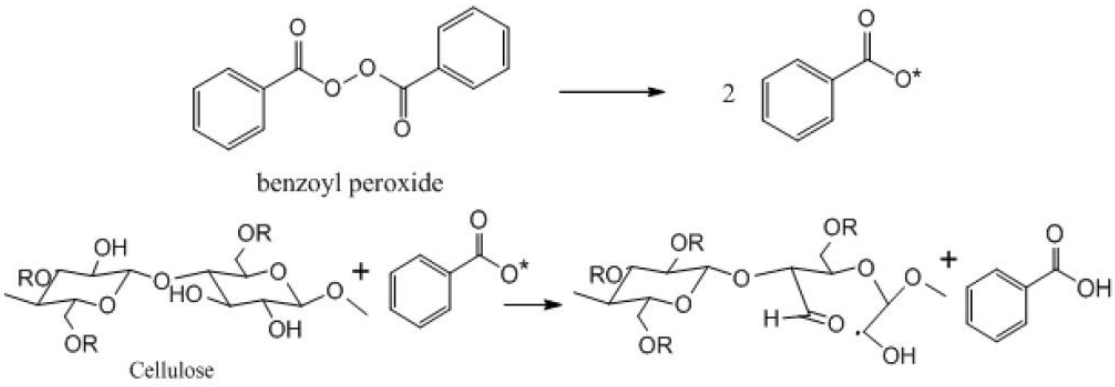

Figure 2. 6: Sisal fibre reaction with benzoyl peroxide [7]

$$RO\text{-}OR \rightarrow -2RO \quad \text{.....(2.11)}$$

$$RO + PE\text{-}H \rightarrow ROH + PE \quad \text{.....(2.12)}$$

$$RO + Cellulose\text{-}H \rightarrow ROH + Cellulose \quad \text{.....(2.13)}$$

$$PE + Cellulose \rightarrow PE\text{-}Cellulose \quad \text{.....(2.14)}$$

Kaushik *et al.* [7] in their research soaked fibres in different concentrations of peroxide treatments namely dicumyl peroxide (DCP, $(C_6H_5C(CH_3)_2O_2)$ and benzoyl peroxide (BP, $(C_6H_5CO)_2O_2$) in acetone solution for different times. They found that peroxide treatments enhanced crystallinity and fibre thermal stability while consequently improving the fibre and composite mechanical performance.

2.4.3 Benzoylation Treatment

In the treatment of natural fibres, benzoyl chloride is largely utilized. It involves the use of benzoyl ($C_6H_5C=O$), which makes the treated fibres more hyrophobic and also enhances

bonding with the hydrophobic matrix. The fibre hydroxyl group and benzoyl chloride react as shown below.

$$\text{Fibre-OH} + \text{NaOH} \rightarrow \text{Fibre-O}^{+}\text{Na}^{+} + \text{H}_2\text{O} \text{.....(2.15)}$$

$$\text{Fibre-OH} + \text{NaOH} \rightarrow \text{Fibre-O}^{+}\text{Na}^{+} + \text{H}_2\text{O} \text{.....(2.16)}$$

Fahim and Chand [54] established that benzoylation improves the adhesion of fibre to the matrix, thus remarkably reducing water absorption and increasing composite thermal stability and strength.

2.4.4 Permanganate Treatment

The permanganate compound has the permanganate group MnO^{-}_{4}. Treatment of fibres using permanganate forms cellulose radical through MnO^{-}_{3} ion formation. Next, highly reactive Mn^{3+} ions initiate graft copolymerization as indicated in figure 2.7 [55].

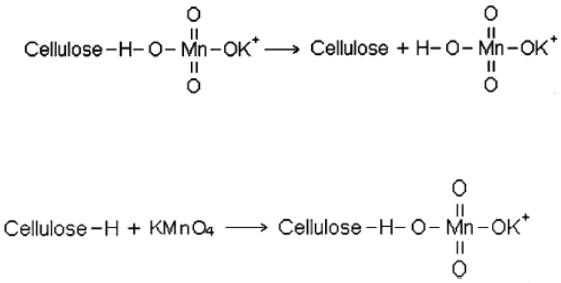

Figure 2. 7: Sisal fibre reaction with Potassium Permanganate

Potassium permanganate ($KMnO_4$) solution in acetone is mostly used to carry out permanganate treatments. Different concentrations are used with soaking durations varying from 1 to 3 minutes [56, 57]. Paul *et al.* [56] soaked sisal fibres treated in alkaline solution in permanganate solution at different concentrations of 0.033, 0.0625 and 0.125% for 1 min. Due to the permanganate treatment, the hydrophilic nature of the fibres was reduced and, therefore, the fibre-reinforced composites water absorption tendency reduced further. Ezeamaku *et al.* [58] in their investigation of selected chemical treatment on banana fibres have recommended

$KMnO_4$ citing increased surface roughness and a reduction of the water absorbency of the fibres. This informed the choice of $KMnO_4$ for the surface-modification of Giant Cavendish banana fibres in the current study. However, according to Paul *et al.* [56], as the $KMnO_4$ concentration is increased, the hydrophilic tendency of the fibre is reduced. Beyond 1% concentration of $KMnO_4$, the cellulosic fibres become degraded, which leads to the formation of polar groups between the matrix and the fibre.

2.4.5 Acetylation Treatment

The acetylation technique involves using acetic anhydride to soak banana fibres with or without the use of an acid as catalyst. Since acetic acid reacts with cellulose inadequately, acetic anhydride is preferred. On the contrary, acetic anhydride does not cause sufficient cellulose swelling, thus fibres are normally soaked first in acetic acid then acetic anhydride is applied at a higher temperature for 1-3 hours. This speeds up the reaction process where the hydroxyl group causes swelling in the fibre cell wall and minimizes the hygroscopic behaviour of the cellulosic fibre thereby increasing the composite's dimensional and thermal stability [59].

Fahim and Chand [54] discussed that acetylation involves introducing into an organic compound an acetyl functional group (CH_3COO-). In cellulosic fibres, plasticization is as a result of acetylation. Therefore, before the fibre is used, acetic acid (CH3COOH), which is one of the reaction's by-product must be removed from the fibre. This means when acetic anhydride (CH3-C(=O)-O-C(=O)-CH3) is used in the chemical modification; it substitutes the hydroxyl group of the polymer with acetyl groups. This modifies the properties of this polymers to be hydrophobic as shown in equation 2.17 and figure 2.8.

$$\text{Fibre-OH-}CH_3\text{-O(=O)-C(=O)} + CH_3 \rightarrow \text{Fibre-OCO}CH_3 + CH_3COOH \quad (2.17)$$

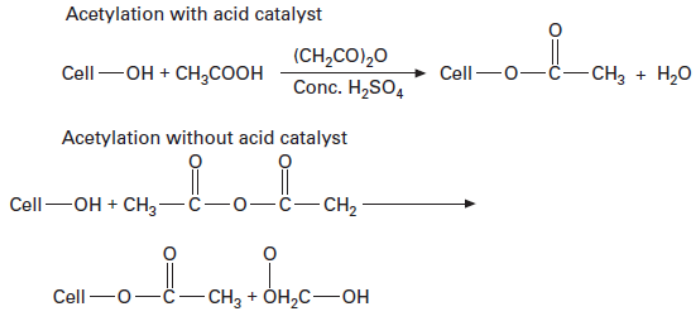

Figure 2. 8: Acetylation of natural fibre [54]

2.5 Extraction and Decortication of Banana Fibres

2.5.1Fibre Extraction

The manner in which natural fibres and in this case banana fibres are extracted is critical in determining the amount of yield and quality of fibre extracted. Fibres are extracted by decortication from the pseudo-stem of the banana plant. This involves the separation of fibres from the pulpy matter. Water retting and scraping are the most common practices [60].

In extraction, the first step is tuxing. This is the separation fibre bundles from the main plant. This can be carried out mechanically by a machine or manually. From the cut pseudo-stems, the leaves are peeled and then a knife is used to pull out the outer and middle layers of the leaf shaft. The second step involves removing non-fibrous part and any other residual material after the tuxing step. Next, fibres are washed thoroughly and dried [61].

Subagyo and Chafidz [60] built a decorticator machine which can be used to extract fibre from banana pseudo-stem as shown in figure 2.9.

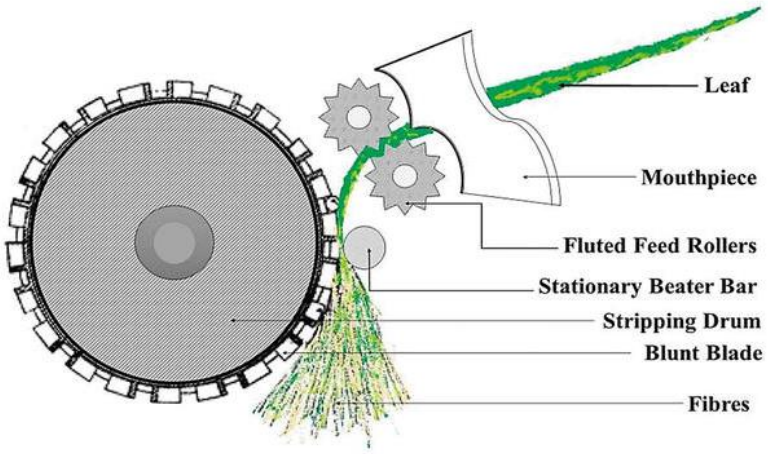

Figure 2. 9: Pseudo-stem fibre decorticator machine [44]

2.5.2 Retting of Banana Fibres

Retting is the separation of banana fibres from the cortex (outer stem layer). This leads to loosened lignin and hemicellulose (cementing materials). The retting process is two stage; the first stage involves the absorption of water where swelling occurs and then some soluble materials are extracted. This stage is also known as the physical stage. The second stage occurs due to the action of fungi or bacteria, which can either be aerobically or anaerobically process.

According to Subagyo and Chafidz [60], factors such as temperature, retting time, pure culture of microorganisms and chemical additives used (e.g., magnesium oxide) can shorten the time taken in retting by 78%. They found that at room temperature, a retting time of 28 hours was satisfactory and the process controlled at a pH of 6.8-7.4 with sodium carbonate.

Retting improves the mechanical properties of banana plant pseudo-stem [62]. Tensile and flexural tests carried on the fibre showed that removing pectin through retting did not significantly affect the strength of the fibre except when over-retting is done. Moreover, retting considerably reduced hemicellulose and lignin available in the pseudo-stem fibre. Likewise, Khan *et al.* [63] concluded that during pulping of retted fibres, pulps with good strength and

chemical properties were produced in comparison to pulps from fibres that had not undergone retting.

2.5.3 Degumming of fibres

A decorticator machine produces banana fibre pseudo-stems with a huge amount of gum and non-fibrous cell material (approx. 30-35%). Before the mechanical spinning of fibres into yarn, these gums and non-fibrous material are extracted since they are not water-soluble. The fundamental degumming process is as follows: In an aqueous alkaline solution, the fibres are boiled repeatedly with or without applying pressure and with or without using reducing agents. Thereafter, water is used to wash the fibres so as to neutralize them.

Next, the fibres are bleached with dilute hypochlorite or hydrogen peroxide. Finally, the fibres are washed with water for neutralization and oiled by applying a sulfonated hydrocarbon. Caustic soda is used in a number of processes to remove residual lignin, gum and pectin while recent literature studies report the use of ultrasonic vibrations to accelerate degumming [61].

2.6 Epoxy Resin

Epoxy resins are a class of thermoplastic resin that are isotropic, brittle and do not melt upon heating [64]. They are also known as polyepoxides and are typically used as adhesives [65]. They usually come in 2:1 or 4:1 resin to hardener mixing ratios. There are several types of epoxy resins that are currently in use both in domestic and industrial applications. These include:

- Aliphatic Epoxy Resins – these are generally low viscosity, low dielectric constant all weather epoxies that have found uses in both domestic and industrial applications.
- Bisphenol Epoxy Resins – These types of epoxy resins are characterised by low molecular weight.

- Epoxy Resin Diluents – These are usually either monofunctional (dodecanol glycidyl ethers), difunctional (butanediol diglycidyl ether) or higher functionality (trimethylolpropane triglycidyl ether) epoxy resins.
- Glycidyl amine Epoxy Resins – These are epoxies formed by the reaction of an epoxide 'resin' and polyamine 'hardener'. They have a high functionality and are usually industrial grade. They have low to medium viscosity at room temperature and also have easier processing ability.
- Halogenated Epoxy Resins – These are epoxies, which are formed by reacting an epoxy resin with a polyhydric phenolic compound where at least one reactant contains a halogen atom.
- Novolac Epoxy Resins – These types of epoxies are formed from a chemical reaction between phenols and methanol (formaldehyde). They are characterised by their high adhesive strength and good durability.

Generally, all epoxies are characterised by strong adhesion, toughness and superior chemical resistance when compared to other thermoplastics such as polyester resins [66, 67]. They (epoxies) also have lower heat generated during the crosslinking reaction and better thermal symmetry compared to both unsaturated and saturated polyester resins [68].

Hernandez Michelena *et al.* [69] in their study of the sustainable manufacture of natural fibre reinforced epoxy resin composites with coupling agent in the hardener, used flax fibre and glycidyl amine epoxy resin. They found out that the longitudinal tensile modulus and strength fibres reinforced epoxy composites improved.

For the purposes of this study, a clear 2:1 resin to hardener ratio, low-viscosity glycidyl amine epoxy resinsupplied by Druntech Dev EA construction chemicals was used. The chemical structure is shown in figure 2.10 below. The resin had a working time of 45 minutes

which gave ample time for the hand lay-up method to be used in the reinforcement of the epoxy matrix with untreated and surface-modified Giant Cavendish banana fibres.

An epoxy to hardener ratio of 2:1 was utilized in the current study following recommendation by Shin *et al.* [70] that a 2:1 epoxy mixture exhibited the best interfacial adhesion and resulted in high mechanical, interfacial and thermal properties of the resulting composite.

Figure 2. 10: Epoxy reaction with amine [64]

2.7 Natural Fibre Density Determination

A study by Cullen *et al.* [71] has presented a method for determining the density of natural fibres that are to be used as fibrous composite reinforcement. In their study, they used Archimedes principle in combination with vacuum degassing of the fibre samples. Jute fibres were prepared in small bundles and dried at 60^0C for 30 minutes and then immediately weighed in air using a digital scale. The fibres were then suspended, immersed in the test fluid, and degassed in a vacuum chamber; first in water at a vacuum level of −990mbar and then in in acetone at a vacuum level of −500mbar. They found that the densities of jute fibre in water and acetone were 1669±37kg·m^{-3} in water/Ilfotol at 22.4^{0}C and 1652±37kg·m^{-3} in acetone at 20.3^{0}C respectively.

Cullen *et al.* [71] concluded that these densities were higher than those indicated in natural fibre literature [72]. This is because most fibre density determination methods do not use degassed fibres.

Shah *et al.* [73] used gas pycnometry to determine composite and fibre density (flax and jute). Similar to the study by Cullen *et al.* [71], Shah *et al.* [73] found that the densities

of the fibres were considerably higher. This has been supported by research done by Neuba *et al.* [74] who also found that natural fibre density results obtained from other methods other than the linear geometric method were higher.

After a review of the above methods of determining density of plant fibres and given the hygroscopic nature of lignocellulosic fibres, conventional fibre density determination methods couldn't work for Giant Cavendish banana fibres. In light of this, the modified linear density and diameter calculation method used by Soykeabkaew *et al.* [75] was employed.

2.8 Testing Standards

2.8.1 Tensile Test

Tensile tests are normally used to generate stress-strain curves and also to calculate the tensile modulus. Therefore, for unreinforced and reinforced polymer composites, BS 2782-3 standard methods for testing plastics mechanical properties, tensile strength, elongation and elastic modulus is used to prepare and test the specimens [76]. For BS 2782-3 test, samples are placed in a Universal Test Machine (UTS) or tensometer at a specified gauge length and pulled until failure. Typical test speed is between 2 to 4 mm/min for standard samples [77]. Specimens are usually of rectangular cross-section since dog bone shaped specimens when subjected to a tensile load, have been shown by Staab [78] to result in matrix cracks and premature failure (see Figure 2.11).

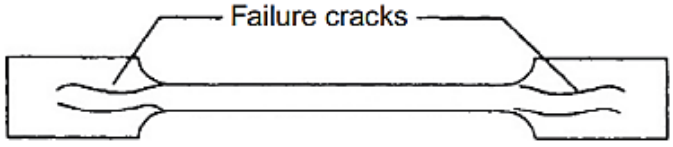

Figure 2. 11: Image showing matrix cracks for a dog bone shaped fibre reinforced composite

Irawan and Sukania [79] carried out tensile tests to determine the tensile strength of banana fibre reinforced epoxy composites materials as per ASTM D3039 standard. They found that the tensile strength of banana fibre epoxy composite yield strength was between (44-50) MPa with a modulus of elasticity of 1.9 GPa. The tensile results they obtained were comparable to those obtained by Bhosale and Asabe [43].

2.8.2 Flexural Test

To determine flexural properties BS 2782-3 was used in this study [76]. This international standard specifies a method for testing plastics mechanical properties, tensile strength, elongation and elastic modulus. Typical cross-head speeds are between 2 to 4 mm/min.

Maleque *et al.* [80] in their study of mechanical properties of pseudo-stem banana fibre reinforced epoxy composite carried out their flexural test as per BS EN ISO 14125:1998 [81]. They used specimens with dimension 15mm ×100mm×5mm and three-point bend flexural method. They found that the flexural strength increased from 53.38 MPa to 73.58 MPa when banana woven fabric was used with epoxy material. The flexural modulus which is used as an indication of a material's stiffness in static bending condition showed an increase from 1563.2 MPa to 1834.6 MPa for the banana fibre reinforced composite.

2.9 Data Analysis

2.9.1 Weibull Cumulative Distribution Function

Nominally identical brittle material specimens' exhibit large variation of tensile fracture stresses [82]. For such materials to be of any use in engineering it is imperative that their strengths be statistically characterised [82, 83]. The Weibull Cumulative Distribution Function (CDF) is a statistical distribution that is well suited with dealing with highly scattered data. It is also referred to by statisticians as the 'third asymptotic distribution of the smallest

extreme value' [83]. As such, Weibull statistics is based on the 'weakest link-hypothesis' which suggests that the most serious specimen flaw will control specimen strength [24, 83, 84]. It was developed and described in detail by Swedish mathematician Waloddi Weibull [85] in the year 1951 for dealing with data sets in scientific fields that present significant levels of scatter. Recently, the Weibull distribution has proven to be a valuable tool in studying the deformation and fracture mechanics of engineering materials [86].

Jianghong [87] has noted that the scatter in natural fibre tensile strength can be optimally modelled as Weibull CDF and the graphical approach used to calculate the Weibull modulus *m* as follows;

$$\log_e\left(\log_e\left({}^{1}/_{(1-F)}\right)\right) = m\log_e\sigma_f - m\log_e\sigma_0 \ldots\ldots (2.18)$$

where F is the probability of failure,, *m* is the gradient of the curve generated and the scale parameter σ_0 calculated from the Y intercept of the curve, which is equal to $(-m\log_e\sigma_0)$.

The Weibull (CDF) has also been shown to be an accurate tool in estimating the diameter of lignocellulosic fibres [88–92], due to the wide variation that exists in natural fibre diameters. Lingyan *et al.* [93] used the following Weibull CDF equation to characterize fibre diameter distribution.

$$Mean\ diameter = D_o\Gamma\left(1 + {}^{1}/_{m}\right) \ldots\ldots\ldots\ldots\ldots\ldots (2.19)$$

where:

D_o - Reference diameter (scale parameter)

Γ - Gamma function, defined as $\Gamma_{(n)} = \int_0^\infty (x^{n-1}e^{-x})dx$

m - Weibull Modulus (shape parameter)

These Weibull CDF expressions were used in analysing the data in the current study.

