

Extraction and characterisation of the mechanical properties of cotton stalk bastfibres

Nkosilathi Z. Nkomo, Londiwe C Nkiwane, David Njuguna, Eric Oyondi

Abstract -Cotton stalks are a waste by-product of cotton farming and a problem to dispose of as they tend to harbour parasites such as pink bollworm. The stalks are normally disposed of by burning, which contributes to the emission of harmful greenhouse gases which pollute the environment. Cotton stalks were collected from Umguza region in Zimbabwe which is located 53km from Bulawayo town. The stalks were subjected to retting for 3 weeks and there after fibre extraction carried out by means of manual decortication. The fibres were then subjected to a number of tests such as tensile strength, moisture regain, linear density, density and fibre length measurement test. The fibres were characterised according to their position relative to the cotton stalk and segmented as fibres from the top section, middle section and bottom section. The test results from characterisation of the fibres were analysed using SPSS statistical software. The cotton stalk fibres have a light brownish colour and the fibre length was approximately 8.18cm. The moisture regain of the fibres was highest with fibres extracted from the root area having regain of 11.14%, fibres from the top half had moisture regain of 10.68% and fibres from the bottom half of 10.20%. The diameter of the cotton stalk fibres is 0.23mm which is similar to the diameter found in sisal fibres. The fibres have an elongation of 1.5%. The fibre yield from the cotton stalks is 23%. The cotton stalk fibres have density of approximately 1.45g/cm³. These fibres have possibility in various application which include fibreboards, for wall partitions, furniture applications and ceiling boards to replace solid wood materials.

Keywords: Composites, cotton stalks, extraction, fibres

I. INTRODUCTION

Cotton popularly known as “White Gold” is grown primarily for fibre and oil seed all over the world. On average about two to three tonnes of cotton stalk are generated per hectare of land farmed [1]. The cotton stalk is a great resource as a raw biomass material for manufacturing value-added bio-composite products[2].

Cotton stalks kept in the fields after harvest are a breeding ground for pink bollworm (pectinophoragossypiella), boll weevil and other pests. The cotton stalks must be destroyed to prevent these pests from breeding. Burning of cotton stalks in the field is the preferred method so as to try to eradicate several insects and pests which would be harmful to the future crop[1]. By law in Zimbabwe cotton stalks must be destroyed promptly after harvest to create a “dead period” or closed

season to prevent the build-up of pink bollworm and boll weevil[4].

As much as it is a desirable and easy method of destroying pests, burning of cotton stalks however, contributes to greenhouse gases (GHG) emission. Approximately 0.85million metric tonnes of CO₂ is produced per million metric tonnes of cotton stalk burnt[5]. Table I shows the emission of GHG per million tonnes of cotton stalks burnt.

TABLE I
EMISSION OF GREENHOUSE GAS PER MILLION
TONNES OF COTTON STALKS BURNED IN FIELD[6]

Green House Gas	Emission Factor (g.kg ⁻¹)	Total Emission (Mn MT)	Total Emission (Mn Mt Co ₂ e)
NO _x	2.68	0.00265	0.7898
CH ₄	2.7	0.0027	0.0675

*NO –Nitrous oxide, *CH₄ – Methane, *Mn Mt Co₂e – Million Metric tonnes of carbon dioxide equivalent

Utilisation of cotton stalks for the purposes of fibre will create value addition to the cotton farmer especially in these harsh times when returns from cotton farming are low in Zimbabwe. The national output of cotton in Zimbabwe declined from 250000 tonnes in 2012/13 to 143000 tonnes in 2013/14 season a decrease of 42% [7]. This is due to the low returns from farming the cotton crop. This has resulted in some farmers growing ratooned cotton. Re-growth of cotton or ratooned cotton provides an ideal food source for insects such as aphids and sweet potato whitefly[8]. White flies and aphids build on cotton regrowth, creating a larger population for the next crop[8]. The cotton stalk differ slightly in their structure depending on the origin of the cotton.

