PRODUCTION AND CHARACTERISATION OF A BIO-COMPOSITE FROM COTTON STALK FIBRE AND PHENOL FORMALDEHYDE RESIN

BY

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DECLARATION

DECLARATION BY THE CANDIDATE:
I declare that this thesis is my original work and has not been presented for a degree in any other University or educational institute. No part of this thesis may be reproduced in any form without the prior written permission of the author and/or Moi University.

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DEDICATION

My humble effort I dedicate to my sweet and loving parents

Mr. George Nkomo and Mrs. Sikhangezile Nkomo

Whose affection, love, encouragement and prayer make me able to get such success and honour

ABSTRACT

Cotton stalks are a by-product of cotton farming. Approximately two to three tonnes of cotton stalk are generated per hectare of cotton farmed, making available in Zimbabwe about a million tonnes of cotton stalks every season. The cotton stalk is normally burnt to avoid pest infestations such as pink bollworm and mealybug, but this pollutes air emitting greenhouse gases. The current study, therefore, aims at finding an alternative use of the cotton stalks through production of a bio-composite based on phenol formaldehyde resin. Cotton stalks were collected from Umguza cotton farming district in Zimbabwe. The stalks were subjected to natural retting for 3 weeks followed by manual decortications to extract fibres. The fibre yield from extraction process was about 23%. The physical and mechanical properties of extracted fibres were characterized and categorized according to their relative position along the cotton stalk as top section, middle section and root section fibres. The cotton stalk fibres had a light brownish colour and their fibre length was determined as 8.18 cm. The moisture regain of the fibres was 11.14%, 10.68% and 10.20% for root, middle and top fibres, respectively. The fibres had an average diameter of 0.23 mm, breaking extension of 1.5% and density of 1.45g/cm^3. The test results were analysed using Statistical Package for the Social Science and Minitab statistical software. The fibres were used to fabricate a composite using phenol formaldehyde resin following a hand layout process. The mass fraction (M_f) was increased from 0-38%and the density maintained between 650-900 kg/m^3. The cost of producing the bio-composite was \$5.80/m^2 which was cheaper than boards available in the market which cost approximately \$5.56/m^2. The board tensile strength varied between 2.3 MPa to 6.8 MPa depending on the M_f while the flexural strength ranged between 46.39-170.00MPa. From the determined properties of the fabricated composite, it can be concluded that it has adequate mechanical properties comparable to solid wood in several applications such as ceiling panels, partition boards and table tops. As a recommendation steam explosion for fibre extraction can be studied as faster method to extract cotton stalk fibres. As further study the shive that is a by-product from fibre extraction can be ground and used as a potential composite filler material.

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LIST OF ACRONYMS AND ABBREVIATIONS

ABBREVIATION	DEFINITION
AMA	Agricultural Marketing Authority
ASTM	American Society for Testing and Materials
CRI	Cotton Research Institute
EC	Electrical conductivity
EPA	Environmental Protection Agency
GHG	Green House Gases (GHGs)
MDF	Medium Density Fibreboards
MDG's	Millennium Development Goals
MDI	Methylene Diphenyl Dilsocynate
MF	Melamine Formaldehyde
NUST	National University of Science and Technology
PB	Particle Boards
RTM	Resin Transfer Moulding
SDG's	Sustainable Development Goals
UF	Urea Formaldehyde
VARTM	Vacuum Assisted Resin Transfer Moulding

LIST OF SYMBOLS AND NOMENCLATURE

SYMBOL	DEFINITION
ρ_f	Density of fibre
ρ_m	Density of resin
M_f	Fibre mass fraction
V_f	Fibre volume fraction
μS/cm	Micro-Siemens/cm
ε	Strain
ε	Strain
σ , τ	Stress
W_f	Weight of fibres
W_m	Weight of resin

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CHAPTER 1 : INTRODUCTION

1.0 INTRODUCTION

Cotton farming in Zimbabwe is of great importance to the economy of the country as it is the second largest export crop after tobacco (Esterhuizen, 2015). Cotton stalks are a by-product of cotton farming and the current use of cotton stalks is reviewed in this project. The abundance of waste cotton stalks in the country and their suitability in the fabrication of bio-composite leads to the concept of this project. This study will be limited to cotton stalks collected from Umguza district in Zimbabwe. Problems associated with the disposal of cotton stalks are also highlighted.

1.1 BACKGROUND OF THE STUDY

Cotton (the *Gossypium hirsutum L* species) is one of the most economically viable crops in Zimbabwe. Cotton popularly known as "White Gold" is grown primarily for fibre and oil seed all over the world. In the 2014 farming season Zimbabwe produced 145000 tonnes of cotton (Nyamwanza Tonderai, 2014). On average about two to three tonnes of cotton stalk are generated per hectare of land farmed (R.M.Gurgar, 2007). Most of the cotton stalk produced is treated as waste, fuel or stock feed for cattle (R.M.Gurgar, 2007). The bulk of the cotton stalk is burnt in the fields after the harvest of the cotton crop although this is not desirable as it causes air pollution.

The cotton crop is farmed mainly in the western part of Zimbabwe in regions of Gokwe, Sanyati, Umguza region and in the northern areas such as Guruve, Muzarabani and Mt Darwin. Checheche also have cotton farms. On a large scale, cotton is grown in Chinhoyi, Mazowe, Rafingora and Triangle. Cotton growing continues to sustain livelihoods of farmers and is a major income generation sector for Zimbabwe (C.KAravina, 2012). Cotton in Zimbabwe is predominantly farmed by small scale farmers situated in marginal

rainfall areas on plots of average size of between one and two hectares (Esterhuizen, 2010).

The yield of biomass of the cotton stalk varies from species to species; it is highest in case of hybrids and lowest in the case of *Gossypium arboreum* species. The cotton stalk is a great resource as a raw biomass material for manufacturing value-added bio-composite products (Tao Lin, 2011).

Zimbabwe's forest and woodland resources are under increasing threat from the expansion of agriculture, urbanisation and local use for construction and fuel. Despite their importance, the current tenure systems and incentives do not encourage investments in forest and woodlands (Yemi Katerere, 1998). This necessitates the development of alternate material for furniture and wooden board applications to reduce the rate of deforestation. Cotton stalks can be fabricated into a composite such as fibreboard and this will help to alleviate the problem of dwindling forest resources as it will be an alternative to solid wood boards working towards meeting Sustainable Development Goals 15 (SDG 15) which emphasises the preservation of natural resources. Figure 1-1 shows a map of the cotton farming areas in Zimbabwe.

Figure 1-1– Cotton growing areas in Zimbabwe (Stabex 1996 cotton training centre, 1995)

Cotton stalks have potential end uses in the manufacture of medium density fibreboard, preparation of pulp and paper, hard boards, corrugated boards & boxes, microcrystalline cellulose, cellulose derivatives and as a substrate for growing edible mushrooms (A.J.Shaikh, 2010). Medium density fibreboard [MDF] is defined as "a composite panel product typically consisting of cellulosic fibres combined with a synthetic resin or other suitable bonding system and joined together under heat and pressure" (A.J.Shaikh, 2010). Cotton stalk fibres can be used as reinforcement for medium density fibreboards. In this project cotton stalk fibres will be used as reinforcement in a bio-composite with phenol formaldehyde as the resin in the manufacture of fibreboards.

1.2 STATEMENT OF THE PROBLEM

Cotton stalks kept in the fields after harvest are a breeding ground for pink bollworm (*pectinophora gossypiella*), boll weevil, cotton mealybug (*phenacoccus solenopsis*) and other pests. The cotton stalks must be destroyed to prevent these pests from breeding. This presents a disposal problem to the cotton farmer. The farmers burn these cotton stalks in the field as the disposal method. Burning of cotton stalks causes air pollution contributing to global warming. Approximately 0.85 million metric tonnes of CO_2 is produced per million metric tonnes of cotton stalk burnt (C.Sundaramoorthy, 2009). There is therefore a need to come up with more environmentally friendly methods of disposing of the cotton stalks. Due to the low cotton prices and expensive implements some cotton farmers tend to grow ratooned cotton due to the perennial nature of cotton. The Agricultural, Technical and Extension Services (AGRITEX) has warned farmers in Muzarabani and Mt Darwin against growing ratooned cotton in their districts (The Herald, 2007). This gives poor yield of cotton and poor quality fibre. It also encourages the carryover of pests and creates a quality problem. The current deforestation rate in Zimbabwe is pegged at 326 000 hectares per year (Fao forestry paper 163, 2010). Deforestation has many ramifications and there is a need to curb this massive deforestation. According to the National forestry commission, in 50 years there is a possibility of complete deforestation of certain parts of the country (Fao forestry paper 163, 2010). Various methods have been tried to curb deforestation among these was the need for artificial timber which can be used as a substitute to the real timber. Use of waste bio materials such as cotton stalks, bamboo and other bast plants to fabricate artificial boards such as fibreboards and particleboards as alternative product to solid wood boards may help reduce deforestation.

1.3 JUSTIFICATION OF THE STUDY

In accordance with lean manufacturing there is need to eliminate or minimise waste generated in processing. Utilisation of waste cotton stalks will help to streamline the cotton farming process and limit wastage and this will help in accomplishing lean processing of cotton.

Fabrication of composites such as fibreboards from cotton stalks can create an industry which can be adopted on a commercial scale. This research can bring out an industry of converting waste cotton stalks into usable manufactured products such as fibreboards and in the process create employment opportunities and generate additional revenue for cotton farmers.

The research will contribute in reducing the problem of deforestation in Zimbabwe. In 2010 total forested area in Zimbabwe was 15.6 million hectares, but the country has been losing its forest at a rate of 326,000 hectares per year (Fao forestry paper 163, 2010). From 1990 to 2010, the country was one of ten countries with the largest annual net loss of forest area (Fao forestry paper 163, 2010). The study has relevance in that fibreboards can replace solid wood in some of the application putting less strain on the forests there by reducing rate of deforestation.

The study will help to alleviate the problem of air pollution due to burning of cotton stalks. The practice of burning of the cotton stalks results in the emission of greenhouse gases (GHGs) (C.Sundaramoorthy, 2009). The growing challenge of growing emissions from greenhouse gases is one of the most significant challenges facing the world community.

The resin normally used to produce particle boards is urea formaldehyde which is carcinogenic (Gary Davis, 2001) and not environmentally friendly. This is due to the high emission of formaldehyde from the resin. Formaldehyde is a probable human carcinogen

when inhaled or ingested (Gary Davis, 2001). Chronic formaldehyde can cause menstrual disorders and pregnancy problems in women workers exposed to higher levels. Short term inhalation exposure can result in eye, nose and throat irritation and respiratory symptoms (Gary Davis, 2001). However, use of an alternative resin such as phenol formaldehyde which has 90% less formaldehyde emission can help in overcoming this problem. Urea formaldehyde resin also has low resistance to water compared to phenol formaldehyde resin. Boards made using urea formaldehyde tend to undergo unfavourable reaction when exposed to water which weakens the boards. Phenol formaldehyde resin has better resistance to water and will be used in this project due to its advantages and lower formaldehyde emission (Sivasubramanian, 2009). Phenol formaldehyde has higher cross linking density which makes it have lower formaldehyde emissions in use.

1.4 SIGNIFICANCE OF THE STUDY

i. This study will help to reduce rate of deforestation in Zimbabwe as the developed fibreboard will give an alternative to solid wood in certain applications.

ii. The research can create value addition to cotton farming through utilisation of the waste cotton stalks making the crop more profitable for cotton farmers especially during these trying times when the cotton prices are low and cotton farming is facing viability challenges.

iii. The study if implemented can create a means of disposing of cotton stalks in an environmentally friendly manner unlike the current method where the cotton stalks are burnt causing air pollution.

iv. The study has potential to create small industries with people employed in processing waste cotton stalks to make fibreboards. This can help in reducing the high rate of unemployment that the country is currently facing.

1.5 MAIN OBJECTIVE

To produce a bio-composite consisting of phenol formaldehyde resin and cotton stalk fibers and assessing its properties for structural applications.

1.6 SPECIFIC OBJECTIVES

The specific objectives of the study are:

i. To extract and characterize mechanical and physical properties of cotton stalk fibres.
ii. To fabricate a bio-composite from cotton stalk fibre and phenol formaldehyde resin.
iii. To characterize mechanical and physical properties of the produced bio-composite.
iv. To compare the mechanical properties of the bio-composite to commercially available similar materials: fibreboards, particleboards and solid wood boards.

1.7 SCOPE OF THE STUDY

The study is restricted to cotton stalks collected from farms in Umguza district in Zimbabwe. This area was selected as it representative of the cotton species farmed in the country and supervised by a resident cotton research institute officer hence proper procedures used in cotton farming were followed religiously. Umguza was also selected for its close vicinity to Bulawayo town making the transporting of cotton stalks easier. Figure 1-2 shows a map of Matabeleland region showing Umguza cotton farming area.

Figure 1-2 – Umguza cotton stalk sampling area on map of Bulawayo

CHAPTER 2 : LITERATURE REVIEW

2.0 INTRODUCTION

Environmental concerns have in the recent year's stimulated research in the exploitation of renewable resources. Such resources make economic sense when they relate to utilisation of waste material such as cotton stalks in the manufacture of composite materials. A composite material is composed of two or more materials joined together to form a new medium with properties superior to those of its individual components. Often, the term composite is used for fibre-reinforced composites, although other different forms of reinforcement exist.

2.1 COTTON IN ZIMBABWE

The cotton industry in Zimbabwe remains under severe stress (CRI, 2015). As price of cotton started to decline, most farmers abandoned the cotton crop for more lucrative crops such as tobacco. The graph in Figure 2-1 shows the trend in cotton production in Zimbabwe from 2004 to 2013.

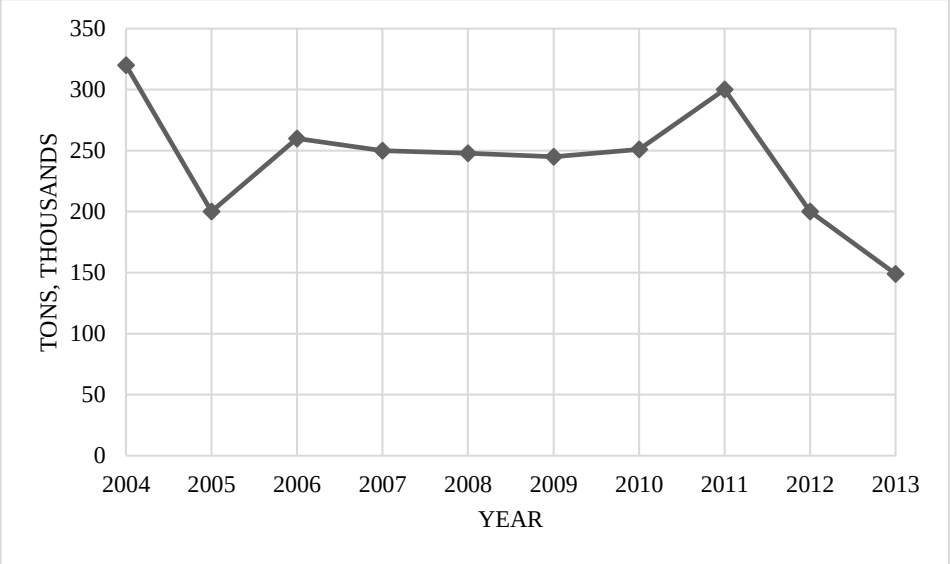

Figure 2-1 – Graph showing trend in Zimbabwean seed cotton production 2004-2013 (Zimbabwe cotton to clothing strategy 2014-2019)

National output of cotton declined from 250 000 tonnes in 2012/13 to 143 000 tonnes in 2013/2014 season, a decrease of 42% (Nyamwanza Tonderai, 2014). Cotton planting in the low veld region of Zimbabwe is carried out from 5 October and in the middle veld region from 20 October (Mseva, 2011).

There are three types of cotton varieties farmed in Zimbabwe the commercial variety Albar SC 9314 and two other varieties still under research CRI MS1 and CRI MS2. The properties of these cotton varieties are summarized in Table 2-1.

Table 2-1 – Cotton varieties farmed in Zimbabwe (CRI, 2015)

Key attributes	**Albar SC 9314**	**CRI MS1**	**CRI MS2**
Staple Type	Medium	Medium	Medium
Altitude	200-1150m asl (Middleveld, Lowveld)	200-1500m asl (Middleveld and also Lowveld)	200-1500m asl (Lowveld and also middleveld)
Yield Potential: Dryland Irrigated	1500-2000Kg/ha	1500-2600Kg	1600-2300Kg/ha
Yield Potential irrigated	2000-4000Kg/ha	2600-4300Kg/ha	3400-4200Kg/ha
Harvest Time	5-8 months	5-8 months	5-8 months
Preferred spacing	0.3mX1.0m	0.3m X1.0m	0.3mX1.0m
Maturity	Late maturity especially under high input conditions	Early maturity	Early maturity
Strength of cotton fibres (HVI)g/tex	28.6-29.4mm	28-29mm	28-29mm
Micronaire of cotton fibres	3.8-4.5	4.1-4.6	4.1-4.6
Length Uniformity	48%	>80%	>80%

Cotton is an important cash crop for many rural households in Zimbabwe and also of great importance to Zimbabwe's economy, representing the major source of cash income for some farmers and principal source of export earnings for the country as a whole. Table 2-2 shows the percentage dependency of farmers on the cotton crop according to districts.

Table 2-2 – Extent of farmer dependency on cotton (Mahofa, 2007)

Area	**Percentage Dependency**
Gokwe and parts of Sanyati	90%
Hurugwe, Chinhoyi, Karoi, Doma, Kadoma	70%
Glendale, Bindura, Mount Darwin, Rushinga, Mukumbura, Guruve, Greater Part of Muzabani, Ngundu, Zaka	50%
Checheche, Chipinge	60%

2.2 COTTON STALK

Cotton is cultivated primarily for textile fibres, and little use is made of the cotton plant stalk. The cultivation of cotton generates plant residues equivalent to three to five times the weight of the fibre produced (Reddy N, 2009). After harvesting the cotton bolls, the entire plant consisting of the stalk and leaves is a residue which remains in the field and the farmers usually destroy it by burning (Binod P, 2011). Burning of cotton stalks in the field is the preferred method as they would harbour several insects and pests which would be harmful to the future crop (A.J.Shaikh, 2010). The cotton mealybug Phenacoccus solenopsis Tinsley (Hemiptera: Pseudococcidae) has been described as a serious invasive polyphagous pest with a vast host range (M.Vinobaba, 2014). This mealybug is now a threat to Zimbabwe cotton crops and finds its food supply from the cotton stalk. It has become a substantial threat to the cotton crop. Figure 2-2 shows an image of the polyphagous mealybug.

Figure 2-2 - Picture of highly destructive, polyphagous mealybug (Silva, 2012)

Most of the cotton stalk is treated as waste and a small part of it is used as fuel by the rural people and some as animal feed. 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 (C.Sundaramoorthy, 2009). By law in Zimbabwe cotton stalks must be destroyed promptly after harvest to create a "dead period" or closed season to prevent build-up of pink bollworm, mealybug and boll weevil (Mseva, 2011). Besides the management of boll weevil and pink bollworm, suppression of other pests is also enhanced by prompt stalk destruction. The adult boll weevil feeding on squares or bolls for approximately 3 weeks commonly enters a state known as diapause which allows it to survive throughout the off season in a dormant state (Kate Hake, 1991).

Re-growth of cotton or ratooned cotton provides an ideal food source for insects such as aphids and sweet potato whitefly (Kate Hake, 1991). White flies and aphids build on cotton regrowth, creating a larger population for the next crop (Kate Hake, 1991).

Several herbicides have been developed for cotton stalk destruction these include 2,4-D (ester and salt formulations), several dicamba products and Harmony Extra (thifensulfuron-methyl + tribenuron-methyl). However, research regarding the best

approach for using herbicides for cotton stalk destruction is somewhat limited and continued field research is necessary to determine the best approach of their application (Robert Lemon, 2003).

Burning agricultural residues causes environmental problems such as air pollution, soil erosion and decreases soil biological activity (Copur Y, 2007). On average around 0.85 million metric tonnes of CO_2 equivalent is released per million tonnes of cotton stalks burnt (Alban Yzombard, 2014). Table 2-3 shows a quantification of greenhouse gases emitted per million metric tonnes of cotton stalk burnt in the field.

Table 2-3 – Showing emission of greenhouse gas per million tonnes of cotton stalks burned in field (al, 2008)

Green House Gas	**Emission Factor ($g.kg^{-1}$)**	**Total Emission (Mn MT)**	**Total Emission (Mn Mt Co_2e)**
NO_x	2.68	0.00265	0.7898
CH_4	2.7	0.0027	0.0675

**NO –Nitrous oxide, *CH_4 – Methane, *Mn Mt Co_2e – Million Metric tonnes of carbon dioxide equivalent*

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. (A.J.Shaikh, 2010).

With respect to structure and dimensions, cotton stalk is similar to common species of hardwood fibre (Mbarak, 1975). The stalk is about 33% bark and quite fibrous. For particleboard production cotton stalks can be hammer milled like other materials. For fibreboards, cotton stalks can be refined with or without chemical treatment depending on the quality of fibre desired (Brent English, 1997). Newsprint quality paper can be made from whole cotton stalks.

Cotton stalk contains about 69% holocellulose, 27% lignin and 7% ash (CFC, 2010). The chemical constitution of the cotton stalk is dependent on the species grown. Table 2-4 shows a comparison of the chemical constituents of cotton stalks compared to hardwood.

Table 2-4 – Showing properties of cotton stalks compared to hardwood (Solution for Making Good Cotton Stalk Pellets, 2012), (P.G & R.M, 2007)

Property	**Cotton Stalk**	**Hardwoods**
Hemicellulose (%)	30.00 - 31.50	19.0 - 30.6
Cellulose (%)	45.00 - 47.80	40.0 – 50.0
Lignin (%)	20.00 - 21.20	30.0 -35.0

Cellulose which is a major constituent of all natural plant life constitutes 45-47.80% of the cotton stalk chemical structure in comparison to hardwood which has between 45-50% cellulose content. Cellulose is a natural polymer consisting of D-anhydroglucose ($C_6H_{11}O_5$) repeating units joined by 1,4-b-D-glycosidic linkages at C1 and C4 position (Nevell, 1985). Cellulose is a skeletal polysaccharide, ubiquitous in the plant kingdom and one of the commonest naturally occurring fibrous materials (Mwaikambo, 2006). Each repeating unit contains three hydroxyl groups.

Hemicellulose is a dominant part of the cotton stalk making up about 31.5% of the chemical constituent. It is not a form of cellulose and the name is a misnomer (Maya Jacob John, 2007). It comprises of a group of polysaccharides composed of a combination of 5- and 6-carbon ring sugars. These hydroxyl groups and their ability to hydrogen bond play a major role in directing the crystalline packing and also govern the physical properties of cellulose.

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. Lignin is totally amorphous and hydrophobic in nature it is the compound that gives rigidity to the plants. It is thought to be a complex, three-dimensional co-polymer of aliphatic and aromatic constituents with very high molecular weight.

Cotton stalks consist of an outer bark 33% by weight and an inner pith. The outer bark is fibrous and can be utilized as a source of fibres (Narendra, 2014). Cotton stalk contains

about 16% strong bast fibres (M Miao, 2015) these fibres can be used as reinforcement in polymeric composite materials (M Miao, 2015). The cotton stalk fibres have breaking tenacity of 2.9g/den, breaking elongation of 3% and modulus of 144g/den (Narendra R, 2009). The bast fibres extracted from cotton stalk have been shown to be a good reinforcement for polymer composites with mechanical performance similar to that of flax and hemp fibre reinforced composites (M Miao, 2015). The cotton stalk is plagued with parasites, and stored stalks can serve as breeding ground for parasites to nest and attack the next batch of crop. Attempted commercialization of cotton stalk particleboard in Iran was unsuccessful for this reasons (Roger M. Rowell, 1997).

The use of cotton stalk in particle board industry has two fold benefits. Value added utilisation of cotton stalk such as in the manufacture of particle boards can bring income for the cotton farmer as well as the removal of stalks from the farm averting the carryover of pests likely to be hibernating in immature and unpicked bolls left in the plant (CFC, 2010). Furthermore, the use of cotton stalk for board manufacture will have benefit of partially reducing the demand for solid wood resulting in decreased rate of deforestation. Utilisation of cotton stalk in particleboard and fibreboard industry also reduces the environmental problem of air pollution resulting from disposing of cotton stalks by burning them in the fields. Cotton stalks can be subjected to a cleaning system prior to storage by use of water jets an air blowing chamber and air suction system to remove any pests that are in the stalks and prevent their breeding.

2.3 BAST FIBRES AND EXTRACTION METHODS

Bio-fibres can be considered to be composites of hollow cellulose fibrils held together by a lignin and hemicellulose matrix (Jayyaraman, 2003). There are various methods of extraction of bast fibres. The fibres are usually freed from the stalk by retting but can sometimes be obtained by decortication, a manual or mechanical peeling operation.

Another method of extraction uses steam explosion, also known as steam explosion pulping, flash auto hydrolysis or steam cracking. The principle of steam explosion works by means of applying saturated steam usually at pressures of up to 40 atmospheres to biomass material which can involve wood or non-wood forest material, agricultural waste and fibre material (Xiuliang Hou, 2014). The treatment time varies from some seconds to some minutes (Silvija Kukle, 2011). After the desired time, the ball valve is opened which results in explosive decompression and disintegration of the biomass material (Maha M. Ibrahim, 2010). This methods outlined have the disadvantage of requiring specialised equipment in order to accomplish fibre extraction. Retting is a much more simple method with minimum requirements and much cheaper to carry out.

Retting is a process of controlled degradation of the plant stem to allow the fibres to be separated from the woody core and thereby improving the ease of extraction of the fibres from the plant stems (Das PK, 2010). Retting dissolves the pectin glue between the bast fibre bundles (Sultana C, 1992). Effective retting involves degradation of pectin and other cementing materials, which act as binding agents between the individual bast fibres as well as between fibre bundles and the epidermal and core tissues (W.H. Morrison III, 1999).