2.9.2 Polynomial Regression Analysis

Regression analysis is a useful statistical tool for use where there is reason to believe that a curvilinear relationship exists between a dependent and one or more independent variables [94]. This statistical method has proven useful in many scientific fields, engineering, business studies and economics. Polynomial regression, also referred to as multiple regression is a regression technique where the dependent variable(s) is/are regressed onto powers of the independent variable.

A standard polynomial regression equation generally takes the following form:

$$f_{(x)} = Ax^n + Bx^{n-1} + Cx^{n-2} + Dx^{n-3} + Ex^{n-4} + \cdots \alpha x^{n-n} \ldots\ldots\ldots (2.20)$$

Where 'x' is the independent variable (e.g. % fibre volume fraction), and '$f_{(x)}$' is the dependent variable (e.g. Modulus of rupture in the case of a flexural strength test) and, A, B, C, D…...α are all correlation constants.

2.10 Summary of Literature Review

Chemical fibre-surface modification has been reported to improve both the strength properties and interfacial bonding between cellulose based fibres and polymeric (resin based) matrices [56, 58]. The improvement of Giant Cavendish banana fibres strength properties following NaOH and $KMnO_4$ is yet to be determined. The current study represents the first species specific study where the strength properties of the untreated and surface-modified fibres were investigated, and their effectiveness at reinforcing a polymeric matrix (epoxy resin) experimentally investigated in the laboratory.

CHAPTER 3: METHODOLOGY

3.1 MATERIALS AND METHODS

The main objective of this study was to chemically treat banana fibres, determine the tensile and flexural properties of the untreated and chemically treated fibres and ultimately, determine the effect of chemical treatment of banana fibres on the tensile and flexural properties of banana fibre-reinforced epoxy composites.

The study was carried out between January 2021and September 2021 at the following workshops and laboratories:

1. Department of mechanical and manufacturing engineering workshops and laboratories, University of Nairobi.
1. Timber workshop, department of civil and construction engineering, University of Nairobi.

In this study, the banana fibres (Giant Cavendish) were extracted from the pseudo-stem (stalk) of the banana plant (Musaceae family) by decortication. The banana stems were sourced from UoN's College of Agriculture and Veterinary Sciences. The species used was the Giant Cavendish. This is because it has long stems of approximately 4-5m. The bananas were grown in an area with latitude, longitude and altitude of S 01° 14.706', E 36° 44.880' and 1807 meters respectively [95]. The region has a mean annual rainfall of 1006 mm [96]. The fibres were harvested from the banana pseudostem when the plants were 9 months old. Figure 3.1 shows the Giant Cavendish banana grove at the College of Architecture and Veterinary Sciences, from which the banana pseudostems used in the current study were obtained.

Figure 3. 1: Giant Cavendish plantation at college of agriculture and veterinary sciences

The stalks were cut to 100cm length and the outer sheath stripped. The fibres were then decorticated from the stalks using a 6 blade decorticator machine (Figure 3.2) set at 2mm gap size and a rotating speed of 900 r.p.m.

Figure 3. 2: Decorticator machine

These sections were decorticated by passing them between two roller drums with scraping blades at the circumference of the decorticator drum for purposes of removing pulpy material between the fibres.

The fibres were then thoroughly washed with water to eliminate any residual material (dirt and small fibre particles) and thereafter sun-dried for 3-4 days. The fibres were surface modified and their strength properties determined. They were then ultimately used as reinforcement in an epoxy resin composite.

3.2 Experimental Procedures

3.2.1 Experimental Procedure I – Banana Fibres

3.2.1.1 Fibre Diameter

The banana fibre diameter was measured using an Optical Microscope (set to an accuracy of 0.01μm). A single fibre strand was selected randomly and observed under the optical microscope. The diagonals in the optical attachment were then aligned with one side of

the fibre strand and once this was achieved, the machine was reset to read zero. Fibre diameter measurements (in micrometres) were then taken by moving one of the diagonals to the other side of the fibre strand and reading them off the machines LCD display. Figure 3.3 is an image showing the banana fibre diameter being measured on the Optical Microscope.

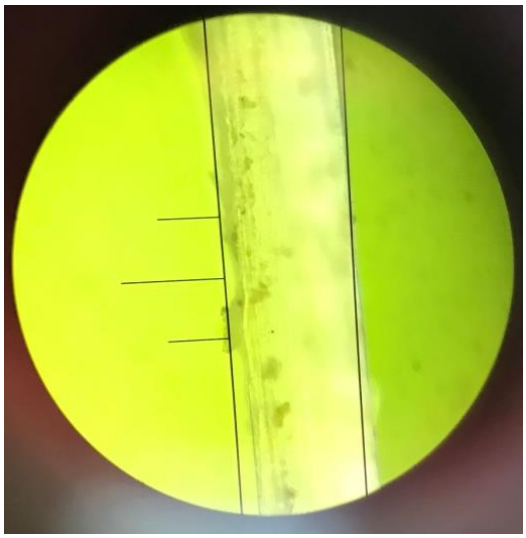

Figure 3. 3: Banana fibre diameter being measured on an Optical Microscope

The mean banana fibre diameter (sample of 50 fibres) was then determined by modelling the fibre diameters using the Weibull CDF (see Appendix A Table A1). The Weibull CDF has been shown to be an accurate tool in estimating the diameter of lignocellulosic fibres [88–92]. The Weibull CDF equations used to determine the mean Giant Cavendish banana fibre diameter were:

$$Mean\ diameter = D_o\Gamma\left(1 + {}^{1}/_{m}\right) \quad \text{.....(3. 1)}$$

$$Standard\ error = \frac{\sqrt[2]{\left(D_0{}^2\left[\Gamma\left(1+{}^{2}/_{m}\right)-\Gamma^2\left(1+{}^{1}/_{m}\right)\right]\right)}}{\sqrt[2]{n}} \quad \text{.....(3. 2)}$$

where:

D_o - Reference diameter (scale parameter)

Γ - Gamma function, defined as $\Gamma_{(n)} = \int_0^\infty (x^{n-1}e^{-x})dx$

m - Weibull Modulus (shape parameter)

n - Number of samples = 50 fibre diameters

3.2.1.2 Fibre Density

Given the hygroscopic nature of lignocellulosic fibres, conventional fibre density determination methods couldn't work for Giant Cavendish banana fibres. In light of this, a modified linear density and diameter calculation method was employed [75]. Banana fibres were randomly selected from a bunch and cut into 100 mm lengths. Figure 3.4 shows decorticated banana fibres that were used in this research being air-dried.

Figure 3. 4: Decorticated banana fibres that were used in the current study.

The fibres were then grouped into several bunches each comprising of 60 fibre strands. These fibre bunches were dried at 60°C for 1 hour in an ELSKLO (type JN 200R) convection oven. The fibres were then wrapped tightly in pre-weighed cling-wrap (to remove as much trapped air as possible and then weighed on a Denver XL-3100D electronic weighing scale (see Figure 3.5).

Figure 3. 5: Denver XL-3100D electronic weighing scale

The density of each bunch was then calculated from the mass of the bunch and the volume of the bunch (with the volume being calculated using the mean fibre diameter as presented in **section 3.2.1.1** of this report).

3.2.1.3 Fibre Surface Modification

Banana fibre surface modification was done using 0.02M, 0.06M, 0.1M NaOH and 0.0006M, 0.003M, 0.006M $KMnO_4$ solutions. A Molar solution is a measure of chemical concentration defined as one mole of a substance dissolved in 1000 ml of solvent.

The various Molar solutions used in the current study were diluted from a 1 Molar solution and were prepared as follows:

a) 1M Sodium Hydroxide Solution (NaOH)

The sodium hydroxide employed in this study was a 97% pure NaOH pellets supplied by Griffchem™ India. A 1 Molar NaOH solution was prepared as follows:

$$100\% = 1Molar = \ Molecular\ mass\ x\ \frac{100\%}{Solute\ Purity\ \%}\ gl^{-1} \tag{3. 3}$$

$$= 39.997\ x\ \frac{100\%}{97\%}\ gl^{-1} = 41.23\ gl^{-1} \tag{3. 4}$$

Therefore, 41.23 grams of NaOH were diluted in 1 litre of distilled water to make 1M NaOH

The glacial acetic acid employed in this study was 99.5% pure CH_3COOH supplied by Griffchem™ India. A 1 Molar CH_3COOH solution was prepared as follows:

$$100\% = 1\ Molar = \frac{Acid\ Molecular\ mass\ (in\ grams)}{Acid\ Density\ (in\ grams.cm^{-3})}\ x\ \frac{100\%}{Acid\ Purity\ \%}\ cm^3 l^{-1} \tag{3.5}$$

$$= \frac{60.05g}{1.05g.cm^{-3}}\ x\ \frac{100\%}{99.5\%} = 57.48\ ml$$

$$\cong 57.48ml\ CH_3COOH\ were\ diluted\ in\ 942.52\ ml\ of\ distilled\ Water \tag{3.6}$$

$$to\ make\ 1\ litre\ of\ 1\ Molar\ CH_3COOH\ solution$$

b) 1M Potassium Permanganate Solution ($KMnO_4$)

The potassium permanganate crystals employed in this study was 99% pure $KMnO_4$ supplied by Griffchem™ India. A 1 Molar $KMnO_4$ solution was prepared as follows:

$$100\% = 1Molar = \ Molecular\ mass\ x\ \frac{100\%}{Solute\ Purity\ \%}\ gl^{-1} \tag{3.7}$$

$$= 158.034\ x\ \frac{100\%}{99\%}\ gl^{-1} = 159.63\ gl^{-1}.$$

$$Therefore, 159.63\ grams\ of\ KMnO_4\ were\ diluted\ in$$

$$1\ litre\ of\ distilled\ water\ to\ make\ 1M\ KMnO_4\ solution \tag{3.8}$$

c) 1M Acetone Solution ($(CH3)_2CO$)

The acetone employed in this study was 99.9% pure $(CH_3)_2CO$ supplied by Griffchem™ India. A 1 Molar $(CH_3)_2CO$ solution was prepared as follows:

$$100\% = 1\ Molar = \frac{Acetone\ Molecular\ Mass\ (in\ grams)}{Acetone\ Density\ (in\ grams.cm^{-3})}\ x\ \frac{100\%}{Acetone\ Purity\ \%}\ cm^3l^{-1} \tag{3.9}$$

$$= \frac{58.08g}{0.7845gcm^{-3}}\ x\ \frac{100\%}{99.9\%} = 74.11\ ml$$

$$\cong 74.11ml\ (\mathrm{CH_3})_2\mathrm{CO}\ were\ diluted\ in\ 925.89\ ml\ of\ distilled\ Water$$

$$to\ make\ 1\ litre\ of\ 1\ Molar\ Acetone\ solution \tag{3.10}$$

Mercerisation of Banana Fibres

Giant Cavendish Banana were mercerised at a fibre-liquor ratio of 1:15 (g: ml ratio). 20 grams of combed banana fibres were each immersed in 300 ml of 0.02M, 0.06M and 0.1M NaOH solutions respectively for 5 hours. The fibres were then removed from the alkali solution and rinsed 4 times using tap water, and then rinsed in a 0.001M glacial acetic acid solution to neutralise excess alkali. This treatment was done in order to potentially reduce the hemicellulose and lignin proportion in the fibres, ultimately increasing the surface roughness and tensile strength of the fibres. Figure 3.6 shows banana fibres mercerising in a 0.1M NaOH solution.

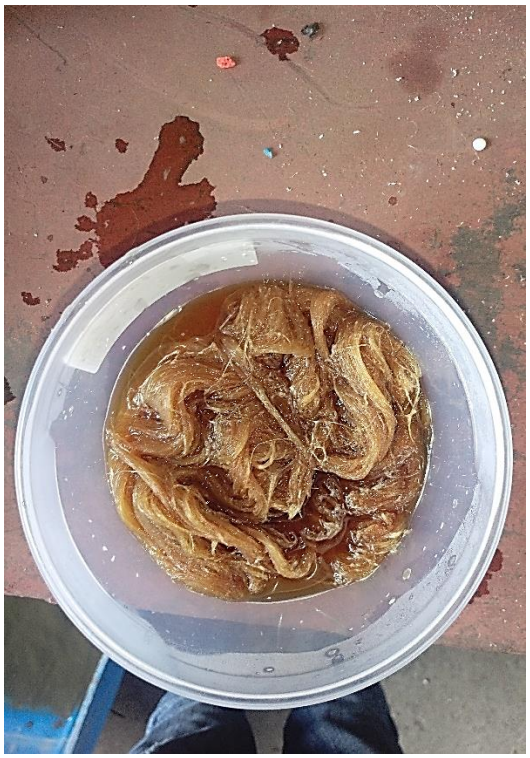

Figure 3. 6: Banana fibres mercerising in a 0.1M NaOH solution.

Potassium Permanganate Treatment of Banana Fibres

In this study, Giant Cavendish Banana were mercerised at a fibre-liquor ratio of 1:15 (g: ml ratio). 20 grams of combed banana fibres were each immersed in 300 ml of 0.0006M,

0.003M and 0.006M $KMnO_4$ solutions respectively for 3 minutes. The fibres were then removed from the permanganate solution and immediately rinsed using 0.0001M acetone solution $(CH3)_2CO$ solution to neutralize any residual $KMnO_4$ and prevent the reaction from progressing any further. The fibres were then rinsed 4 times using tap water. This treatment was done in order to potentially reduce the hemicellulose and lignin proportion in the fibres, ultimately increasing the surface roughness and tensile strength of the fibres. Figure 3.7 shows banana fibres ready to be treated in a 0.003M potassium permanganate solution.

Figure 3. 7: Banana fibres ready to be treated in a 0.003M potassium permanganate.

3.2.1.4 Fibre Tensile Test

The banana fibre tensile test was performed using a Hounsfield Tensometer *(Type W)*. The test involved subjecting the fibres to direct tension at increasing loads until the fibres ultimately failed under fracture. The magnification was set at x8 and the cross-head speed was a constant 3.75 mm min^{-1}. A low cross-head speed has been shown by Vimoth *et al.* [97] to facilitate the crystalisation of the fibres' amorphous regions, allowing for load-sharing with the crystalline regions of the fibre when the fibre specimen is subjected to a tensile load.

Banana fibres were selected randomly from each batch of untreated and surface-modified (at various chemical concentrations) fibres, cut into 130mm lengths and grouped into

bunches of 60 fibre strands. The random selection and bunching was done due to the inverse relationship that has been shown to exist between fibre diameter and fibre strength by Denise *et al.* [98]. The fibre bunching method was used in the current study following Kiruthika and Veluraja [99], Hassan *et al.* [100] and Mokhtar et. al [101] successful employment of the fibre bunching method in testing the tensile strength of sisal, pineapple and coir fibres.

The fibre bunches were then glued at the ends onto manila paper using wood-glue and the glue allowed to cure for 24 hrs before tensile tests were carried out. Figure 3.8 is an image showing 60 fibre-strand banana bunches glued at the ends ready for tensile testing.

Figure 3. 8: 60 fibre-strand banana bunches glued at the ends ready for tensile testing.

Each of the fibre bunches was then individually tested on the Hounsfield tensometer and Load-extension curves plotted. Figure 3.9 shows a banana fibre bunch tensile test in progress on a Hounsfield tensometer.

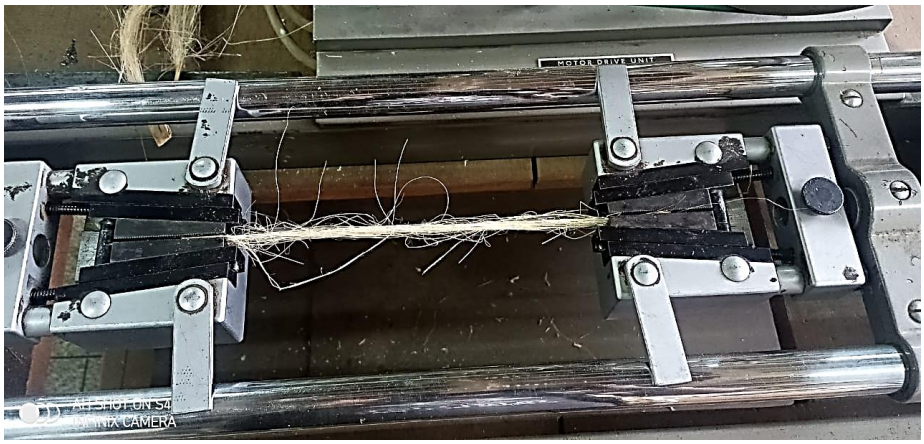

Figure 3. 9: 60 fibre-strand banana fibre bunch tensile test in progress on a Hounsfield tensometer.

From the load-extension curves, engineering stress-strain curves were generated by multiplying the y-axis (load) and the x-axis (extension) with the reciprocals of the specimen's cross-sectional area and gauge length as shown in the following expression:

$$(\Delta l \quad P)\begin{bmatrix} {}^{1}/_{l_o} & 0 \\ 0 & {}^{1}/_{A_o} \end{bmatrix} = (\varepsilon \quad \sigma) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.11)$$

where:

Δl – specimen deformation

P – load

l_o – specimen gauge length

A_o – original cross sectional area ($\left(n\pi \, {}^{d_f^2}/_{4}\right)$ where *'n'* = 60 (the number of fibre strands))

The Young's Modulus was calculated from the linear portion of the stress-strain curve using the following equation:

$$E = \frac{\Delta\sigma}{\Delta\varepsilon} = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1} \text{.....(3. 12)}$$

where;

ε – engineering strain

σ – engineering stress

The fibre fracture stress was modelled as a Weibull CDF [92, 102, 103]. Detailed calculations are shown in Appendix A, Table A10 in the form of MS excel® (2013) spreadsheets.

The Weibull Modulus of Giant Cavendish banana fibres was calculated from the following two-parameter Weibull Cumulative Distribution function:

$$F = 1 - exp\left[-\left(\frac{\sigma_{fr}}{\sigma_0}\right)^m\right] \text{.....(3. 13)}$$

where:

F - Cumulative probability of failure as a function of fibre fracture stress

σ_{fr} - Fibre fracture stress

σ_0 - Reference stress (scale parameter)

m - Weibull Modulus (shape parameter)

The probability index *F* in equation 3.13 was calculated using the following expression:

$$F_i = \frac{i - \alpha}{n + \beta} \text{.....(3. 14)}$$

where

F_i – is the probability of failure for the i^{th} ranked stress data

i- is the rank of the specimen in the data.

n – Sample size (n=10)

In the current study, the values of α and β were taken as 0.68 and 0.82 respectively. These values have been shown by Lingyan *et al.* [93] to be the optimal values of α and β for a sample size where n=10.

The mean untreated and surface-modified Giant Cavendish banana fibre fracture stress and standard errors were then calculated using the following equations:

$$\mu = \sigma_0 \Gamma\left(1 + {}^{1}/_{m}\right) \quad (3.\ 15)$$

$$Standard\ error = \frac{\sqrt[2]{\left(\sigma_0{}^2\left[\Gamma\left(1+{}^{2}/_{m}\right) - \Gamma^2\left(1+{}^{1}/_{m}\right)\right]\right)}}{\sqrt[2]{n}} \quad (3.\ 16).$$

where

μ - Mean fibre fracture stress

σ_0 - Reference stress (scale parameter)

Γ – Mathematical Gamma function ($\Gamma_{(n)} = \int_0^{\infty}(x^{n-1}e^{-x})dx$)

m - Weibull Modulus

n - Number of test samples

3.2.2 Experimental Procedure II – Epoxy Resin Composites

3.2.2.1 Preparation of Banana Fibres for Epoxy Resin Reinforcement

Banana fibres were selected randomly from the untreated and surface-modified banana fibre batches. The fibres were then chopped into 300mm lengths, weighed and then stored in zip-lock bags to prevent ingression of moisture. Each of the zip-lock bags was clearly labelled to show from which batch the fibres were picked from.