Depending upon the variety and the crop condition the stalks are between 1 to 1.75 metres long and their diameter above the ground may vary between 1 to 2.5cm[5]. With respect to structure and dimensions, cotton stalk is similar to common species of hardwood fibre[9]. Table II shows a comparison of cotton stalk fibre chemical constituent to common hardwood species.

TABLE II– PROPERTIES OF COTTON STALKS COMPARED TO HARDWOOD[10]

Property	Cotton Stalk	Hardwoods
Hemicellulose (%)	77.50	70-78
Cellulose (%)	47.80	45-50
Lignin (%)	21.20	30-35

Cellulose which is a major constituent of all natural plant life constitutes 47.8% of the cotton stalk chemical structure in comparison to hardwood which has between 45-50% cellulose content. Hemicellulose is a dominant part of the cotton stalk

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making up about 77.5% of the chemical constituent. It is not a form of cellulose and the name is a misnomer. Lignin is the smallest chemical constituent part of the cotton stalk making up 21.2% of the total chemical structure of the cotton stalk. Lignin is a complex hydrocarbon polymer with both aliphatic and aromatic constituents.

The stalk is about 33% bark and quite fibrous. For particleboard production cotton stalks can be hammer milled like other plant materials such as bamboo and wood used for particleboard manufacture. For fibreboards, cotton stalks can be refined with or without chemical treatment depending on the quality of fibre desired[11]. Newsprint quality paper can be made from whole cotton stalks. Cotton stalks have potential end uses in manufacture of particle boards, preparation of pulp and paper, hard boards, corrugated boards & boxes, microcrystalline cellulose, cellulose derivatives and as a substrate for growing edible mushrooms. [3].

The chemical constitution of the cotton stalk is dependent on the species grown. The cotton stalk contains about 7% ash [12]. Table III shows the chemical constituent of different species of the cotton crop.

II. METHODOLOGY

Cotton stalks were collected from Umguza region which is located 53km from Bulawayo in Zimbabwe. These stalks were collected 3 weeks after the harvest time of all the cotton bolls this is normally the time that the farmers start to uproot the stalks.

A. Fibre Extraction

Fibres were extracted by retting for a period of 3 weeks in 200Litre plastic drums. The weight loss percentage represents how much of all the materials had been removed during the retting process. This allowed the determination of the most efficient retting time. The initial water used for retting was tested to determine its initial pH, Conductivity and Total dissolved solids (TDS).



Fig.1 Water retting of cotton stalks

Fibres were extracted by manual decortication method by beating the fibres with a rubber coated hammer as shown in Fig 2 and then carrying out hackling and scutching to remove adhering particles on the cotton stalk fibres.

TABLE III
CHEMICAL CONSTITUENT OF COTTON STALKS
FROM DIFFERENT SPECIES [12]

Species	Holo-Cellulose (%)	Lignin (%)	Ash (%)
G. arboretum	67.3	25.8	7.0
G. herbaceum	69.1	28.1	8.3
G. hirsutum	70.0	27.1	6.7
G. barbadense	69.2	28.2	8.1
Desi Hybrids	67.3	27.6	6.8
Hirsutum Hybrids	68.6	24.3	5.9
Mean Value	69.1	27.0	7.1
Range of values	67.3 to 70.0	24.3 to 28.2	5.9 to 8.3



Fig. 2 Fibre extraction

B. Fibre Characterisation

The extracted cotton stalk fibres were characterised. A number of tests were carried out such as fibre length, fibre tenacity, moisture regain, fibre density and linear density to determine the mechanical and physical properties of the cotton stalk fibre. The fibres were conditioned under standard atmospheric conditions (21 \pm 1 $^{\circ}$ C and 65 \pm 2% relative humidity) for a period of 24 hours prior to testing and characterised according to the part of the cotton stalkstem they were collected from as shown in fig 3.