Imperfect retting cause defects in fibres which cause processing difficulties for the industry. There are a number of common defects. Rooty fibre, centre root, runner, *hunka* in all these defects the fibre is masked by barks. In rooty fibre, barks remain at the bottom, in centre root at the central region, in runners along the entire half of the bottom and in *hunka* all over the stem. Figure 2-3 shows photographs of common bast fibres.

Figure 2-3 – Picture of Common bast fibres (M.Nayeem Ahmed, 2013)

This is normally due to unusual developments in some portions of the plant or due to improper retting (Akhter, 2001).

If fibres are not well cleaned after extraction it leads them to form what is known as creepy fibres. Creepy fibres is where the top ends of the fibres are rough and hard and those held together by undissolved and undecomposed gummy substances are called gummy. Sticky fibres are those that are not properly cleaned after extraction and these may contain adhering sticks.

If the retting water used has strong iron content it gives rise to *shamla* fibres which are dark coloured. *Shamla* fibres is where by the presence of iron in retting water or the use of weighting materials rich in tannin impart dark colour to the fibre.

In bast stems the useful fibres are present as bundles towards the outer area of the stem. For composite reinforcement, the aim is usually to obtain fibres which are 50-100 μm in diameter and can be 100-300mm long. These technical fibres are actually themselves bundles of approximately 40 elementary fibres (cells) which may be 10-20 μm and 20-50mm long. Bast fibres are found in the outer portion of the stem, with woody core

material known as shive (Hughes, 2015). Figure 2-4 shows how a typical cross section of a bast fibre looks like.

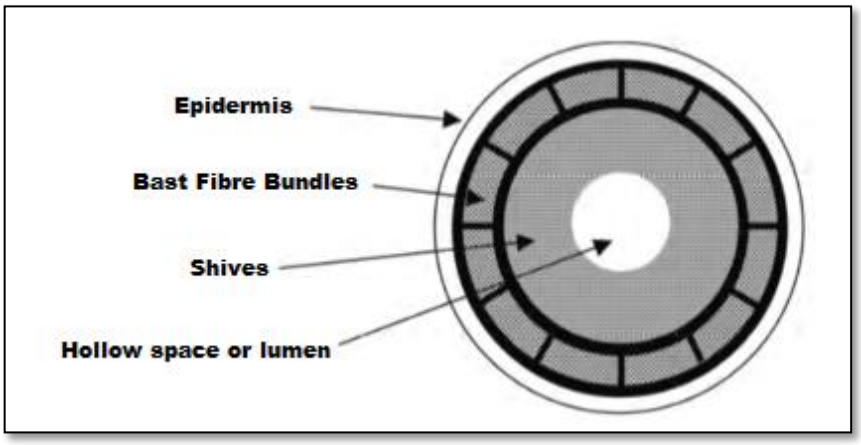

Figure 2-4 – Cross section of a bast stem (Eriksen, 2002)

Most available methods of retting rely on the biological activity of microorganism, bacteria and fungi from the environment to degrade the pectin polysaccharides from the non-tissue and, thereby, separate the fibre bundles. Microbial/enzymatic retting is one of the widely used techniques (S.Kalia, 2011). The quality of the fibres is largely determined by retting condition and duration. The quality of the water also affects the quality of the fibres. Apparently there is no single method that can give optimum results in terms of retting period, fibre strength, environmental pollution and cost.

Bast fibres are obtained from the stems of various dicotyledonous plants. Botanically the term bast fibre is synonymous with phloem, the food conducting tissue of vascular plants. Table 2-5 shows some of the properties of common bast fibres. Most of the natural fibres are relatively cheap to extract and prepare for use. Hence natural fibres have attracted the attention of scientists and engineers for applications in the consumer industry.

Table 2-5 – Mechanical and physical properties of plant fibres (Review of the history, 2006), (J Holbery and D.Houston, 2006)

Fibre Type	*Diameter*	*Density*	*Elongation*	*Length*	*Tensile Strength*	*Aspect ratio*	*Moisture regain*	*Specific Tensile Strength*	*Young modulus*	*Specific Young's modulus*	*Failure Strain*
	um	*g/cm³*	*%*	*mm*	*MPa*	*(l/d)*	*%*	*MPa*	*GPa*	*GPa*	*%*
Bamboo	10-40	-		2.7	575	-	-	383	27	18	-
Flax	17.8-21.6	1.5	2.7-3.2	27.4-36.1	500-900	1258	12.00	345-620	50-70	34-48	1.3-3.3
Hemp	17.0-22.8	1.47	2-4	8.3-14.1	310-750	549	12.00	210 - 510	30-60	20-41	2-4
Jute	15.9-20.7	1.3	1.5-1.8	1.9-3.2	200-450	157	17.00	140-320	20-55	14-39	2-3
Kenaf	17.7-21.9	1.45	1.6	2.0-2.7	295-1191	119	17.00	-	22-60	-	-
Ramie	28.1-35.0	-	3.6-3.8	60-250	915	463.9	8.550	590	23	15	3.7

It has been observed that the natural fibre reinforced composites provide better electrical, thermal and acoustic insulation while they offer higher resistance to fracture (Girisha K G, 2014).

2.3.1 Retting methods

The following section outlines the possible retting methods that can be used for bast fibres.

2.3.1.1 Chemical retting

Chemical and surfactant retting refers to retting in which the fibre crop is submerged in heated tanks containing water solutions of sulphuric acid, chlorinated lime, sodium or potassium hydroxide and soda ash to dissolve the pectin component. The surface active agents in retting allow the simple removal of unwanted non-cellulosic components adhering to the fibres by dispersion and emulsion-forming process. Chemical retting is more harmful than other retting methods to both the environment and the fibres themselves (Deck Towel, 2015).

2.3.1.2 Water Retting

This is a process of retting fibres by leaving the stalks in ponds or tanks of water. The ponds used contain running water. Water retting is the most widely employed practice and produces the highest quality fibres. This practice is an extremely low cost method of retting (Nabilah Huda A.H, 2012). It is best done in stagnant or slowly moving waters

like ponds, bogs and streams (Deck Towel, 2015). The stalks are soaked in freshwater tanks where a pectinolytic bacterial community is developed (Donaught J.A, 1990) the bacteria rots the stalk separating the fibres from the woody core. The water, penetrating to the central stalk portion, swells the inner cells, bursting the outermost layer, thus increasing absorption of both moisture and decay producing bacteria. This process takes 2-4 weeks for dam retting and can also be done in tanks containing warm water which reduces the retting time to a few days (Sustainable Fibres and Fabrics, 2010). As a general rule the more stagnant the water source, the more abundant the bacterial fauna and the faster the retting process.

Tank retting takes place in large vats that are normally made of cement, as the acidic waste products of the bacteria corrodes the metal. Retting must be carefully judged; under retting makes separation difficult and over retting weakens the fibre. Water retting gives a more uniform quality product. However, the nutrients from the decaying stalks mean that this method is highly polluting to the water source. The effluent from retting process can be filtered prior to disposal and treated to make it safe.

2.3.1.3 Dew Retting

In dew retting method the bast fibre stalks are left out in the field for 6 weeks and acted upon by the dew, sun and fungi. It is most effective in climates with heavy night time dews and warm daytime temperatures.

Dew retting tends to yield dark coloured fibre it is however less labour intensive and less expensive than water retting (Sustainable Fibres and Fabrics, 2010). Dew retted fibres are typically of poorer quality and more darkly pigmented than natural water retted fibres (Deck Towel, 2015). Dew retting is preferred in areas where the water sources are limited but have warm daytime temperatures and heavy night time dews. The stalks are spread out evenly in a grassy field where the combination of air, sun and dew cause fermentation

which dissolves much of the stem. Table 2-6 shows a comparison of the different type of retting methods and their duration.

2.3.1.4 Enzymatic Retting

During microbial retting the bacteria multiply and produce extracellular pectinases, which release the bast fibre from the surrounding cortex by dissolving the pectin (Paridah Md. Tahir, 2011).

2.3.1.5 Methods of steeping in retting

As stalks are harder at the bottom end and require more time to ret/rot there are steeping methods that can be followed such as the vertical and horizontal steeping method (Vastrad, 2013). In vertical and horizontal stepping method the bundles are placed in an upright position in the retting tank for a certain duration and then placed horizontally. As the stalks are harder at the bottom end they require a longer time to ret than the thinner top part, hence if the butt which is thicker is fully retted the top ends are over retted and damaged. This can be avoided by stacking the bundles of stems upright with the butt ends in water for few days before immersing the whole stem.

In horizontal steeping during retting process which is a traditional method followed by farmers the stalks are properly steeped into water horizontally by tying stones to the bundles.

Table 2-6 – Comparison of bast fibre extraction methods (Paridah Md. Tahir, 2011)

Type of Retting	Description	Advantages	Disadvantages	Duration of Retting
Dew Retting	Plant stems are cut or pulled out and left in the field to rot.	Pectin material could easily be removed by bacteria.	Reduced strength, low and inconsistent quality; restriction to certain climatic change and product contaminated with soil.	2-3 Weeks
Water Retting	Plant stems are immersed in water (rivers, pods) this is microbial retting.	Produces fibre of greater uniformity and good quality.	Extensive stench and pollution arising from anaerobic bacterial fermentation of the plant, high cost and putrid odor, environmental problems and low grade fibre. Requires high water treatment maintenance.	7-14 days
Enzymatic retting	Enzymes such as pectinase, xylanases etc. are used to attack the gum and pectin material in the bast. The process is carried out under controlled conditions based on the type of enzyme.	Easier refining particularly for pulping purposes that degrades and provides selective properties for different applications. The enzymatic reactions cause a partial degradation of the components separating the cellulosic fibre from non-fibre tissues. The process is faster and cleaner.	Low fibre strength	12-24 hours
Chemical Retting	Boiling and applying chemicals normally sodium hydroxide, sodium benzoate, hydrogen peroxide.	It is more efficient and can produce clean and consistent long and smooth bast fibre within a short time.	The fibre retted in more than 1% NaOH the tensile strength decreases. Unfavorable color and high processing cost.	75 minutes – 1 hour
Mechanical Retting	Hammering or fibres separated by hammer mill or decorticator.	Produces massive quantities of short fibre in short time.	High cost and lower fibre quality.	

2.3.2 Degumming rate

The efficiency of the retting process can be ascertained by the weight loss during retting. The weight loss represents how much of all the materials has been removed during the retting process (Peiying Ruan, 2015). The trend for degumming is consistent with the trend for weight loss such that in retting of flax the first 2 days of water retting contributed largely to both the degumming rate and weight loss, both of which become stable after 6 days. Table 2-7 shows the weight loss in the water retting of flax with different durations.

Table 2-7 – Weight loss of water retting with different durations for flax (Peiying Ruan, 2015)

Treatment	Weight loss (%)
2 days of water retting	5.54
6 days of water retting	8.69
10 days of water retting	9.66

Pectin which is a generic name for the acidic polysaccharides in the plant cell wall, contain both soluble and dissoluble pectin substances. At the beginning of the retting process, some of the soluble components of pectin, together with contaminating inorganic salts and dust, dissolve and settle in water (Sharma H. a., 1992) contributing to the weight loss in water retting. As the water retting progresses, the rest of the pectin components are degraded by enzymes generated from microorganisms and then dissolve, which contributes to the weight loss and degumming rate as well.

To increase pectin solubility and susceptibility to the degrading enzymes, the water used in the retting process should not be high in hardness and instead softened water with minimum amounts of calcium and magnesium should be used, since calcium bridges formed inside of pectin molecules in the presence of hard water restrain these effects (D.J, 1991). Water used should have a hardness of between 0-60mg/L.

2.3.3 Breaking or scutching

After the stem has been subjected to retting it is passed through fluted rolls to break up the woody material into pieces of shive. The shive can be used with lime cement to make bricks or can be made as animal bedding.

2.3.4 Hackling

Hackling involves mechanically combing or carding fibre bundles to separate the short and long fibres whilst aligning them and removing further debris.

2.3.5 Water quality

Water is an essential constituent of all forms of life. The retting process generates effluent water which must be characterised to facilitate safe disposal. Retting effluent is fully biodegradable. However, the quality of water after retting becomes degraded transitorily. The microbial load increases excessively and the water becomes discoloured (Biswapriya Das, 2011).

2.3.5.1 pH

pH is a measure of a solution's acidity. In water small number of water molecules will break apart or disassociate into hydrogen ions (H+) and hydroxide ions (OH-). Other compounds entering the water may react with these leaving an imbalance in the numbers of hydrogen and hydroxide ions. pH is measured on a logarithmic scale between 1 and 14 with 1 being extremely acid, 7 neutral and 14 extremely basic. Because it is a logarithmic scale there is a tenfold increase in acidity for a change of one unit of pH. It has been observed that with jute water retting there is a lowering of the pH of water and there is reduction in bicarbonate alkalinity (Saha M.N, 1999).

2.3.5.2 Total dissolved solids

Total dissolved solids (TDS) combines the sum of all ion particles that are smaller than 2 microns (0.0002 cm). This includes all the disassociated electrolytes that make up salinity concentrations, as well as other compounds such as dissolved organic matter. TDS is directly related to the purity and quality of water and affects everything that consumes,

lives in or uses water whether organic or inorganic. Dissolved solids refer to any minerals, salts, metals, cations or anions dissolved in water. This include anything present in water other than pure water and suspended solids. In general, total dissolved solids concentration is the sum of the cations and anions in the water. Parts per million (ppm) is the weight to weight ratio of any ion to water. The TDS increases after retting process due to the heavy organic matter that is deposited into the water restricting light penetration (Dipankar Ghosh, 2015).

2.3.5.3 Electrical conductivity of water

Electrical conductivity (EC) is a measure of water's ability to conduct an electrical current (Cobbina, 2013). The electrical conductivity of water estimates the total amount of solids dissolved in water TDS, which stands for Total Dissolved Solids. TDS is measured in ppm (parts per million) or in mg/l. The electrical conductivity gives a good indication of the salinity of the water but does not provide full information on the ion composition in the water. Electrical conductivity therefore indicates the presence of contaminants such as sodium, potassium, chloride or sulfate (Association, 1998). Significant increases in conductivity may be an indicator that polluting discharges have entered the water (Sharon Behar, 1997). In jute water retting the water used for retting becomes richer in nutrients this leads to an increase in the water conductivity due to the free ions introduced into the water (Dipankar Ghosh, 2015).

2.4 FIBRE CHARACTERISATION

There are a number of tests that are carried out on fibres to determine the behaviour and nature of the fibres. The physical and mechanical tests include tests for fibre length, fibre strength, fibre fineness and moisture regain of fibres.

2.4.1 Fibre strength

Single fibre tests are often carried out for research purposes not as routine industrial control tasks. Tests on single fibres can be carried out on a universal tensile tester with

the appropriate load cell and lightweight clamps. If fibres cannot be gripped directly in the testing machine jaws they are often cemented into individual cardboard frames which are themselves then gripped by the jaws. Factors affecting the strength of fibres are molecular weight, number and intensity of weak places, coarseness or fineness of fibre, relative humidity and elasticity (NPTEL, 2009):

The US standard (ASTM D3822) for single fibre strength test specifies gauge length of 12.7 mm or 25.4 mm and up to 40 fibres should be tested. The British standard specifies gauge length of 10, 20 or 50mm with testing speed adjusted in a manner that the sample fibre breaks in 20-30 seconds. The minimum number of tests is 50 and pretension is 0.5gf/tex. The results obtained are normally subject to less error if the gauge length is selected to be as large as possible, consistent with the length of the fibres to be tested.

In bundle fibre strength testing a bunch of fibres are put into two jaws of a universal tensile tester. The jaws are moved until the fibres break. The breaking load and elongation at break are noted and calculated as shown in equation 2.1.

$$\text{Tenacity of the fibre } \left(\frac{\text{G}}{\text{Tex}}\right) = \frac{\text{Breaking load in kg*Length of sample in mm}}{\text{mass of the fibres in mg}} \qquad \text{Equation 2.1}$$

When comparisons are to be made between different fibres or where it is necessary to obtain comparable results in different laboratories, it is advisable to use the same gauge length for all tests, selecting it to accommodate the shortest fibre of interest (ASTM, 2014).

Universal Tensile Tester

The Instron tensile tester works on the principle of constant rate of elongation. In constant rate of elongation, the specimen is extended at a constant rate and the force is a dependent quantity. One end of the sample is clamped into jaws which are controlled by a cross head that is traversed at a constant rate by mechanical drive. The drive originates from a computer controlled stepper motor. The other end of the sample is clamped in jaws that

are mounted on a stiff load cell containing a strain gauge. The load and elongation test results are transferred to a computer software and the data is plotted in graphs for analysis.

2.4.2 Fibre length

After fineness, fibre length is the most important property of a fibre. Natural fibres tend to vary in their thickness this creates difficulty in measurement of the mean length.

When calculating mean length there are three possible ways of deriving the mean length:

- Mean length based on number of fibres (unbiased mean length) L.
- Mean length based on fibre cross section (cross-section biased mean length) Hauteur H.
- Mean length based o fibre mass (mass biased mean length) Barbe B.

Using the calculation of mean length L each fibre is given an equal weighting regardless of its diameter as shown in equation 2.2.

$$L = \frac{l1+l2+l3}{3} \qquad \text{Equation 2.2}$$

2.4.3 Moisture regain measuring

Measurement of moisture regain involves weighing of the material followed by oven drying it to constant mass. The difference between the masses is the mass of water contained within the sample and calculated as shown in equation 2.3.

$$\text{Moisture Regain} = \frac{\text{mass of water X } 100\%}{\text{oven dry mass}} \qquad \text{Equation 2.3}$$

Moisture Regain is obtained by measuring of the use of oven dry mass at a temperature of 105°C±2°C. Constant mass is achieved by drying and weighing repeatedly until successive weighing differ by less than 0.05%. The relevant British Standard specifies that successive weighing should be carried out at intervals of 15 min when using a ventilated oven, or at 5 min intervals if using a forced air oven (B.P.Saville, 1999).

There are two main types of ovens that are used when measuring moisture regain the forced air oven and ventilated oven. A conditioning oven is used as shown in figure 2.5 which contains fibres enclosed in a mesh container which is suspended inside the oven with a facility for showing true weight of fibres at any given point in time.

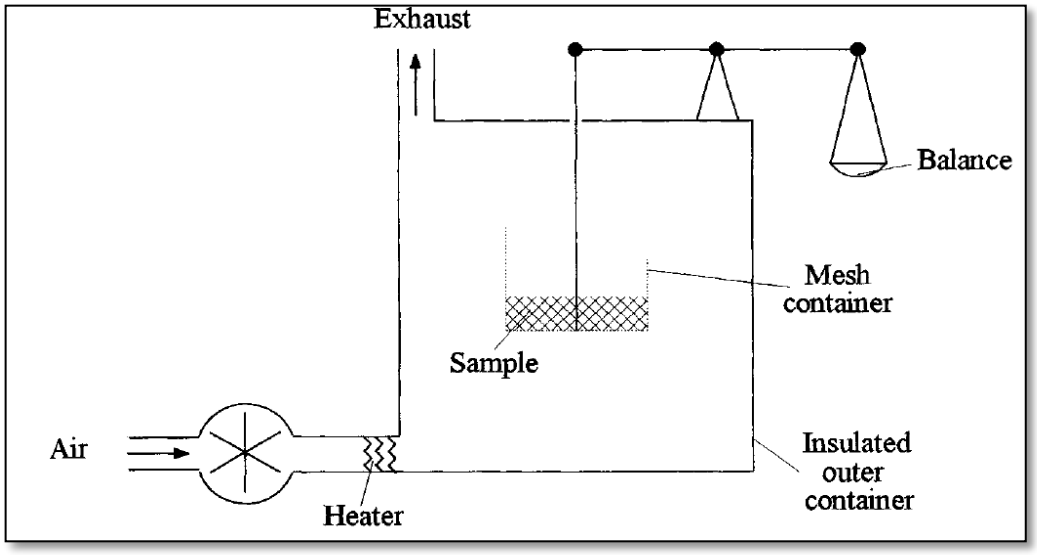

Figure 2-5 – Conditioning oven (B.P.Saville, 1999)

A correction factor is introduced when measuring the dry weight of the fibre samples as shown below:

$$\text{Percentage correction} = 0.5(1\text{-}6.48 \text{ X } 10^{4} \text{X E X R})\% \qquad \text{Equation 2.4}$$

Where

R – Relative humidity %/100

E – Saturation vapour pressure in Pascal's at temperature of air entering the oven.

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 (Nadlene Razali M. S., 2015). Composites combined with less moisture content fibre are less likely to decay in contrast to composites combined with high moisture content (Rowell, 2000). This is probably due

to the ability of a fibre to retain water within the composites which may promote degradation of the composites.

2.5 COMPOSITES

Composites are materials consisting of two or more chemically distinct constituents, on a macro-scale having a distinct interface separating them. Composites have two constituents, a matrix phase and dispersion phase. One constituent is called the reinforcing phase and the one in which it is embedded is called the matrix. The first composites could arguably be identified as the sun dried bricks composed of clay and straw that were used to construct the adobe clay buildings of early civilizations (L.Pilato, 2010). Materials can be customized by reinforcing them with rods, fibres, whiskers and even large particles of a dissimilar material. Materials that include such enhancements are called composites. In contrast to metallic alloys, each material retains its separate chemical, physical and mechanical properties. The main advantage of composites are their high strength and stiffness, combined with low density allowing for a weight reduction in the finished part.

The reinforcement used is harder, stronger and stiffer than the matrix. The reinforcement can be in the form of a fibre or particulate. Particulate composites tend to be weaker in comparison to fibre reinforced composites and they may be less stiff. It is however cheaper to make particulate composites in comparison to fibre composites. Particulate reinforced composites usually contain less reinforcement (up to 50 volume percent) due to processing difficulties and brittleness (F.C.Campbell, 2010).

A fibre has length that is much greater than its diameter. The length to diameter ratio is known as aspect ratio and varies with continuous fibres having high aspect ratio while short fibre having low aspect ratio.

A composite material works by taking an applied stress and distributing it on the matrix and predominantly on its reinforcements. The mechanical properties of a natural-reinforced composite depend on many parameters, such as fibre strength, modulus and orientation, fibre volume, aspect ratio in addition to the fibre-matrix interfacial bond strength. A good interface bond is required for effective stress transfer from the matrix to the fibre where by maximum utilization of the composite is accomplished (Karnani R, 1997). In composites, materials are combined in such a way to enable better use of their virtues while minimising to some extent the effects of their deficiencies. The concept of composites is not in itself a human invention, wood is a natural composite material.

Composite consists of resin and reinforcing fibres, the properties of the resulting composite material will combine the properties of the resin on its own with that of the fibres on their own.

The properties of the resultant composite are determined by the properties of the fibre, properties of the resin, ratio of fibre to resin in the composite (V_f) and the geometry and orientation of the fibres in the composite.

Composites are finding increasing applications in the engineering field due to their lightweight and strength.

During the manufacture of a composite voids are introduced in the composite. This causes the theoretical density of the composite to be higher than the actual density. The void content is detrimental to the mechanical properties of the composite and lowers the following shear stiffness and strength, compressive strengths, transverse tensile strengths, fatigue resistance, moisture resistance (K.Kaw, 2006):

The ideal density of the composite is calculated using the equation shown below:

$$p = p_f V_f + p_m(1 - V_f) \qquad \text{Equation 2.5}$$

Where

ρ - density of composite

ρ_f – density of fibre

V_f - fibre volume fraction

ρ_m – density of matrix

The V_f is the theoretical fibre volume fraction and calculated as shown:

$$V_f = \frac{\text{Volume of fibres}}{\text{Volume of fibres} + \text{Volume of matrix}} \qquad \text{Equation 2.6}$$

2.5.1 Bio-composites

Broadly defined, bio composites are composite materials made from natural/bio fibre and petroleum derived non-biodegradable polymers or biodegradable polymers. Biodegradable composites are derived from plant derived fibre and bio derived plastics are normally termed green composites (Maya Jacob John, 2007). Figure 2-6 below shows the broad classification of natural fibres.