Epoxy Resin

The epoxy resin used in the current study was a clear, 2:1 resin to hardener ratio, room temperature curing epoxy resin that was supplied by Epoxy Druntech Dev EA construction chemicals.

Unreinforced Epoxy Resin Specimens

Unreinforced polyester resin specimens were prepared in wooden moulds that had been lined with a thin layer of petroleum jelly to prevent sticking. Figure 3.10 shows a drawing of the mould used in the fabrication.

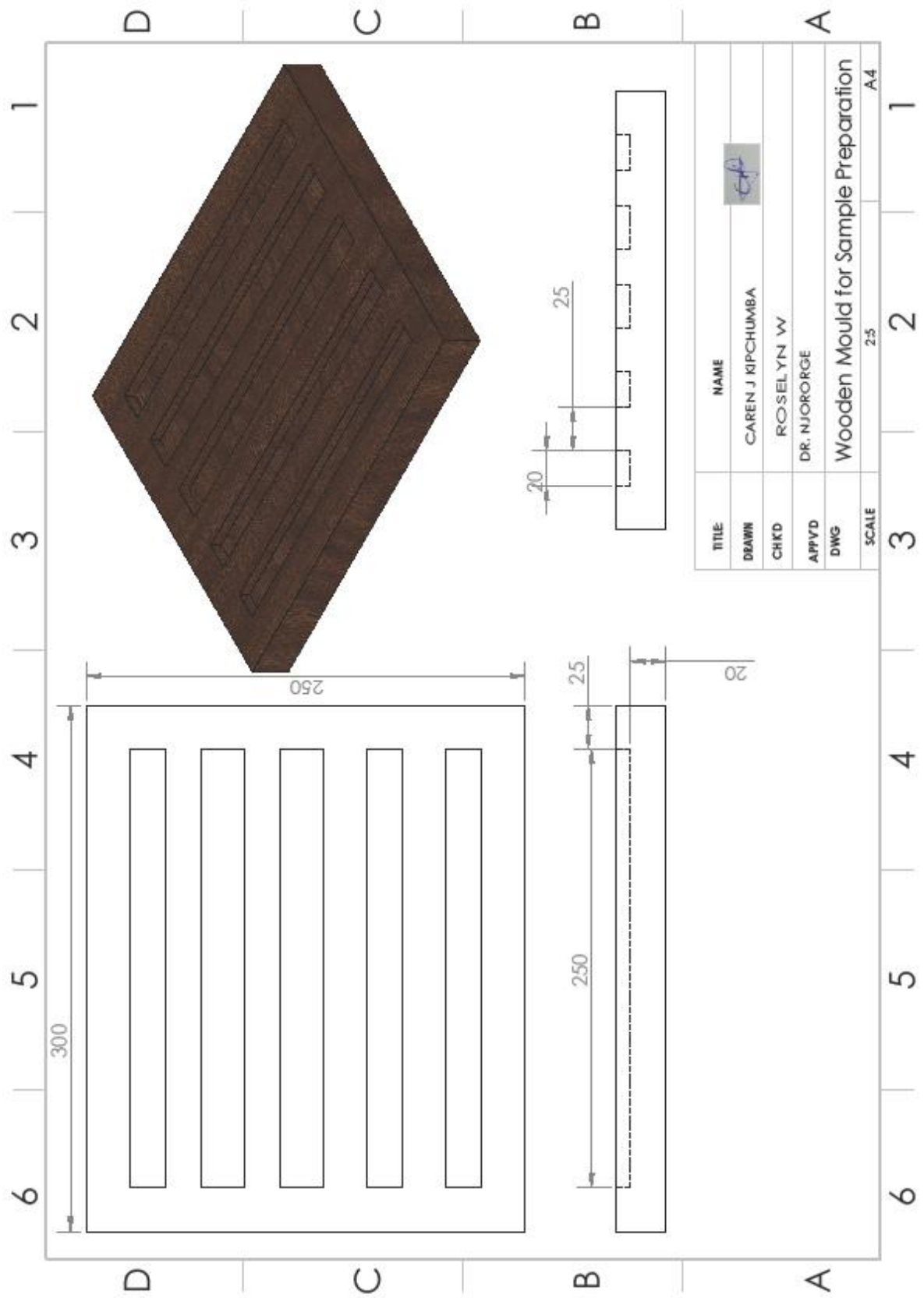

Figure 3. 10: Drawings used in the fabrication of the wooden moulds.

Epoxy resin was mixed following manufacturer's instructions and slowly poured into the wooden moulds with care being taken to minimize introduction of air bubbles. The moulds were then covered and allowed to cure for 24 hrs. The samples were then demoulded and either used as is (for the flexural test) or cut into rectangular specimens measuring approx. 5mm x 20 mm x 200 mm (for the tensile test). All strength tests were carried out on a Hounsfield tensometer *(Type W)*. Figure 3.11 shows banana fibre-reinforced epoxy resin specimens ready for demoulding.

Figure 3. 11: Banana fibre-reinforced epoxy resin specimens ready for demoulding.

Banana Fibre Reinforced Epoxy Resin Specimens

A thin film of petroleum jelly was applied to the inside of the wooden moulds to prevent sticking. The hand lay-up method was used whereby, a small layer of approx. 3mm of pre-mixed 2:1 epoxy resin was then poured into the mould followed by a small quantity of fibres whose mass was determined by multiplying the fibre density with the expected volume of the composite that the fibres were expected to occupy (i.e. expected volume of fibres in the

composite). Since $\rho = m/v$, where ρ – density, m – mass and v – volume, this effectively transformed the volume fraction to a mass fraction that could easily be determined by weighing the fibres as opposed to measuring their volume, which is an arduous if not an impossible task. This process was repeated up until all the banana fibres had been used up and the mould had been filled to the brim. The moulds were then covered and allowed to cure for 24 hrs. The samples were then demoulded and either used as is (for the flexural test) or cut into rectangular specimens measuring approx. 5mm x 20 mm x 200 mm (for the tensile test). All strength tests carried out on a Hounsfield tensometer *(Type W)*. Figure 3.12 shows 1 (one) unreinforced and 22 (twenty-two) banana fibre-reinforced epoxy resin specimens ready for mechanical testing.

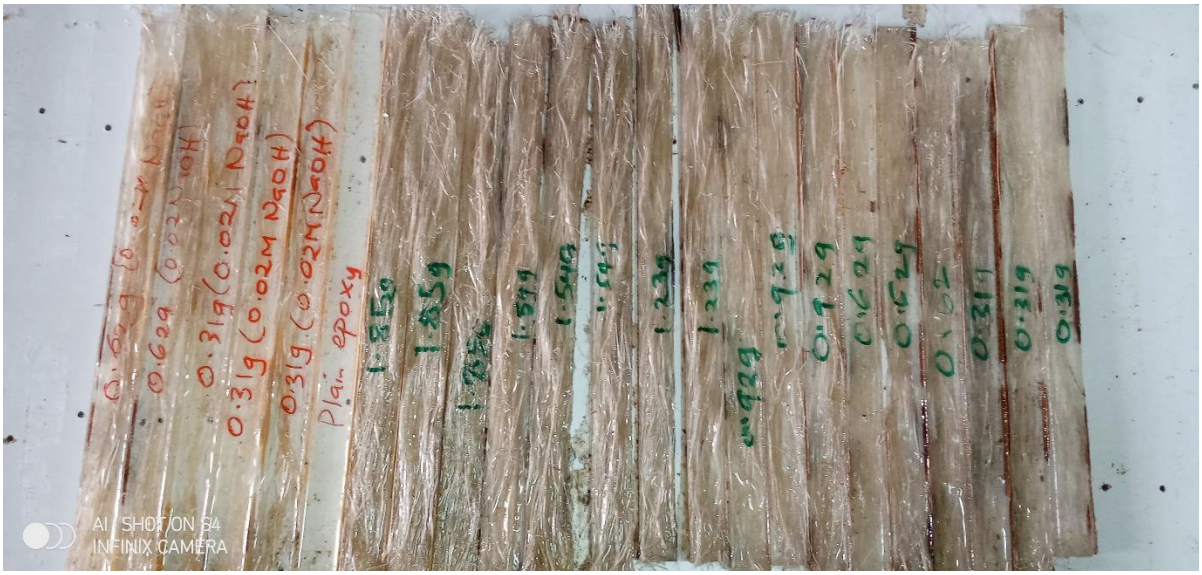

Figure 3. 12: (1) one unreinforced and 22 (twenty-two) banana fibre-reinforced epoxy resin specimens ready for mechanical testing.

3.3 Mechanical Testing of Epoxy Resin Specimens

3.3.1 Tensile Test

The specimens were prepared and tested in direct tension in accordance with BS-2782-3 standard method for testing plastics [76]. Rectangular specimens measuring 5 mm x 20 mm x 200 mm were cut using a band saw from both the unreinforced and banana fibre-reinforced

epoxy resin composites and tested in direct tension on the Hounsfield tensometer *(Type W)*. The specimens were tested at a constant 3.75 mm min $^{-1}$ crosshead speed. The specimens were loaded onto the machine such that, the specimen major axis was in the machine's direction of pull as shown in figure 3.13.

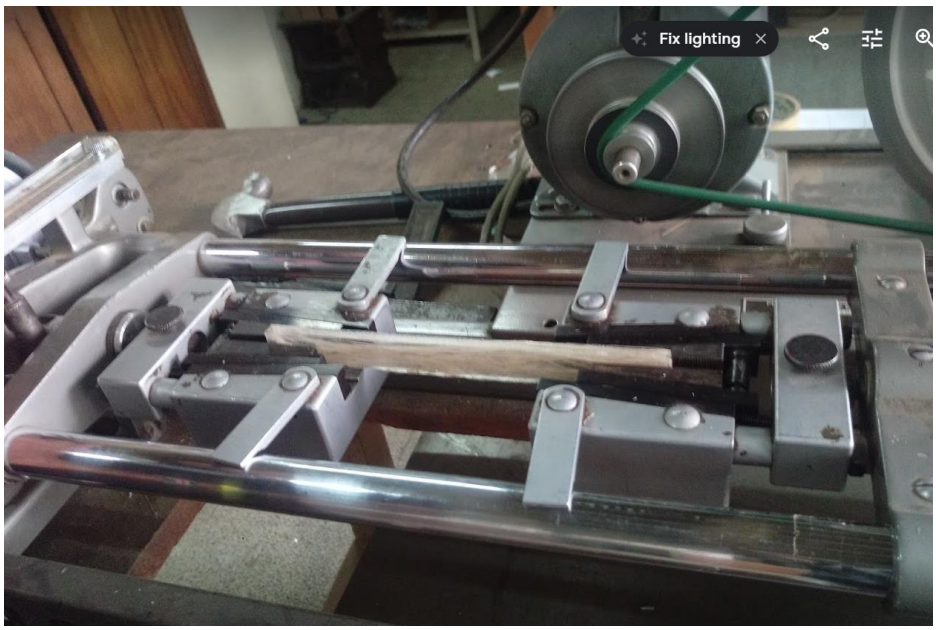

Figure 3. 13: A fibre-reinforced epoxy resin specimen tensile test in progress on a Hounsfield tensometer

Rectangular shaped specimens were used in the current study since it has been shown by Staab [78] that the regular dog-bone shaped specimen is unsuitable for laminates, leading to formation of matrix cracks and premature specimen failure.

3.3.2 Flexural Test

The specimens were prepared and tested in accordance with BS-2782-3 standard method for testing plastics [76]. Unreinforced and banana fibre-reinforced epoxy resin specimens measuring 20 mm x 8 mm x 300 mm were tested in 3-point bending on a Hounsfield

tensometer *(Type W)* at a constant 3.75 mm min $^{-1}$ crosshead speed as shown in figure 3.14. A span of 280mm was maintained throughout the duration of the test.

Figure 3. 14: A fibre-reinforced epoxy resin specimen flexural test in progress on a Hounsfield tensometer.

3.4 Data Analysis and Interpretation

Once experimental work was completed, the data collected was entered into and analysed using Ms Excel® (2013). Epoxy Resin tensile and flexural results were modelled as polynomial regression equations and analysed using the analysis tool pack 'add-in' ANOVA that is available in most Ms Excel applications. The polynomial regression equations were of the form:

$$f_{(x)} = Ax^m + Bx^{m-1} + Cx^{m-2} + Dx^{m-3} + Ex^{m-4} + \cdots \alpha x^{m-m} \ldots\ldots (3.\ 17)$$

Where the independent variable 'x' was equal to the fibre volume fraction embedded in the epoxy resin matrix and the dependent variable '$f_{(x)}$' was equal to either the Modulus of Rupture (MOR) or the fracture stress of the epoxy resin composite. The constants A, B,….. α were the regression equations constants of correlation.

Due to the scatter observed in the fibre tensile strength results, the data was modelled as a Weibull CDF and the graphical approach was used to determine the value of the Weibull

Modulus. To do this, equation 3.13 was linearized by taking the natural logarithm of the equation twice to obtain:

$$\log_e\left(\log_e\left({}^{1}/_{(1-F)}\right)\right) = m\log_e\sigma_f - m\log_e\sigma_0 \ldots..(3.\ 18)$$

A linear regression line (a line of best fit) was plotted from equation 3.18. From the regression line, the gradient *(m)* was equal to the shape parameter while the scale parameter (σ_0) was calculated from the value of the Y- intercept ($-m\log_e\sigma_0$).

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Banana Fibres

The following results were obtained from **experimental procedure I.**

4.1.1 Banana Fibre Diameter

The mean diameter of the Giant Cavendish banana fibres (see Appendix A, Table A1) was determined using equations 3.1 and 3.2 and found to equal 183.05 μm (standard error $\pm$ 5.03 μm). This result is consistent with banana fibre diameter readings reported by previous researchers including Kulkarni *et al.* [24] reported 250 μm, Ronald Aseer *et al.* [104] reported 150 ± 0.08 μm and Vishnu, Vardini and Murugan [105] reported 253.07 μm. Interestingly, Preethi and Balakrishna [106] have also reported a 188 μm fibre diameter for the Grand Naine variety of the Giant Cavendish banana. The results reported by Preethi and Balakrishna [106] are comparable with the results of the current study.

The diameters of lignocellulosic fibres, which include banana fibres, have been shown to vary depending on the age of the plant, growth environment, genetics and even on the decortication method [107–109]. The banana fibres used in the current study were harvested from 9-month old banana pseudo stems that had been grown at an altitude of 1807 meters [95] in an area that receives an annual rainfall of 1006 mm [96].

It is more often the case that researchers who measure the diameter of banana fibres, do so without specifying the age at which the fibres were harvested from the pseudostem, nor the prevalent weather conditions (rainfall) under which the banana grew. Figure 4.1 shows the Weibull CDF plot of the banana fibre diameters measured in the current study (see Appendix A, Table A1 for detailed Weibull CDF analysis).

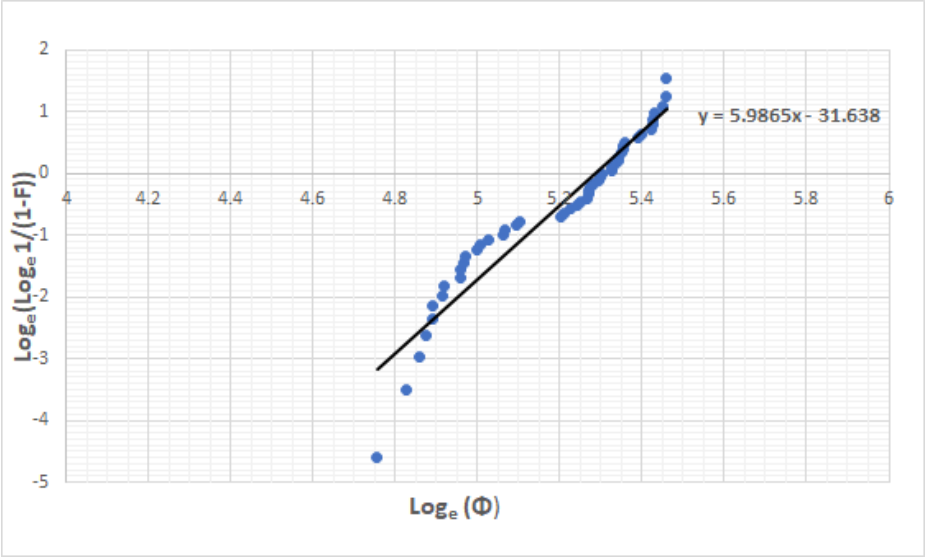

Figure 4. 1: Weibull (CDF) plot of Giant Cavendish banana fibre diameters used in the current study

The Weibull CDF has been shown by Poudel [88], Zhang *et al.* [89] and Bailey and Dell [90] to be an extremely accurate tool in characterising diameter distributions. It has been successfully employed to characterise Sisal fibres by Kithiia *et al.* [91] and Inacio *et al.* [92], Pissava fibres by Denise *et al.* [98], and even on Wool fibre by Zhang *et al.* [110].

The Giant Cavendish *(Musa acuminata)* banana fibres used in the current study had a Weibull Modulus of 5.987 ≈ 6 (see equation on Figure 4.1). This relatively high Weibull Modulus value points to a low sample-to-sample variation. Studies by Vishnu Vardhini and Murugan [105] have also reported a low sample-to-sample variation in *Musa paradisiac* banana fibre diameters. In their study, Vishnu Vardhini and Murugan [105] attributed this low variation to the fibre decortication method employed and to the fact that all the banana fibres were harvested from the same part of the banana pseudostem. More so, the difference in diameter between untreated and chemically surface-modified lignocellulosic fibres has been shown by Spinacé et al. [111] to be statistically insignificant.

In another study, Barasa [109] has also shown the effect that extraction and brushing variables have on the properties of hedge-sisal fibres. The low variation in fibre diameter

reported in the current study could well be attributed to the fact that all the banana fibres used were grown within the same environment, under the same annual amount of rainfall, harvested at the same age using the same decortication method corroborating the findings of Vishnu Vardhini and Murugan [105], Barasa *et al.* [109], and reports from several previous studies [107, 108, 112–114]. Also, previous studies into the diameter of banana fibres have not employed the Weibull CDF to quantify the degree to which the diameters vary from sample-to-sample.

4.1.2 Banana Fibre Density

Appendix A (Table A2) is a table showing the density test results obtained for Giant Cavendish banana fibres in the current study. The table shows the number of bunched banana fibres, bunch mass, bunch volume and the calculated fibre bunch density.

The average density of Giant Cavendish banana fibres was calculated using the linear density and diameter calculation method following Soykeabkaew [75] and was found to be 1.35 gcm^{-3} (standard error $\pm$ 0.009 gcm^{-3}). Venkanteshwaran *et al.* [115] also report a density of 1.35 gcm^{-3} for banana fibres without specifying the cultivar from which the banana fibres were harvested from. The results of the current study are lower than the 1.36 gcm^{-3} density given by Aseer *et al.* [104]. Paramasivam [116] report a Giant Cavendish (Grand Naine) banana fibre density value of 1.26 gcm^{-3}. Banana fibre physical and chemical properties are dependent on plant genetics, plant age as well as the growth environment [27, 109, 117]. The results reported in the current study are consistent with the banana fibre density range reported in literature [104, 105, 109, 115].

4.1.3 Banana Fibre Tensile Strength

4.1.3.1 $KMnO_4$ and NaOH Concentrations for Banana Fibre-Surface Modification.