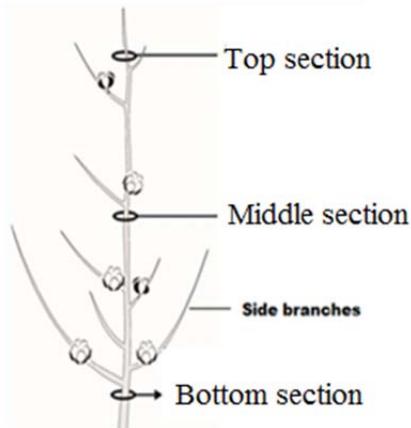


Fig.3 Location of extracted fibres

1) fibre length

The cotton stalk fibre length was measured according to ASTM D6103-01 testing method. The cotton stalk fibres were measured according to the part of the cotton stalk, i.e. top section, middle section and bottom section. The mean length was then calculated.

2) Fibre strength

A Testometric Micro 500 model universal tensile tester machine was used to test for the fibre strength. Bundle fibre testing was carried out according to ASTM 3822. The sample length was set at 35mm and the sample speed at 200mm/min.



Fig.4 Testometric micro 500 used for fibre tenacity testing

3) Linear Density

The gravitational method was used in accordance with ASTM D1677-07 to determine the linear density. The linear density was calculated to the nearest 0.1dex (0.01 denier) using the equation below:

$$T_D = 10000 \frac{W}{L \cdot N} \quad [1]$$

Where:

T_D = average fibre linear density, dtex,
 W = mass of bundle specimen, mg,
 L = length of bundle specimen, mm, and
 N = number of fibres in the bundle specimen

4) Microscopic examination

Microscopic examination of the cotton stalk fibres was carried out using a digital Leica optical microscope with magnification of 10X. The longitudinal image of the fibres was viewed.

5) Moisture regain

Moisture regain of the fibres was ascertained in accordance with ASTM D2654-89a using an oven and a digital scale. The moisture regain was calculated using equation 2.

Moisture Regain (%) =

$$\frac{\text{Weight of conditioned fibres} - \text{Weight of oven dry fibres}}{\text{Weight of conditioned fibres}} \times 100 \quad [2]$$

6) Diameter of fibres

The diameter of the cotton stalk fibres was measured using a travelling optical microscope with Vernier scale attachment for measurement of image size.

7) Density of fibres

The density of the cotton stalk fibres was determined by measuring the mass and volume of a bunch of cotton stalk fibres. The standard used for this test was ASTM D861-01a.

III. RESULTS AND DISCUSSION

The cotton stalk fibres were extracted and conditioned under standard atmospheric conditions prior to testing of the fibres. The tap water used for the retting process had an initial pH of 7.40, conductivity of 204 μ S and TDS of 102ppm. The yield of cotton stalk fibres averaged 20.5% by weight of the cotton stalk.

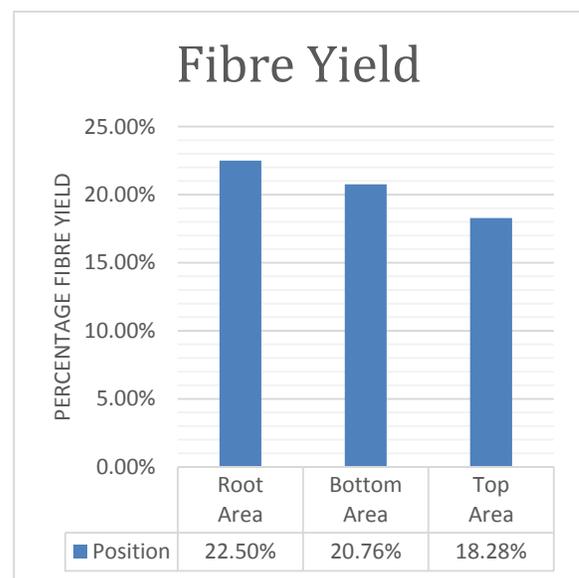


Fig 5 Cotton stalk fibre Yield

The root area gave the highest amount of fibre from the cotton stalk by weight. Approximately 22.5% fibre yield by weight. The bottom area of the stalk gave a fibre yield of approximately 20.76% which was lower than the root area by 1.74%. The top area of the stalk gave the least yield of fibres with approximately 19% fibre yield. The top area had more shive in percentage to useable fibrous bark area. The reason

for this variation in fibre yield can be attributed to the tapering shape of the cotton stalk. The root area has the largest diameter giving a large surface area which gradually reduces up the stalk. The surface area of the bark extracted is hence higher from the root area and reduces going up the stalk toward the top area. However on extraction of the fibres it was noticed that the very tip of the root area failed to yield useable fibre and this part had to be cut off. The fibres in this area could not be easily separated to individual fibres.