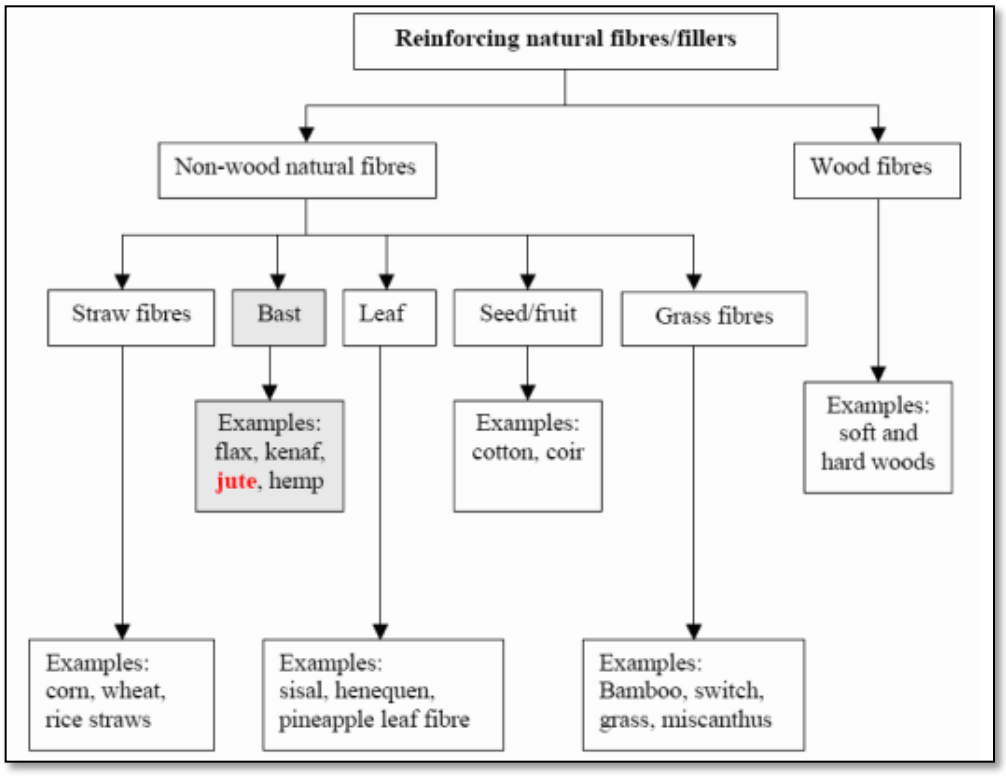

Figure 2-6 – Classification of natural fibres (Debiprasad Gon, 2012)

Interest in fibre reinforced composite materials is on a gradual increase due to the fact that the addition of fibres to polymer resins increases the mechanical strength of the resulting materials. Natural fibre reinforced composites have attracted increasing interest due to their numerous advantages such as biodegradability, dermal non-toxicity and with good mechanical strength (Bledzki, 1999). Additionally they are renewable raw materials and have relatively high strength and stiffness. Their low density values allow producing composites that combine good mechanical properties with a low specific mass. In tropical countries fibrous plants are available in abundance (M.Sakthivei, 2013). Lignocellulose fibres are a kind of biopolymer composite, with different proportions of cellulose, hemicellulose, lignin and other other small components, depending on the species. These mentioned polymers are the basic constituents of the cell wall and are responsible for most physical and mechanical properties such as moisture regain, biodegradability, flammability and thermo plasticity (Srinivasa Chikkol Venkateshappa, 2010). Utilisation of sustainable biodegradable materials in place of synthetic materials can contribute to lowering greenhouse gas emissions.

Wood properties vary among species, between trees of the same species, and between pieces from the same tree, solid wood cannot match reconstituted wood in the range of properties that can be controlled in processing. When processing variables are properly selected, the end result can sometimes surpass nature’s efforts. This has increased the popularity of bio-composite boards to substitute solid wood.

2.5.2 Fibreboards

The term fibreboard includes hardboard, medium density fibreboard (MDF) and insulation boards (Wu, 2015). Several things differentiate fibreboards from particleboards, most notably the physical configuration of the comminute material. The manufacture of wood based panels has brought about the ever increasing cost of logs and

timber which in turn has caused managers of forest resources to investigate ways and means of using trees more efficiently. The first hard-board plant was built in 1926. These fibreboards are part also known as fibre reinforced polymer composites. Fibres are the reinforcement and the main source of strength while matrix glues all the fibres together and transfers stress between the reinforcing fibres. The fibres carry the loads along their longitudinal directions. Sometimes fillers may be added to smooth the manufacturing process, impact special properties to the composites, and/or reduce the product cost. Medium density fibreboards were developed in the United States and their use expanded rapidly in the 1970's (E.Woodson, 1987). Fibres can be made from many lignocellulosics and form the raw material for many composites, most notably fibreboard. Fibres are typically produced by the refining process. Because lignocellulosics are fibrous in nature, fibreboards exploit their inherent strength to a higher degree than particle boards (Brent English, 1997). Medium density fibreboards (MDF) is denser than plywood or particleboards this widens its applications (S.Mahzan, 2011). Reinforcing a polymer matrix with lignocellulosics materials have been attributed to several advantages such as lower density, high stiffness, less abrasive to equipment, biodegradable and lower cost (R.M.rowell, 1993), (M.Jacob, 2004).

To make fibres for composite production, bonds between the fibres in the plant must be broken. This is accomplished by attrition milling where by material is fed between two discs one rotating and one stationary. As the material is forced through the pre-set gap between the discs, it is sheared and abraded into fibres and fibre bundles.

Attrition milling or refining can be augmented by water soaking, steam cooking or chemical treatments. By steaming the lingocellulosic, the lignin bonds between the cellulosic fibres are weakened. As a result, the fibres more readily separate, usually with less damage. Chemical treatments, usually alkali are used to weaken the lignin bonds.

Fibres can also be produced by steam explosion where by the lignocellulosics material is subjected to high pressure steam for a short period of time, usually less than a minute. The pressure is then rapidly dropped. The pressure differential within the lingocellulosic explodes it into fibres and forces the fibres from the vessel (Brent English, 1997). Steam explosion is a novel and a green method with a high efficiency to separate biomass, and it can be performed on a large scale (Oliveira, 2013).

Fibreboards are normally classified by density and can be either dry or wet processes. Dry processes are applicable to boards with high density (hardboards) and medium density (medium density hardboard or MDF). Wet processes on the other hand are applicable to high density hardboards and low density insulation boards as well. Medium Density Fibreboards are distinguished with their good machining, edge screwing and painting properties. MDF is one of the wood composites most widely used in housing furniture (Mohammed S.Alsoufi, 2015).

Fibreboards have several advantages such as having nearly double the strength of particle board (Bloch, 2012), denser than plywood, can be painted, can be drilled and screwed, good insulator, sound proofing attributes, fungus/mold resistant, flammable but difficult to ignite and can be recycled.

Fibreboards tend to use less binder than particle boards (Bloch, 2012). Fibreboards are usually manufactured according to certain standards depending on whether the boards are thin, medium or thick as shown in Table 2-8.

Table 2-8 - Standard MDF manufactured by EWPAA Members (EWPAA, 2008)

Size	**Dimensions**
Thin	2.5, 2.7, 3 ,3.2, 3.6, 4, 4.5, 4.75, 5.5, 6, 7.5, 9 mm
Medium	12, 15, 16,17, 18, 20, 21mm
Thick	24, 25, 30, 32, 32.8 mm

Figure 2-7 shows the typical mechanical properties required in accordance with ASTM D1037-06A for Medium density fibreboards.

PHYSICAL AND MECHANICAL PROPERTY REQUIREMENTS FOR MDF WHEN DETERMINED IN ACCORDANCE WITH ASTM D 1037-06A PART A

ANSI 208.2-2009 MDF for Interior Applications

Grades	Physical and Mechanical Properties											
							Screw-holding				Maximum Thickness Swell (TS)	
	Modulus of Rupture (MOR)		Modulus of Elasticity (MOE)		Internal Bond (IB)		Face		Edge		Panel Thickness ≤15 mm	Panel Thickness >15 mm
	N/mm²	(psi)	N/mm²	(psi)	N/mm²	(psi)	N	(pounds)	N	(pounds)	mm (inch)	percent
115	12.4	1800	1241	180000	0.47	68	703	158	601	135	1.65 (0.065)	11%
130	21.6	3130	2160	313000	0.54	78	988	222	787	177	1.65 (0.065)	11%
155	27.9	4050	2792	405000	0.81	117	1201	270	1001	225	1.65 (0.065)	11%

PROPERTY REQUIREMENTS COMMON TO ALL MDF

Properties	Tolerance Limits
Panel Length or Width ≥ 0.61 m (2 feet)	± 2.0 mm (0 080 inch)
Panel Average from Specified Thickness	± 0.125 mm (0.005 inch)
Variance from Panel Average Thickness	± 0.125 mm (0.005 inch)
Linear Expansion (LE)	≤ 0.33 percent
Formaldehyde Emissions	See below

Formaldehyde Emissions ≤ 0.21 ppm or ≤ 0.11 ppm for MDF with a minimum thickness greater than 8mm.
Formaldehyde Emissions ≤ 0.21 ppm or ≤ 0.13 ppm for MDF with a maximum thickness ≤ 8mm.

Figure 2-7 – Physical and mechanical property requirements for MDF (ASTM D 1037-06A) (Medium Density Fibreboard, 2015)

Medium Density Fibreboard standards according to Australian standards outline the thickness swell of the fibreboard according to the size of the board as ranging from 20-30% for boards below 5mm and for boards exceeding 23mm in thickness at between 5-8% (M.Brooks, 2008). Table 2-9 shows the typical properties of medium density fibreboards.

Table 2-9 - Typical property values for standard MDF (M.Brooks, 2008)

Property	**Units**	**Thickness Class (mm)**			
		<5mm	**6-12**	**13-25**	**>23**
Density	Kg/m^3	800-850	775	725	650-700
Bending Strength (MOR)	MPa	44	42	38	30-40
Bending Stiffness (MOE)	MPa	3800	3500	3300	3200
Internal Bond Strength	MPa	1.15	1.0	0.75	0.6
Thickness Swell (24Hr)	%	20-30	10-20	8-12	5-8
Formaldehyde E1 (Desiccator Method)	mg/L	0.7-1.0	0.7-1.0	0.7-1.0	0.7-1.0

Ajith Joseph et al (2015) researched on preparation and characterisation of banana reinforced phenol formaldehyde composite board and the ASTM standards were followed for testing the composite board. The fibreboard had sufficient strength making it suitable for ceiling board and partition boards. Table 2-10 shows the tensile test results of the banana fibre and phenol formaldehyde composite board. B1 to B4 represented different fibre lengths between 10mm and 40mm respectively used in the composite fabrication. The ultimate stress of the composite board varied between 3.98MPa to 4.58MPa.

Table 2-10 – Tensile test results for banana fibre and phenol formaldehyde resin bio composite

Specimen No.	**Break Load (N)**	**Width (mm)**	**Thickness (mm)**	**Ultimate Stress (Mpa)**	**Break Stress (Mpa)**	**Young's Modulus (Mpa)**	**Yield Stress (Mpa)**	**Percentage Elongation (%)**
B1 (10mm)	68.5	10.18	2.206	3.98	0.622	2824	1.98	1.72
B2 (20mm)	70.32	10.45	2.213	4.24	1.461	3375	4.02	1.81
B3 (30mm)	78.1	10.2	2.208	4.58	0.828	9390	4.58	2.31
B4 (40mm)	66	10.31	2.206	4.19	0.598	2012	2.59	2.65

According to S.D.Asgekar et al (2013) measured the water absorption of coir fibre and phenol formaldehyde composite board range. The water absorption of the fabricated composite was between 47.81% to 101.75% for a board of 6mm thickness (S.D.Asgekar, 2013). The fibre volume fraction was varied between C - S1 with volume fraction between

10 to 50% respectively. The graph in Figure 2-8 shows variation in water absorption of the phenol formaldehyde reinforced with coir/sugarcane fibres.

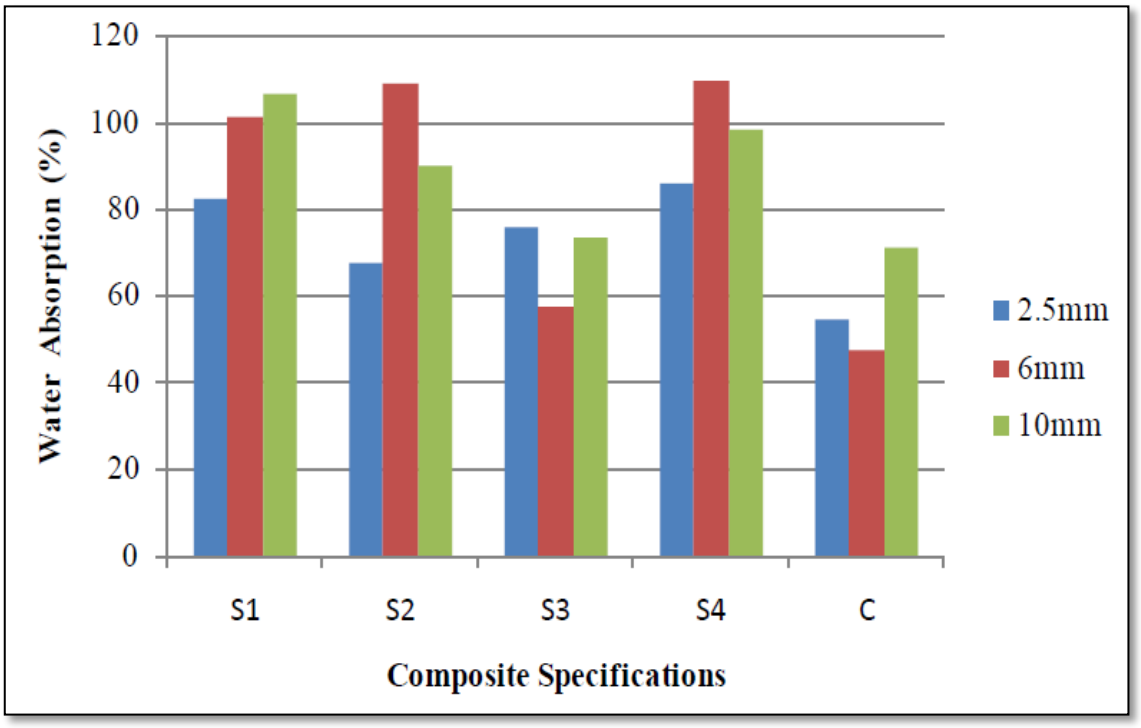

Figure 2-8 – Graph showing water absorption for Coir/Sugarcane fibre bio composite with phenol formaldehyde resin (S.D.Asgekar, 2013)

The graph shows that the water absorption of the fibreboard increases with increase in cellulosic fibre content as fibre volume fraction increases. The composite board with the highest fibre content of 50% had water absorption of more than 100%.

2.5.3 Particle boards

Particleboards are a composite panel product consisting of wood particles such as sawdust, wood chips, sawmills shavings or other agricultural wastes that are bound together with a synthetic resin or other suitable binders under heat and pressure (Paul A.P Mamza, 2014). Particle boards are also known as particle reinforced polymer. The particles are used to increase the modulus of the matrix and to decrease the ductility of the matrix. Particle board, first developed in Germany during World War II, was introduced in the United States in early 1960's. It is an inexpensive alternative to solid

wood and is a substitute for wood in many applications. Particleboards are widely used as component of furniture, doors and cabinets (Hossein Khanjanzadeh, 2012). The various types of particle boards vary with regard to their size and geometry of the particles, the amount of resin adhesives used, and the density to which the panel is pressed.

The technology for making particle boards was developed during the Second World War to meet the shortage of timber (CFC, 2010). The particleboard industry also grew out of a need to dispose large quantities of sawdust, planar shavings and to a lesser extent, the use of mill residues and other relatively homogenous waste materials produced by other waste industries. It is gaining importance in these times when they are dwindling forest resources. Particle boards are often made in three layers. The faces of the boards are made up of fines from particles, while the core is made of the coarser material (Roger M. Rowell, 1997). The major types of substances used for the preparation of the particle boards are: pieces of wood (wood particles or chips) chopped from a block, chips from cotton stalk and other similar fibrous materials, sugarcane bagasse, bamboo and rice husks.

However, particle boards are currently made mostly from wood particles. However, the increased demand for wood and panel materials cannot be met by existing forest resources considering that it takes considerate time for regeneration of forests.

Particle boards have numerous end uses such as door panel inserts, partitions, wall panels, pelmets, furniture items as well as floor and ceiling tiles for buildings (A.J.Shaikh, 2010).

Particle boards have a number of advantages over natural timber boards such as:

- It is free from natural defects since it is fabricated.
- It is easier to fix as some of these particle boards are prepared in a ready to fix form.

- It is generally cheaper than substitute materials such as timber (A.J.Shaikh, 2010).
- With proper protective surface coating and edge covering, particle boards can be made termite proof and fire resistant. It can take a variety of surface finishes like laminations, veneers, paint, varnish and polish. Attractive wall panels can also be used as surface finish for particle boards.

Particle boards from cotton stalks possess all the desirable properties for internal applications such as false ceiling, partitioning and paneling. The standard particleboard is not suitable for exterior use or in interior use where wetting or prolonged high humidity conditions are likely.

The higher the thickness of the board the less thickness percentage swell. There are two main particle types which are hammer mill type and flake type particles. Hammer milled particles are roughly granular or cubic in shape and thus have no significant length to width ratio. The range of particle sizes is 0.2-0.4 mm in thickness, 3.0-30 mm in width and 10.0-60.0 mm in length. Table 2-11 shows typical values for particleboard mechanical properties.

Table 2-11 – Typical property values for standard particleboard (CFC, 2010)

Property	**Units**	**Thickness (mm)**		
		<12	**13-22**	**>23**
Density	Kg/m^3	660-700	660-690	600-660
Bending strength (MOR)	MPa	18	15	14
Bending stiffness (MOE)	MPa	280	2600	2400
Internal Bond Strength	MPa	0.6	0.45	0.40
Thickness Swell (24 Hr.)	%	15	12	8
Formaldehyde E1 (Desiccator Method)	mg/l	1.0-1.5	1.0-1.5	1.0-1.5

The particle geometry also plays a role in the properties of the produced board. The length of the flake type particles is the most important as it influences maximum strength. The

flake type particles are normally produced using cylinder type and rotating disc type machine. In the cylinder type the knives mounted either on the exterior of the cylinder similar to a planer or on the interior of a hollow cylinder. For rotating disc type, the knives are mounted on the face of the disc at various angles.

2.5.4 Other Potential Reinforcement Materials

Several types of raw materials have been used for the manufacture of particle boards. Recently some researchers have focused on the use of various agricultural residues and wastes for particleboard manufacture. Bagasse is also a suitable raw material however the cost is inhibitive. Godavari particleboards Industry in India has attempted to use cotton stalks, wheat straw soya stalks which are available locally in India (Deshpande, 2006). According to Godavari particle board industry, cotton stalks were found as the most suitable raw materials for particle board manufacturing. However, they utilise blend of bagasse and cotton stalks for producing the particle boards as they found they could not use more than 45% of cotton stalks as raw material in blended form with bagasse because they did not have the necessary sanding facilities for surface treatment and it altered the appearance of the board making it unacceptable to the market particularly for pho-lamination. (Deshpande, 2006). Soya stalks and wheat straw had some difficulties in particleboard production. Soya stalks had problems with resin blending while wheat straw does not absorb resin and the boards tend to delaminate after pressing. Particle boards made from bagasse and cotton stalks are acceptable in the Indian market. From experience they state that filler boards produced with 100% cotton stalk chips which is used for door making has a good market potential. Figure 2-9 shows a cotton stalk particle board that has been produced by mixing with bagasse.

Figure 2-9 – Particle Board from bagasse and cotton stalks (Deshpande, 2006)

2.6 RESINS

The resins that are used in fibre reinforced composites are referred to as polymers. These can be classified as either thermoplastic or thermosetting according to the effect of heat on their properties. Thermoplastics soften on heating and eventually melt, hardening again with cooling. This process of crossing the softening or melting point can be repeated without any appreciable effect on the material properties in either state. Thermoplastics include nylon, polypropylene. Thermosets are from chemical reaction in situ, where the resin and hardener or resin and catalyst are mixed and undergo a non-reversible chemical reaction to form a hard, infusible product by the formation of covalently cross-linked, thermally stable networks. Formation of these resins is done in two stages the process involves formation of long chain molecules with reactive groups in the first stage. In the second stage these chains are cross-linked by heat and/or addition of curatives.

Particle boards are normally manufactured from dry wood particles (chips) which are coated with synthetic resin binder and formed into flat sheets or mats. Heat is applied with the pressure, for curing of the resin binder. Production of particleboards and fibreboards involves the use of a binder (resin). Urea Formaldehyde (UF) is commonly used resin for interior board application and phenol formaldehyde is used in boards for

exterior uses (CFC, 2010). Table 2-12 shows comparison of the physical and mechanical properties of thermoset polymers normally used in fibreboard manufacture.

Table 2-12 – Physical and mechanical of the selected thermoset polymers used as matrices of natural composites (Paulo Henrique Fernandes Pereira, 2015)

Thermoset matrix					
Properties	**Units**	**Polyester**	**Epoxy**	**Vinyl ester**	**Phenolic**
Density	g/cm^3	1.0-1.5	1.1-1.6	1.2-1.4	1.29
Tensile modulus	GPa	2.0-4.5	3.0-6.0	3.1-3.8	2.8-4.8
Tensile strength	MPa	40-90	28-100	69-86	35-62
Elongation at break – Tensile mode	%	2.6	1.6	4-7	1.5-2
Compression strength	MPa	90-250	100-200	86	210-360
Water Absorption 24Hr at 20 Deg	%	0.1-0.3	0.1-0.4	0.05-0.6	0.1-0.36
Cure temperature	°C	25-200	25-200	25-150	25-200
Cost	US$/kg	1.5-4.00	3.00-20.00	3.20-6.40	6.50-12.00

The most prominent thermosetting adhesives for wood based composites in the forest product industry are urea formaldehyde resins and melamine modified UF resins (MUF) (Halvarsson, 2010). The UF resins are referred to as a class of thermosetting adhesives defined as amino resins. Other types of formaldehyde resins are phenol formaldehyde (PF), melamine formaldehyde (MF), resorcinol formaldehyde and mixtures of UF, UMF and PF resins. The relatively low cost and proven performance of phenol formaldehyde and urea formaldehyde resins has made these the two most popular resins for wood composite products.

2.6.1 Urea formaldehyde (UF) resin

Approximately 1 million metric tons of urea formaldehyde resins are produced annually. More than 70% of this urea-formaldehyde resin is used by the forest products industry for a variety of purposes (H.Conner, 1996). The use of urea formaldehyde resin as a major adhesive by the forest products industry is due to low cost, low cure temperature, water solubility, lack of colour and ease of use under a wide variety of curing conditions (A.

Gürsesa, 2014). Urea formaldehyde resin is used in the production of an adhesive for bonding particleboards [61% of the urea formaldehyde used by the industry], medium density fibreboard [27%], hardwood plywood [5%] and a laminating adhesive for bonding [7%], for example furniture case goods, overlays to panels and their interior flush doors (H.Conner, 1996). Before the addition of Urea Formaldehyde resin into the medium density fibre board process a hardener (latex curing agent) is mixed into the UF resin as a catalyst, often a salt based ammonium, e.g. ammonium chloride or ammonium sulphate (Halvarsson, 2010). UF resins can be distinguished from other formaldehyde resins such as Melamine formaldehyde and phenol formaldehyde by their high reactivity and hence shorter press times are achievable.

Table 2-13 – Properties of urea formaldehyde resin (Dunky, 1997)

Property	Value
Solid content (%)	60
Density (g/cm3)	1.27
pH	7
Viscosity (cps)	63
Gel time (s)	45

Due to their high content of nitrogen, UF resins are non-flammable and burn only with the support of a flame (H.Conner, 1996). The use of urea formaldehyde in the particle board industry is due to the following advantages: low cost, ease of use under a variety of curing conditions, low temperatures in curing, water solubility, resistance to microorganisms and to abrasion, hardness, excellent thermal properties and lack of colour of cured resin

However when used in the home furniture, sub flooring or stair treads, particle boards and medium density fibreboards made with formaldehyde-based resins continue to release small amounts of formaldehyde gas (Gary Davis, 2001). Formaldehyde is toxic and according to the Environmental Protection Agency (EPA), formaldehyde is a probable human carcinogen when inhaled or digested. Short-term inhalation exposure can

result in eye, nose, throat irritation and respiratory symptoms (Gary Davis, 2001). The formaldehyde emission from panels in use is due to residual formaldehyde in the urea formaldehyde bonded boards trapped as gas in the structure as well as dissolved in the water content of the boards. The hydrolysis of weakly bound formaldehyde from N-methylol groups, acetals and hemiacetals, and in more severe cases, hydrolysis of methylene ether bridges also increases the content of formaldehyde that can be emitted (Dunky, 1997).

A major challenge with Urea formaldehyde is that as a thermosetting polymer its cure is reversible through the addition of water. The reaction to cure is a condensation reaction therefore the board will not perform well under the presence of water (Smith, 2012). The aminomethylene linkage is susceptible to hydrolysis and therefore not stable at higher relative humidity, especially at elevated temperatures (Dunky, 1997). Water causes degradation of the UF resin, the effect being more pronounced with higher water temperature.

2.6.2 Urea formaldehyde and scavenger additives

Urea formaldehyde based resins can be directly mixed with additives called scavengers, which bind with the urea formaldehyde to reduce emissions. Scavengers can help reduce the formaldehyde by 2 to 10 times (Global Health & Safety Initiative, 2008). The most commonly used scavengers are melamine and hexamine. However, it is not clear if scavengers extend over the time which formaldehyde emits from the board.

2.6.3 Melamine formaldehyde (MF)

Melamine formaldehyde has a lower emission rate as compared to Urea Formaldehyde but it does not eliminate the problem of emission completely. It is also more expensive than Urea Formaldehyde (Sivasubramanian, 2009).

2.6.4 Phenol formaldehyde

The first synthetic resins and plastics were produced by polycondensation of phenol with aldehydes. In 1909 Baekeland made the first plastics (A.Gardziella, 2000). He carried out the polycondensation of phenol and formaldehyde to form cross linked thermosets over several steps. Phenol formaldehyde resin was the first industrialization resin in the world (Jian Lu, 2006). Phenolic resins may be considered in four main categories: High temperature setting phenolics, intermediate temperature setting phenolics, resorcinols, and phenol-resorcinols (M.L.Selbo, 1975).

Phenol formaldehyde has higher water resistance than Urea Formaldehyde and is slightly more expensive. However, it has an advantage over UF in that it has 90% less formaldehyde emission. However occupational exposure concerns are an issue (Sivasubramanian, 2009). This phenol formaldehyde has higher cross linking density which makes it have lower formaldehyde emissions in use. Phenol formaldehyde is produced from phenol and formaldehyde units present in coal tar. Formaldehyde as a raw material is generally produced as a 37% or 50% product in aqueous solution. Generally methanol is added to enhance solution stability and prevent paraformaldehyde formation, resulting in precipitation. The analysis of formaldehyde concentration is performed by tests such as the sulphite method (J.Walker, 1975).

Phenol formaldehyde resins have gained popularity because of their low cost, ease of processing, excellent wetting properties with reinforcements, weathering resistance, dimensional stability, thermal resistance, chemical resistance and ablative properties (W.Scheib, 1979). When subjected to high temperatures phenolic resins ablate (transform directly from solid to gas). Table 2-14 shows the typical properties of phenol formaldehyde resin.