The optimum NaOH and $KMnO_4$ concentrations for the surface-modification of banana fibres were determined by tensile testing fibres subjected to different concentrations of the hydroxide and permanganate solutions. This was done on the Hounsfield (Type W) tensometer. The fracture stresses determined during these tests are presented in Appendix A, Tables A3-A9. A summary of the results from these tests is presented in Table 4.1 and Table 4.2.

Table 4. 1: Fracture stress results of untreated and surface-modified banana fibres.

Fracture Stress	
Untreated banana fibres ⟶ 126.16 MNm^{-2} + 9.66 MNm^{-2}	
$KMnO_4$ treated banana fibres	**NaOH** treated banana fibres
(0.0006M) 130.31 MNm^{-2} (± 12.09 MNm^{-2})	**(0.02M)** 160.42 MNm^{-2} (± 19.24 MNm^{-2})
(0.003M) 209.32 MNm^{-2} (± 232.62 MNm^{-2})	**(0.06M)** 162.23 MNm^{-2} (± 87.98 MNm^{-2})
(0.006M) 1910.72 MNm^{-2} (± 17.40 MNm^{-2})	**(0.1M)** 110.41 MNm^{-2} (± 12.12 MNm^{-2})
Legend: ± → standard error	

Table 4. 2: Young's Modulus results of untreated and surface-modified banana fibres.

Young's Modulus	
Untreated banana fibres ⟶ 1.9164 GNm^{-2} + 0.33 GNm^{-2}	
$KMnO_4$ treated banana fibres	**NaOH** treated banana fibres
(0.0006M) 1.431 GNm^{-2} (± 0.330 GNm^{-2})	**(0.02M)** 1.7814 GNm^{-2} (± 1.451 GNm^{-2})
(0.003M) 1.739 GNm^{-2} (± 0.334 GNm^{-2})	**(0.06M)** 2.096 GNm^{-2} (± 0.481 GNm^{-2})
(0.006M) 1.572 GNm^{-2} (± 0.290 GNm^{-2})	**(0.1M)** 1.656 GNm^{-2} (± 0.378GNm^{-2})
Legend: ± → standard error	

From these results, the highest concentrations $KMnO_4$ and NaOH concentrations for the surface-modification of Giant Cavendish banana fibres were determined to be 0.003M and 0.6M respectively. A 0.003M $KMnO_4$ concentration has been shown to be optimal in the surface-treatment of oil palm fibres by Sreekala *et al.* [57]. Oil palm fibres have a chemical constituent profile comparable to banana fibres (see Table 4.3).

Table 4. 3: Chemical properties of selected natural fibres.

Fibre	**Cellulose (%)**	**Lignin (%)**	**Hemicellulose (%)**	**Pectin (%)**	**Ash (%)**	**Reference**
Banana	72.03 69.53	7.27 17.83	- 5.1	- -	1.16 1.54	[104] [105]
Sisal	67.0-78.0	8.0-11.0	10.0-14.2	-	-	[114]
Henequen	77.6	13.1	4.0-8.0	-	-	[118]
Hemp	70.2-74.4	3.7-5.7	17.9-22.4	-	-	[114]
Ramie	68.6-76.2	0.6-0.7	13.1-16.7	1.9	-	[118]
Oil palm fibre	65	19	-	-	2	[57]

A NaOH concentration of 0.06M has also been shown by Mwaikambo and Ansell [6] to be optimal in the surface-modification of sisal fibres. Zin *et al.* [1] have researched and also recommended a 0.06M NaOH concentration to be the optimal in the surface modification of banana fibres.

4.1.3.2 Untreated and Surface-Modified Banana Fibre Tensile Strength

Appendix A (Tables A3, A5 and A8) shows the tensile test results for untreated and surface-modified Giant Cavendish banana fibres. The table shows the calculated engineering stress, engineering fracture strain and the calculated Young's Modulus for the untreated and surface-modified banana fibres. A summary of these results are presented in Table 4.4.

Table 4. 4: Average strength test results for untreated and surface-modified banana fibres.

Fibres	**Mean Fracture Stress (MNm^{-2})**	**Mean Fracture Strain**	**Mean Young's Modulus (GNm^{-2})**
Untreated	126.16 $\pm$ 9.66	0.08 $\pm$ 0.003	1.6 $\pm$ 0.06
(0.06M) Mercerized	162.23 $\pm$ 7.98	0.08 $\pm$ 0.02	2.1 $\pm$ 0.09
(0.003M) $KMnO_4$ treated	209.32 $\pm$ 22.62	0.13 $\pm$ 0.009	1.74 $\pm$ 0.08
Legend: $\pm$ → standard error			

The untreated Giant Cavendish banana fibres had a mean fracture stress value of 126.16 MNm^{-2} (standard error $\pm$ 9.66 MNm^{-2}). This result is lower than that reported by Latif *et al.* [119] of 721 MNm^{-2}, by Idicula *et al.* [120] of 550 MNm^{-2} and by Zin *et al.* [1] of 212 MNm^{-2}. It is however, important to note that the results reported by Zin *et al.* [1], Latif *et al.* [119] and Idicula *et al.* [120] are based on the single-fibre strand tensile test. Kiruthika and Veluraja [99] and Hassan *et al.* [100] have both reported a disparity between single-fibre strand tests and fibre bunching tensile test results.

In their study of oil palm empty fruit bunch fibres' Hassan et al [100] reported a decrease in fibre fracture stress when the fibres are tested as a fibre bunch as opposed to when tested as a single strand. Nasri *et al.* [121] have also reported a lower tensile fracture stress value for twisted oil palm fibre bunches compared to single oil palm fibre strands. Kiruthika and Veluraja [99] reported a similar result for untreated and tamarind seed gum coated sisal

and coir fibres. The single fibre strand method coupled with actual cross-sectional area determination using a scanning electron microscope, gives results that are higher than those of the fibre bunching method. Denise *et al.* [98] has shown that this disparity is largely due to the fibre-to-fibre diametric variation that exists in lignocellulosic plant fibres. Jouannuot-Chesney [122] similarly reported an inverse proportionality relationship between lignocellulosic fibre tensile Modulus and the fibre diameter. This in-turn means that due to the natural taper that exists in natural fibres, fibres from the tip and mid-span sections of the fibre strand are stronger than fibres from the butt-end. This taper is due to the presence of undifferentiated cells where much of the cell-division and growth takes place. This region of undifferentiated cells has been shown by Hassan *et al.* [100] to be predominantly porous and thus a larger fibre diameter corresponds to a fibre structure that is filled with voids hence lower tensile strength properties.

In the current study, the number of banana fibre strands in a test sample was limited to 60 strands. The fibre bunching tensile test results are important since they give the researcher an indication of the collective mechanical properties of fibres when embedded in a matrix [99].

Using untreated fibres as standard control, 0.003M $KMnO_4$ surface-modified Giant Cavendish banana fibres recorded a gain of 65.92% in tensile strength. Sreekala *et al.* [57] reports a 16.53% reduction in the tensile strength of 0.003M $KMnO_4$ treated Oil palm fibres. In the current study, a 0.01M acetone solution was employed to rinse off and neutralize any excess $KMnO_4$ while in the study by Sreekala *et al.* [57], distilled water was used to rinse the $KMnO_4$ treated fibres.

$KMnO_4$ fibre surface-modification is a rapid reaction and it is necessary to neutralize any excess permanganate before commencing the tensile test. This is to prevent overtreatment and subsequent weakening of the fibres. The study conducted by Sreekala *et al.* [57] did not report using acetone as a neutralizing agent.

The 0.06M NaOH treated banana fibres on the other hand, recorded a 28.60% gain in fracture stress with the untreated fibres as standard control. This is lower than the 0.003M $KMnO_4$ surface-modified banana fibres. Rajamanickam [117] reports a 170.12 MNm^{-2} fracture stress value for 5% NaOH treated banana fibres. In their study, Rajamanickam employed a 2.5% HCL acid solution to neutralize residual NaOH while in the current study, a 0.01M CH_3COOH glacial acetic acid solution was used to achieve the same. Zin *et al.* [1] reports a 75% increase in tensile strength of 0.06M NaOH treated banana fibres. However in their study, Zin *et al.* [1] fail to disclose the species of banana from which the fibres were harvested, citing a confidentiality agreement with the research funding authority.

The 0.003M $KMnO_4$ surface-modified banana fibres recorded the highest fracture strain value of 12.67%$\pm$ 0.9% compared to the untreated (8.15%$\pm$ 0.3%) and 0.06M NaOH treated (7.98% $\pm$ 1.5%) fibres. This points to a substantial (and possibly damaging change) in the fibre microfibilar structure. The failure mechanism of lignocellulosic fibres has been shown by Rajesh *et al.* [123] to be as a result of the uncoiling of the microfibrils and tearing of the cell walls. As a result of this, the failure mode of a lignocellulosic fibre is catastrophic with no observable plastic deformation [124]. This could potentially explain the large untreated and surface-modified fibre strains observed in this study.

From Table 4.4, it can be seen that following surface-modification, the mean fracture stress of both 0.003M $KMnO_4$ and 0.06M NaOH treated banana fibres increased compared to the untreated fibres. This result has also been reported by Zin *et al.* [1] following a 0.06M NaOH surface modification of banana fibres. Subramanya *et al.* [125] reports similar results following a 10% NaOH treatment of banana fibres. In their study, Subramanya *et al.* [125] attribute this to the presence of waxes and lignin on the surface of the untreated fibres which serve as ductile phases during tensile loading of the fibres. This is a desirable result since for

effective fibre reinforcement of a matrix using fibres, the tensile Modulus of the fibres should be much higher than that of the matrix i.e. ($E_f >> E_m$) [126].

The Weibull Modulus of the untreated and surface-modified banana fibres was determined using equation 3.18. Figure 4.2 is a graphical representation of the Weibull results.

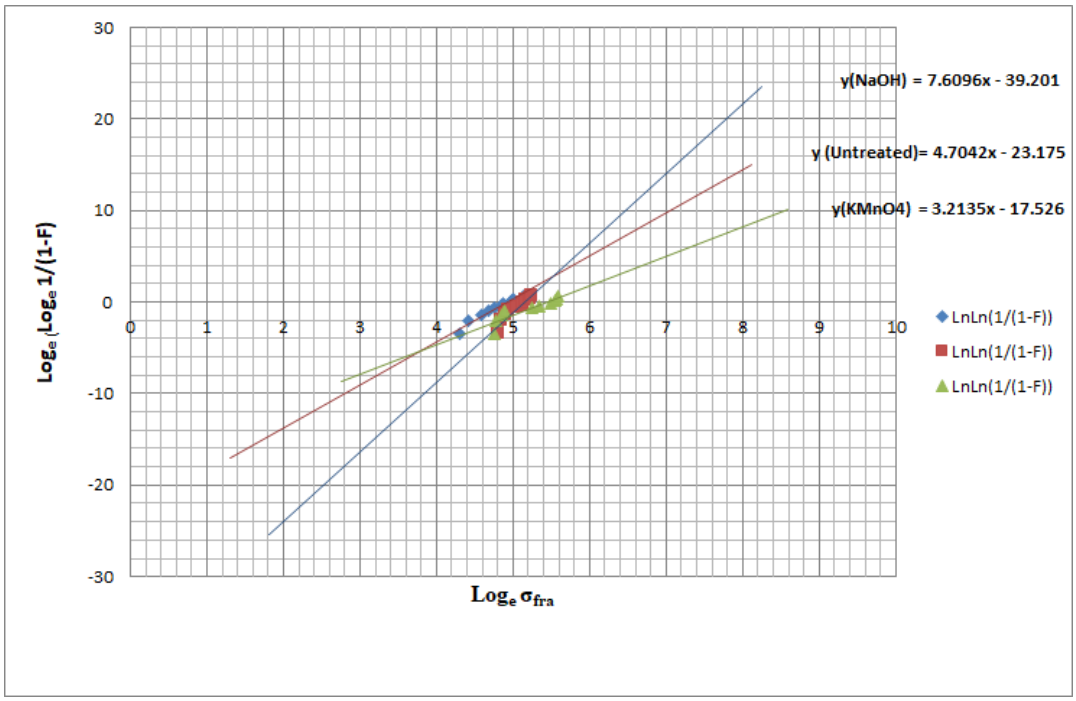

Figure 4. 2: Weibull plot for untreated and surface-modified banana fibres (with plot lines extended for clarity)

Observing the gradients of the three plot lines (gradient = Weibull Modulus), mercerised Giant Cavendish banana fibres recorded a Weibull Modulus of 7.61. A higher Weibull modulus translates to a lower fibre to fibre variation in strength properties. This in turn, makes the fibres more reliable than the untreated fibres (Weibull Modulus 4.704) and 0.003M $KMnO_4$ treated fibres (Weibull Modulus 3.214). The potassium permanganate treated banana fibres in spite having a higher tensile strength value than the untreated and mercerised fibres, had the lowest Weibull Modulus. The reliability of a component is defined as its capability to withstand applied stress [82]. By having the lowest Weibull Modulus, the fibres

failed over a wider range of stresses than in both the untreated and NaOH treated banana fibres. This result means that although the $KMnO_4$ treated fibres were stronger, they were least reliable and prone to premature failure at stresses below the fibres mean fracture stress when subjected to a tensile test.

A low Weibull Modulus value has similarly been reported by Kithiia *et al.* [91] following heat treatment of UG-grade Kenyan sisal fibres. In the study by Kithiia *et al.* [91] it was argued that this could be as a result of worsening of existing surface flaws or introduction of new flaws into the fibre structure. Damage to lignocellulosic fibre (Kenaf) following a high NaOH concentration treatment of Kenaf fibres has also been reported by Asumani *et al.* [127]. This explanation could explain the similar phenomenon reported in the current study after the 0.003M $KMnO_4$ banana fibre surface-modification.

Another way of measuring the reliability of the untreated, $KMnO_4$ and NaOH treated fibres is by calculating the reference stress σ_0 from the Y-intercept of the equations displayed in Figure 4.2. The reference stress is the stress by which 63.2% of the specimen tested had failed during the tensile test. The reference stress for untreated, $KMnO_4$ and NaOH treated Giant Cavendish banana fibres was found to equal 137.99 MNm^{-2}, 233.66 MNm^{-2} and 172.69 MNm^{-2} respectively. By considering the stress range between the mean fracture stress and the reference stress, it is evident that 0.003M $KMnO_4$ surface-modified banana fibres failed over a wider stress range than both the untreated and the 0.06M NaOH treated banana fibres. This means that the 0.003M $KMnO_4$ surface-modified fibres were less reliable given that fibre failure could occur over a wider stress range.

It can thus be concluded that with untreated Giant Cavendish banana fibres as standard control, potassium permanganate-treated banana fibres recorded the greatest gain in strength

properties. However, 0.06M NaOH treated recorded the highest Weibull Modulus and were thus found to be more reliable.

4.2 Banana Fibre Reinforced Epoxy Resin

The following results were obtained from **experimental procedure II.**

4.2.1 Tensile Strength Results

Appendix B (Tables B1, B3 and B5) displays the results for the fracture stress and fracture strain for untreated, 0.003M $KMnO_4$ and 0.06M NaOH surface-modified banana fibre reinforced epoxy resin. The tables show the embedded fibre volume fraction, ultimate load and fracture stress of the banana fibre-reinforced epoxy composite. The analysis of variance (ANOVA) is also included in Appendix B (Tables B2, B4 and B6). The test was conducted at a fibre aspect ratio (*l/d*) of 874.09. Figure 4.3 shows superimposed line graphs of these results for comparison.

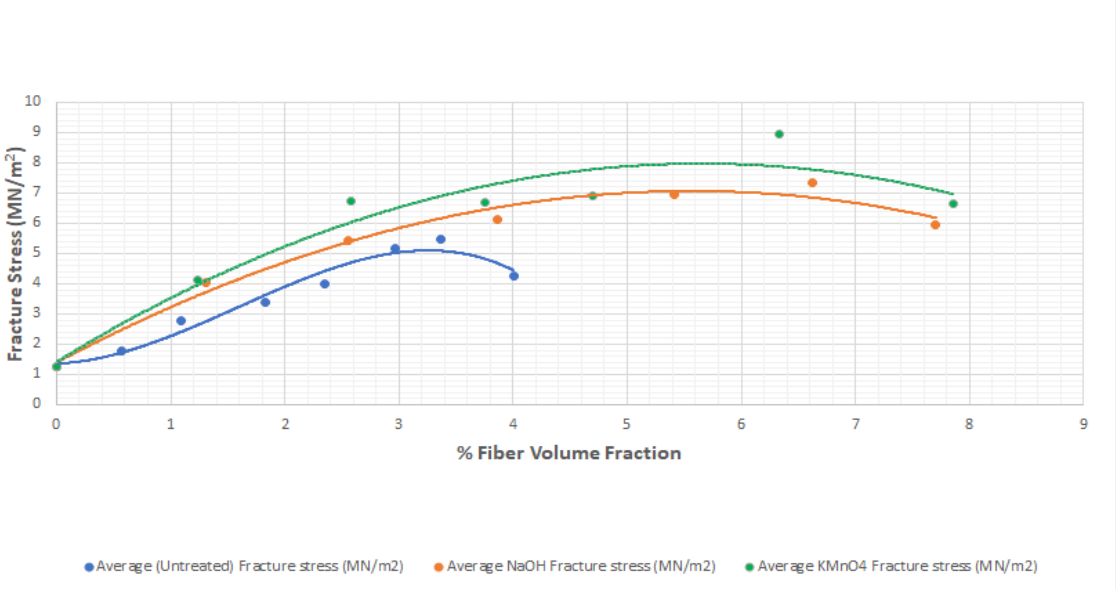

Figure 4. 3: Tensile test results for untreated and surface-modified banana fibre reinforced epoxy resin

The neat epoxy resin had a mean tensile strength value of ≈ 1.3 MNm^{-2} (with an average Young's Modulus of 7.37 MNm^{-2} (± 1.2 MNm^{-2})). The epoxy resin used in the current study had mechanical properties that were very similar to the epoxy resin used by *Saw et al.* [128] in

their experimental analysis of Luffa fibre-reinforced epoxy resin composites. A quick comparison between the Young's Modulus of the untreated, 0.003M $KMnO_4$ treated and 0.06M NaOH treated fibres (1.916 GNm^{-2}, 1.739 GNm^{-2} and 2.096 GNm^{-2} respectively) shows that the Young's Modulus of the fibres was much greater than that of the matrix (7.37 MNm^{-2}). i.e. $E_f >> E_m$. This is an important condition that has to be met if at all the fibre reinforcement is to provide any reinforcement to the matrix (see equation 2.9). With an exception of the untreated fibre reinforced epoxy resin, that exhibited a drop in tensile strength between 0-1% V_f, a trend of increasing tensile strength with increasing banana fibre volume fraction was observed in the surface-modified banana fibre reinforced epoxy resin. This initial drop was attributed to the general difficulty in obtaining proper fibre orientation at low fibre volume fractions. 0.003M $KMnO_4$ treated banana fibre reinforced epoxy resin recorded the greatest gain in tensile strength with maximum fracture stress value of 7.42 MNm^{-2} at a fibre volume fraction of 5.4%. This in turn translated to a 470.77% gain in tensile strength compared to the unreinforced specimen. 0.06M NaOH treated banana fibre-reinforced epoxy resin on the other hand, recorded a maximum tensile strength value of 7.07 MNm^{-2} at a fibre volume fraction of 5.5%. This translated to a 443.85% gain in tensile strength compared to the neat epoxy specimens.

Untreated banana fibre-reinforced epoxy resin had a maximum tensile strength value of 5.10 MNm^{-2} at a fibre volume fraction of 3.3%. This represented a 292.31% gain in tensile strength compared to the neat epoxy specimens. Santhosh *et al.* [129] reports a mean tensile strength value of 6.19 MNm^{-2} for untreated banana fibre reinforced epoxy resin. Bharadiya *et al.* [130] reports a 175% gain in tensile strength of untreated banana fibre-reinforced graphene oxide cetyltrimethylammonium epoxy resin.