A. Fibre length

The fibres from the top section of the stalk had the highest fibre length of approximately 9.4cm. This can be attributed to the ease of removal of these fibres in comparison to those from the other sections there was less fibre breakage.

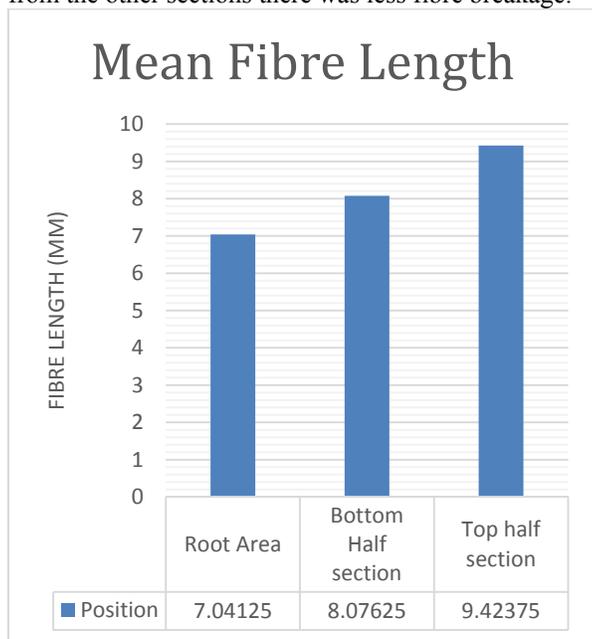


Fig 6 Mean fibre length

Fibres in the bottom and root area were more compactly held and upon fibre extraction fibre breakage occurred. The root area fibres gave the lowest fibre length of average 7.04cm. This also highlighted the need for correct retting of the cotton stalks, as the well retted top area allowed easier fibre extraction in comparison to the root area fibres. Retting can be improved by using vertical and horizontal stepping method to ensure that the whole stalk is well retted. The Zimbabwe cotton stalk fibres are significantly longer than those of Sudanese and Iranian cotton stalks[13].

B. Fibre Strength

The tensile strength, young modulus and strain to failure of the middle section cotton stalk fibres was higher as compared to the top and root area fibres. This was due to the higher cellulose content of the middle section cotton stalk fibres[14]. The middle section fibres were matured whereas the top and root area fibres are immature and over mature, respectively[15]. Generally, the strength and stiffness of plant

fibres depend on the cellulose content and the spiral angle which the bands of microfibrils in the inner secondary cell wall make with the fibre axis. The tensile properties however are not uniform along its length. The root or lower part has low tensile strength and modulus but high fracture strain. The fibres tend to be stronger midway of the stem and the top section has moderate tensile properties[16].

1) Fibres from bottom section

The cotton stalk fibres from the bottom section had the highest load at break. Fig 7 shows the load/extension curve for the bottom section fibres. The graph shows the test results from different samples.