Table 2-14 – Typical properties of phenol formaldehyde adhesive (Atta-Obeng, 2011)

Characteristics	**Liquid PF adhesive**
Appearance	Pale red to brown
Specific gravity	1.1-1.4
pH	10.5
Boiling point	100°C
Solids content	54.957
Free formaldehyde content	< 0.1 by weight

White rot fungus (Phanerochaete chrysos porium) has been shown to be able to degrade phenolic resins (Adam C.Guss, 2006). This will assist with the decomposition of the fibreboards after product life cycle.

Phenol formaldehyde is a hot setting phenolic glue produced with a molar ratio of about 2-2.5 formaldehyde to 1 of phenol. Its storage life is 2-3 months and its pressing temperatures range between 135 to 160°C (Onchieku, 1999). The reaction between phenol and formaldehyde is very exothermic in the presence of a catalyst and was known as a "loaded bomb" during the early manufacturing methods. This was due to a runaway exothermic reaction occurring resulting in an explosion in extreme cases (Pilato, 2010).

Normally phenolic resin addition levels are about 1-2% in wet formed hardboards and up to 5- 6% percent in dry formed hardboard. Most strength and sorption characteristics show little further improvement beyond resin content of 3%. Urea bonded medium density fibreboard dry process, however requires rather high boding resin levels of about 8-11% percent (E.Woodson, 1987).

Phenolic resins are polycondensation products of phenols and aldehydes in particular phenol and formaldehyde. At the start of the reaction, depending on the pH of the catalyst, phenol reacts with formaldehyde to form a methylol phenol, and then dimethylol phenol.

Formaldehyde initially attacks the 2-,4-,6- position of the phenol ring. In the second step of the reaction, the methylol groups condense with other available methylol phenol or phenol, resulting in linear and highly branched structures (A, 1994). The ring hydrogen in the Para and both Ortho positions relative to the hydroxyl group can react with formaldehyde and thus crosslink to form a three dimensional network. The initial reaction in all cases involves the formation of a hydromethyl phenol as shown in equation 2.7.

$$HOC_6H_5 + CH_2O \rightarrow HOC_6H_4CH_2OH \qquad \text{Equation 2.7}$$

The hydromethyl group is capable of reacting with either another free ortho or para site or with another hydroxymethl group. This second reaction forms an ether bridge shown in equation 2.8:

$$HOC_6H_4CH_2OH + HOC_6H_5 \rightarrow (HOC_6H_4)_2CH_2 + H_2O \qquad \text{Equation 2.8}$$

The resultant bisphenol F can further link generating tri and tetra and higher phenol oligomers as shown in equation 2.9.

$$2\ HOC_6H_4CH_2OH \rightarrow (HOC_6H_4CH_2)_2O + H_2O \qquad \text{Equation 2.9}$$

Phenolics are formed from the condensation of polymerization reaction between phenol and formaldehyde. The condensation reaction for phenolics can be carried out under two different conditions, resulting in two different intermediate materials. One of the intermediates is called resoles and the other novolacs (Shackelford, 1992).

2.6.4.1 Resols

In resols the polycondensation is base catalysed and has been stopped deliberately before completion. Characteristic functional groups of this class of phenolic resins are the hydroxymethyl group and the dimethylene ether bridge both are reactive groups. During processing the polycondansation can be restarted by heating and or addition of catalysts. Table 2-15 shows mechanical characteristics of phenolic resins.

Table 2-15 – Characteristics of phenol formaldehyde resin (resol) (M.S.SREEKALA, 2000)

Tensile Strength (MPa)	Young Modulus (MPa)	Elongation at break (%)	Flexural strength (MPa)	Flexural modulus (MPa)	Izod impact strength (kJ/m2)
10	375	2	10	1875	20

A resol is prepared by reacting phenol with an excess of formaldehyde under basic conditions. This results in low molecular weight liquid resols containing 2-3 benzene rings. When the resol is heated cross-linking via the uncondensed methylol groups occurs. This type of resin is referred to as one stage resin and reaction shown in Figure 2-10.

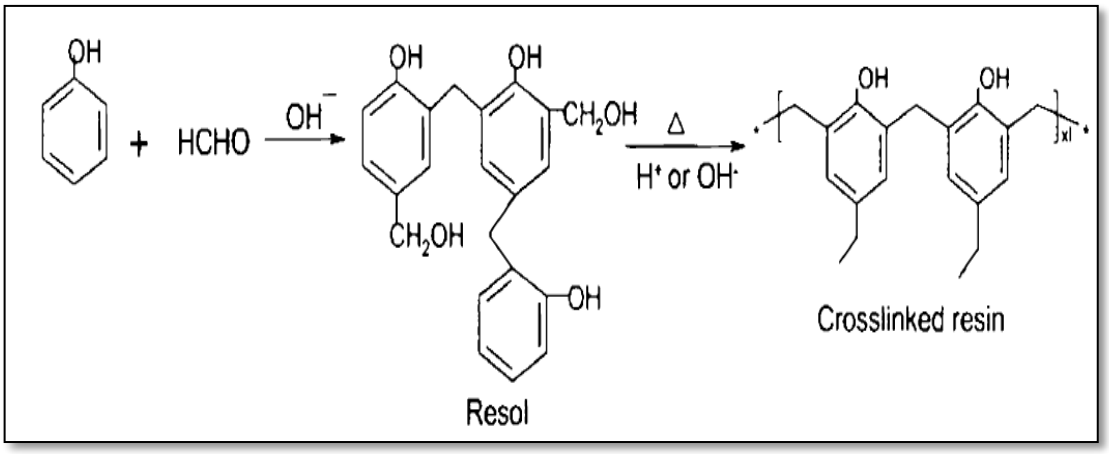

Figure 2-10 – Formation of phenol formaldehyde resol resin

2.6.4.2 Novalac

In novolacs the polycondensation is brought to completion by reacting formaldehyde and a molar excess of phenol under acidic conditions. Novolacs are phenols that are linked by alkylidene bridges without functional groups and can be cross-linked by addition of curing agents such as formaldehyde or hexamethylene-tetramine and will give similar end product to resols (A.Gardziella, 2000). Novalocs are referred to as two stage resins. The reaction between phenol and formaldehyde under acidic conditions occurs as an electrophilic substitution. The catalysts that are commonly employed are oxalic acid, hydrochloric acid, sulphuric acid, p-Tuluenesulfonic acid or phosphoric acid. Figure 2-11 shows reaction in the formation of novalac resin.

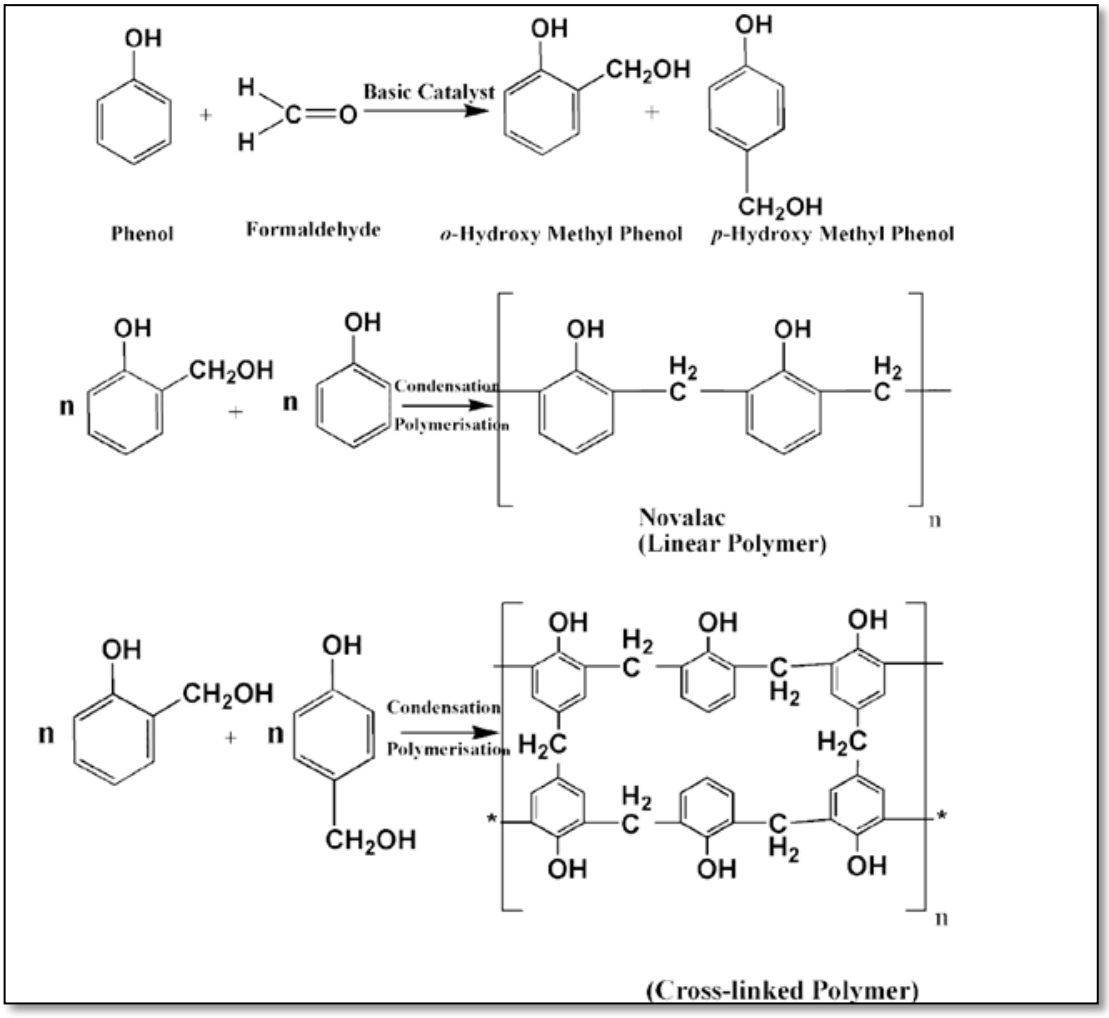

Figure 2-11 – Reaction showing formation of phenol formaldehyde (Novalac resin)

The oxalic acid is preferred because it can give resin with low colour. Approximately 1.6% weight of catalyst is used. Figure 2-12 shows the typical production route used in the formation of novalac resin.

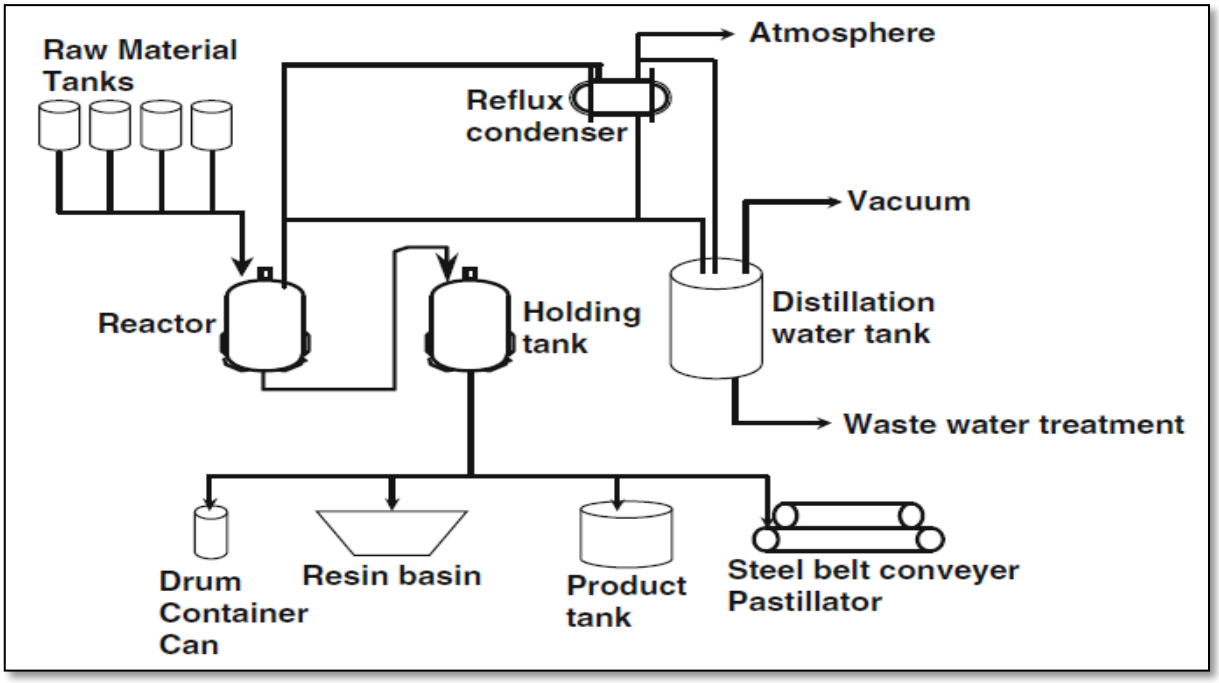

Figure 2-12 – Flow diagram of general production of novalac resin (L.Pilato, 2010)

The water from aqueous formalin and the amount that is generated by the condensation of phenol and formaldehyde, must be removed to obtain the novalac resin after the reflux reaction is complete. For this reason a distillation water tank is used to collect the aqueous distillate. Distillation is usually conducted under atmospheric conditions to control the liquid level of the reactor to avoid boil over into the distillation tank. The novolac liquid level rises due to an increased temperature of >100C as well as the propensity of novolac resins to foam. In some cases water can be removed via a “rough vacuum” method while controlling the liquid level of the mixture. Vacuum is created in the reactor by a vacuum pump pulling through the condenser. The initially recovered aqueous distillate contains some phenol, so that the aqueous distillate is treated by activated sludge or any other environmentally acceptable methods before being discharged into the environment (Pilato, 2010).

The basic difference between resols and novalacs is that the latter contains no hydroxymethyl groups for all practical purposes and hence cannot be converted to

network high polymer simply by heating. Crosslinking is brought about by adding additional formaldehyde or more commonly by adding paraformaldehyde or hexamethylenetetramine.

2.6.5 Non Resin

The main principle in non-resin binding is to activate the outer surface layer of the fibre before pressing and create chemical bonding between adjacent fibres during hot pressing. The MDF dry process generates a lignin rich fibre surface as a result of thermo-mechanical refining. It has been reported that the lignin can be activated by chemical and enzymatic means to give lignin bonding functionality. The subsequent hot-pressing of the fibres is said to be glued together by a self-bonding adhesive. It is known that itinerating lignin is possible with heating by second order transition point (Graupner, 2008). The bonding of the MDF is created by activation of the fibre surface and low molecular degradation components thought to create chemical bonds between activated fibre surfaces during hot pressing (Halvarsson, 2010).

2.7 COMPOSITE FABRICATION TECHNIQUES

There are several types of fabrication methods of composites used for different types and end uses of composites. The manner in which damage occurs in a composite material and the way in which it accumulates to reach some critical level which precipitates final failure depends on many aspects of the composite construction such as fibre type, fibre distribution, fibre aspect ratio (l/d) and the quality of the interfacial adhesive bond between the fibres and the matrix.

2.7.1 Hand lay up

Resins are impregnated by use of manual hand method into the fibres. This is usually accomplished by use of rollers or brushes. There is an increasing use of nip roller type of impregnator for forcing resin into the fabrics by means of rotating rollers and a bath of

resin. A scheme of hand layout process is illustrated in Figure 2-13 and has been used previously to fabricate a banana reinforced phenol formaldehyde (Ajith Joseph, 2015).

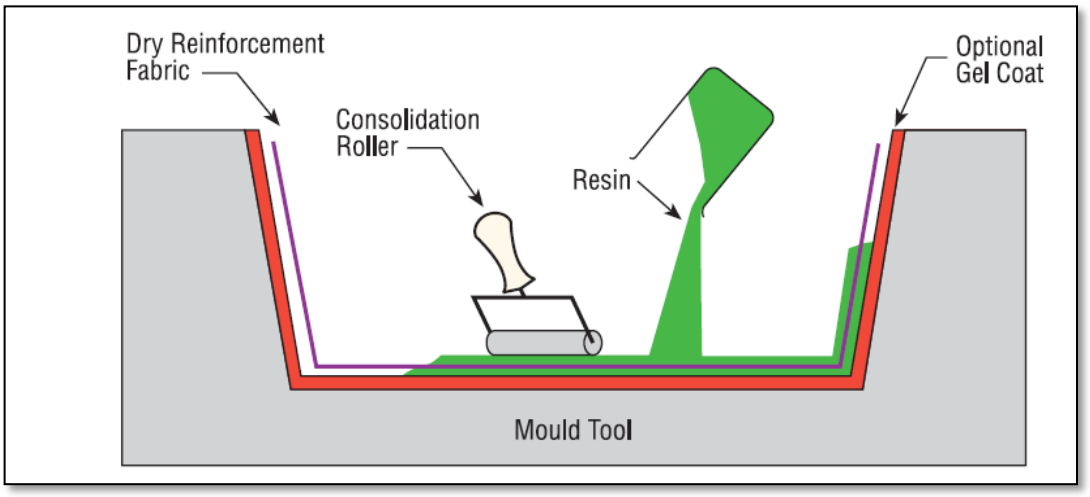

Figure 2-13 – Hand lay-up method (Ajith Joseph, 2015)

Hand laying is a primitive but effective method that is still widely used for prototyping and small batch production. The mould used in hand laying is normally a single sided female mould made from fibre reinforced plastics (GRP). The GRP shell is stiffened with local reinforcement, a wooden frame or light steel work to make it sufficiently stiff to withstand handling loads. The mould surface needs to be smooth to give a good surface finish and release properties. This is provided by a tooling gel that is coated with a release agent. Once the coating gel has hardened the resin is worked into the reinforcement using a brush or roller. This process is repeated until desired thickness is attained. The advantages of hand lay-up method include its simple principle, low cost tooling, wide choice of suppliers and material types and higher fibre content and longer fibres can be used compared with spray up technique.

2.7.2 Spray up

In spray up, resin is sprayed onto a prepared mould surface using a specially designed spray gun. The gun simultaneously chops continuous reinforcement into suitable lengths

as it sprays the resin. The deposited materials are left to cure under standard atmospheric conditions. Figure 2-14 shows how typical spray up composite fabrication is carried out.

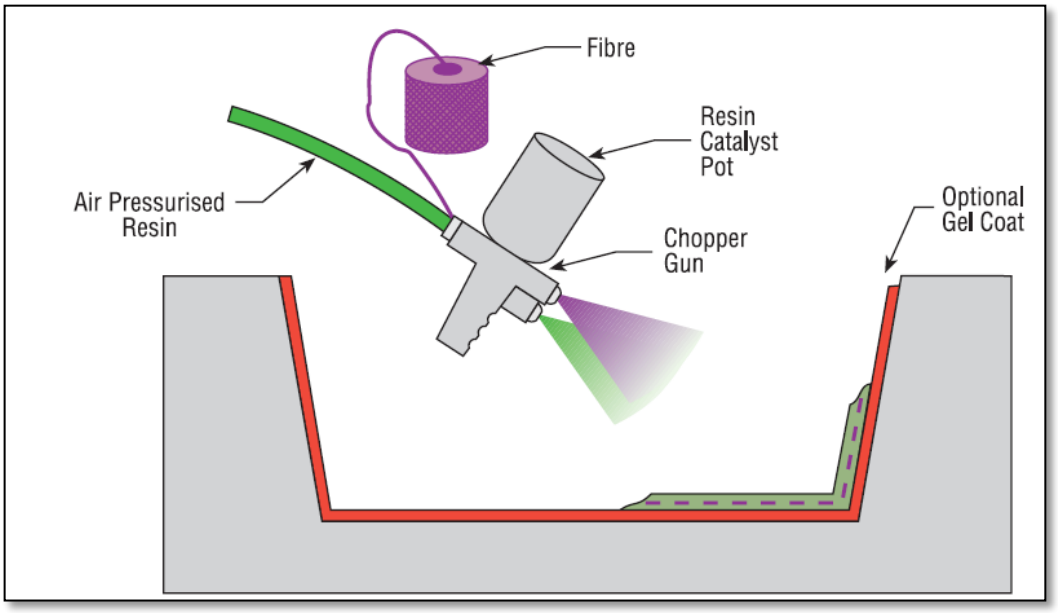

Figure 2-14 – Spray up technique (Guide to Composites, 2015)

2.7.3 Resin injection techniques

Resin Transfer moulding (RTM) consists of filling a mould cavity and the closing valve and injecting a resin through a port. The reinforcements are placed within the mould before closing and locking it. The reinforcement may be continuous strands, cloth, woven roving, long fibre and chopped strand. Heat can also be applied to the mould to shorten the cure time in which case steel moulds may be necessary (L.Pickering, 2008). The advantages of resin injection technique are that accurate fibre spacing can be achieved, uses only low-pressure injection, much uniformity in thickness and fibre loading can be maintained, resulting in uniform shrinkage, mouldings can be manufactured to close dimensional tolerances, ability to mould complex structural and hollow shapes, ability to produce laminates of 0.5-90 mm in thickness, process can be automated, resulting in higher production rates with less scrap and components will have good surface finish on both sides.

Figure 2-15 shows how resin injection moulding in composite fabrication is carried out.

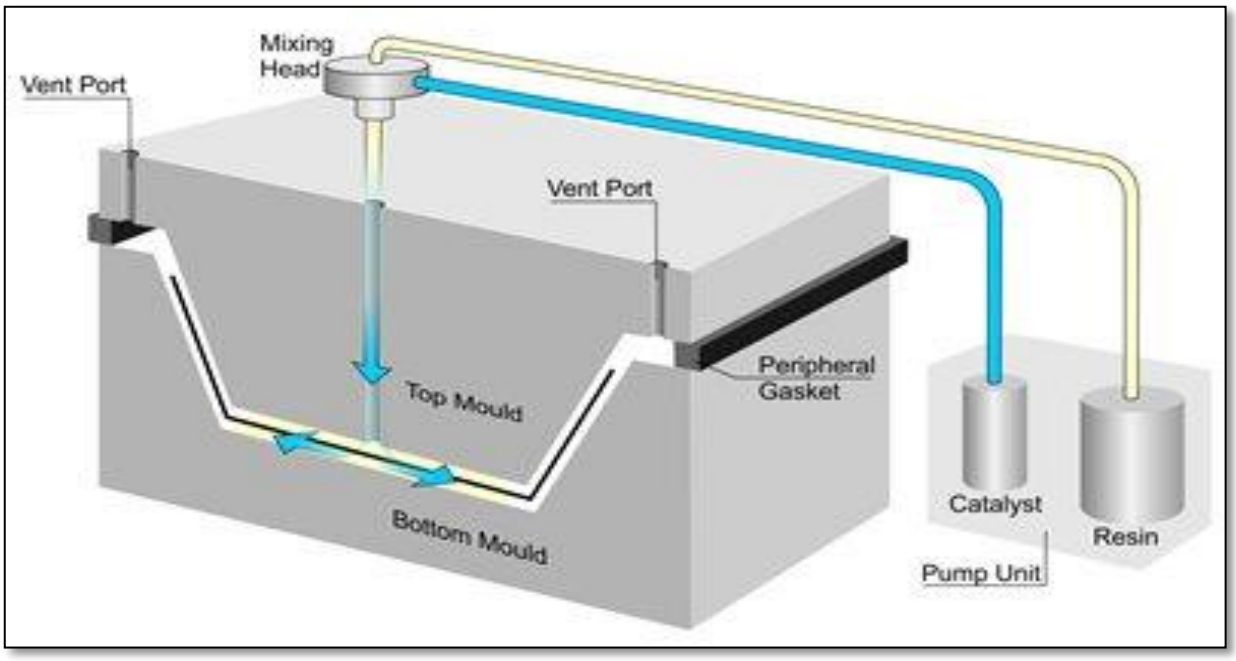

Figure 2-15 - Resin injection moulding (Resin Transfer moulding, 2014)

Resin transfer moulding or "RTM" produces large, complex items such as bath and shower enclosures, cabinets, aircraft parts, and automotive components (Engineers, 2000). RTM uses two matched moulds, a bottom mould and a top mould, brought together thus producing parts with two finished surfaces.

2.7.4 Filament winding

This process is used to make composite structures such as pressure vessels, storage tanks or pipes. Filament winding is achieved by continuous roving or monofilaments are wound on a rotating mandrel. It is a continuous fabrication method that can be highly automated and repeatable. In most thermoset applications, the filament winding apparatus passes the fibre material through a resin bath just before the material touches the mandrel. This is known as wet winding. A variation of this system is to use continuous fibre pre-impregnated with resin eliminating the need of a resin bath. Filament winding is typically applied using either hoop or helical winding. In hoop winding, the tow is almost perpendicular to the axis of the rotating mandrel. Following this process is an autoclave

for curing the mandrel which either remains in place to become part of the wound component or typically it is removed.

2.7.5 Pultrusion

This is a composite manufacturing process in which the reinforcing material is typically pulled through a heated resin bath and then formed into specific shapes as it passes through one or more forming guides or bushings. The material then moves through a heated die, where it takes its net shape and cures. Further along the process cooling takes place and the resulting profile is cut to the desired length.

2.7.6 Vacuum assisted resin transfer moulding (VARTM)

In VARTM (Vacuum Assisted Resin Transfer Moulding) the reinforcing fabrics are laid up as a dry stack of material. The fibre stack is covered with a peel ply and knitted type of non-structural fabric. The resin is then drawn into the dry reinforcement on a vacuum bagged tool, using only partial vacuum to drive the resin as shown in Figure 2-16.

Figure 2-16 shows how resin transfer moulding in composite fabrication is carried out.