In their study, Bharadiya [130] harvested the banana fibres via retting while in the current study, decortication was used as the method of fibre extraction. Following NaOH fibre

surface-treatment, a 253.57% increase in interfacial bond strength between banana fibre and epoxy matrix has been reported by Zin *et al.* [1] in their study titled 'the effects of alkali treatment on the mechanical and chemical properties of banana fibre adhesion to epoxy resin.' Zin *et al.* [1] in their study, as is the case in the current study, used a 0.06M NaOH solution to treat the banana fibres prior to incorporation in the epoxy resin matrix. An improvement in interfacial bond strength following a 10% NaOH banana fibre surface modification has also been observed by Subramanya *et al.* [125] using a scanning electron microscope on banana fibre reinforced epoxy resin.

The Rule of Mixtures (eq. 2.9) predicts the fibre reinforced composite strength properties. By comparing the tensile strength values predicted by the rule of mixtures with the results of the current study, the following 3 graphs for the untreated, 0.003M $KMnO_4$ and 0.06M NaOH treated banana fibre-reinforced epoxy resin (Tables 4.4-4.6).

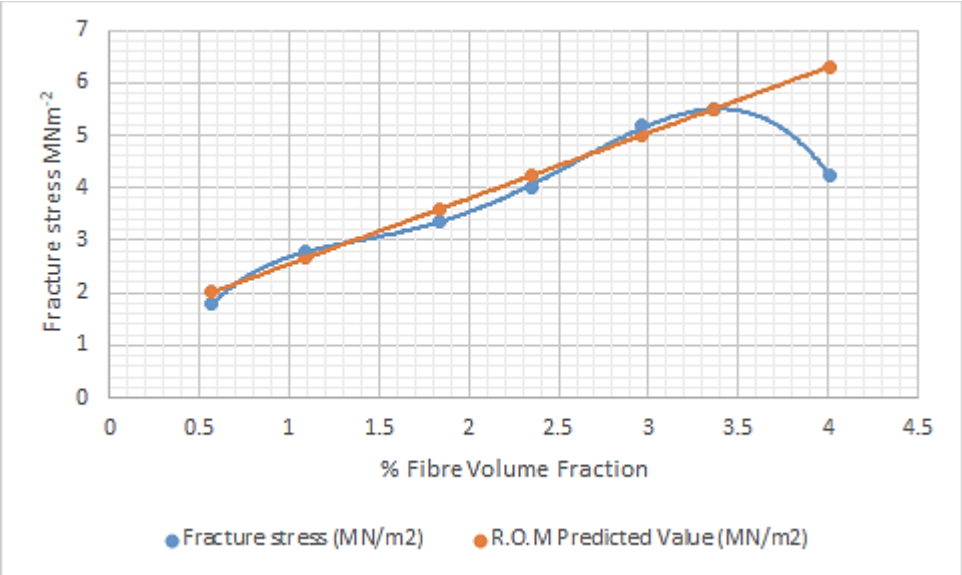

Figure 4. 4: Graph comparing the fracture stress of untreated banana-epoxy composite vs Rule of Mixtures prediction

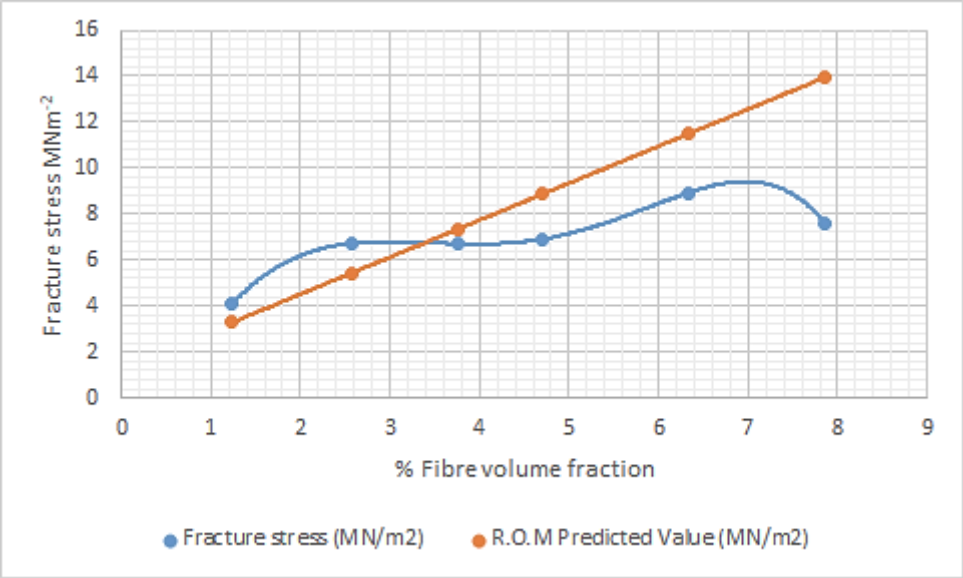

Figure 4. 5: Graph comparing the fracture stress of 0.003M $KMnO_4$ treated banana-epoxy composite vs Rule of Mixtures prediction

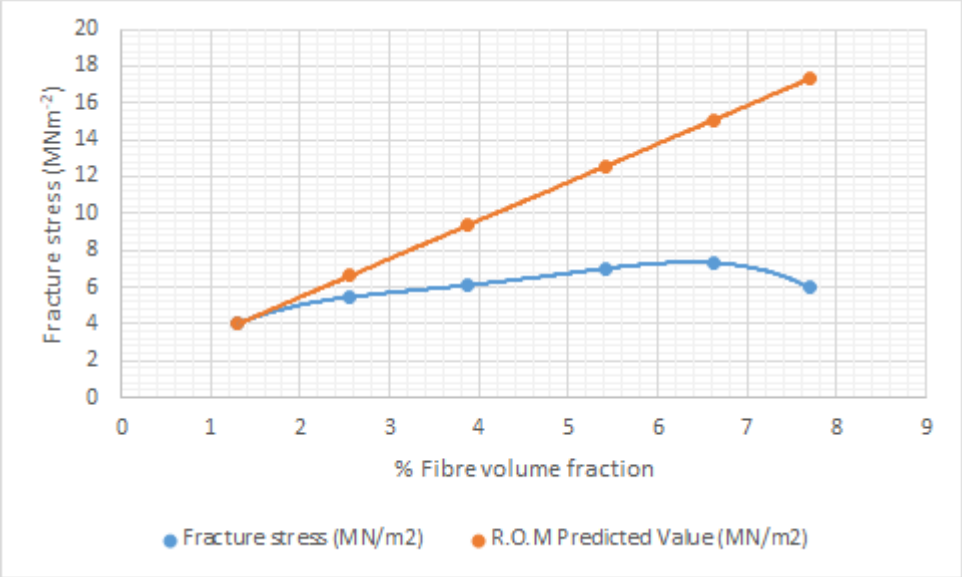

Figure 4. 6: Graph comparing the fracture stress of 0.06M NaOH treated banana-epoxy composite vs Rule of Mixtures prediction

The graphs (Fig 4.4-4.6) compare the fibre fracture stress with the predicted Rule of Mixtures fracture stress for untreated, 0.06M NaOH, and 0.003M $KMnO_4$ treated banana fibre reinforced epoxy resin respectively. From the graphs, it can be seen that the untreated banana fibre reinforced epoxy resin composite followed the Rule of Mixtures better than the surface

modified banana fibre reinforced composite. This can also be inferred from the Weibull modulus of the fibres where untreated banana fibres recorded a Weibull modulus of 4.704. 0.06M NaOH treated banana fibre reinforced epoxy resin had a Weibull modulus of 7.6096 and by comparing the composite fracture stress with that predicted by the rule of mixtures, it can be seen from Figure 4.5 that the composite more or less obeyed the Rule of Mixtures up to a fibre volume fraction of 3.4%. Beyond this fibre volume fraction, drop in strength can be attributed to the formation of voids within the composite, rendering the fibre reinforcement less effective. The 0.003M $KMnO_4$ treated banana fibre reinforced epoxy resin fracture stress results are compared against the values predicted by the Rule of Mixtures in Figure 4.6. The clear deviation of the composite fracture stresses from those predicted by the Rule of Mixtures can be expected from the low Weibull Modulus of the treated fibres (3.2135). The Weibull Modulus can thus be used to predict the behaviour of banana fibres in a composite with a higher modulus translating to a better correlation to the Rule of Mixtures predicted values.

4.2.2 Flexural Strength Results

The flexural test results for untreated and surface-modified continuous banana fibre reinforced epoxy resin composites are displayed in Appendix B (Tables B7, B9 and B10). The tables show the embedded fibre volume fraction, the specimen cross-sectional dimensions, ultimate load and Modulus of Rupture (MOR). The analysis of variance (ANOVA) is also included in Appendix B (Tables B8, B10 and B12). The tests were all conducted at a fibre aspect ratio (l/d) of 1638.92. Figure 4.7 shows superimposed line graphs of these results for comparison purposes.

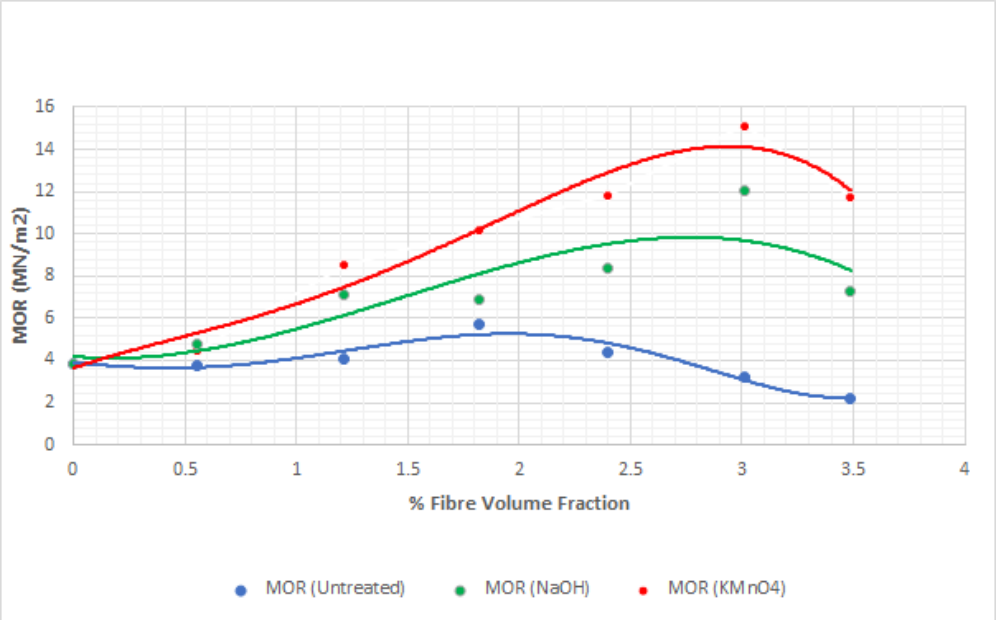

Figure 4. 7: Flexural test results for untreated and surface-modified banana fibre reinforced epoxy resin

The neat epoxy resin had a flexural strength value of ≈ 3.97 MNm^{-2} and a trend of increasing flexural strength with increasing banana fibre volume fraction was observed in both the untreated and surface-modified banana fibre reinforced epoxy resin. The observed trend of an increase in the MOR with increasing fibre volume fraction is an indication that the fibre length employed in the current study is greater than the fibre's critical fibre length. The critical fibre length is the fibre reinforcement length at which a complete load transfer from the matrix to the fibre reinforcement takes place [131].

0.003M $KMnO_4$ treated banana fibre-reinforced epoxy resin recorded the greatest gain in flexural strength with a maximum MOR of 14.15 MNm^{-2} at a fibre volume fraction of 2.9%. This translated to a 256.42% increase in flexural strength compared to the neat epoxy resin specimens. 0.06M NaOH treated banana fibre-reinforced epoxy resin had a maximum MOR of 9.83 MNm^{-2} at a fibre volume fraction of 2.8%. This in turn, translated to a 147.61% gain in flexural strength compared to the unreinforced specimens.

Untreated banana fibre reinforced epoxy resin had a maximum MOR value of 5.26 MNm^{-2} at a fibre volume fraction of 2%. This was a 32.49% gain in flexural strength compared to the neat epoxy specimens.

In a polymeric composite, the MOR is a combination of both the tensile and compressive strength of the specimen and is dependent on the interfacial bond strength of between the fibre reinforcement and the matrix [129, 132, 133]. The higher MOR recorded in both 0.06M NaOH and 0.003M $KMnO_4$ treated Giant Cavendish banana fibres can thus be attributed to better interfacial bonding between surface-modified banana fibres and the epoxy resin. At increasingly higher fibre volume fractions (≥3%), there is inefficient wetting of the fibres by the matrix and consequently, formation of voids/bubbles within the composite. This results in a reduction of interfacial adhesion, weakening of the composite and thus the observed reduction in the Modulus of rupture. This phenomenon has similarly been reported by Ngala [64], Mutuli [134] and Kithiia *et al.* [135] in sisal fibre reinforced cementitious and polymeric matrices. Karthick *et al.* [136] and Gairola *et al.* [137] have similarly reported this observation for banana fibre-reinforced epoxy resin composites. The results of the current study are in agreement with the findings reported by Zin *et al.* [1] on the interfacial bond strength of surface-modified banana fibres embedded in an epoxy resin matrix.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The following conclusions were made from this study:

1) The tensile strength of untreated and surface-modified Giant Cavendish banana fibres was determined and found to be 126.16 MNm^{-2}, 162.23 MNm^{-2} (0.06M NaOH treated) and 209.32 MNm^{-2} (0.003M $KMnO_4$ treated).
2) The 0.003M potassium permanganate ($KMnO_4$) treated banana fibres in spite having a higher tensile strength value than the untreated and (0.06M NaOH) mercerised fibres, had the lowest Weibull Modulus. This result means that although the $KMnO_4$ treated fibres were stronger, they were least reliable and prone to premature failure when subjected to a tensile load.
3) $KMnO_4$ surface-modified banana fibre-reinforced epoxy resin recorded the greatest gain in tensile strength of 7.42 MNm^{-2} (↑470.77%) compared to the mercerised banana fibre-reinforced epoxy of 7.07 MNm^{-2} (↑443.85%) and untreated banana fibre-reinforced epoxy specimens of 5.10 MNm^{-2} (↑292.31%)
4) $KMnO_4$ surface-modified banana fibre-reinforced epoxy resin recorded the greatest gain in flexural strength with a MOR of 14.15 MNm^{-2} (↑256.42%) compared to the mercerised banana fibre-reinforced specimens MOR of 9.83 MNm^{-2} (↑147.61%) and untreated banana fibre-reinforced specimens MOR of 5.26 MNm^{-2} (↑32.49%).

5.2 Recommendations

The following are recommendations for future study:

1) In the current study, the density of Giant Cavendish banana fibres was determined using the linear density and diameter method [75]. A more precise density determination method needs to be employed to determine whether the surface-modification had any significant effect on the density of the fibres.
2) The effect of reaction time on the Weibull Modulus of 0.003M $KMnO_4$ treated Giant Cavendish banana fibres needs further investigation.
3) The reinforcing effect of a hybrid blend consisting of both discontinuous, randomly oriented untreated and surface-modified banana fibre reinforcements in an epoxy matrix needs to be studied. There is a likelihood of better reinforcement in the 'blended' composite as has been shown by Idicula *et al.* [120] in their study of short banana/sisal fibre reinforced polyester composites.
4) The reinforcing effect of untreated and surface-modified Giant Cavendish banana fibres in hydrophilic matrices such as cement paste and mortar needs to be investigated.
5) Fibre surface-modification via 0.006M NaOH treatment resulted in fibres with improved tensile strength and the highest Weibull Modulus. These fibres are thus more reliable and are recommended for use as reinforcement in epoxy resin matrices.

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APPENDIX A – GIANT CAVENDISH BANANA FIBRE

Table A1: Giant Cavendish Banana Fibre Diameter Readings and Weibull Analysis

RANK	DIAMETER READINGS	F VALUE	Ln(1/(1-F))	X VALUE	Y VALUE	
1	116.27	0.01	0.010050336	4.755915	-4.60015	
2	124.73	0.03	0.030459207	4.826151	-3.49137	
3	128.85	0.05	0.051293294	4.858649	-2.9702	
4	130.82	0.07	0.072570693	4.873822	-2.62319	
5	132.8	0.09	0.094310679	4.888844	-2.36116	
6	133.01	0.11	0.116533816	4.890424	-2.14957	
7	136.29	0.13	0.139262067	4.914785	-1.9714	
8	136.82	0.15	0.162518929	4.918666	-1.81696	
9	142.43	0.17	0.186329578	4.958851	-1.68024	
10	142.58	0.19	0.210721031	4.959903	-1.55722	
11	143.52	0.21	0.235722334	4.966474	-1.4451	
12	143.97	0.23	0.261364764	4.969605	-1.34184	
13	148.42	0.25	0.287682072	5.000046	-1.2459	
14	149.64	0.27	0.314710745	5.008232	-1.1561	
15	152.14	0.29	0.342490309	5.024801	-1.07151	
16	157.94	0.31	0.371063681	5.062215	-0.99138	
17	158.76	0.33	0.400477567	5.067394	-0.9151	
18	163.15	0.35	0.430782916	5.09467	-0.84215	
19	164.54	0.37	0.46203546	5.103154	-0.77211	
20	181.83	0.39	0.494296322	5.203072	-0.70462	
21	183.02	0.41	0.527632742	5.209595	-0.63935	
22	185.76	0.43	0.562118918	5.224456	-0.57604	
23	188.75	0.45	0.597837001	5.240423	-0.51444	
24	190.67	0.47	0.634878272	5.250544	-0.45432	
25	193.42	0.49	0.673344553	5.264864	-0.3955	
26	194.09	0.51	0.713349888	5.268322	-0.33778	
27	194.72	0.53	0.755022584	5.271563	-0.28101	
28	195.47	0.55	0.798507696	5.275407	-0.22501	
29	196.51	0.57	0.84397007	5.280713	-0.16964	
30	199.32	0.59	0.891598119	5.294912	-0.11474	
31	199.89	0.61	0.94160854	5.297767	-0.06017	
32	200.79	0.63	0.994252273	5.30226	-0.00576	
33	205.42	0.65	1.049822124	5.325057	0.048621	
34	205.95	0.67	1.108662625	5.327633	0.103154	
35	207.5	0.69	1.171182982	5.335131	0.158014	
36	208.64	0.71	1.237874356	5.34061	0.213396	
37	208.71	0.73	1.30933332	5.340946	0.269518	
38	210.78	0.75	1.386294361	5.350815	0.326634	
39	211.24	0.77	1.46967597	5.352995	0.385042	
40	211.36	0.79	1.560647748	5.353563	0.445101	
41	212.48	0.81	1.660731207	5.358848	0.507258	
42	218.96	0.83	1.771956842	5.388889	0.572084	
43	220.75	0.85	1.897119985	5.397031	0.640337	
44	226.19	0.87	2.040220829	5.421375	0.713058	
45	227.29	0.89	2.207274913	5.426227	0.791759	
46	227.31	0.91	2.407945609	5.426315	0.878774	
47	227.97	0.93	2.659260037	5.429214	0.978048	
48	233.17	0.95	2.995732274	5.451768	1.097189	
49	234.3	0.97	3.506557897	5.456602	1.254635	
50	235.11	0.99	4.605170186	5.460053	1.52718	
Reference Diameter Do	Shape Parameter (m)	Mean	Variance	Standard Deviation		Standard Error
197.332674	5.9865	183.0465	1263.324213	35.54327		5.026577788