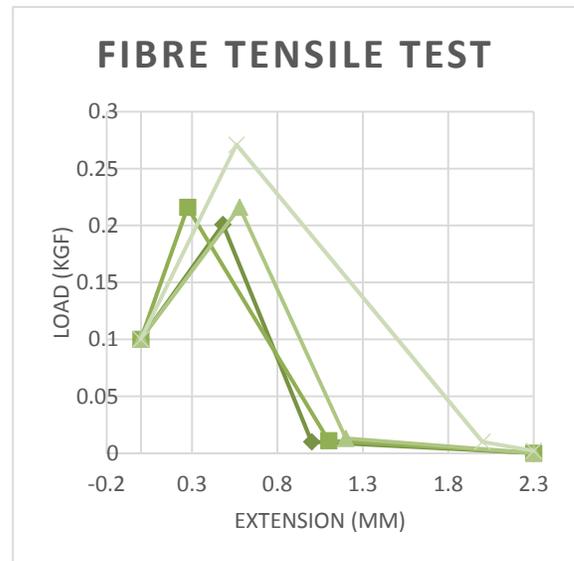


Fig 7- Load/Extension curve for cotton stalk fibres from bottom section

The mean fibre load at peak is 2.26kgf. The fibres had good elongation with the mean elongation of 0.4734. The tenacity of the bottom section fibres was 56.3cN/tex which was the highest off all fibres extracted from the cotton stalk. The tensile strength, young modulus and strain to failure of middle section of cotton stalk fibres was higher as compared to the top and root section fibres. This was due to the higher cellulose content of the middle portion[14]. The tenacity of the fibres was slightly higher than the tenacity of flax fibres which is approximately 55cN/tex[17]. The middle section fibres were mature whereas the top and root area fibres are immature and over mature, respectively[15] this made middle section fibres stronger. The middle section fibres had elongation of 1.35%. This elongation is almost similar to elongation of jute fibres which have a low extension at break of 1-2%[17].

2) Fibres from the top section

The top section fibres had an average strength of 0.1494kgf. This gave the fibres a tenacity of 39.79cN/tex the strength of these fibres is within the range for jute fibres which have a tenacity of between 30-45cN/tex[17]. This strength is intermediate strength between bottom half and the weaker root section fibres. The strength can be attributed to higher fibre maturity of the top section fibres in comparison to the root area fibres. The top section fibres had elongation of 1.17%.

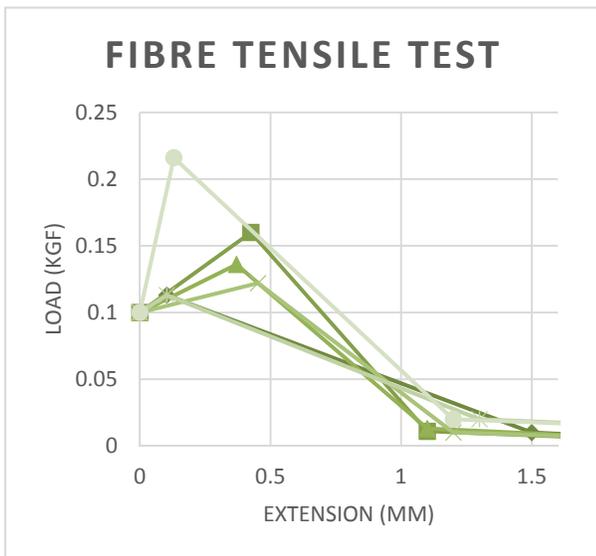


Fig 8–Load/extension curve for Cotton stalk fibres from top section

3) Fibres from the Root Section

The fibres from the root area of the cotton stalks had the lowest strength in comparison to fibre from the top and bottom section of the cotton stalk. This could be attributed to the low fibre maturity of the fibres.

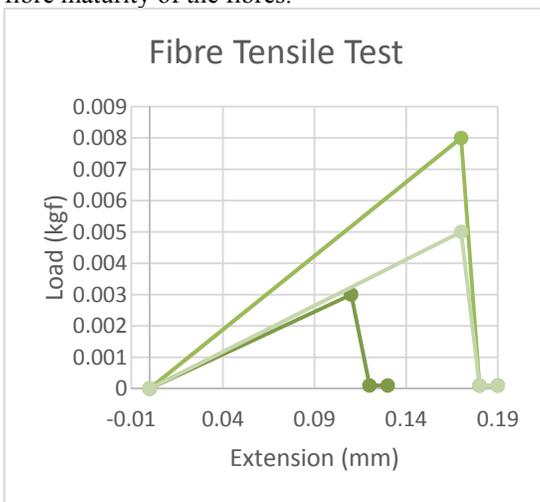


Fig 9– Load/extension curve for Cotton stalk fibres from root section

The mean fibre tenacity for fibres from the root section was 0.00533kgf. The calculated fibre tenacity of gave the fibres a tenacity of 2.21cN/tex. This tenacity is very low these fibres were over matured and had little strength. The elongation of the root area fibres is 0.43%. These fibres have the lowest strength and elongation of all the fibre from different sections of the cotton stalk.