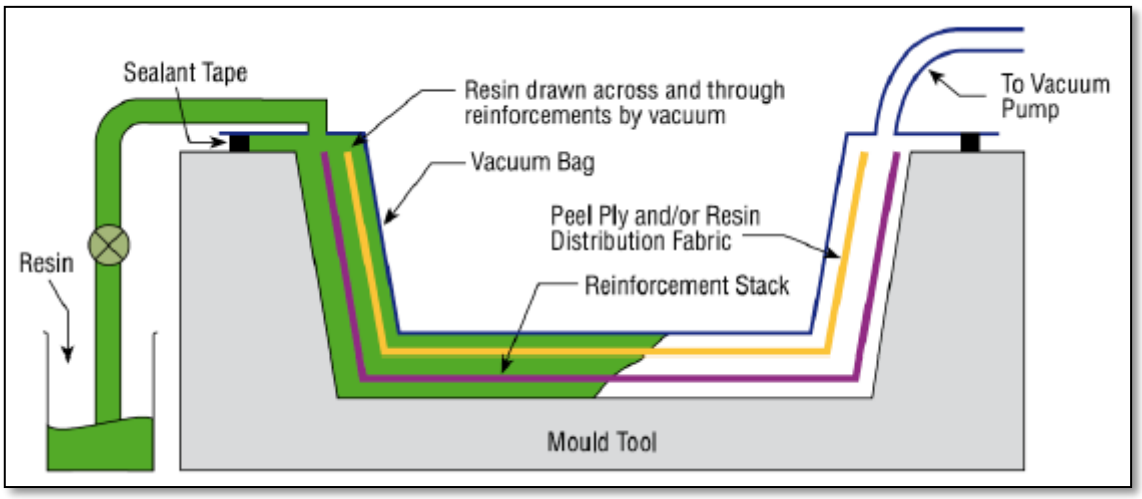

Figure 2-16 – Schematic of resin transfer moulding (Guide to Composites, 2015)

2.7.7 Compression moulding

Compression moulding is done with matched metal moulds utilising sheet moulding compound (SMC), bulk moulding compound (BMC) or preformed mat. Resin is added with the preform and heat and pressure is applied to cure the parts. Cycles range from less than one to five minutes. Typical thermoset resins used in compression moulded parts are polyesters, vinyl esters, epoxies and phenolic. In compression moulder, base plate is stationary while upper plate is movable. The material placed in between the moulding plates flows due to the application of pressure and heat and acquire the shape of the mould cavity with high dimensional accuracy which depends on the mould design. If the pressure applied is too low, it can lead to insufficient or poor interfacial adhesion of fibre and matrix. If pressure is too high, it may cause fibre breakage, expulsion of enough resin from the composite system. If temperature used is too high, some properties of the fibre and matrix may be damaged. If temperature is too low on the other hand fibres may not get properly wetted due to high viscosity of polymers especially thermoplastics. Time of application is also of great importance. If the time is not sufficient it may cause any of the defects associated with insufficient pressure or temperature. Other parameters such as mould wall heating, closing rate of two matched plates and de-moulding time also affect the production process.

The typical set up used in compression moulding is shown in Figure 2-17.

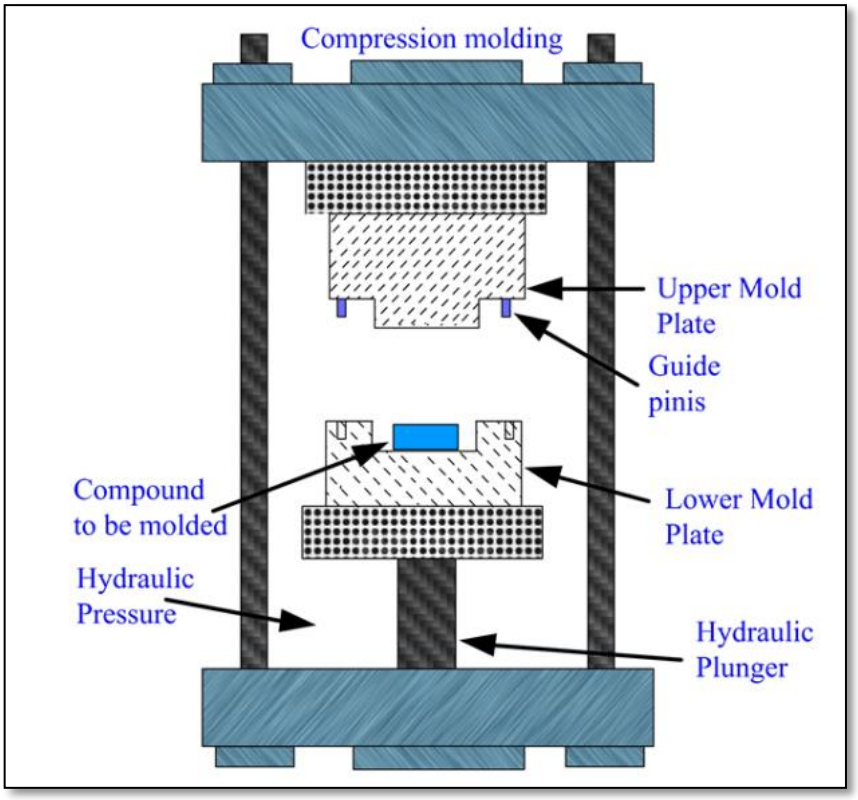

Figure 2-17 – Compression moulding (Compression Moulding, 2012)

2.8 BIO COMPOSITE PROPERTIES

Testing is important in order to gain an understanding of the composite material its properties and limitations. In this section, a review of test mostly performed on composite materials will be given.

2.8.1 Tensile strength

Tensile tests gives properties such as modulus of elasticity, Poisson's ratio, tensile strength, and ultimate tensile strain (O.Adams, 2014). The principle of testing involves taking a thin strip of composite material and placing it into the wedge grips of a mechanical testing machine and loading it slowly in tension. Loading continues to ultimate failure, the point at which tensile strength and ultimate tensile strain are determined. The ends of the specimen are usually tabbed with a material such as aluminium as shown in Figure 2-18, to protect the specimen from being crushed by the

grips. This test specimen can be used for longitudinal, transverse, cross ply and angle-ply testing. It is recommended to polish the specimen sides to remove surface flaws especially for transverse tests (Mechanical Testing of Composites, 2012).

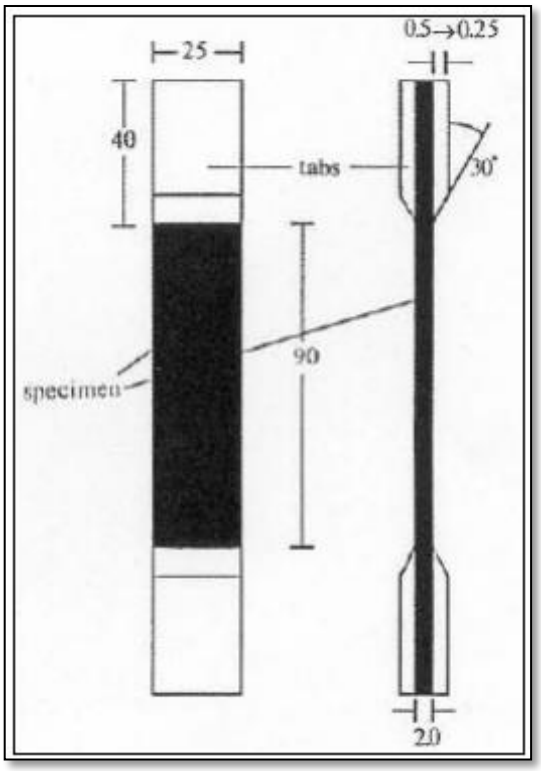

Figure 2-18- Typical tensile composite test specimen dimensions (all dimensions in mm) (Mechanical Testing of Composites, 2012)

2.8.2 Compression strength

Compression test is dependent on the type of compression fixture used. The gauge length is conical and if not set correctly the specimen will buckle and flex this results in premature failure. The most widely used technique for doing compression testing is the Celanese fixture (Mechanical Testing of Composites, 2012) shown in Figure 2-19.

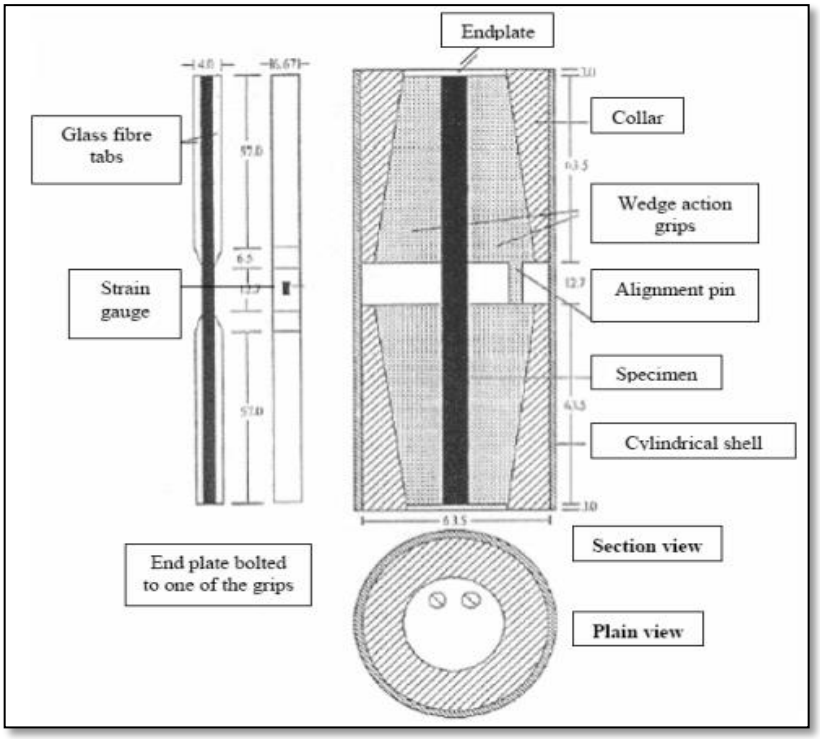

Figure 2-19 - Celanese compressive fixture and specimen (all dimensions in mm) (Mechanical Testing of Composites, 2012)

In compression failure when the fibre buckles, the matrix-fibre interface may fracture in shear and lead to ultimate failure (El-Tayeb, 2008). The compressive strength increases as volume fraction increases due to the load distribution among greater quantity of fibres hence increasing resistance to local buckling or kinking within each fibre. Fibre crushing occurs when the axial strain in the composite attains a critical value equal to the crushing strain of the fibres (N.A.Fleck P. a., 1990). Micro buckling or kinking of fibres are now understood to be the mechanism by which fibre reinforced composites fail under compression. Micro buckling is the buckling of fibre embedded in matrix foundation. Kinking on the other hand, is a highly localised fibre buckling. Kink bands are formed after attainment of the peak compressive load when the region between the fibre breaks is deformed plastically (S.Kumar, 1999).

The compression failure can be explained using Rosen's model which is one of the most quoted work on compression modelling (Rosen, 1965). His analysis was based on the

micro buckling approach considering the composite to be 2D. He postulated two modes of failure namely, extension mode in which the fibres buckle out of phase and shear mode in which fibres buckle in phase (S.Kumar, 1999) as shown in Figure 2-20.

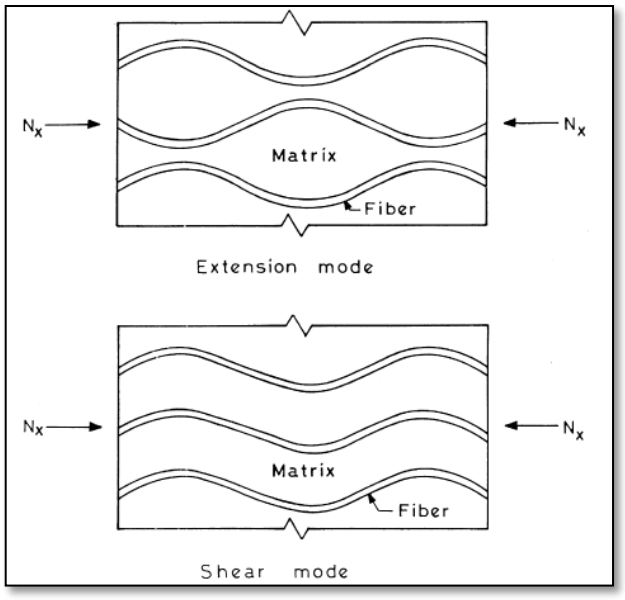

Figure 2-20 – Micro buckling failure modes according to Reson (S.Kumar, 1999)

2.8.3 Three-point bending (flexure) strength

This test is used for measuring shear delamination where by a specimen (<30mm) is loaded in three-point bending until a delamination forms in the centre plane at either end of the specimen. The flexure tests monitor behaviour of materials in simple beam loading or transverse beam tests. Specimens are supported as a simple beam, with the compressive load applied at midpoint and maximum fibre stress and strain calculated. The three point bending flexural test measures bend or fracture strength, modulus of rapture, yield strength, modulus of elasticity in bending, flexural stress, flexural strain, and flexural stress strain materials response. The standard for the test is ASTM D-1037 for fibreboards (Test Resources, 2015). Reliable data on the bending properties of fibreboards is important to end users, such as manufacturers and design professionals. Flexure testing is often done on relatively flexible materials such as polymers, wood and composites.

There are two test types; 3-point flex and 4-point flex. In a 3-point test the area of uniform stress is quite small and concentrated under the centre loading point. In a 4-point test, the area of uniform stress exists between the inner span loading points (typically half the outer span length). The 4-point flexure test is common for wood and composites. The 4-point test requires a deflectometer to accurately measure specimen deflection at the centre of the support span. Test results will include flexural strength and flexural modulus. Figure 2-21 shows set up for three point bending flexural test.

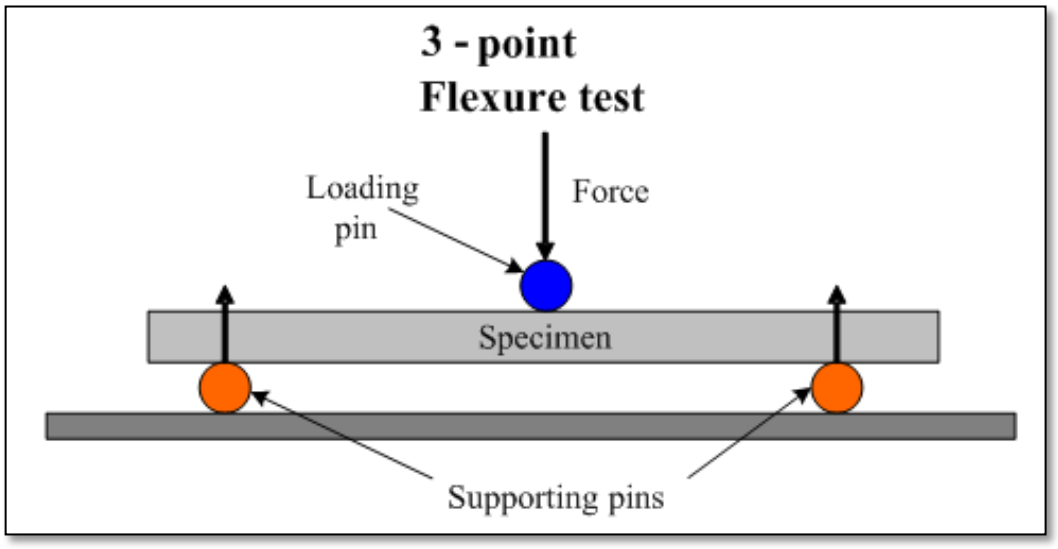

Figure 2-21 – Illustration of 3 point flexure test (Kopeliovich, 2012)

The modulus of rupture or flexural strength is the stress of the extreme fibre of a specimen at its failure in the flexure test. Flexural strength is calculated as follows:

$\delta = \frac{3LF}{2bd^2}$ (Kopeliovich, 2012) Equation 2.10

Where

δ – Flexural strength of specimen

L – Specimen length

F – Total force applied to the specimen by two loading pins

b - Specimen width

d – Specimen thickness

2.8.4 Water absorption

Water absorption test is used to determine the amount of water absorbed under specified conditions. The factors that affect the water absorption include the materials used, temperature and length of exposure. This test gives an idea of performance of composite in water or humid environment (Intertek, 2010). Water absorbed in composites is generally divided into free water and bound water. Water molecules that are contained in the free volume of the composite are free to travel through the micro voids and holes and identified as free water, whereas, water molecules that are dispersed in the fibre-matrix and attached to the polar groups of a fibre are known as bound water. Water can penetrate into the cellulose network of the fibre and into the capillaries and spaces between the fibrils and less bound areas of the fibrils. Water may attach itself by chemical links to group in the cellulose molecules (Tay Chen Chiang, 2012).

2.9 CONCLUSION

From the current literature survey, the use of cotton stalk fibre for composite manufacture is limited and therefore a research in this area will contribute to knowledge in this field. There is a loss of revenue in cotton production in the country and hence there is benefit in utilising the waste cotton stalks to generate additional revenue for cotton farmers. Revenue can be generated from the cotton stalks and in the process reduce pollution to the environment by utilisation of these waste cotton stalks which would have been burnt in the fields causing air pollution. The use of cotton stalk in fibre form has advantage of higher aspect ratio leading to a stronger fibre board as compared to particle boards of cotton stalks in which research has been carried out upon. Literature survey shows the rate of depletion of forests is high leading to high rate of deforestation in Zimbabwe hence need to come up with substitute for solid wood hence this research. Fibreboards find use in panel inserts, partitions, wall panels, pelmets, furniture items as well as floor and ceiling tiles for buildings (A.J.Shaikh, 2010).

CHAPTER 3 : EXPERIMENTAL METHODS

3.0 INTRODUCTION

The experimental methods of the study involved collection of cotton stalks from selected farms in Umguza district in Zimbabwe, cotton stalk retting, manual fibre extraction, fibre properties characterization, composite fabrication and its characterization. Thereafter the bio-composite was characterised and compared to available fibreboards and standards.

3.1 COLLECTION AND CLEANING OF COTTON STALKS

Cotton stalks were collected from Umguza district in Zimbabwe which is located 53km from Bulawayo city centre. The cotton was planted in December 2014 and harvested between June and August 2015. This district has been selected because it is representative of the cotton species farmed in Zimbabwe according to the Zimbabwe Cotton Research Institute (CRI). The collection time of the stalks was done immediately after June/July 2015 harvest period. The cotton stalks were uprooted two months after the harvest season when clearing is normally done. The cotton stalks used were randomly sampled. The stalks were tied together into bundles and transported in a van from the cotton farms.

In the workshop the stalks were cleaned by beating to remove adhering dirt. The side branches were chopped off from the stem. Only cotton stalks between 1.0-1.2 metres in length were selected for use. The cotton stalks were left for two weeks so that shedding of the leaves could take place. The boll rinds were then removed by beating the stalks with a wooden mallet.

3.2 RETTING OF COTTON STALK FIBRES

Cotton stalk fibres were extracted by retting and mechanical means. The cotton stalks were first washed to remove contaminants such as sand and dirt that was adhering to the cotton stalk using tap water.

3.2.1 Laboratory retting of cotton stalks

Water retting of sample stalks was carried out using tap water at room temperature and efficiency measured at interval of 2, 3 and 4 weeks. This was carried out in order to ascertain the optimum retting time of cotton stalks. The efficiency of the retting process for each time frame was ascertained by subjective and quantitative means (M.Nayeem Ahmed, 2013). In the subjective method the ease of extraction of fibres was the measure of retting quality. In the quantitative method the oven dry weight of the cotton stalk was taken before and after retting interval of 1, 2 and 3 weeks. Decrease in weight was taken as an indication of the retting efficiency.

Procedure

i. Cotton stalks were measured into small sizes of length ≤ 30cm and cut to make them suitable to place in a laboratory retting container.
ii. The stalks were then oven dried at 110°C for a period of 3hrs.
iii. The weight of the cotton stalks was then measured using an analytical scale to 0.001g accuracy and this weight recorded as the initial weight of the stalks.
iv. The stalks were then retted for a period of 1, 2 and 3 weeks and the oven dry weight obtained by heating the stalks at 110°C for 3hrs after each weekly retting interval and recorded.

3.2.2 Bulk retting of cotton stalks

The side branches of the cotton stalks were removed with an axe and the stalks were retted in 150litre plastic drums.

Tap water was used to fill the plastic drums and the stalks were submerged in the water with weights to prevent the stalks from floating to the surface. Retting was started on 08 September 2015 from 12:30Hrs in two plastic drums and carried out for a period of 3 weeks at room temperature. After the 3 week period the stalks were removed from the water and fibre extraction was carried out. Figure 3-1 shows the retting set up.

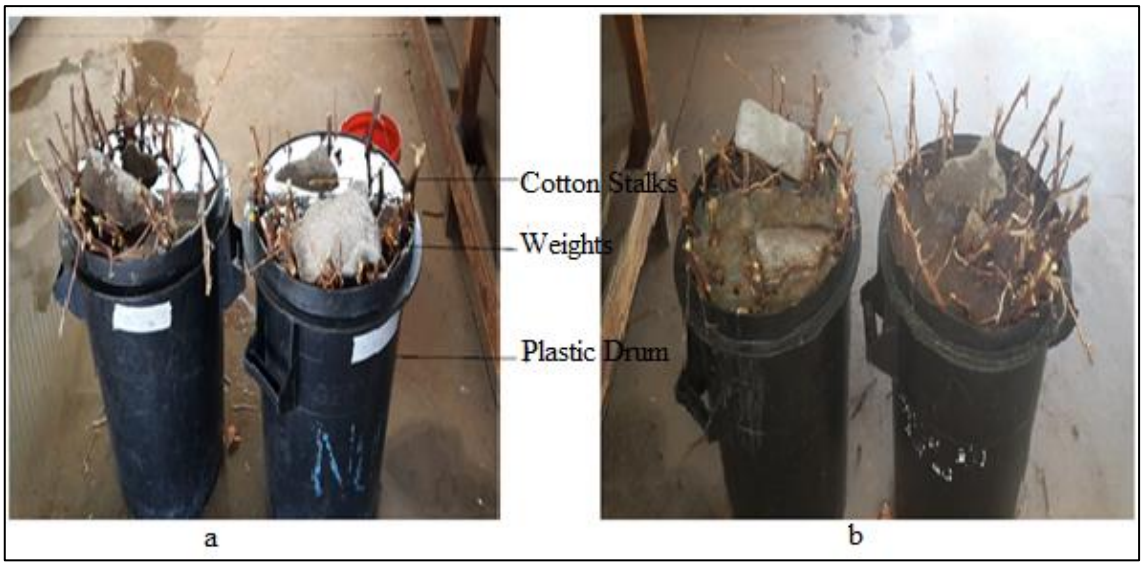

Figure 3-1– a) Water retting of cotton stalks b) Water retting after 1 week

3.2.3 Water quality determination

The water quality was measured to ascertain effect of the retting of cotton stalks on the effluent water quality. Tests were carried out to measure the pH, conductivity and Total dissolved solids (TDS) of the water before and after carrying out retting.

Procedure

i. Water was collected from the tap used to fill the polyvinyl chloride (PVC) retting containers and tested as the control.
ii. Water was collected from the retting containers at week 1, week 2 and week 3 and put in glass beakers and tested.
iii. A hand held pH meter (Oakton pH/mV/°C/°F meter RS232 110 series) was used to measure the pH.
iv. A handheld Conductivity and TDS meter (Oakton TDS/Conductivity/°C meter Con 11 Series) was used to measure these parameters.

3.3 EXTRACTION OF COTTON STALKS FIBRES

The fibres were extracted by manual decortication method. The principle of operation involved crushing the cotton stalks and then scrapping them using a flat blunt knife to remove the residual adhering particles from the fibres.

Procedure

i. A rubber coated hammer was used to crush the stalks. The stalks were struck repeatedly with the rubber coated hammer crushing them.

ii. The shive generated was put aside in a container and the fibres collected.

iii. After crushing the stalk, it was subjected to hackling which involves combing out residual particles adhering to the fibres.

iv. The fibres used were collected from the top, middle and root section of the cotton stalk and stored separately.

v. The oven dry weight of cotton stalks and fibres was established. From these values it was possible to calculate the percentage fibre yield. The fibre yield was calculated as shown in equation 3.1.

Figure 3-2 shows how the cotton stalk fibres were crushed after retting to extract the fibres.

Figure 3-2 – Method of crushing cotton stalk fibres after retting

$$\text{Yield of fibres (\%)} = \frac{\text{Weight of extracted cotton stalk fibres (g)}}{\text{Weight of cotton stalks (g)}} \text{ X } 100 \qquad \text{Equation 3.1}$$

3.4 CHARACTERISATION OF THE COTTON STALK FIBRES

After extraction the 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±1°C and 65±2% relative humidity) for a period of 24hours prior to testing and characterised according to their origin relative to the cotton stalk. Only stalks between the lengths of 1-1.2m were used and these were divided into three equal sections which are the top, bottom and root section as shown in Figure 3-3 depending on the section of cotton stalk, extracted fibres were categorized as top section (TF), middle section (MF) and root section (RF) fibres.

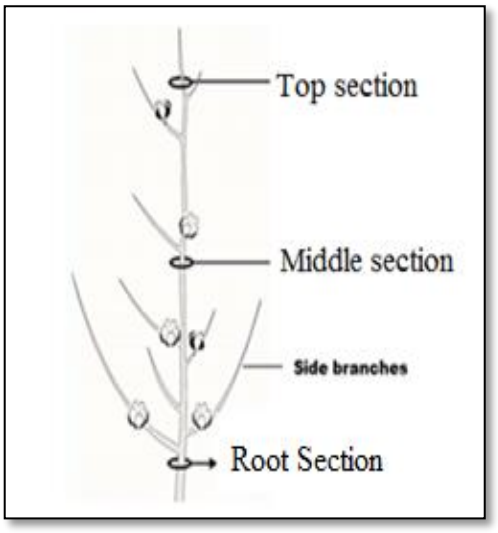

Figure 3-3 – Showing the location of extracted fibres on the cotton stalk

3.4.1 Fibre length

The cotton stalk fibre length was measured using a 30cm ruler. The mean length could then be calculated from these figures. This test was also carried out to grade fibres and only have those exceeding the critical length used for composite manufacture. The standard for the test was ASTM D6103-01.