Table A2: Giant Cavendish Banana Fibre Density Data

Weight of Fibre Bunch (gm)	Vol. of Fibres (cm^{-3})	Calculated Density (g/cm^{-3})
0.347	0.263157113	1.31860392
0.352	0.263157113	1.337603976
0.3551	0.263157113	1.349384011
0.3607	0.263157113	1.370664074
0.3491	0.263157113	1.326583943
0.3574	0.263157113	1.358124037
0.3708	0.263157113	1.409044188
0.3468	0.263157113	1.317843917
0.3539	0.263157113	1.344823997
0.3591	0.263157113	1.364584056
	MEAN	**1.349726012**
	STDEV	**0.027768958**
	STD ERROR	**0.008781316**

Table A3: Untreated Giant Cavendish Banana Fibre Fracture Stress Results

No of Fibre strands	Cross sectional area	Breaking load	Fracture stress (MN/m2)	Fracture strain	Young's Modulus (GN/m2)
60	1.57894268	201.724	127.7589127	0.0607955	2.101453441
60	1.57894268	117.241	74.25285381	0.06590909	1.126595039
60	1.57894268	168.966	107.0121178	0.0534091	2.0036308
60	1.57894268	232.759	147.4144711	0.05795455	2.543622046
60	1.57894268	201.724	127.7589127	0.0607955	2.101453441
60	1.57894268	131.035	82.98907976	0.0636364	1.304113365
60	1.57894268	231.035	146.3226011	0.0818182	1.78838695
60	1.57894268	182.759	115.7477104	0.052272727	2.214304036
60	1.57894268	155.172	98.27589181	0.060227273	1.631750657
60	1.57894268	265.517	168.161266	0.07159091	2.348919241

Table A4: 0.02M NaOH treated Giant Cavendish Banana Fibre Fracture Stress Results

No of Fibre strands	Cross sectional area (x10^-6)m2	Breaking load (N)	Fracture stress (MN/m2)	Fracture strain	Young's Modulus (GN/m2)
60	1.57894268	232.759	147.4144711	0.09545455	1.544342004
60	1.57894268	341.379	216.207342	0.09318182	2.320273869
60	1.57894268	182.759	115.7477104	0.11364	1.018547258
60	1.57894268	431.035	272.9896439	0.05	5.459792879
60	1.57894268	151.724	96.092152	0.1091	0.880771329
60	1.57894268	289.655	183.4487114	0.12273	1.494734062
60	1.57894268	279.31	176.8968586	0.1273	1.389606116
60	1.57894268	200	126.6670428	0.13409	0.944641978
60	1.57894268	172.413	109.1952242	0.111364	0.980525342

Table A5: 0.06M NaOH treated Giant Cavendish Banana Fibre Fracture Stress Results

No of Fibre strands	Cross sectional area (x10^-6)m2	Breaking load (N)	Fracture stress (MN/m2)	Fracture strain	Young's Modulus (GN/m2)
60	1.57894268	193.104	122.2995631	0.06136	1.99314803
60	1.57894268	293.104	185.6330845	0.1	1.856330845
60	1.57894268	203.448	128.8507826	0.05455	2.362067509
60	1.57894268	275.862	174.7131188	0.09091	1.921825088
60	1.57894268	268.966	170.3456391	0.0727273	2.34225166
60	1.57894268	213.793	135.4026354	0.056818	2.383094009
60	1.57894268	300	190.0005642	0.0727	2.613487815
60	1.57894268	220.69	139.7707484	0.13864	1.008156004
60	1.57894268	265.517	168.161266	0.07046	2.386620295

Table A6: 0.1M NaOH treated Giant Cavendish Banana Fibre Fracture Stress Results

No of Fibre strands	Cross sectional area (x10^-6)m2	Breaking load (N)	Fracture stress (MN/m2)	Fracture strain	Young's Modulus (GN/m2)
60	1.57894268	303.448	192.184304	0.1273	1.509696025
60	1.57894268	172.414	109.1958576	0.06136	1.779593507
60	1.57894268	162.069	102.6440048	0.084091	1.220630089
60	1.57894268	103.448	65.51726121	0.05227	1.25343909
60	1.57894268	175.862	111.3795974	0.04773	2.33353441
60	1.57894268	168.966	107.0121178	0.061364	1.743890844
60	1.57894268	124.138	78.62096679	0.04091	1.921803148
60	1.57894268	210.345	133.2188956	0.070455	1.890836641
60	1.57894268	148.276	93.90841218	0.075	1.252112162

Table A7: 0.0006M $KMnO_4$ treated Giant Cavendish Banana Fibre Fracture Stress Results

No of Fibre strands	Cross sectional area (x10^-6)m2	Breaking load (N)	Fracture stress (MN/m2)	Fracture strain	Young's Modulus (GN/m2)
60	1.57894268	134.483	85.17281957	0.07275	1.170760407
60	1.57894268	172.414	109.1958576	0.1023	1.067408187
60	1.57894268	210.345	133.2188956	0.1	1.332188956
60	1.57894268	210.345	133.2188956	0.0693	1.922350585
60	1.57894268	262.069	165.9775262	0.1216	1.364946761
60	1.57894268	244.828	155.0581938	0.0898	1.726705944

Table A8: 0.003M $KMnO_4$ treated Giant Cavendish Banana Fibre Fracture Stress Results

No of Fibre strands	Cross sectional area (x10^-6)m2	Breaking load (N)	Fracture stress (MN/m2)	Fracture strain	Young's Modulus (GN/m2)
60	1.57894268	406.897	257.7021985	0.1477	1.744767763
60	1.57894268	300	190.0005642	0.1159	1.63934913
60	1.57894268	386.207	244.598493	0.1489	1.642703109
60	1.57894268	421.035	266.6562918	0.1193	2.235174282
60	1.57894268	413.448	261.8511775	0.1352	1.936769065
60	1.57894268	182.069	115.3107091	0.0932	1.237239368

Table A9: 0.006M $KMnO_4$ treated Giant Cavendish Banana Fibre Fracture Stress Results

No of Fibre strands	Cross sectional area (x10^-6)m2	Breaking load (N)	Fracture stress (MN/m2)	Fracture strain	Young's Modulus (GN/m2)
60	1.57894268	268.966	170.3456391	0.1239	1.374863916
60	1.57894268	403.448	255.5178254	0.15	1.703452169
60	1.57894268	324.138	205.2880096	0.1466	1.400327487
60	1.57894268	331.035	209.6561225	0.1443	1.452918382
60	1.57894268	206.897	131.0351558	0.09432	1.389261617
60	1.57894268	272.414	172.529379	0.08182	2.108645551

Table A10: Fracture Stress Weibull (CDF) Analysis – Untreated and Surface-Modified Giant Cavendish Banana Fibres

RANK	Stress(Untreated)	Stress(Merc)	Stress(KMnO4)	X(Untreated)	X(mercerized)	X(KMnO4)	F Value	Ln (1/(1-F))	LnLn(1/(1-F))
1	74.25285381	122.299563	115.3107091	4.307476212	4.806473471	4.747630303	0.029574861	0.030021016	-3.5058576
2	82.98907976	128.850783	117.9547757	4.41870903	4.858655011	4.770301294	0.121996303	0.130104475	-2.0394175
3	98.27589181	135.402635	126.8645273	4.587778746	4.908252824	4.843119803	0.214417745	0.24133011	-1.42158953
4	107.0121178	139.770748	133.4524765	4.672942078	4.940003569	4.893745433	0.306839187	0.366493253	-1.00377517
5	115.7477104	156.869543	190.0005642	4.751412912	5.055414526	5.247027041	0.399260628	0.509594097	-0.67414076
6	127.7589127	168.161266	210.3572325	4.850144993	5.124923436	5.348807193	0.49168207	0.676648181	-0.39060381
7	131.0351558	170.345639	244.598493	4.875465652	5.137829544	5.499618062	0.584103512	0.877318877	-0.13088475
8	146.3226011	174.713119	257.7021985	4.985813781	5.163145308	5.551804649	0.676524954	1.128633305	0.121007436
9	147.4144711	185.633085	261.8511775	4.99324815	5.223772062	5.567776318	0.768946396	1.465105542	0.381927282
10	168.161266	190.000564	266.6562918	5.124923436	5.247027041	5.585960532	0.861367837	1.975931165	0.681039763

	shape(m)	scale(σ_o)	mean	Variance	Stdev
Untreated	4.7042	137.889	126.1585809	933.2874761	30.54975411
Mercerized	7.6096	172.694	162.2332542	636.1066079	25.22115398
KMnO4	3.2135	233.6599	209.3211678	5116.083757	71.52680447

Output Commands:

Fibre mean strength	{=σₒ*EXP((GAMMALN(1+1/m)))}
Variance	{=((σₒ^2)*(EXP(GAMMALN(1+2/m))-EXP(GAMMALN(1+1/m))^2))}
Fibre strength Stdev	{=SQRT((σₒ^2)*(EXP(GAMMALN(1+2/m))-EXP(GAMMALN(1+1/m))^2))}

APPENDIX B – GIANT CAVENDISH BANANA FIBRE REINFORCED EPOXY RESIN

Table B1: Tensile Test Results – Untreated Giant Cavendish Banana Fibre Reinforced Epoxy Resin

Breadth(mm)	Depth (mm)	mass of fibre (grams)	%Vf	Ultimate Load (N)	Fracture stress (MN/m2)
20.1	5.9	0.14	0.582982	240	2.023779408
20.2	6.5	0.14	0.526548	226.67	1.726351866
20.3	5.7	0.14	0.597492	186.67	1.613257281
20.4	6.5	0.27	1.00553	386.67	2.916063348
20	5.5	0.27	1.212121	360	3.272727273
20.5	6.1	0.27	1.06624	266.67	2.132506997
20	5.9	0.42	1.75769	400	3.389830508
20.1	5.5	0.42	1.876141	346.667	3.135838987
19.8	5.6	0.42	1.870557	400	3.607503608
19.8	5.6	0.55	2.449539	373.333	3.367000361
20.3	5.6	0.55	2.389206	506.67	4.456984518
20.2	6.1	0.55	2.204228	520	4.220094141
19.9	5.7	0.69	3.003974	560	4.936965529
20.3	6	0.69	2.797543	573.333	4.707167488
20	5.5	0.69	3.097643	646.67	5.878818182
19.9	6.4	0.83	3.218252	666.667	5.23450848
19.9	6.1	0.83	3.376526	626.667	5.162426889
20.2	5.8	0.83	3.498434	706.667	6.031640492
19.9	5.7	0.98	4.266513	511.33	4.507890329
19.8	6.1	0.98	4.006877	529.667	4.385386653
19.9	6.5	0.98	3.741404	499.33	3.860301508

Table B2: ANOVA (Tensile) Results – Untreated Giant Cavendish Banana Fibre Reinforced Epoxy Resin

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.981589029
R Square	0.963517021
Adjusted R Square	0.936154787
Standard Error	0.383177373
Observations	8

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	15.51060719	5.170202398	35.21338981	0.002465079
Residual	4	0.587299595	0.146824899		
Total	7	16.09790679			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	1.360249155	0.362511131	3.752296244	0.019907381	0.3537569	2.366741409	0.3537569	2.366741409
%Vf	0.145755867	0.851115636	0.17125272	0.872339218	-2.217319974	2.508831709	-2.217319974	2.508831709
%Vf^2	0.968922294	0.508957945	1.903737437	0.129678695	-0.444171501	2.38201609	-0.444171501	2.38201609
%Vf^3	-0.202984844	0.082700357	-2.454461528	0.070107811	-0.432597846	0.026628157	-0.432597846	0.026628157

$$y = -0.203x^3 + 0.9689x^2 + 0.1458x + 1.3602$$

$$R^2 = 0.9635$$

Table B3: Tensile Test Results – 0.06M NaOH Treated Giant Cavendish Banana Fibre Reinforced Epoxy Resin

Breadth(mm)	Depth (mm)	mass of fibre (grams)	%Vf (KMnO4)	Ultimate Load (N)	Fracture stress (MN/m2)
20	6.4	0.31	1.195987654	466.67	3.645859375
20.1	5.7	0.31	1.336182419	453.33	3.956794973
20.5	6.3	0.31	1.185338132	613.33	4.748974061
20.1	5.6	0.62	2.720085639	786.67	6.988894812
20	6.3	0.62	2.429943171	813.33	6.455
20.4	5.8	0.62	2.587667677	800	6.76132522
19.8	6.1	0.92	3.761558103	826.667	6.844403047
20.5	6.1	0.92	3.633114655	840	6.717313075
20	5.9	0.92	3.850177861	773.33	6.553644068
20.4	6.5	1.23	4.580749679	862.67	6.505806938
20.4	6.2	1.23	4.802398857	893.33	7.063013915
20.4	6.3	1.23	4.726170304	923.33	7.184329287
20.3	6.4	1.54	5.853554704	1056.33	8.130618842
19.9	5.8	1.54	6.588925898	1053.333	9.126087333
20.3	5.7	1.54	6.572412299	1105.33	9.552588367
19.9	5.5	1.85	8.347010022	820	7.492005482
20.2	5.8	1.85	7.797714637	933.333	7.966311028
20.5	6	1.85	7.427481682	913.33	7.425447154

Table B4: ANOVA (Tensile) Results – 0.06M NaOH Treated Giant Cavendish Banana Fibre Reinforced Epoxy Resin

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.988742504
R Square	0.97761174
Adjusted R Square	0.955223479
Standard Error	0.441823689
Observations	7

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	25.57203614	8.524012047	43.66626639	0.005648599
Residual	3	0.585624517	0.195208172		
Total	6	26.15766066			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	1.396549682	0.426284798	3.27609544	0.046562571	0.039921202	2.753178162	0.039921202	2.753178162
%Vf	2.002254615	0.520242149	3.84869742	0.030967427	0.346611912	3.657897319	0.346611912	3.657897319
%Vf^2	-0.169907063	0.165962522	-1.02376766	0.381290692	-0.698073877	0.358259752	-0.698073877	0.358259752
%Vf^3	-0.001209928	0.014216655	-0.085106348	0.937538362	-0.046453668	0.044033813	-0.046453668	0.044033813

$$y = -0.0012x^3 - 0.1699x^2 + 2.0023x + 1.3965$$

$$R^2 = 0.9776$$

Table B5: Tensile Test Results – 0.003M $KMnO_4$ treated Giant Cavendish Banana Fibre Reinforced Epoxy Resin

Breadth(mm)	Depth (mm)	mass of fibre (grams)	%Vf(NaOH)	Ultimate Load (N)	Fracture stress (MN/m2)
20.3	5.5	0.31	1.371127808	477.333	4.275261979
19.7	5.8	0.31	1.33980763	461.6667	4.040492736
19.6	6.5	0.31	1.201620249	483.6667	3.796441915
20.3	6.4	0.62	2.35662592	615.57	4.738069581
19.9	5.7	0.62	2.699222776	644.333	5.68044609
19.5	6	0.62	2.616861876	691.667	5.911683761
19.9	6.1	0.92	3.742655801	744.1667	6.130378944
20.4	5.9	0.92	3.774684178	699.333	5.810343968
19.9	5.6	0.92	4.076821497	721.6676	6.475839914
20.2	5.5	1.23	5.467213388	752.6667	6.774677768
19.8	5.8	1.23	5.289162377	812.57	7.075670498
19.5	5.7	1.23	5.464754003	783.6667	7.050532614
20.3	6.2	1.54	6.042379049	871.57	6.924916574
19.5	5.5	1.54	7.090851535	809.333	7.546228438
20.2	5.6	1.54	6.722894512	856.111	7.568166549
20.3	6.4	1.85	7.031867664	699.667	5.385367919
19.7	6.1	1.85	7.60239866	714.333	5.944353832
19.6	5.5	1.85	8.47477038	703.667	6.527523191

Table B6: ANOVA (Tensile) Results – 0.003M $KMnO_4$ treated Giant Cavendish Banana Fibre Reinforced Epoxy Resin

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.961178207
R Square	0.923863546
Adjusted R Square	0.847727092
Standard Error	0.968806981
Observations	7

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	34.16732349	11.38910783	12.13431279	0.034838608
Residual	3	2.8157609	0.938586967		
Total	6	36.98308439			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	1.419675204	0.927992419	1.529834916	0.223543285	-1.533610842	4.372961251	-1.533610842	4.372961251
%Vf	2.313447051	1.141233585	2.02714596	0.135716974	-1.318467556	5.945361659	-1.318467556	5.945361659
%Vf^2	-0.203117627	0.362382346	-0.560506408	0.614269019	-1.356379986	0.950144732	-1.356379986	0.950144732
%Vf^3	-0.000186055	0.030387776	-0.006122688	0.995499218	-0.096893519	0.09652141	-0.096893519	0.09652141

$y = -0.0002x3 - 0.2031x2 + 2.3134x + 1.4197$

$R^2 = 0.9239$

Table B7: Flexural Test Results – Untreated Giant Cavendish Banana Fibre Reinforced Epoxy Resin

Breadth(mm)	Depth (mm)	mass of fibre (grams)	%Vf	Ultimate Load (N)	MOR (MN/m2)
19.9	13.1	0	0	31.655	3.893103417
20.1	12.8	0	0	32.517	4.147092905
20	14.6	0	0	36.442	3.590176393
20.1	13.6	0.65	0.58711526	34.37452535	3.8834
20	15	0.65	0.53497942	41.90464286	3.9111
20.1	14.7	0.65	0.54318146	37.21474197	3.5986
20.1	12.2	1.29	1.29890922	29.41965061	4.1302
20	13.9	1.29	1.14575007	36.0318249	3.9163
19.8	13.4	1.29	1.200507	36.18013438	4.2741
19.8	13.1	1.94	1.84675899	46.79363417	5.784
20	12.4	1.94	1.93150139	43.10551771	5.8872
20	14.3	1.94	1.67486834	53.59488148	5.5039
19.8	14.9	2.59	2.16767057	46.23228216	4.4173
19.8	13.2	2.59	2.44684027	38.26982469	4.659
20.1	12.3	2.59	2.58668516	30.35136754	4.192
20	12.6	3.23	3.16480502	23.82156	3.151
20.1	14.4	3.23	2.75542725	35.91768466	3.6194
19.9	12.9	3.23	3.10673859	23.47658791	2.9775
19.8	12.8	3.88	3.7800848	19.41784869	2.514
19.8	15	3.88	3.22567236	23.21585357	2.1887
19.8	14	3.88	3.45607753	18.18432	1.968

Table B8: ANOVA (Flexural) Results – Untreated Giant Cavendish Banana Fibre Reinforced Epoxy Resin

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.957348749
R Square	0.916516627
Adjusted R Square	0.499099763
Standard Error	0.758429696
Observations	7

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	5	6.314966041	1.262993208	2.195686629	0.470295357
Residual	1	0.575215603	0.575215603		
Total	6	6.890181644			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	3.902763783	0.757984837	5.148867886	0.122122316	-5.728346738	13.53387431	-5.728346738	13.53387431
%Vf	-1.040136737	6.365894781	-0.163392072	0.896892487	-81.92649915	79.84622568	-81.92649915	79.84622568
%Vf^2	0.500933283	13.71389343	0.03652743	0.97675625	-173.7506043	174.7524709	-173.7506043	174.7524709
%Vf^3	1.617502082	10.67120435	0.151576338	0.904232497	-133.9730052	137.2080093	-133.9730052	137.2080093
%Vf^4	-1.025483248	3.439690969	-0.298132378	0.815544195	-44.73090093	42.67993443	-44.73090093	42.67993443
%Vf^5	0.15310033	0.390976769	0.391584212	0.762394147	-4.814730542	5.120931202	-4.814730542	5.120931202

$$y = 0.1531x^5 - 1.0255x^4 + 1.6175x^3 + 0.5009x^2 - 1.0401x + 3.9028$$

$$R^2 = 0.9165$$

Table B9: Flexural Test Results – 0.06M NaOH Treated Giant Cavendish Banana Fibre Reinforced Epoxy Resin