C. Moisture Regain

Moisture content of natural fibre is an important criteria that needs to be considered in choosing natural fibre as reinforcement material. This is due to the fact that moisture content affects dimensional stability, electrical resistivity,

tensile strength, porosity and swelling behaviour of natural fibre in composite material [18]. Fig 10 shows the moisture regain of cotton stalk fibres from different sections of the cotton stalk.

The fibres located in the root section had the highest moisture regain which was 11.14%. The fibres located in bottom section of cotton stalk had a moisture regain of 10.2% which is lowest due to the higher fibre maturity.

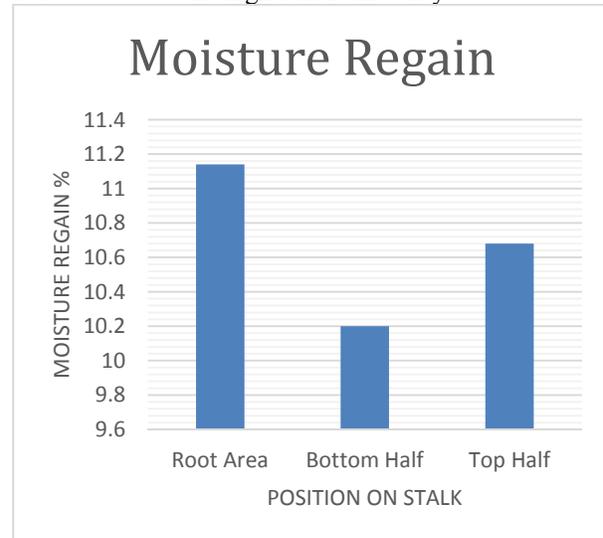


Fig 10 Moisture Regain for cotton stalk fibres

The diameter of the fibre increases as the plant matures however in contrast the moisture content and water absorption seems to decrease [18]. The fibres located in the top section of the stalk had a moisture regain of 10.68% which was less than the root area but higher than the bottom half of the stalk. The moisture regain of cotton stalk fibres is slightly less than that of hemp which has a moisture regain of 12% [19].

D. Fibre Diameter

The diameter of the cotton stalk fibres decreases from the root section going up the stalk. The root section fibres have the highest diameter at 0.2900mm. The diameter of the fibres in the bottom section is 0.2335mm a decrease in diameter of 19.48%.

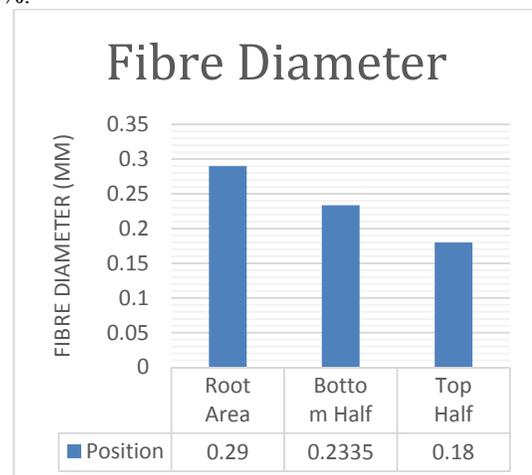


Fig 11–Fibre Diameter for cotton stalk fibres

The diameter of the fibres located at the top area of the cotton stalks is 0.18mm a decrease of 22.91% from the fibres in the bottom half of the stalk. The diameter of the cotton stalk fibre is similar to that of sisal fibres which range from 0.2-0.4mm in diameter. The diameter of Zimbabwe cotton stalk fibres is higher than that of Sudanese and Iranian cotton stalk fibres. The fibre diameter of Sudanese cotton stalk fibres is 18.2um and that of Iranian cotton stalk fibres is 23.88um[13].