Procedure

i. Cotton stalk fibres were separated to individual fibres and laid out straight on a flat surface and gripped with forceps on either end during measurement.

ii. 40 Fibres from each section were measured using a 30 cm ruler with minimum graduations to the nearest mm.

iii. Fibre lengths were recorded to the nearest 1.0mm according to the origin of the fibre i.e. top section, middle section and root section.

3.4.2 Fibre strength

Tests were done to determine fibre strength of the cotton stalk fibres. A Testometric Micro 500 model universal tensile tester machine was used to test the fibre strength. The serial number of the machine was S/N 500-327. Bundle fibre testing was carried out according to ASTM D3822 (ASTM-D3822, 2014). The sample length was set at 35 mm and the sample speed at 200 mm/min. The fibre tensile strength has a direct relation to the ultimate composite strength.

Procedure

i. The fibres were preconditioned to standard atmospheric conditions [21±1°C and 65±2% relative humidity].

ii. Cotton stalk fibres were segmented according to their origin and a bundle of 20 fibres mounted on a board using clear sticky tape as shown in Figure 3-4.

iii. The board was then mounted on the jaws of the tensile tester removing slack without stretching the specimen.

iv. The specimen was aligned in such a manner that it lies on the line of action between the force measuring device and the point where the fibre leaves the moving jaw face.

v. The board was cut to allow the fibre to bear the load as testing was started.

vi. The fibres were tested under standard atmospheric conditions for testing textiles which is 21±1°C and 65±2% relative humidity.

vii. The universal tensile tester was then started together with its auxiliary compressor and the fibre specimen extended to break.

viii. After fibre breakage the result was saved on the computer and the machine was returned to its starting position with all pieces of broken fibre remaining in the jaws removed from the clamp faces.

ix. If a specimen slipped at the jaws, broke at the edge or in the jaws or for any other reason attributed to faulty machine operation the result fell below 20% of the average breaking force for the set specimen the results were discarded and another specimen tested until required number of breaks had been obtained.

x. The decision to discard the results of the break were based on observation of the specimen during the test and upon the inherent variability of the fibre. If the jaw break was caused by damage to the specimen by the jaws the results were discarded. However, if it was due to randomly distributed weak places this was deemed a legitimate result.

xi. Five specimens containing 10 fibres each were tested. In total 50 fibres were tested from different areas of the stalk i.e. top section, middle section and root section.

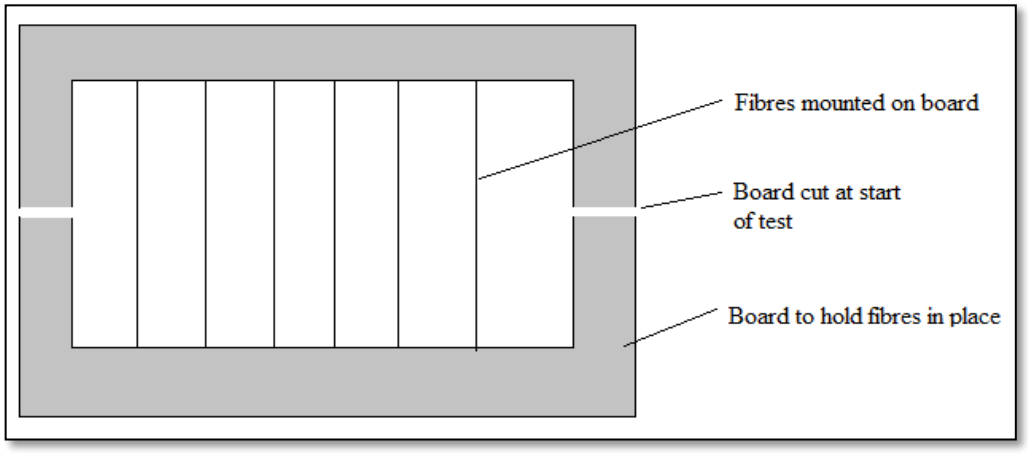

Figure 3-4 – Illustration of fibre testing set-up (Shao, 2014)

3.4.3 Linear density

Tests were carried out to determine the linear density of the cotton stalk fibre. The gravitational method was used in accordance with ASTM D1577-07 (ASTM-D1577-07, 2012) where by a precision balance of tolerance 0.0001g was used to determine the weight of each group which contained 40 fibres.

Procedure

i. 40 Fibres were selected according to their origin on the cotton stalks top section, middle section and root area of the cotton stalks.
ii. The fibres samples were tested under standard atmosphere for testing textiles which is 21±°C and 65±2% relative humidity.
iii. The fibres were measured using a ruler and their length recorded.
iv. The fibres were then weighed in their groups of 40 using an analytical scale with tolerance of 0.0001g and reading taken to the nearest 0.005mg

The mass of each group was the total mass of the selected fibres and the length of the group was the sum of the individual fibre lengths. The linear density was calculated to the nearest 0.1dex (0.01 denier) using the

$$D = 9000\frac{W}{LXN}$$ Equation 3.2

Where:

D = average fibre linear density, denier,

W = mass of bundle specimen, mg,

L = length of bundle specimen, mm, and

N = number of fibres in the bundle specimen

The mean of the average of the linear density for each laboratory sampling and for the lot sample was then calculated.

3.4.4 Microscopic examination

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

3.4.5 Moisture regain

Moisture regain of the fibres was ascertained in accordance with ASTM D2654-89a (ASTM-D2654-89a, 2012) using an oven and a digital scale. The moisture regain of the cotton stalk fibres was measured according to their location relative to the cotton stalk. The absorption of the fibres has a direct bearing on the composite moisture absorption hence the importance of this test.

Procedure

i. The fibres were segmented according to their origin from the cotton stalks. Top section, middle section and root section fibres were tested separately.
ii. 40 fibres were selected and conditioned under standard atmospheric conditions for 24hours and then weighed on an analytical scale.
iii. The fibres were then put in an oven at temp of 105°C +/- 2°C for 15mins. The oven dry weight was measured and taken after 2hours at 130°C and thereafter at 15 minutes intervals to ensure that the correct oven dry weight had been obtained.
iv. The fibres were then weighed thereafter on an analytical scale and their mass noted.

The moisture regain was calculated using the formula below:

$$Moisture\ Regain\ (\%) = \frac{Weight\ of\ conditioned\ fibres - Weight\ of\ oven\ dry\ fibres}{Weight\ of\ conditioned\ fibres}\ X\ 100 \quad \text{Equation 3.3}$$

3.4.6 Diameter of fibres

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

Procedure

i. Fibre was mounted on a stand ready for viewing in a vertical orientation.

ii. A travelling microscope manufactured by Philip Harris Co. was used and focused on the image.

iii. Initial reading for fibre position was taken.

iv. Adjustment was made on the travelling microscope to move it to the other end of fibre getting the diameter of fibre.

v. The difference between the new reading and old reading gave the fibre diameter.

3.4.7 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 for this test was ASTM D861-01a (ASTM-D861-01a, 2012). The density of the fibres as well as density of the resin allowed calculation of the composite density.

Procedure

i. Each fibre was weighed to an accuracy of 0.01g by using an analytical balance.

ii. The mass of each bunch was obtained by calculating the arithmetic mean of the mass of all test samples.

iii. The diameter of each fibre was measured using a travelling microscope.

iv. Volume of the fibre was obtained by multiplying the length and cross section area of the samples.

v. Density was then calculated using the formula:

$$\text{Density}\left(\frac{\text{g}}{\text{mm}^3}\right) = \frac{\text{Mass (g)}}{\text{Volume (mm}^3\text{)}} \qquad \text{Equation 3.4}$$

3.5 COMPOSITE FABRICATION

A bio-composite consisting of cotton stalk fibre and phenol formaldehyde matrix was fabricated using hand layup method.

3.5.1 Fabrication of mould

A mould was fabricated. This mould was made from stainless steel sheet metal with beadings along the edges and with a facility for compressing the fibres within the mould as illustrated in Figure 3-6. The mould dimensions were as shown in Figure 3-5.

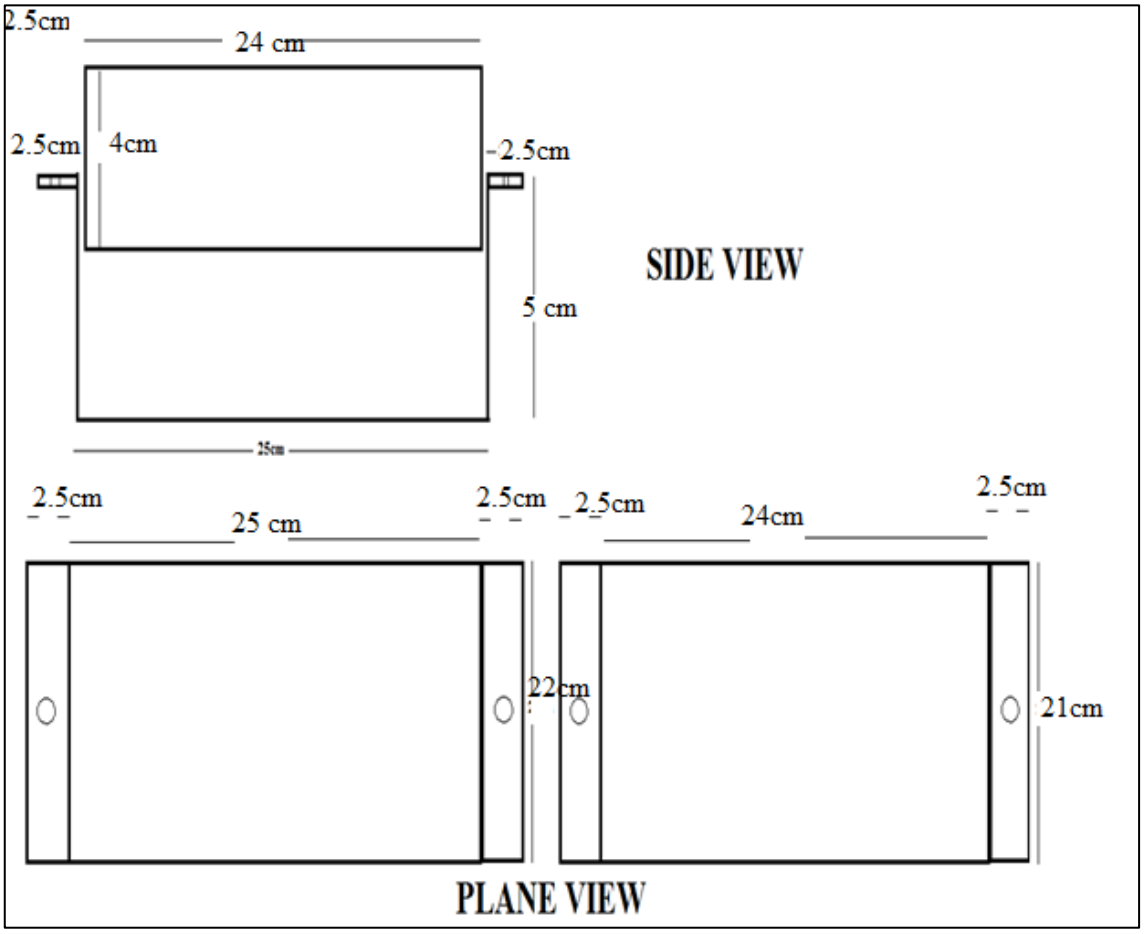

Figure 3-5 – Showing the schematic of composite mould used

Table 3-1 shows the additional dimensions that were used in fabrication of the composite mould.

Table 3-1 – Additional mould dimensions

Parameter	Measurement
Thickness of metal sheet	0.51 mm
Bolt length	3.5 cm
Bolt diameter	5 mm

Figure 3-6 shows image of the mould used to fabricate the fibreboard.

Figure 3-6 – Showing the mould used for composite manufacture

3.5.2 Experimental design

For fabrication of the bio-composite the fibre mass fraction was varied from 0% to 40%. The target density of the composite was between 500-800 kg/m^3. The mould volume was calculated as follows:

$$\text{Volume of mould} = L*W*H$$

$$\text{Volume of mould} = 24cm*21cm*0.5cm$$

$$\textbf{Volume of fabricated mould} = \mathbf{252cm^3}$$

The volume of the mould was used to calculate the equivalent amount of resin and fibres to be added in the fabrication of the composite. The fibre mass fraction was varied as outlined in the experimental design shown in table 3.2. The fibre mass fraction was calculated after fabrication using equation below:

$$M_f = \frac{W_f}{W_m} X100 \qquad \text{Equation 3.5}$$

Table 3-2 – Experimental design for composite fabrication

No.	Fibre Mass Fraction	Fibre weight	Resin	Resin Volume Fraction	Resin weight
	%	g	ml	%	g
1	0%	-----	140ml	100%	155.4
2	10.96%	25	140ml	89.04%	155.4
3	19.76%	50	140ml	80.24%	155.4
4	26.98%	75	140ml	73.02%	155.4
5	33.00%	100	140ml	67.00%	155.4
6	38.11%	125	140ml	61.89%	155.4

The fibre weight was varied at the following intervals 0g, 25g, 50g, 75g, 100g and 125g. The resin quantity was maintained at 140ml after calculation had been made using the largest fibre ratio of 125g to ascertain the minimum amount of fibre to resin ratio required. The minimum ratio of cotton stalk fibre to phenol formaldehyde in grams is 1:1.23 respectively. The cotton stalk fibres have very good wettability as was seen during composite manufacture. However due to the high absorption of the cotton stalk fibres which have a moisture regain of about 11% they absorb a lot for the resin necessitating the higher ratio of resin to the fibre for composite manufacture.

3.5.3 Fabrication of composite

The formation of the fibre mat was carried out prior to consolidation of the composite.

Procedure

i. The required amount of cotton stalk fibre was measured using a digital scale of accuracy 0.0001g.

ii. The phenol formaldehyde resin was measured in terms of volume in a glass beaker.

iii. The surface of the mold was covered with aluminum foil which was coated with a polyvinyl release agent MR6 to allow easy removal of the composite.

iv. The cotton stalk fibres were then laid onto the mould. Only fibres exceeding 3cm in length were used.

v. The fibres were then pre-compressed to make a fibre mat of 25g, 50g, 75g, 100g and 125g.

vi. 140 ml of phenol resin was then poured onto the mould over the fibre mat and then by use of a roller evenly distributed.

vii. The fibre mat with the resin was then subjected to cold pre compression to remove air pockets trapped within the mat by use of the compression lid and weights.

viii. Three composites from each fibre mass fraction value were fabricated.

3.5.4 Composite curing

The pre-compressed mat within the composite mould was then taken to the oven for curing.

Procedure

i. The mould with the fibre mat contained within was then placed in the oven and heated to 130°C for 45 minutes. By experimentation and monitoring of temperature it has been ascertained that the stainless steel mould took approximately 15mins to reach operating temperature of 130°C. Hence the time to cure the composite was a total of 45mins which included 15mins time for the mould to reach operating temperature and 30mins for the resin to cure well. Thickness was maintained at 50 mm.

ii. The mould was then removed from the oven and allowed to cool for 2 hours under compression. This gave the composite strength and allowed ease of removal from the mould.

iii. The board was then removed from the mould and the edges of the board trimmed.

3.6 CHARACTERISATION OF COMPOSITE

The fabricated composite was tested to determine its tensile strength, compressive strength, flexural strength, bulk density, water absorption, and staining resistance.

3.6.1 Tensile test

The tensile test was carried out using a Testometric Micro 500 model universal tensile tester. The test was carried out according to ASTM D638 (ASTM-D638, 2002)

.

Procedure

i. The fibreboard was cut into 15 cm*2.5 cm dimension using a hack saw cutter.

ii. The sample fibre board was gripped between appropriate jaws on the universal tensile testing machine and then the test program run.

iii. The specimen was placed in the grips of a Universal Test Machine taking care to align the long axis of the specimen and the grips with an imaginary line joining the points of attachment of the grips to the machine. Four specimens were tested for each sample.

iv. The speed of the testing was set at 200 mm/min.

v. The load-extension curve of the tests were recorded.

vi. The load extension at the yield point and the load and extension at the moment of rupture was recorded.

vii. Printout from the machine was obtained with the test results.

Tensile strength of the board was calculated as shown in equation 3.6 by converting the load (kgf) to Newtons and then dividing by the surface area of the testing specimens to obtain the tensile strength.

$$\text{Tensile Strength} = \frac{\text{Force (N)}}{\text{Area (mm}^2\text{)}} \qquad \text{Equation 3.6}$$

The maximum strain was calculated from the results of the tensile test. Strain is defined as deformation of a solid due to stress and can be expressed using the equation:

$$\varepsilon = \frac{dl}{l_o} \qquad \text{Equation 3.7}$$

Where

dl - change of length

l_o - initial length

ϵ - unit less measure of engineering strain

Formulae was used to calculate ultimate tensile stress, strain, and young modulus of elasticity as shown in equations 3.9, 3.10 and 3.11.

$$\text{Ultimate tensile stress} = \frac{\text{Force (N)}}{\text{Area (mm}^2\text{)}} \qquad \text{Equation 3.8}$$

$$\text{Strain} = \frac{\text{Extension}}{\text{Length}} \qquad \text{Equation 3.9}$$

$$\text{Young's modulus of elasticity} = \frac{\text{Stress}}{\text{Strain}} \qquad \text{Equation 3.10}$$

3.6.2 Compression test

Compression test was carried out to determine the yield stress and compressive strength. The standard used for the compressive tests was ASTM D695 (ASTM-D695, 2015). The machine used was a beam press CCT24 (serial number 210/6).

Procedure

i. The width of the specimen used was 25mm, thickness of 5mm and length of 150mm was measured to the nearest 0.01mm at several points along its length.
ii. Calculation was made of the cross sectional area of the specimen.
iii. Prior to testing all specimens were checked that they are free of any visible surface flaws.
iv. The specimen was placed between surfaces of the compression machine taking care to align the centre line of its long axis with the centre line of the plunger to

ensure that the ends of the specimen are parallel with the surface of the compression tool.

v. The specimens were compressively loaded at a rate of 1.3mm/min until fracture in accordance with ASTM D695 (ASTM-D695, 2015). Only failure load was recorded in this case.

The test speed used for compression test was calculated by use of a standard chart for the compression tester machine shown in Table 3-3 which indicates the conversion factor.

$$Area\ of\ test\ specimen\ (mm^2) = L(mm) * W(mm)$$

$$Area\ of\ test\ specimen = 25mm * 100mm$$

$$\boldsymbol{Area\ of\ test\ specimen = 2500mm^2}$$

Table 3-3 – Extract of machine standard with the loading rates

Area in mm^2	**Loading rate kN/minute**	**Conversion factor :kN to MPa divide by**
2500	45	2.5
4900	88	4.9
10000	180	10.0
22500	405	22.5

Hence the loading rate used was 45kN/minute for compressing the fibreboard samples. The conversion factor used is 2.5 as indicated in Table 3-3.

The compressional strength (MPa) was calculated as shown:

$$\text{Compressional Strength (MPa)} = \frac{\text{Ultimate strength (kN)}}{\text{Conversion factor}} \qquad \text{Equation 3.11}$$

3.6.3 Three point (flexural) bending test

The composite flexural strength and modulus were determined on a Universal Tensile Machine (CCT24 Beam Test serial no. 214/16) according to ASTM D790 (ASTM-D790, 2015) using three-point bending test method. A span of 100mm was used in a 5KN load cell. The load was placed midway between supports. The crosshead speed applied was 0.05KN/sec.

Procedure

i. The fibreboard sample was cut to required dimensions of 25mm X 100mm.

ii. The sample was mounted on the flexural tester machine as shown in Figure 3-7.

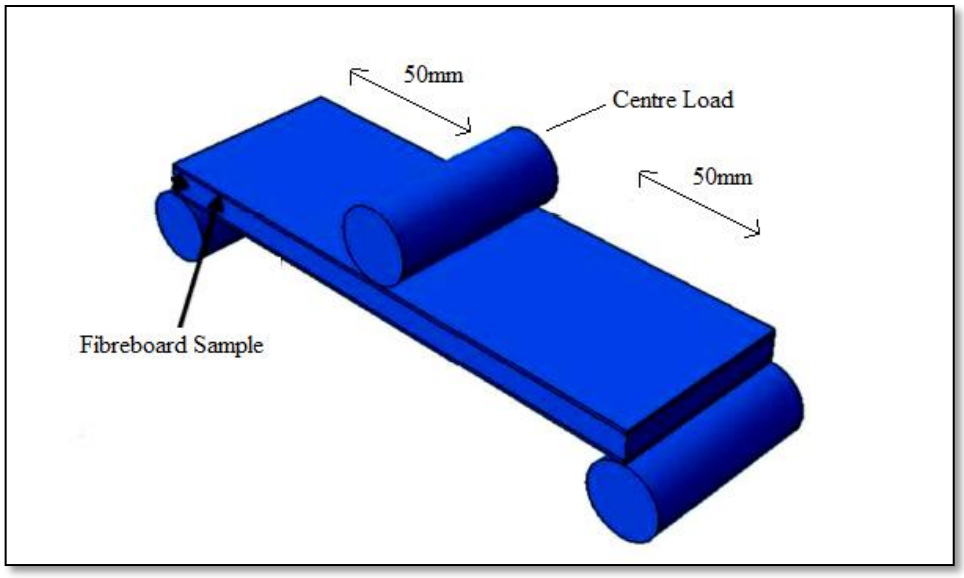

Figure 3-7 – Mounting of fibreboard sample on flexural tester

iii. The test was run until the sample broke and the maximum breaking load noted.

iv. The flexural strength was calculated at the surface of the specimen on the convex or tension side. The flexural strength was studied in relation to the fibre mass fraction. The formula used to calculate the flexural strength in MPa was:

$$f_{cf} = \frac{3F \text{ X } l}{2b \text{ X } d^2} \qquad \text{Equation 3.12}$$

Where

f_{cf} – Flexural Strength (MPa)

F – Maximum load (N)

l - Distance between axes (mm)

b – Width of specimen (mm)

d - thickness (mm)

3.6.4 Density determination

The actual density of the bio-composite was obtained by dividing the weight of the specimen with its corresponding volume in accordance with ASTM D792.

Procedure

i. The weight of the samples fibreboards with the varying fibre mass fraction was obtained using an analytical weighing balance of accuracy 0.0001g.

ii. The volume was obtained by multiplying the dimensions of the fibreboards using their respective length, width and thickness.

iii. The density of the composites was calculated using the following formula:

$$\text{Þ} = \frac{\text{Mass}}{\text{Volume}} \qquad \text{Equation 3.13}$$

3.6.5 Water absorption test

Water absorption was carried out using the standard ASTM D570-99 (ASTM standards, 2010). The samples were dried in an oven at 100°C for 2 hours, then cooled and immediately weighed on a scale of sensitivity 0.001g. The dried and weighed samples were immersed in water bath at room temperature for 2, 4 and 24 hours as described in ASTM D570-99 (ASTM standards, 2010). Excess water on the surface of the samples was removed and the weight of the samples were taken.

Procedure

i. Rectangular specimens were cut according to ASTM D570-99 of dimensions 24mm X 15mm.

ii. The composite samples were first dried in a heating oven at 50°C±3°C for 24hours then cooled.

iii. Immediately upon cooling the specimens are weighed to the nearest 0.001g and weight noted as (W_i).

iv. The samples are then completely submerged in distilled water at room temp of 23°C±2°C for 2hrs, 4hrs and 24 hours intervals.

v. At the end of 24hrs± ½ hour the specimens were removed one at a time and all surfaces wiped off with a dry cloth and weighed to the nearest 0.001g immediately.

vi. Water absorption was calculated by using the formulae:

$$\text{Percent water absorption} = \frac{W_a - W_i}{W_i} X\ 100 \qquad \text{Equation 3.14}$$

3.6.6 Resistance to staining

Glacial Acetic acid was used as the staining material for the fibreboard.

Procedure

i. Staining agent was applied to samples and covered with a glass cover and allowed to stand for 24 hours.

ii. Samples were washed with suitable wetting agent and denatured spirit then allowed to dry

iii. After one hour the samples were viewed under fluorescent light of intensity 800 to 1100 lumens/m^2 and viewed at 90 °C angle.

3.7 CONCLUSION

The methodology of this study included collecting of cotton stalk samples from Umguza district in Zimbabwe and extraction of the fibres by retting and mechanical means. The extracted fibres were characterised to determine their mechanical and physical properties. A cotton stalk fibre/phenol formaldehyde resin bio-composite was then fabricated using hand lay and compression moulding to achieve composite consolidation. The fabricated fibreboard was characterised to ascertain its mechanical and physical properties.

CHAPTER 4 : RESULTS AND DISCUSSION

4.0 INTRODUCTION

Cotton stalks were collected in Zimbabwe and fibres extracted from the cotton stalks. Physical and mechanical properties of the cotton stalk fibres were tested and analysed. A composite was developed using cotton stalk fibres and phenol formaldehyde resin and the mechanical and physical properties of the developed composite were determined and analysed. The characterization tests carried out include tensile strength, flexural strength, compressional strength and water absorption. The mechanical and physical properties of the produced board were compared to the mechanical and physical properties of available fibreboards, particleboards and solid wood boards in the Zimbabwean market to assess suitability of fabricated bio-composite for similar applications.

4.1 EXTRACTION OF FIBRES

The cotton stalks were retted in 150 litre plastic drums using tap water. The efficiency of retting was measured in the laboratory on a weekly basis to establish the optimum retting time for the cotton stalks. Figure 4-1 shows a photograph of the extracted cotton stalk fibres.