Breadth(mm)	Depth (mm)	mass of fibre (grams)	%Vf	Ultimate Load (N)	MOR (MN/m2)
19.9	13.1	0	0	31.655	3.893103417
20.1	12.8	0	0	32.517	4.147092905
20	14.6	0	0	36.442	3.590176393
19.9	14.3	0.31	0.268978	48.276	4.982593047
20.1	14.9	0.31	0.255579	44.828	4.219199485
19.8	12.7	0.31	0.304395	39.655	5.215243764
20.1	14.2	0.62	0.536355	86.207	8.933447225
19.9	13.5	0.62	0.569836	41.379	4.791910168
20	14.7	0.62	0.520702	77.586	7.539941691
20.1	12.4	0.92	0.911413	55.172	7.497709165
20	14.5	0.92	0.783312	51.724	5.166249703
19.9	12.2	0.92	0.935664	56.897	8.068000578
19.8	12.4	1.23	1.236982	67.241	9.276302305
19.8	13.6	1.23	1.127836	63.793	7.316094553
20	12.2	1.23	1.244687	60.345	8.514142704
20	12	1.54	1.584362	143.103	20.8691875
19.8	12.2	1.54	1.57413	150	21.37744008
19.9	13.2	1.54	1.447567	139.655	16.91627905
20	13.6	1.85	1.679375	70.69	8.026005623
20	13.4	1.85	1.704441	63.793	7.460754065
20	13.6	1.85	1.679375	55.172	6.264121972

Table B10: ANOVA (Flexural) Results – 0.06M NaOH Treated Giant Cavendish Banana Fibre Reinforced Epoxy Resin

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.907144085
R Square	0.822910391
Adjusted R Square	0.468731173
Standard Error	1.923966448
Observations	7

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	4	34.40206019	8.600515047	2.323429353	0.322818488
Residual	2	7.403293788	3.701646894		
Total	6	41.80535398			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	3.578314251	1.909362455	1.874088517	0.201771352	-4.637009327	11.79363783	-4.637009327	11.79363783
%Vf	19.10456048	19.14812286	0.997724979	0.423526383	-63.2831626	101.4922836	-63.2831626	101.4922836
%Vf^2	-51.84116572	53.35736362	-0.971584093	0.433743384	-281.4193719	177.7370405	-281.4193719	177.7370405
%Vf^3	54.36575989	50.18205651	1.083370505	0.3918725	-161.5502025	270.2817223	-161.5502025	270.2817223
%Vf^4	-17.4441433	14.94451286	-1.167260751	0.363443603	-81.74519233	46.85690574	-81.74519233	46.85690574

$$y = -17.4441x^4 + 54.3658x^3 - 51.8412x^2 + 19.1046x + 3.5783$$

$$R^2 = 0.8229$$

Table B11: Flexural Test Results – 0.003M $KMnO_4$ treated Giant Cavendish Banana Fibre Reinforced Epoxy Resin

Breadth(mm)	Depth (mm)	mass of fibre (grams)	%Vf	Ultimate Load (N)	MOR (MN/m2)
19.9	13.1	0	0	31.655	3.893103417
20.1	12.8	0	0	32.517	4.147092905
20	14.6	0	0	36.442	3.590176393
20.1	12.8	0.31	0.297509367	43.103	5.497190561
20.1	12.2	0.31	0.312140975	32.759	4.599008451
20.1	14.9	0.31	0.255578516	36.207	3.407793249
20	13	0.62	0.588793922	75.862	9.426639053
19.8	13.2	0.62	0.585730103	67.241	8.185974761
20.1	13.7	0.62	0.555929912	70.69	7.869915699
19.9	14.8	0.92	0.771290554	96.552	9.303236416
19.8	12.6	0.92	0.91053589	91.379	12.20926193
19.8	14.8	0.92	0.77518596	93.103	9.01621677
20	12.1	1.23	1.254973982	113.793	16.32165153
19.8	14.7	1.23	1.043440197	98.276	9.647102708
20	14.2	1.23	1.069379238	91.379	9.516757588
19.8	14.6	1.54	1.315369149	146.552	14.58378114
19.8	13.3	1.54	1.443939066	141.379	16.95374801
20	14.3	1.54	1.329534663	134.483	13.81066556
20	13.7	1.85	1.667117239	108.621	12.15323672
19.8	13.7	1.85	1.683956807	101.724	11.49651989
19.8	12.8	1.85	1.80236002	89.655	11.60749956

Table B12: ANOVA (Flexural) Results – 0.003M $KMnO_4$ treated Giant Cavendish Banana Fibre Reinforced Epoxy Resin

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.987981733
R Square	0.976107905
Adjusted R Square	0.928323714
Standard Error	1.093145564
Observations	7

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	4	97.64040611	24.41010153	20.42742349	0.047213359
Residual	2	2.389934446	1.194967223		
Total	6	100.0303406			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	3.607920626	1.076276005	3.352226202	0.078635163	-1.022921266	8.238762517	-1.022921266	8.238762517
%Vf	5.007419959	8.051617549	0.62191478	0.597445333	-29.63589427	39.65073419	-29.63589427	39.65073419
%Vf^2	4.668022184	15.66150819	0.298057002	0.793772322	-62.71800878	72.05405315	-62.71800878	72.05405315
%Vf^3	-1.87887609	8.606852893	-0.218300012	0.847445375	-38.91117518	35.153423	-38.91117518	35.153423
%Vf^4	0.123416511	0.62500617	0.197464469	0.861713057	-2.565767991	2.812601014	-2.565767991	2.812601014

$$y = 0.1234x^4 - 1.8789x^3 + 4.6680x^2 + 5.0074x + 3.6079$$

$$R^2 = 0.9761$$

APPENDIX C –SAMPLE CALCULATIONS

C1: Sample Calculations using Equation 3.1

Diameter

$Mean\ diameter = D_o\Gamma\left(1 + {}^{1}/_{m}\right)$……. Eq. 3.1

Reference diameter D_o, = Diameter which 63.2% of the fibres sampled fall within is calculated from equation 2.18 as follows:

$$\log_e\left(\log_e\left({}^{1}/_{(1-F)}\right)\right) = m\log_e\sigma_f - m\log_e\sigma_0 \qquad \text{Eq. 2.18}$$

Replacing σ_f and σ_0 with D and D_o respectively so as to work with diameters, we get

$$\log_e\left(\log_e\left({}^{1}/_{(1-F)}\right)\right) = m\log_e D - m\log_e D_0$$

Now, from Appendix A, Table A1 we can pick any row of data entries, say row number 5 where we have D = 132.8, F=0.09 and the gradient of the Weibull 'line of best fit = shape parameter = 5.9865 (see figure 4.1)

Substituting for these values in the equation yields

$$\log_e\left(\log_e\left({}^{1}/_{(1-0.09)}\right)\right) = 5.9865\log_e 132.8 - 5.9865\log_e D_0$$

$$5.9865\log_e 132.8 - \log_e\left(\log_e\left({}^{1}/_{(1-0.09)}\right)\right) = 5.9865\log_e D_0$$

$$29.26706603 + 2.361160846 = 5.9865\log_e D_0$$

$$31.62822687 = 5.9865\log_e D_0$$

$$5.283258477 = \log_e D_0$$

Therefore exponential (5.283258477)= D_0= 197.0107857μm which is the reference diameter of the banana fibres.

Substituting this value in Eq. 3.1 yields:

$$Mean\ diameter = 197.0107857\Gamma\left(1 + {}^{1}/_{5.9865}\right)$$

$$= 197.0107857\Gamma(1.167042512)$$

Input the expression as `{=197.0107857*GAMMA(1.167042512)}` in Microsoft excel® (2013)

$Output\ Mean\ banana\ fibre\ diameter = 182.7479\mu m$

C2: Sample Calculations using Equation 3.2

Standard error

$$Standard\ error = \frac{\sqrt[2]{\left({D_0}^2\left[\Gamma\left(1 + {}^{2}/_{m}\right) - \Gamma^2\left(1 + {}^{1}/_{m}\right)\right]\right)}}{\sqrt[2]{n}}$$

By substituting for the value of m =5.9865 (gradient of the 'line of best fit' of the Weibull plot shown in Figure 4.1), the reference diameter D_o calculated using Eq. 3.1 (182.7479μm) and taking note that the number of specimen diameters = 50 (see Appendix A, Table A1),

The standard error is calculated as:

$$Standard\ error = \frac{\sqrt[2]{\left(182.7479^2\left[\Gamma\left(1 + {}^{2}/_{5.9865}\right) - \Gamma^2\left(1 + {}^{1}/_{5.9865}\right)\right]\right)}}{\sqrt[2]{50}}$$

And the Microsoft excel® (2013) command input is:

```
{{=SQRT((Do^2*(EXP(GAMMALN(1+2/m))EXP(GAMMALN(1+1/m))^2))}/(SQRT50)}
```

Which outputs the standard error as equal to $\pm$ 5.03μm.

APPENDIX D –SAMPLE LOAD-EXTENSION CURVES

D1: Typical Stress-Strain Curve for a banana fibre as given by Kulkarni *et. al* [24]

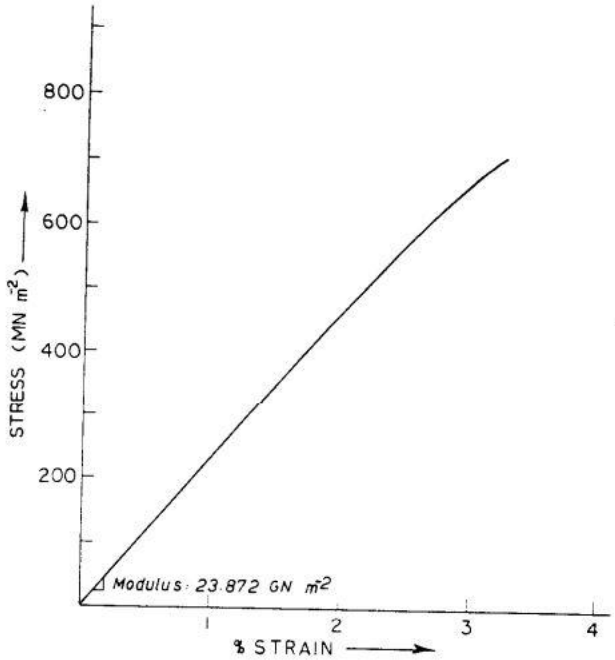
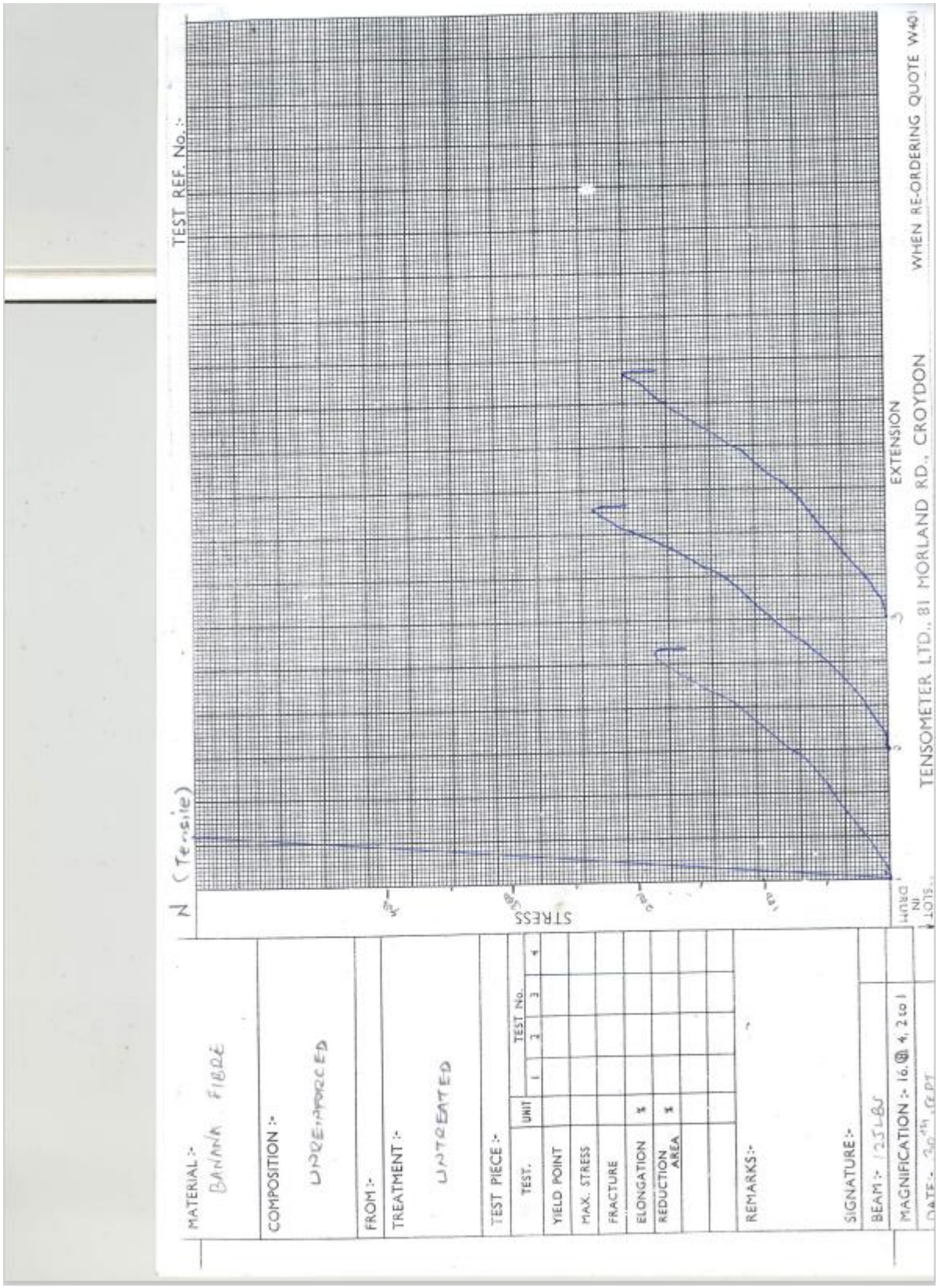
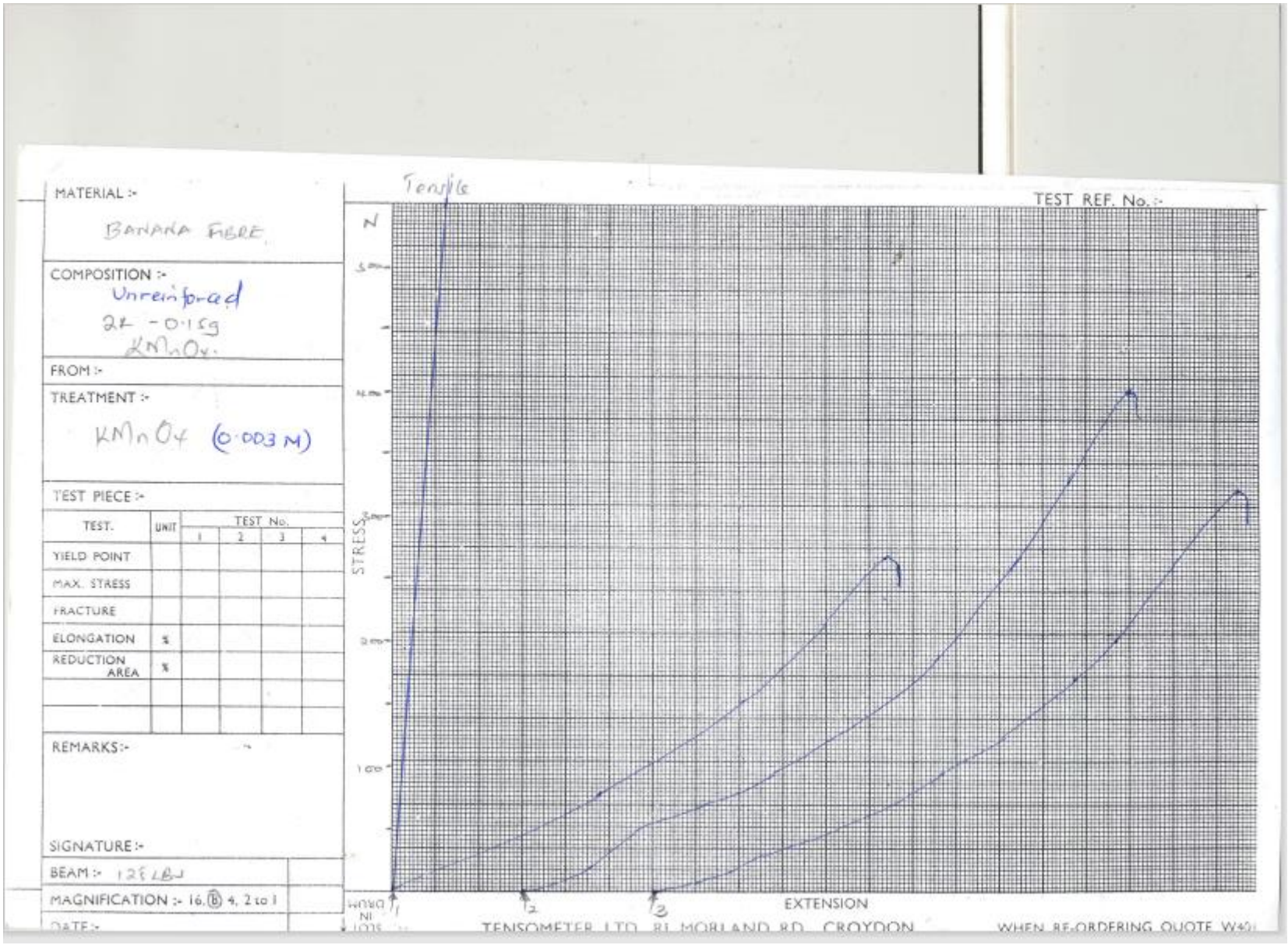
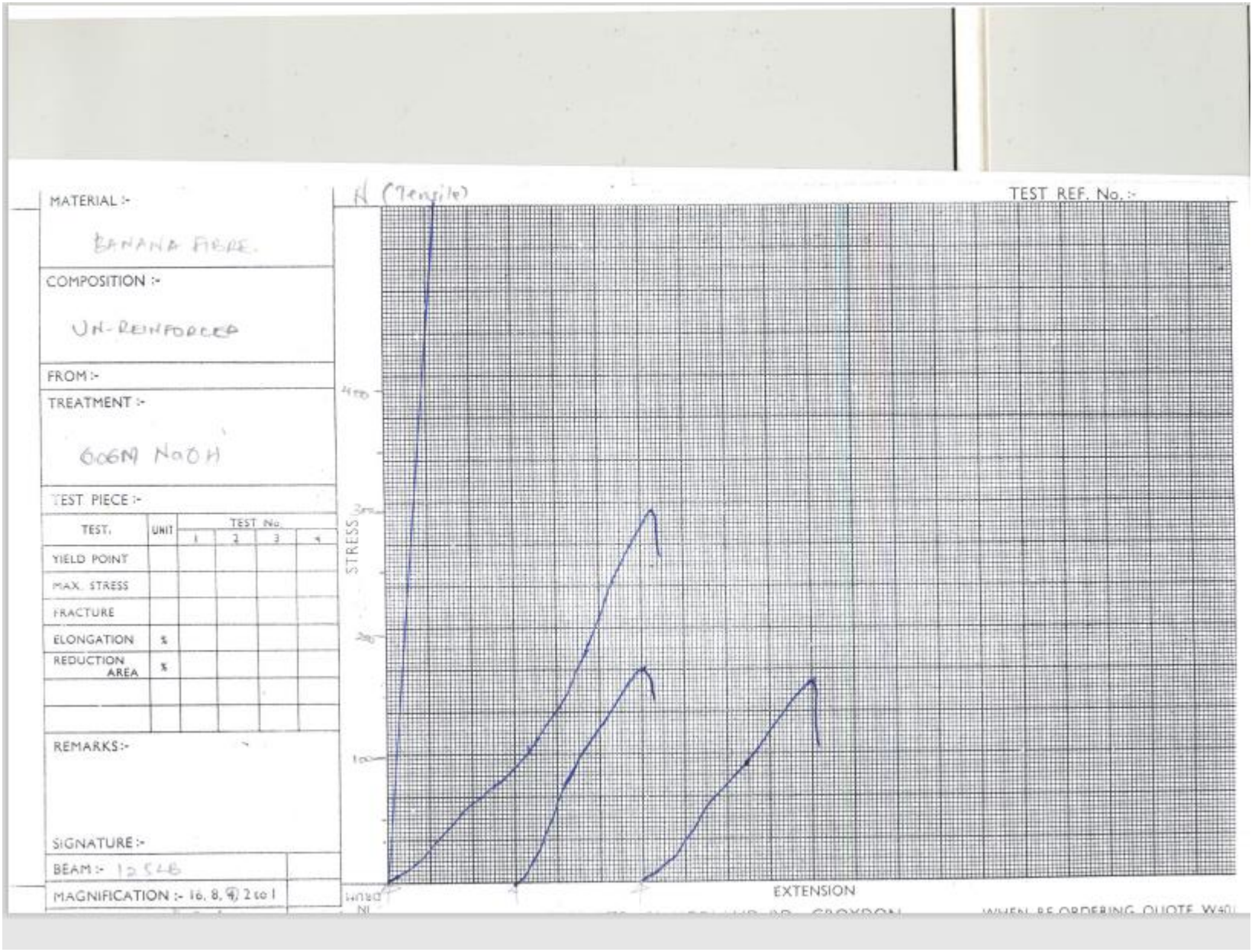


Figure 2 Typical stress-strain curve for a banana fibre of diameter 0.2×10^{-3} m tested at a speed of 0.5×10^{-3} m min^{-1}.