E. Fibre Fineness

The fibres from the root area have average linear density of 2.36tex. This section gives fibres with the lowest linear density from the cotton stalk. The bottom section fibres give linear density of 3.938tex which is an increase of 66.86% from the root area fibres. The bottom section fibres have the highest linear density relative to the stalk. The top section fibres have linear density of 3.683tex which is less than the bottom section fibres but more than root section fibres.

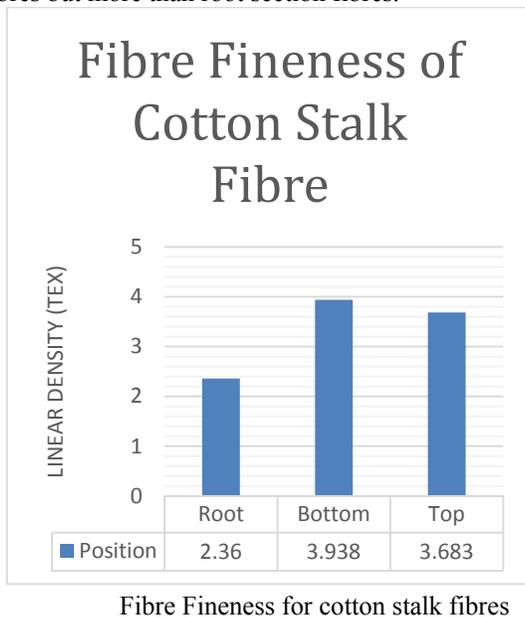


Fig 12 –

Fibre Fineness for cotton stalk fibres

F. Fibre Density

The bottom section fibres of the cotton stalk had density of 1.72g/cm³. This could be attributed to the high fibre maturity in this region. The root area fibres had the lowest density at 1.45g/cm³. The top area fibres had density of 1.85g/cm³.

G. Microscopic Examination

The cross sectional view shows that cotton stalk fibre is made up of several fibre cells. These fibre cells are held together by resin like material called lignin. The elementary fibrils and bundles are cemented by lignin and pectin intercellular substances[17]. The microscope image showed micro fibrils held in a shiny brown resin like material. There were less pores and voids on the top section as compared to the middle and bottom section fibres.

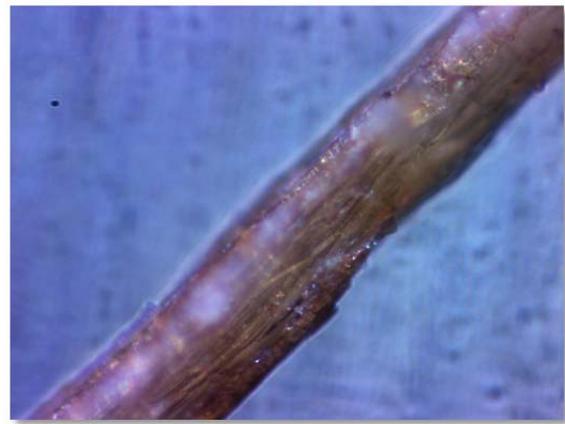


Fig 13 Microscopic image of cotton stalk fibre 4X magnification

The cotton stalk fibres are similar in appearance to jute fibres which are colourful and glassy[14].

IV. CONCLUSION

The extracted cotton stalk fibres had properties that made them suitable for use in fibreboard manufacture with resins such as urea formaldehyde and phenol formaldehyde for use as partition boards and furniture applications. The cotton stalk fibres from the bottom section have very good tenacity of 56.3cN/tex and the highest extension of 1.35%. Fibres from the top section of the stalk had tenacity of 39.79cN/tex and fibres from the root section were over mature and had very little strength of 2.21cN/tex. The cotton stalk fibre has length of 7.04cm for root section fibres, 9.08cm for bottom section fibres and 9.42cm for top section fibres. Effective utilisation of the cotton stalk to create fibre board has the potential to create value addition to the cotton farmer as more revenue can be obtained from the cotton plant especially in these difficult times when the price of cotton is at a low in Zimbabwe.

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