Figure 4-1– Image of extracted cotton stalk fibres

4.1.1 Efficiency of water retting with time

The efficiency of the retting process was measured by analysing the effect of changing weight of cotton stalks after retting on a weekly basis. The weight loss represents how much of all the materials has been removed during the retting process and hence is an indication of the efficiency of the retting process. The trend for degumming is consistent with the trend for weight loss (Peiying Ruan, 2015). The weights used in calculations were the oven dry weights of the cotton stalks before and after retting. The raw data for measurements of the oven dry weight of the stalks with time is attached in Appendix B. Table 4-1 shows a summary of the mean statistics of retting efficiency in the three week duration.

Table 4-1 – Summary statistics showing retting efficiency in terms of weight loss

Time	**Week 1**	**Week 2**	**Week 3**
Drum A (%)	8.31	4.38	3.38
Drum B (%)	8.39	4.81	2.68
Mean (%)	8.35	4.60	3.03
Standard deviation	0.0570	0.3041	0.4950

The weight loss percentage represents how much of all the materials had been removed during the retting process. The retting was highest during the first week with weight loss of 8.35% and started to decline by almost half to 4.60% in the second week and then to 3.03% in the third week. During the first week the high weight loss can be attributed to removal of dirt and adhering particles as well as degumming process. During the second week most of the dirt had been removed and the weight loss can be attributed to dissolutions of pectin. In the third week the weight loss reduces to 3.03% showing that the first two weeks of retting have the most impact on pectin dissolution. This indicates that the most economic and efficient time for retting of cotton stalks is 3 weeks based on these results. Figure 4-2 shows the decline in retting efficiency with time.

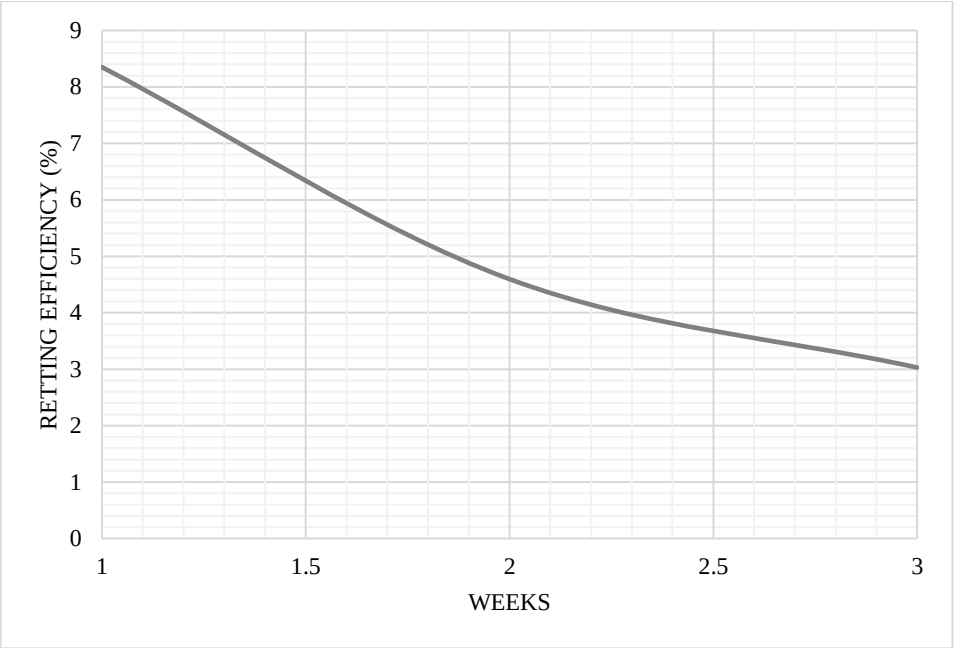

Figure 4-2 – Graph showing change of retting efficiency with time

4.1.2 Effluent from retting process

The water from the retting tanks was tested on a weekly basis to find out the build-up of contamination in the water as this would dictate the suitable disposal method of the waste water. As a control, tap water used to fill up the drums was analysed first. Table 4-2 shows the results of water quality from testing of water from the two retting tanks with time.

Table 4-2 – Physio-chemical water quality parameters

Type of water	Water Quality Parameter	Units	Retting Time (Days)		
			15	21	28
Tap Water	pH		7.40		
	Temp	°C	22.3		
	Conductivity	µS	204		
	Temp	°C	22.5		
	TDS	ppm	102		
	Temp	°C	22.3		
Sample 1	pH		5.32	5.32	
	Temp	°C	22.9	24.5	
	Conductivity	µS	1269	1280	
	Temp	°C	22.1	24.4	
	TDS	ppm	102	626	
	Temp	°C	22.3	24.4	
Sample 2	pH		5.35	5.62	7.17
	Temp	°C	23.2	23.9	27.3
	Conductivity	µS	1036	1339	1546
	Temp	°C	22.3	24.5	27.4
	TDS	ppm	513	647	700
	Temp	°C	22.3	24.4	27.4

The results showed that pH of water decreased sharply during the first week of retting from 7.4 to 5.32. The lowering of pH values for post retting water is related to release of organic acids like butyric, acetic and lactic acid during microbial metabolism of sugars, pectins and other gummy materials (Ahmed, 2001).

The TDS increased sharply from 102ppm to 513ppm in the first week. In the following week a marginal increase to 647ppm and final TDS of 700ppm was recorded. This rendered the water unfit for drinking and past the accepted maximum contamination levels according to EPA for drinking water. Figure 4-3 shows a TDS scale on water quality.

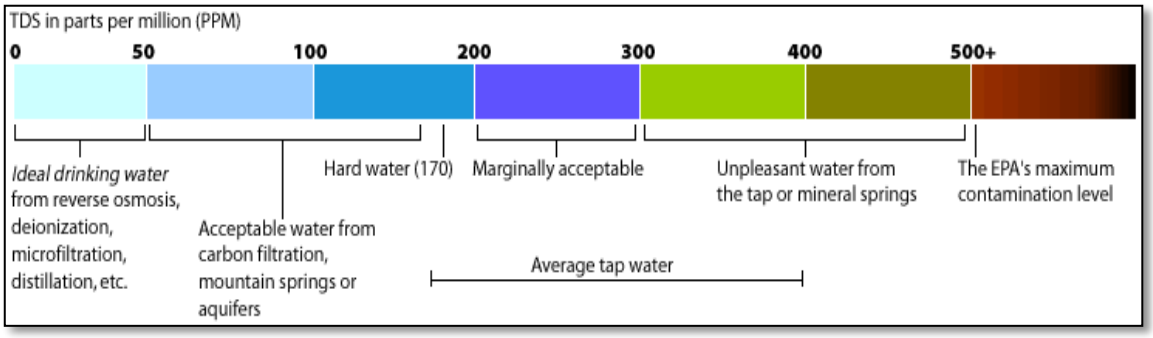

Figure 4-3 – TDS in parts per million scale (What is TDS, 2005)

The Total Dissolved Solids (TDS) is directly related to electrical conductivity of water. As the TDS of the water increased with time so did the conductivity. The conductivity of the water increased from 204 µS to 1036 µS this is attributed to the minerals such as calcium and magnesium released from the cotton stalks during the retting process. From the second week to the third week there was a marginal increase from 1036 µS to 1339 µS. From second week to the final week of retting the increase was slight with the final conductivity of the water being 1546µS. The reason for the marginal increase in conductivity is due to the fact that when salt concentration reaches a certain level, electrical conductivity is no longer directly related to its salts concentration. This is

because ion pairs are formed. Ion pairs weaken each other's charge, so that above this level, higher TDS will not result in equally higher electrical conductivity.

The retting process also generated a strong sweet odour that necessitated ventilation of the retting shed to dispel the odour.

4.1.3 Yield of cotton stalk fibres

The yield of fibres was found to vary depending on the position of origin of the fibres on the cotton stalk. The retted sample cotton stalks were oven dried and weighed to get initial weight. The raw data for calculated of percentage fibre yield from the different section of the cotton stalk can be found in Appendix C. Figure 4-4 shows the yield in percentages obtained from the cotton stalks.

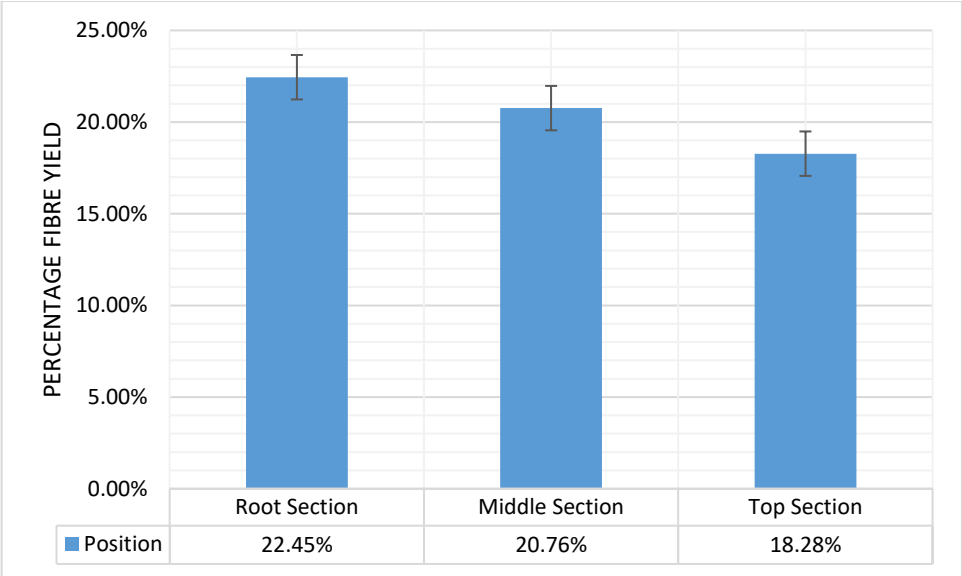

Figure 4-4 – Graph showing fibre yield of cotton stalk fibres from the stalk in percentages

The root section gave the highest amount of fibre yield from the cotton stalk. The fibre yield was determined as 22.45%, 20.76% and 18.28% for root, middle and top section respectively. The middle section of the stalk gave a fibre yield of approximately 20.76% which was lower than the root area by 3.24%. The top section of the stalk gave the least yield of fibres with approximately 19% fibre yield. The top section 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 section 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 section and reduces going up the stalk toward the top section. However on extraction of the fibres it was noticed that the very tip of the root section failed to yield useable fibre and this part was not included in the study.

4.1.4 By-product from fibre extraction (shive)

The woody inner core of the cotton stalks (shive) is the by-product that remained after the extraction of fibres which are on the outer bark layer. This shive makes up approximately 70% of the cotton stalk by weight. If left out to dry in the sun the shive as shown in Figure 4-5 makes for excellent kindle fuel for making cooking fires as it dries very quickly and ignites easily.

Figure 4-5– By-product of cotton stalk fibre extraction (shive)

4.2 CHARACTERISATION OF COTTON STALK FIBRE

The extracted cotton stalk fibres were tested to ascertain their mechanical and physical properties. This serves as a guideline to possible end uses of the fibres.

4.2.1 Colour

The cotton stalk fibres extracted were brownish in colour. Generally speaking, extending the water retting duration significantly increased the whiteness of the cotton stalk fibres. Water retting is able to improve the whiteness of fibres because coloured materials and contaminating substances, such as dust, dissolve and settle in the retting water (Sharma H. a., 1992). The fibres from the top section of the stalk were dark brown in colour while the fibres from the root section were light brown in colour.

4.2.2 Microscopic examination

The microscope image shown in Figure 4-6 shows micro fibrils held in a shiny brown resin like material. The cotton stalk fibre is in itself a natural composite as the micro fibrils are held together with a resin like material giving strength to the fibres.

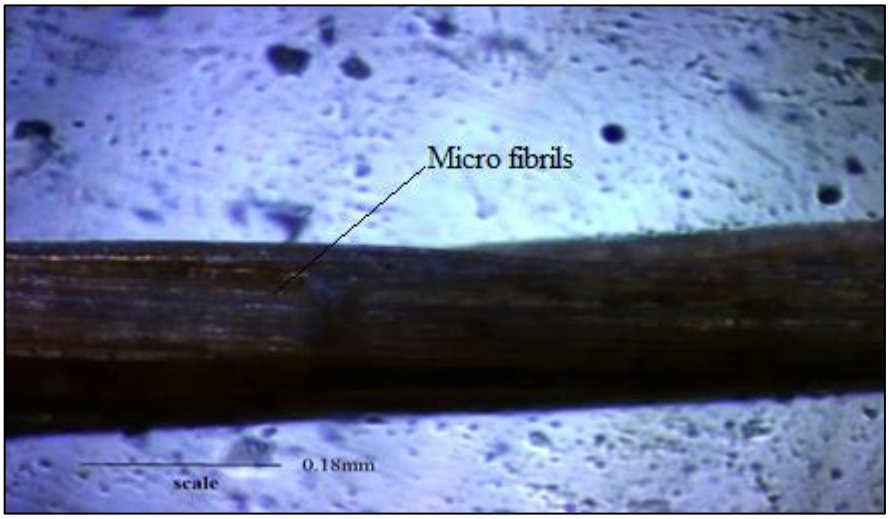

Figure 4-6 – Cross sectional microscopic image of cotton stalk fibre x10 magnification

Image J software was used to scale the fibre and take measurements of its mean diameter. The mean fibre diameter of these fibres was 0.189 mm. Table 4-3 shows the fibre diameter measurement that was taken for top section cotton stalk fibre. The mean fibre diameter of these fibres was 0.189 mm.

Table 4-3 – Measurement of fibre diameter and scale input using image J software

	Label	Area	Mean	Std Dev	Min	Max	Angle	Length
1		5.52E-05	29.867	65.115	0	222.667	0	0.18
2		5.93E-05	27.518	14.836	4.333	75.333	-89.637	0.193
3		5.93E-05	27.518	14.836	4.333	75.333	-89.637	0.193
4		5.67E-05	26.859	17.307	2.567	99.667	-89.621	0.185
5		5.60E-05	21.551	15.627	3.098	66.667	-89.615	0.182
6		5.60E-05	21.551	15.627	3.098	66.667	-89.615	0.182
7		6.31E-05	27.444	16.992	5.333	96	-89.659	0.206
8	Mean	5.79E-05	26.044	22.906	3.252	100.333	-76.826	0.189
9	SD	2.80E-06	3.213	18.638	1.721	55.53	33.877	0.009
10	Min	5.52E-05	21.551	14.836	0	66.667	-89.659	0.18
11	Max	6.31E-05	29.867	65.115	5.333	222.667	0	0.206

From the table it can be seen that the mean fibre diameter of the top section cotton fibre used for microscopic examination was 0.189mm.

4.2.3 Fibre Length

The cotton stalk fibre length was measured and the average fibre length from different areas of the cotton stalk ascertained. Forty fibres were tested from each area of the stalk (i.e. top, bottom and root section). Figure 4-7, Figure 4-8 show the distribution of fibre lengths for each section of the cotton stalk the top area, bottom area and root area.

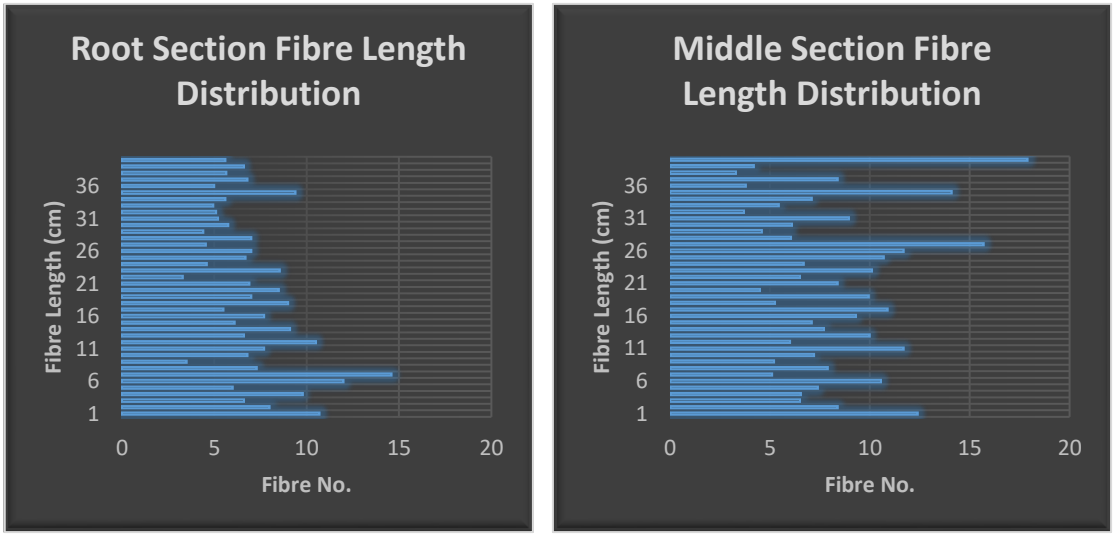

Figure 4-7 – Root section and middle section fibre length distribution

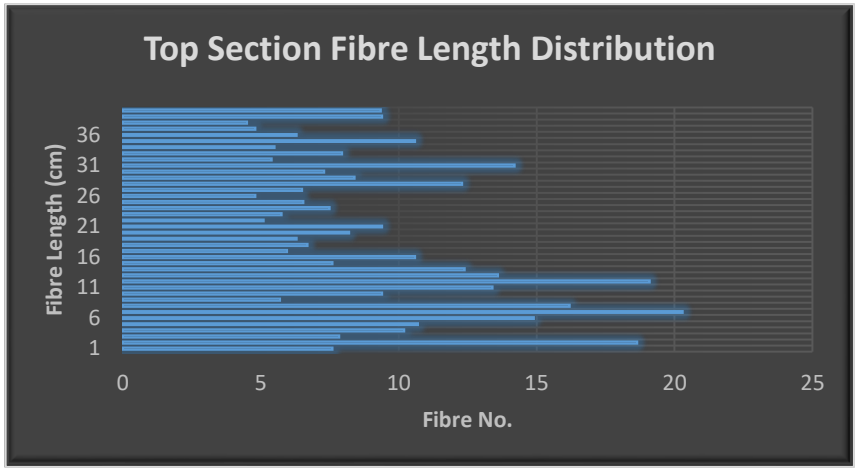

Figure 4-8 – Top section fibre length distribution

Table 4-4 shows the summary results obtained and the calculated mean lengths of the fibres.

Table 4-4 – Summary of results for fibre length

Parameters	Root Section	Middle Section	Top Section
Mean Length (cm)	7.04	8.08	9.42
St Dev	2.314	3.312	4.156
Minimum	3.300	3.300	4.5
Maximum	14.6	17.900	20.300
Variance	5.357	10.967	17.273
Coef Var	32.87	41.00	44.10

Figure 4-9 shows the variation of the mean length of the fibres from different sections of the cotton stalk more clearly.

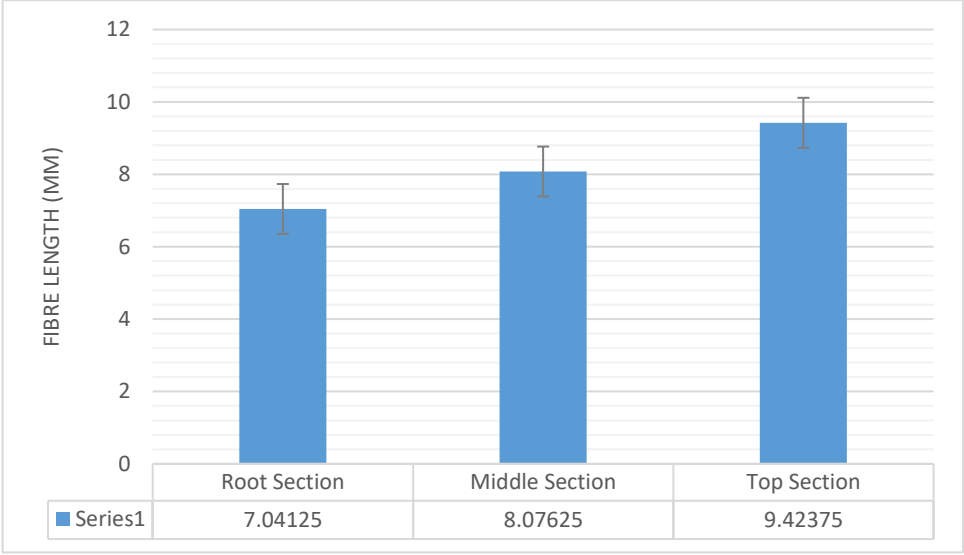

Figure 4-9 – Graph showing mean fibre length of cotton stalk fibres from different sections of the cotton stalk

The fibres from the top section of the stalk had the highest mean fibre length of 9.4mm. 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 on extraction. Fibres in the middle and root section were more compactly held and upon fibre extraction some fibre breakage would occur. The root section fibres gave the lowest fibre length of approximately 7mm. This difference in fibre length showed the need for correct retting of the cotton stalks as the well retted top section of the cotton stalk allowed easier fibre extraction in comparison to the root section fibres. This could be alleviated by using vertical and horizontal stepping method to ensure that the whole stalk is well retted. The Zimbabwe cotton stalk fibres are significantly greater in length than that of Sudanese and Iranian cotton stalks. The Sudanese Cotton stalks have average fibre length of 0.79mm and the Iranian cotton stalk fibres are 0.926mm in length (Tarig Osman Khiider, 2012).

4.2.4 Fibre strength

Tensile strength testing of the fibres was done on a Testometric universal tensile tester machine, Micro 500 model. The fibres were tested according to their position of origin on the cotton stalk. Bundle fibre testing method was used for testing the tenacity of the fibres with each bundle consisting of 10 fibres.

4.2.4.1 Fibres from top section of stem

The fibres from the top half of the cotton stalk were tested. Table 4-5 shows the results obtained for fibre bundle testing of 10 fibres per test run for top section fibres.

Ref 1: Cotton Stalk Fibres Date : 25/11/2015
Ref 2: Top Section Cotton stalks Test Speed : 200 mm/min

Table 4-5 – Fibre properties from the top section bundle testing (10 Fibres per bundle)

No.	Load @ Peak	Elongation @ Peak	Strain @ Peak	Energy @ Peak	Load @ break	Elongation @ Break	Strain @ break	Energy @ break
	kgf	mm	%	kgf	kgf	mm	%	Kgf
1	1.13	0.1028	0.0511	0.0010	0.03	18.883	9.386	0.0019
2	2.16	1.0322	0.5121	0.0019	0.02	22.512	11.167	0.0055
3	1.60	0.4250	0.2090	0.0006	0.05	13.935	6.852	0.0021
4	1.36	0.3697	0.1812	0.0004	0.13	31.570	15.471	0.0055
5	1.22	0.4520	0.2238	0.0005	0.06	15.922	7.884	0.0027
Min	1.13	0.1028	0.1812	0.0010	0.06	13.935	6.852	0.0019
Mean	1.49	0.4763	0.2354	0.0009	0.06	20.564	10.152	0.0035
Max	2.16	1.0322	0.5121	0.0019	0.13	31.570	15.471	0.0055
Std Dev	0.41	0.3403	0.1690	0.0061	0.43	6.951	3.389	0.0018
Co-Eff Va.	27.60	71.4900	71.7900	697.7300	745.52	33.800	33.380	51.2200

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 (M.Sfiligoj Smole, 2013). The strength of top section fibres is intermediate strength of middle section 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 section fibres. The top section fibres had elongation of 1.17%.

4.2.4.2 Fibre from middle section of the stem

The fibres from the middle section of the cotton stalk were tested. Table 4-6 shows the results obtained for fibre bundle testing of 10 fibres per test run of fibres from the middle section of the stalk.

Ref 1: Cotton stalk fibres
Ref 2: Middle section fibres

Date : 25/11/2015
Test Speed : 200 mm/min
Sample Length : 35 mm
Pre-tension : 1 kgf

Table 4-6 – Fibre properties from middle section of the stem

No.	Load @ Peak	Elongation @ Peak	Strain @ Peak	Energy @ Peak	Load @ break	Elongation @ Brea3k	Strain @ break	Energy @ break
	kgf	mm	%	kgf	kgf	mm	%	kgf
1	2.01	0.4808	0.2387	0.0007	-	21.811	10.828	0.0016
2	2.16	0.2739	0.1362	0.0004	-	18.014	8.961	0.0014
3	2.16	0.5785	0.2874	0.0009	0.02	18.709	9.292	0.0028
4	2.71	0.5604	0.2789	0.0011	0.02	21.310	10.606	0.0021
Min	2.01	0.2739	0.1362	0.0200	18.01	8.961	8.961	0.0014
Mean	2.26	0.4734	0.2353	0	19.96	9.922	9.922	0.0020
Max	2.71	0.5785	0.2874	0.0200	21.81	10.828	10.828	0.0028
Std Dev	0.31	0.1396	0.0694	0.0283	1.88	0.933	0.933	0.0006
Co-Eff Va.	13.64	29.4900	29.4800	0	9.42	9.400	9.400	32.5600
Lower C.L.	1.77	0.2512	0.1249	0.0450	16.97	8.438	8.438	0.0010
Upper C.L	2.75	0.6956	0.3457	0.0450	22.95	11.406	11.406	0.0030

The tenacity of the middle section fibres was 56.3cN/tex which was the highest off all the extracted fibres 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 (Sweety Shahinur, 2015). The tenacity of the fibres was slightly higher than the tenacity of flax fibres which is approximately 55cN/tex (M.Sfiligoj Smole, 2013). The middle section fibres were mature whereas the top and root section fibres are immature and over mature, respectively (S.Shahinur, 2013) 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% (M.Sfiligoj Smole, 2013). The middle section fibres had higher elongation than fibre from the top section.

4.2.4.3 Fibre from the root section

The fibres from the root section of the cotton stalk were tested. Table 4-7 below shows the results obtained for bundle testing of 10 fibres per test run.