D2: Sample banana fibre load-extension curves obtained in the current study




Tensile
TEST REF. No. :-
MATERIAL :-
BANANA FIBRE
COMPOSITION :-
Unreinforced
2g - 0·15g
KMnO4.
FROM :-
TREATMENT :-
KMnO4 (0·003 M)
TEST PIECE :-
TEST.
UNIT
TEST No.
1
2
3
4
YIELD POINT
MAX. STRESS
FRACTURE
ELONGATION
%
REDUCTION AREA
%
REMARKS :-
SIGNATURE :-
BEAM :- 12§ LBJ
MAGNIFICATION :- 16.(b) 4, 2 to 1
DATE :-
N
STRESS
EXTENSION
TENSOMETER LTD. 81 MORLAND RD. CROYDON
WHEN RE-ORDERING QUOTE W40



MATERIAL :- BANANA FIBRE.

COMPOSITION :- UN-REINFORCED

FROM :-

TREATMENT :- 6.06M NaOH

TEST PIECE :-

TEST.	UNIT	TEST No. 1	2	3	4
YIELD POINT					
MAX. STRESS					
FRACTURE					
ELONGATION	%				
REDUCTION AREA	%				

REMARKS :-

SIGNATURE :-

BEAM :- 12 S 46

MAGNIFICATION :- 16, 8, 4, 2 to 1

N (Tensile)

TEST REF. No. :-

STRESS

EXTENSION

APPENDIX E –FCE 245 LABORATORY MANUAL: TENSILE TEST USING A HOUNSFIELD TENSOMETER

UNIVERSITY OF NAIROBI
DEPARTMENT OF CIVIL ENGINEERING

FCE 245 — MATERIALS SCIENCE FOR 2ND YEAR CIVIL ENGINEERS
TENSILE TESTS USING A HOUNSFIELD TENSOMETER

INTRODUCTION

The Hounsfield Tensometer is a portable machine combining a loading frame and graphical extensometer in one instrument. It is a very versatile machine; with the aid of attachments it can perform many types of test (bending, compression, hardness etc). One important application is in performing autographic tensile tests i.e. a load extension curve for the specimen is plotted as the test proceeds.

Extension is applied by hand through gearing and the corresponding load is measured by the deflection of a calibrated, simply—supported beam this deflection being measured by the movement of mercury in a glass tube. The beam can be chosen to give loads within the expected load range of the specimen, and the glass tube is calibrated accordingly by using the corresponding removable scale.

Extension is measured by rotation, magnified to a suitable scale of the drum carrying the graph paper. However, this rotation includes deformation of the machine itself. From the manufacturer's data it is ascertained that this machine extension is proportional to load, and thus the true extension curve for the specimen is obtained by superimposing on the graph paper the characteristic straight line for the machine, which then forms the datum line for extension measurements.

OBJECT

To perform teansile tests using a Hounsfiel Tensometer in order to:-

1. Obtain the stress—strain curves of mild steel (0.1%C, N.900°C), Aluminum (Alloy HE.14, N.360°C), brass (70/30, Hard drawn) and copper (H.C., Bard drawn).

2. Assess the performance of the Hounsfiel Tensometer.

THEORY

The graph produced by the machine is a load deflection curve for the specimen, and must be converted to a stress—strain curve. This is done by simply changing the scale on the ordinate and abscissa. Use the following equations:-

Ordinate: Stress, $\delta = {}^{P}/_{A}$
Abscissa: Strain, $(- = \delta/_{16} = {}^{1}/_{L}$

where: P = Applied load from scale on machine (newtons) (for the machine near the door the load is in Kg and must be converted to newtons)

A = Specimen cross sectional area mm^2

δ = Specimen elongatiun x 16. This is the measured length of the graph abscissa — mm.

L = Specimen gage length 27.15mm.

PROCEDURE

The same beam (either 2000 kg or 2 ton, depending on the machine) will be used for all specimens. This will already be assembled in the machine.

1. Ensure that the magnification ratio for extension is set at 16 to 1.
2. Set the Universal Reduction in Area Gauge and the Universal Elongation gauge.
3. Attach the graph paper to the drum and assemble the drum into the machine.
4. Set the mercury to zero, by first drawing the mercury out of the tube and then bringing it up to zero. Take care to remove any entrapped air.
5. Set the needle to zero load on the graph paper.
6. Assemble the test—piece in the machine using the chucks and containing rings. Chuck halves are numbered 13 or 14; chucks halves of the same number must be used together.
7. Tighten the chucks using the high—geared handle until they become rigid and a small load is applied. Rotate the drum until the needle comes to a convenient starting place. Puncture the graph paper. This is the first point on the curve which, due to the slight load, will not be zero. Thus, DO NOT RESET THE NEEDLE BACK TO ZERO.

8. Using the low—geared handle, make further extension increments following the mercury column with the cursor and needle, punching the paper at regular intervals. Take readings frequently, particularly in the region of yield and near failure.

9. After fracture, remove the specimen and take readings for percentage reduction in area and percentage elongation.

10. Repeat for other specimens.

RESULTS AND DISCUSSIONS

A load extension curve is obtained for each specimen. Plot onto each curve the characteristic line for the machine and appropriate beam. This will be made available at the time of the test. Also mark a stress (N/mm^2) scale on the ordinate and a strain scale on the abscissa.

Mark as well the stress scale onto the load ordinate. For each specimen record yield stress (or 0.2% proof stress), ultimate tensile strength, fracture stress, percentage reduction in area and percentage elongation. Comment on your results and in particular compare the behaviour of the materials. Also comment on the Hounsfield tensometer and its procedure in tensile testing.

CHARACTERISTIC LINES

OLD MACHINE (in corner)
Line for 16:1 ratio add 2^T bean is such that at l0KN LOAD AN Extension of 21mm on the graph paper is required.

NEW MACHINE (near door)
Line for 16:1 ratio and 2000 Kg.beam is such that at I000Kg load an extension of l9mm on the graph paper is required.

GAUGE LENGTH OF SPCIMENS (No. 14)
Assume gauge length for purposes of calculating proof stresses is 27.15mm.

DIAMETER OP SPECIMEN (No.14)
5.00mm for use with stress calculations.

tecquipment

Plain Carbon Steel. Code A

HOUNSFIELD METRIC SPECIMEN

Gauge Diameter, d 5.04/5.06mm
Gauge Length, 5d 25.25mm
Cross-Sectional Area 20mm²

CHEMICAL ANALYSIS

Carbon 0.10%
Silicon 0.17%
Manganese 0.37%
Sulphur 0.026%
Phosphorous 0.026%

STRUCTURAL CONDITION

Normalised at .....900°C
Relevant B.S.S. EN2A

TYPICAL APPLICATIONS

Rod and wire for nails, rivets. Strip and bar for general purposes.

Microstructure on longitudinal section (x 200)

AVERAGE MECHANICAL PROPERTIES

Lower yield point
x 10^7 N/m² 26

Upper yield point
x 10^7 N/m² 35

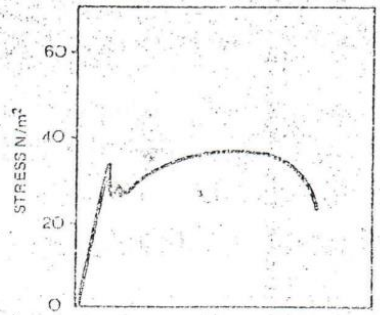
Ultimate tensile strength
x 10^7 N/m² 36.5

% Elongation 40

% Reduction in area 70

Hardness (V.P.N.) 122

TYPICAL TENSILE CURVE



TENSOMETER VARIABLES

Chuck ..... B

Beam 10kN

Magnification 4:1
(Autographic Recorder)

Strain rate 3cm/min

Code Ref. A. test specimens can be conveniently used for the following laboratory experiments;

1. Strain ageing behaviour of mild steel.
2. Work hardening behaviour.
3. Tensile testing at elevated temperature.
4. Hydrogen embrittlement following cathodic charging.

Tecquipment Limited reserve the right to accept deliveries of steel from their Sheffield Steel Manufacturers with carbon contents within 0.02% of the figures specified on this sheet.

tecquipment LIMITED
HOOTON STREET, CARLTON ROAD
NOTTINGHAM NG3 2NJ ENGLAND

tecquipment — High Conductivity Copper: Code W

HOUNSFIELD METRIC SPECIMEN

Gauge Diameter, d 5.04/5.06mm
Gauge Length, 5d 25.25mm
Cross–Sectional Area 20mm²

CHEMICAL ANALYSIS

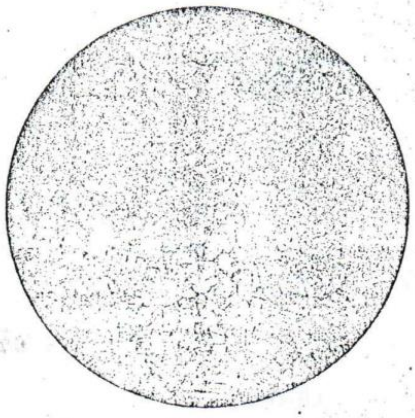
Copper 99.9%
Lead 0.005%
Bismuth 0.001%

STRUCTURAL CONDITION

Hard drawn
Relevant B.S.S. 2874/C10

TYPICAL APPLICATIONS

Electrical conductors and cold heading applications.

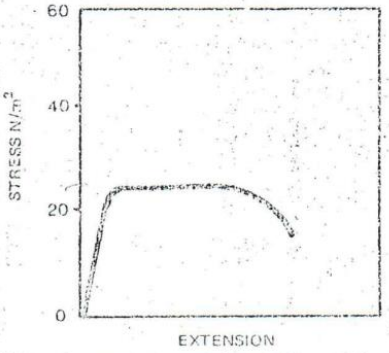


Microstructure on transverse section (x 150)

AVERAGE MECHANICAL PROPERTIES

Limit of proportionality x 10⁷ N/m²	22
Ultimate tensile strength x 10⁷ N/m²	25
% Elongation	32
% Reduction in area	70
Hardness (V.P.N.)	46

TYPICAL TENSILE CURVE



TENSOMETER VARIABLES

Chuck ..... D
Beam 10kN
Magnification 1:1
(Autographic Recorder)
Strain rate 3cm/min

Code Ref. W test specimens can be conveniently used for the following laboratory experiments;

1. Tensile testing after annealing.
2. Comparison with brasses e.g. effect of solute addition.

tecquipment LIMITED
HOOTON STREET CARLTON ROAD
NOTTINGHAM NG3 2NJ ENGLAND
TELEPHONE · NOTTINGHAM 50181 TELEX CHANGUM 37268 TECQUIP G
CABLES · EQUIPMENT NOTTINGHAM
Printed in England P25/73

tecquipment

70/30 Brass. Code X

HOUNSFIELD METRIC SPECIMEN

Gauge Diameter, d 5.04/5.06mm
Gauge Length, 5d 25.25mm
Cross-Sectional Area ..... .20mm²

CHEMICAL ANALYSIS

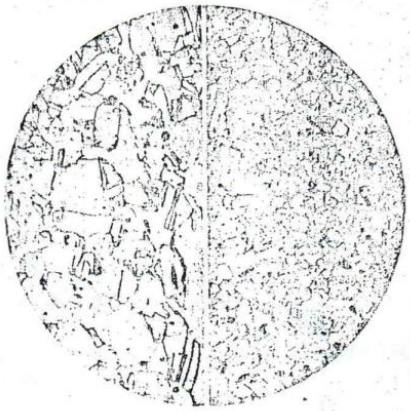
Copper 70%
Zinc 30%

STRUCTURAL CONDITION

As drawn
Relevant B.S.S. CZ106

TYPICAL APPLICATIONS

Wide variety of deep drawn and spun components, cartridge cases, carburettor parts and radiator tanks.



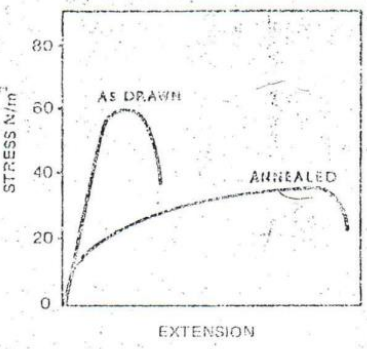
Microstructure on longitudinal section

(As drawn x 100) (Annealed x 100)

AVERAGE MECHANICAL PROPERTIES

	As Drawn	Annealed
Limit of proportionality x 10⁷ N/m²	60	15
Ultimate tensile strength x 10⁷ N/m²	69	36
% Elongation	18	65
% Reduction in area	66	82
Hardness (V.P.N.)	70	51

TYPICAL TENSILE CURVE



TENSOMETER VARIABLES

Chuck ..... S
Beam 10kN
Magnification ..... 4:1 (Automatic Recorder)
Strain rate 3cm/min

Code Ref. X test specimens can be conveniently used for the following laboratory experiments;

1. Tensile testing after differenft thermal treatments.
2. Tensile testing at elevated temperatures.
3. Comparison with two phase brass, Code Ref. Q.

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High Conductivity Copper. Code W

HOUNSFIELD METRIC SPECIMEN

Gauge Diameter, d 5.04/5.06mm
Gauge Length, 5d 25.25mm
Cross–Sectional Area 20mm²

CHEMICAL ANALYSIS

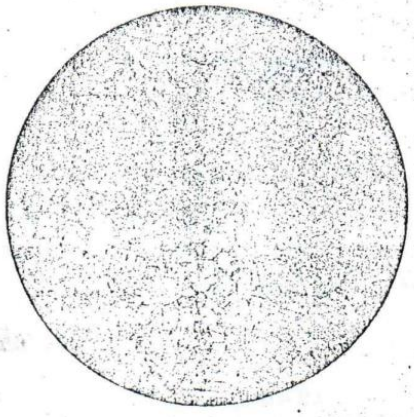
Copper 99.9%
Lead 0.005%
Bismuth 0.001%

STRUCTURAL CONDITION

Hard drawn
Relevant B.S.S. 2874/C10

TYPICAL APPLICATIONS

Electrical conductors and cold heading applications.

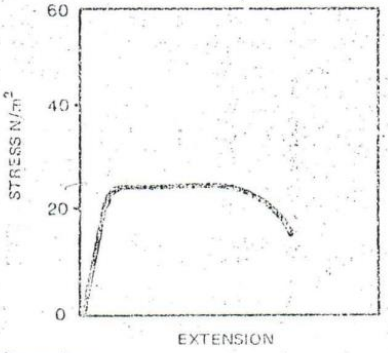


Microstructure on transverse section (x 150)

AVERAGE MECHANICAL PROPERTIES

Limit of proportionality x10⁷ N/m² 22
Ultimate tensile strength x10⁷ N/m² 25
% Elongation 32
% Reduction in area 70
Hardness (V.P.N.) 46

TYPICAL TENSILE CURVE



TENSOMETER VARIABLES

Chuck 0
Beam 10kN
Magnification 4:1
(Autographic Recorder)
Strain rate 3cm/min

Code Ref. W test specimens can be conveniently used for the following laboratory experiments;

1. Tensile testing after annealing.
2. Comparison with brasses e.g. effect of solute addition.

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Aluminium Alloy. Codes R & S

HOUNSFIELD METRIC SPECIMENS

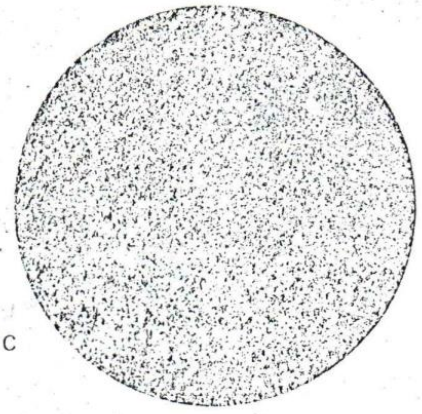
Gauge Diameter, d 5.04/5.06mm
Gauge Length, 5d 25.25mm
Cross-Sectional Area 20mm²

CHEMICAL ANALYSIS

Copper 0.3%
Magnesium 1.0%
Silicon 0.6%
Manganese 0.5%
Aluminium 97.6%

STRUCTURAL CONDITIONS

	R	S
	Annealed at 380°C	Solution heat treated 505°C water quenched and naturally aged.
Relevant B.S.S.	HE9—0	HE9—TB



Microstructure on transverse section Code Ref. R(x 200)

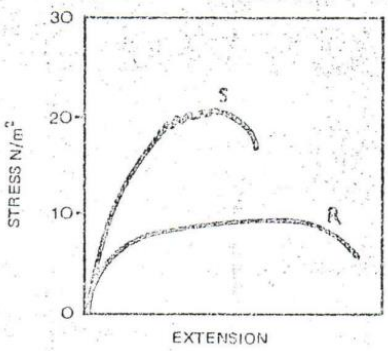
TYPICAL APPLICATIONS

High conductivity, used for overhead conductors, can be welded and worked easily.

AVERAGE MECHANICAL PROPERTIES

	R	S
Limit of proportionality $\times 10^7$ N/m²	1.5	8.5
Ultimate tensile strength $\times 10^7$ N/m²	9.5	21
% Elongation	43	23
% Reduction in area	80	48
Hardness (V.P.N.)	29	62

TYPICAL TENSILE CURVE



TENSOMETER VARIABLES

Chuck ..... B
Beam 5kN
Magnification ..... 4:1 (Automatic Recorder)
Strain rate 3cm/min

Code Ref. R and S test specimens can be conveniently used for the following laboratory experiments.

1. Tensile testing after different thermal treatments.
2. Comparison with other aluminium alloys e.g. effect of copper additions.

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