Ref 1: Cotton stalk fibres
Ref 2: Middle section fibres
Ref 3: 10 Fibres per test

Date : 25/11/2015
Test Speed : 200 mm/min
Sample Length : 35 mm
Pre-tension : 0 kgf

Table 4-7 – Bundle test fibre properties from the root section

No.	Load @ Peak	Elongation @ Peak	Strain @ Peak	Energy @ Peak	Load @ break	Strain @ break	Strain @ break	Energy @ break
	kgf	mm	%	kgf	kgf	%	%	kgf
1	0.03	0.11	0.055	-	0.03	0.11	0.055	-
2	0.05	0.17	0.850	-	0.05	0.17	0.085	-
3	0.08	0.17	0.850	-	0.08	0.17	0.085	-
Min	0.03	0.11	0.055	0	0.03	0.11	0.055	0
Mean	0.05	0.15	0.075	0	0.05	0.15	0.075	0
Max	0.08	0.17	0.085	0	0.08	0.17	0.085	0
Std Dev	0.03	0.03	0.0170	0	0.03	0.03	0.017	0
Co-Eff Va.	47.19	23.09	23.090	0	47.19	23.09	23.090	0
Lower C.L.	0.01	0.06	0.032	0	0.01	0.06	0.032	0
Upper C.L	0.01	0.24	0.118	0	0.12	0.24	0.118	0

The fibres from the root section of the cotton stalks had the lowest strength in comparison to fibre from the top and middle section of the cotton stalk. This could be attributed to the low fibre maturity of the fibres. The fibres from the root section of the cotton stalks had the lowest strength in comparison to fibre from the top and middle section of the cotton stalk. This could be attributed to the low fibre maturity of the fibres. The mean fibre tenacity for fibres from the root section was 0.00533kgf. This gave the fibres a tenacity of 2.21cN/tex. This tenacity is very low for root section fibres. The reason for this is the fibre were over matured and had little strength. The elongation of the root section fibres is calculated as 0.43%.

The graph in Figure 4-10 shows comparison of the tensile strength of fibres from different sections of the cotton stalk

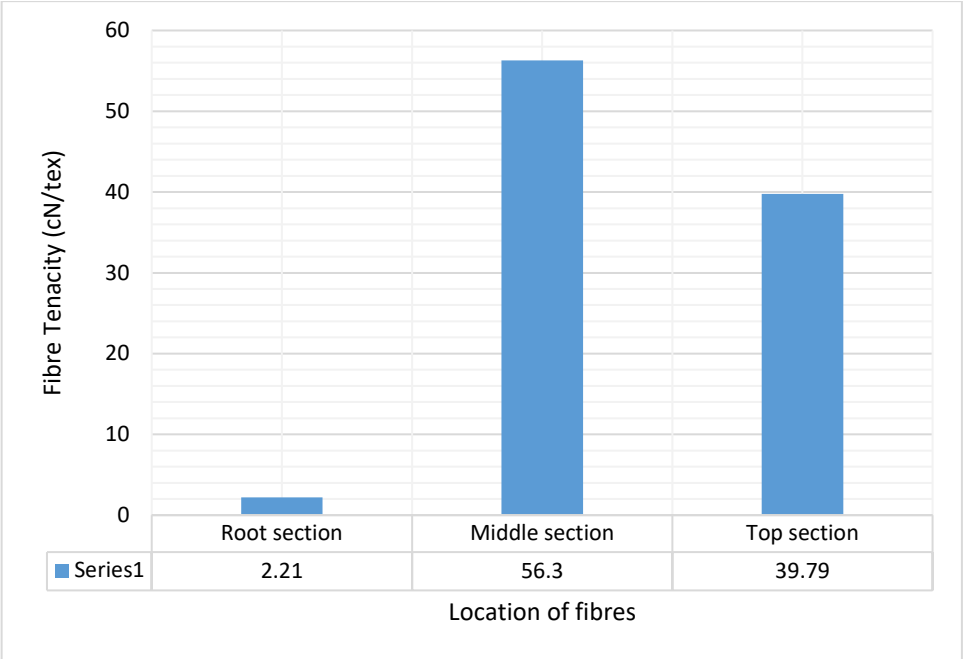

Figure 4-10 – Fibre tenacity results for fibres from different sections of the cotton stalk

The root section fibres have the lowest strength which is far much lower than the strength of the fibres from the other sections as shown in Figure 4-10. The root section fibres also have the lowest elongation of all the fibre from different sections of the cotton stalk.

4.2.5 Linear density

The linear density was calculated by first measuring the fibre length and then the weight of the fibre bundle was measured. The linear density was then computed from these figures. The expected fibre fineness was approximately 3.08tex (Long Li, 2011). The raw data for the fibre linear density measurement can be found in Appendix C.

The graph in Figure 4-11 shows a comparison of the fibre fineness of cotton stalk fibres from different sections of the cotton stalks.

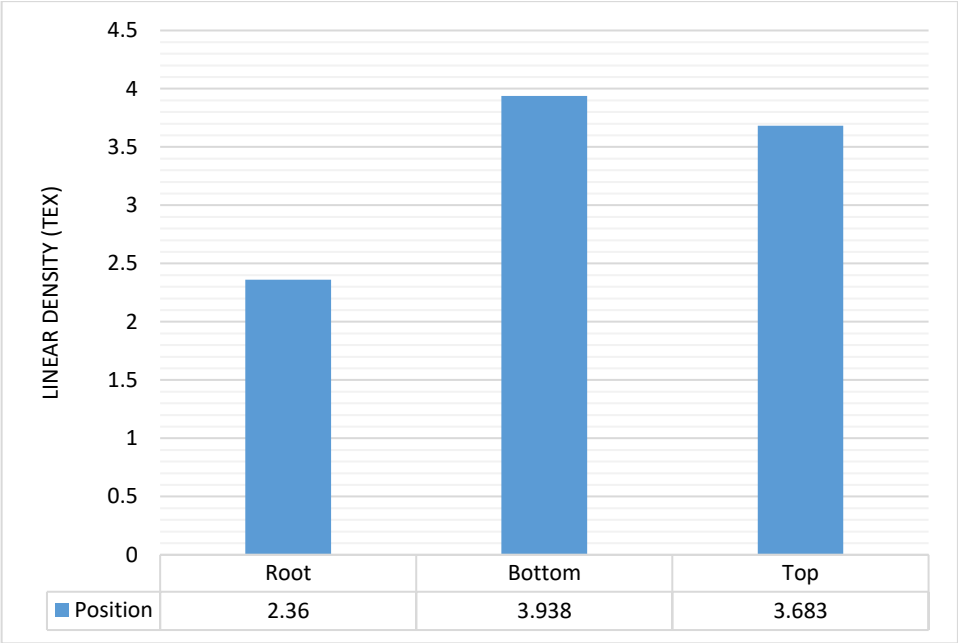

Figure 4-11 – Graph showing the fibre fineness of cotton stalk fibres from different sections of the cotton stalk

The fibres from the root section have average linear density of 2.36tex. This section gives fibres with the lowest linear density from the cotton stalk. The middle section fibres give linear density of 3.938tex which is an increase of 66.86% from the root section 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 middle section fibres but more than root section fibres.

4.2.6 Moisture regain

Figure 4-12 shows moisture regain of cotton stalk fibres from the different sections of the stalk. The raw data for moisture regain measurement is found in Appendix I.

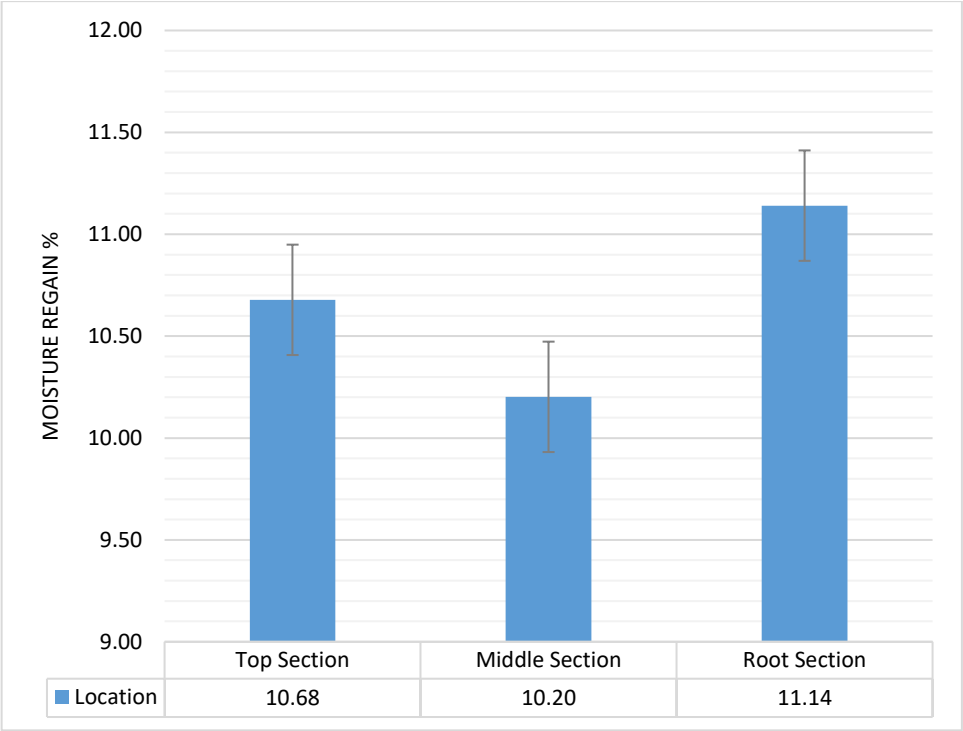

Figure 4-12 – Graph showing moisture regain of cotton stalk fibres from different sections of the stalk

The fibres located in the root section had the highest moisture regain which was 11.14%. The fibres located in middle section of the cotton stalk had a moisture regain of 10.2% which is lowest due to the higher fibre maturity. The diameter of the fibre increases as the plant matures however in contrast the moisture content and water absorption seems to decrease (Nadlene Razali M. S., 2015). These fibres located in the middle section due to their low moisture regain are most suited for composite manufacture. The fibres located in the top section of the stalk had a moisture regain of 10.68% which was less than the root section but higher than the middle section of the stalk. The moisture regain of cotton stalk fibres is greater than that of cotton boll fibres which have a moisture regain of 8% (Rajalakshmi M, 2012).

4.2.7 Fibre diameter

The fibre diameter was measured using a microscope with an attachment for a Vernier scale. The raw data for fibre diameter measurement can be found in Appendix J. Figure 4-13 shows a summary of the mean fibre diameter of the cotton stalk fibres.

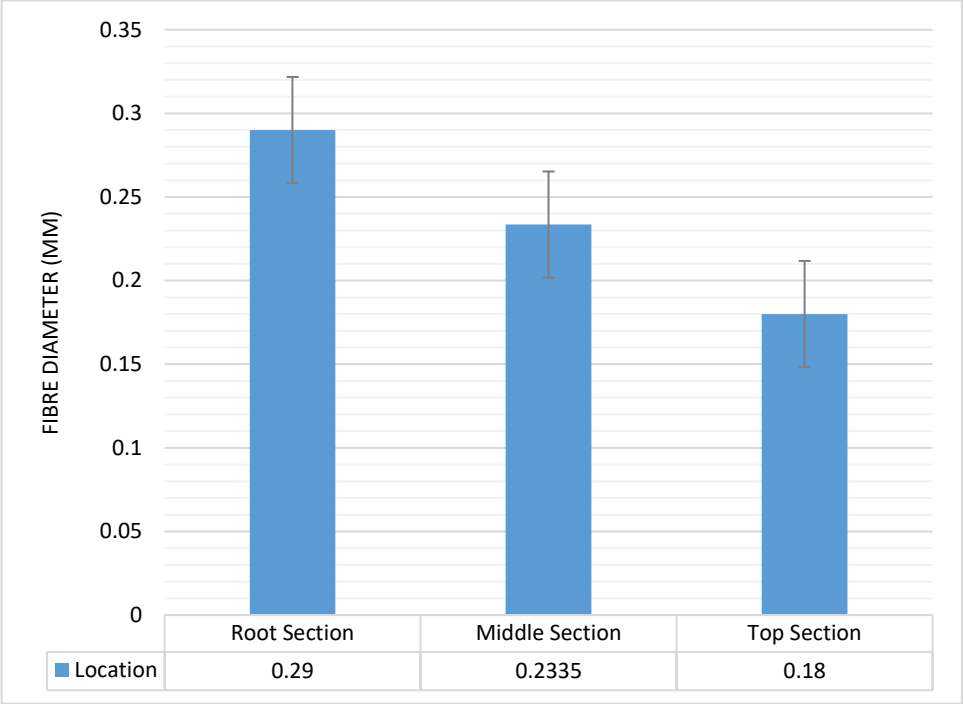

Figure 4-13 – Graph showing fibre diameter of cotton stalk fibres from different sections of the cotton stalk

The diameter of the cotton stalks 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 middle section is 0.2335mm a decrease in diameter of 19.48%. The diameter of the fibres located at the top section of the cotton stalks is 0.1800mm a decrease of 22.91% from the fibres in the middle section of the stalk. The diameter of the cotton stalk fibre is similar to that of sisal fibres which range from 100-300um in diameter (Kuruvilla Joseph, 1999). 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 18.2µm and that of Iranian cotton stalk fibres is 23.88µm (Tarig Osman Khiider, 2012)

4.2.8 Density of fibres

The density of the cotton stalk fibres was measured by obtaining the mass of 40 fibres from the root section, middle section and top section of the cotton stalk fibres as well as the length of the fibres and then calculating the volume of the fibres. The volume obtained and the mass of the fibres was able to give the density.

The raw data for measurement of fibre length can be found in Appendix K. The determined density for root, middle and top section fibres was 1.45 g/cm^3, 1.72 g/cm^3 and 1.85 g/cm^3 respectively.

The middle section fibres of the stalk had the highest density this may be attributed to the high fibre maturity in this region. The root section fibres had the lowest density at 1.45g/cm^3. The top section fibres had intermediate density of 1.85g/cm^3. The density of cotton stalk is similar to that of sisal fibre which has a density of 1.45g/cm^3 (Kuruvilla Joseph, 1999).

4.2.9 Statistical analysis of average properties of fibres

The properties of fibres from the different sections were analysed using one way Multi-variance Analysis (MANOVA) on SPSS software to access the significance of the difference in properties between the fibres from different locations of the cotton stalk.

The sample size was 40 fibres tested for each of the properties from 3 levels of the stalk which were top section, bottom section and root section. Table 4-8 shows the test results for the manova multivariate test.

Table 4-8 – Multivariate tests

Effect		Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Powerb
Intercept	Pillai's Trace	0.995	7.892E3a	3	115	0	0.995	23676.72	1
	Wilks' Lambda	0.005	7.892E3a	3	115	0	0.995	23676.72	1
	Hotelling's Trace	205.885	7.892E3a	3	115	0	0.995	23676.72	1
	Roy's Largest Root	205.885	7.892E3a	3	115	0	0.995	23676.72	1
Location	Pillai's Trace	0.701	20.862	6	232	0	0.35	125.172	1
	Wilks' Lambda	0.357	25.814a	6	230	0	0.402	154.886	1
	Hotelling's Trace	1.638	31.12	6	228	0	0.45	186.719	1
	Roy's Largest Root	1.532	59.232c	3	116	0	0.605	177.695	1

a. Exact statistic

b. Computed using
alpha = .05

c. The statistic is an upper bound on F that yields a lower
bound on the significance level.

d. Design: Intercept +
Location

From the multivariate tests Pillai's Trace shows there is a significant difference between groups as it is less than the computed alpha of 0.05.There was significant difference between fibres from different location when considered jointly on the variables tensile strength, elongation, fibre density, fibre diameter, fibre length, linear density and moisture regain, Wilk's A= 0.357, $F(6, 230) = 25.81$, $p < 0.0005$, partial $n^2 = .402$.

The between subjects test results are attached in the appendix section. The test of between subject effects shows that location has a statistically significant effect on Fibre diameter ($F(2,117) = 76.34$; $p<0.0005$; partial n2 = 0.566 and Moisture Regain ($F(2,117) = 8.917$; $p<0.0005$; partial n2 = 0.132 and Fibre length ($F(2,117) = 5.524$; partial n2 = .086. It was necessary to make an alpha correction to account for multiple ANOVAs being run, such as a Bonferroni correction. As such in this case we accept statistical significance at $p <0.025$.

Attached in the appendix section is the manova multiple comparisons post hoc tests which show results from tuskeys HSD post hoc tests.

The significant ANOVAS can be followed up with Tuskey's HSD post-hoc tests. The table shows that for mean Fibre diameter was statically significantly different between middle and top ($p < .0005$), and middle and root ($p<.0005$), root and middle ($p<.005$), root and top ($p<.0005$). Moisture regain was not statistically significant between middle and top ($P=0.086$), between root and top ($p=0.098$) but was statistically significant between middle and root ($p<.005$). Fibre length was not statistically significantly different

between middle section and root section (p=0.279), between middle and top (p=0.178). Was statistically significant between root and top (p< .005).

4.3 CHARACTERISATION OF COMPOSITE

The fabricated composite was characterized in terms of density, tensile strength, flexural strength, density and water absorption tests as summarised in Table 4-9.

Table 4-9 – Showing summary of measured parameters of the composite board

Fibre Mass Fraction	Tensile Strength	Compressional Strength	Flexural Strength	Density	Water Absorption
%	MPa	MPa	Mpa	Kg/m^3	%
10.96	2.25	0.67	580	644.16	74.31
19.76	2.79	0.76	980	734.22	76.89
26.98	3.58	0.88	1400	856.23	78.85
33.00	4.18	1.82	1500	895.19	92.10
38.11	6.84	1.85	2400	1004.34	100.89

Table 4-10 shows the composite fabrication specifications used.

Table 4-10 – Composite specifications

No.	Fibre Mass Fraction	Fibre weight	Resin	Resin Volume Fraction	Resin weight	Total Weight	Calculated Density
	%	g	ml	%	g	g	kg/m^3
1	0%	0	140ml	100.00%	155.4	155.4	586.4151
2	10.96%	25	140ml	89.04%	155.4	180.4	680.7547
3	19.76%	50	140ml	80.24%	155.4	205.4	775.0943
4	26.98%	75	140ml	73.02%	155.4	230.4	869.4340
5	33.00%	100	140ml	67.00%	155.4	255.4	963.7736
6	38.11%	125	140ml	61.89%	155.4	280.4	1058.1132

The density of particleboards that are manufactured from cotton stalk is about 671 kg/m^3 (Mr. P. G. Patil, 2007). The density of the manufactured fibre boards in this project varied between 586.42kg/m^3 – 1058.11kg/m^3. This falls into the region of medium density fibreboards (E.Woodson, 1987). The fibre mass fraction was varied by increasing the fibre content in the composite between 0g to 125g. This gave a fibre mass fraction of

between 0 – 38.11%. Any value exceeding this percentage is extremely difficult to fabricate due to the fibre to resin ratio.

The density of the resin was calculated from the previous experiment and found to be 1.11g/cm^3. The density of the fibre was calculated as an average at 1.45g/cm^3. Figure 4-14 shows a picture of some of the fabricated fibreboards.

Figure 4-14 – Samples of fabricated fibreboards

Tests were carried out on the produced cotton stalk fibre boards to better understand its properties and limitations and hence predict its possible end uses. The mechanical properties of natural fibre composites depend on many parameters such as fibre strength, modulus, fibre length and orientation, in addition to the fibre matrix interfacial bond strength (M. Sumaila, 2013).

4.3.1 Composite tensile strength

The fibreboard samples were tested for tensile strength using a Testometric universal tensile tester machine. Attached in the appendix P, Q, R and S is the raw data from the tensile strength test. Figure 4-15 shows shows the relationship between the load and the extension of the biocomposite.

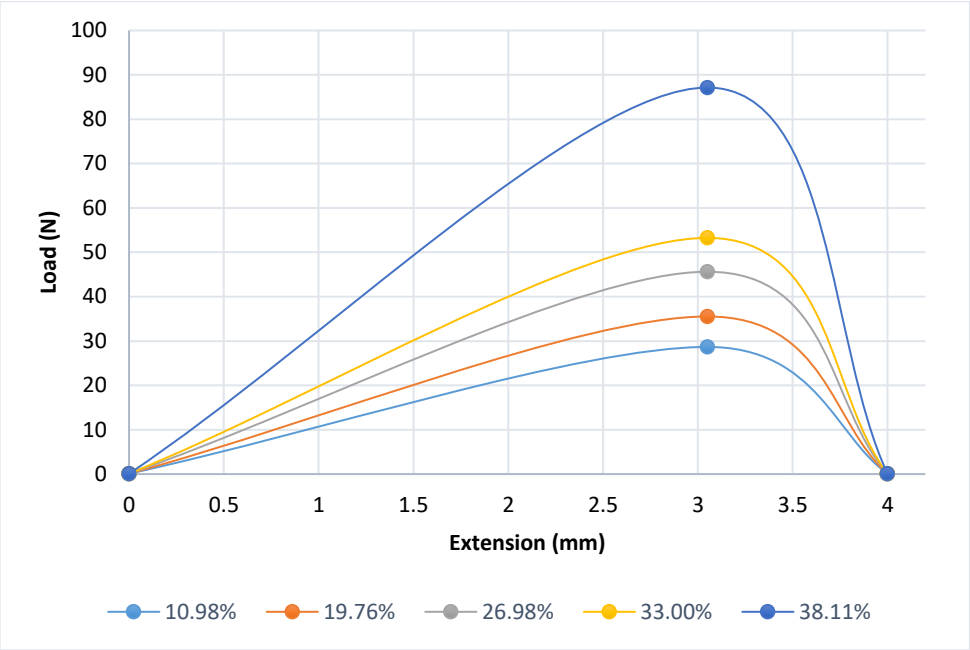

Figure 4-15 – Graph of load vs extension for bio composite

From Figure 4-15 it can be seen that the fibreboard tensile strength increases with increase in fibre content. The modulus of elasticity and extension to break of the composite also increases with the amount of cotton stalk fibres up to a certain threshold. The tensile strength of the fibreboard increases with increase in fibre content. The fibreboard with 10.98% M_f fibre had the least load at break of 28.67N. As the fibre content increased the corresponding strength increased. The fibreboard with 38.11% M_f had the highest load at break of 83.24 due to greater fibre content to distribute the stress and increased fibre pull out failure mode. It was noticed that the increase in fibre content produced a more serrated and uneven fracture surface as the composite failure is fibre controlled. The composite failure as fibre content increased had a higher fibre pull out length implying an increase in toughness. The extension of the fibreboard increases slightly as the fibre content increases this can be attributed to increased fibre pull out as failure of board becomes more fibre dependent. Table 4-11 shows the results for the strain and modulus of the fabricated fibreboard.

Table 4-11 – Summary of tensile properties of fibreboard

M_f	Tensile Strength (MPa)	Strain	Young Modulus	% Elongation
10.98%	2.25	1.5235	1.4764	3.05
19.76%	2.79	3.3561	0.8305	1.67
26.98%	3.58	4.0373	0.8864	2.01
33.00%	4.18	4.0907	1.0211	2.04
38.11%	6.84	3.5802	1.9093	1.78

As the fibre mass fraction increases the tensile strength and the strain increase. However at 38.11% fibre mass fraction the strain and maximum elongation percentage starts to reduce. Figure 4-16 shows change in tensile strength of fibreboard with increase in fibre mass fraction.

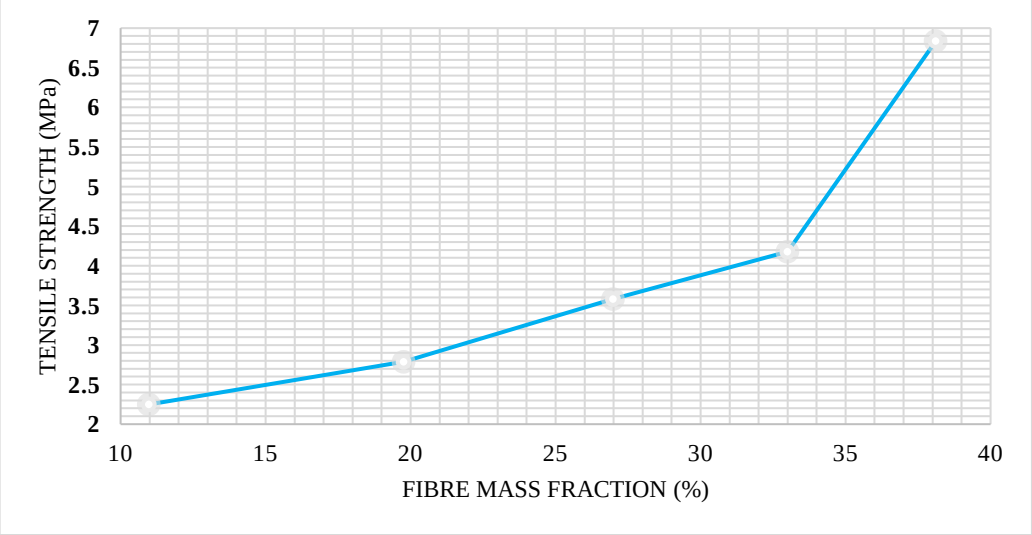

Figure 4-16 – Graph showing change in tensile strength of fibreboard with increase in fibre mass fraction.

Figure 4-16 shows that as the fibre mass fraction increases there is a steady increase in the corresponding tensile strength. At the lowest fibre mass fraction of 10.98% the tensile strength is 2.25MPa. As the fibre mass fraction increases there is steady increase in the tensile strength. At fibre mass fraction of 38.11% the tensile strength is 6.84MPa. Generally the tensile properties of composites are markedly improved by adding fibre to a polymer matrix since fibre have higher strength and stiffness values than those of matrices (Ku H., 2011).

4.3.2 Composite compression strength

A compression test determines behaviour of materials under crushing loads. In compression, it is usually known that that the ultimate compressive strength of the composite is mainly dependent on the strength of the matrix and the extent of fibre/matrix adhesion (Mylsamy, 2011).

The raw data for the compression strength test is attached in the appendix W. Figure 4-17 shows the fitted line plot for compressional strength (MPa) vs fibre mass fraction (%).

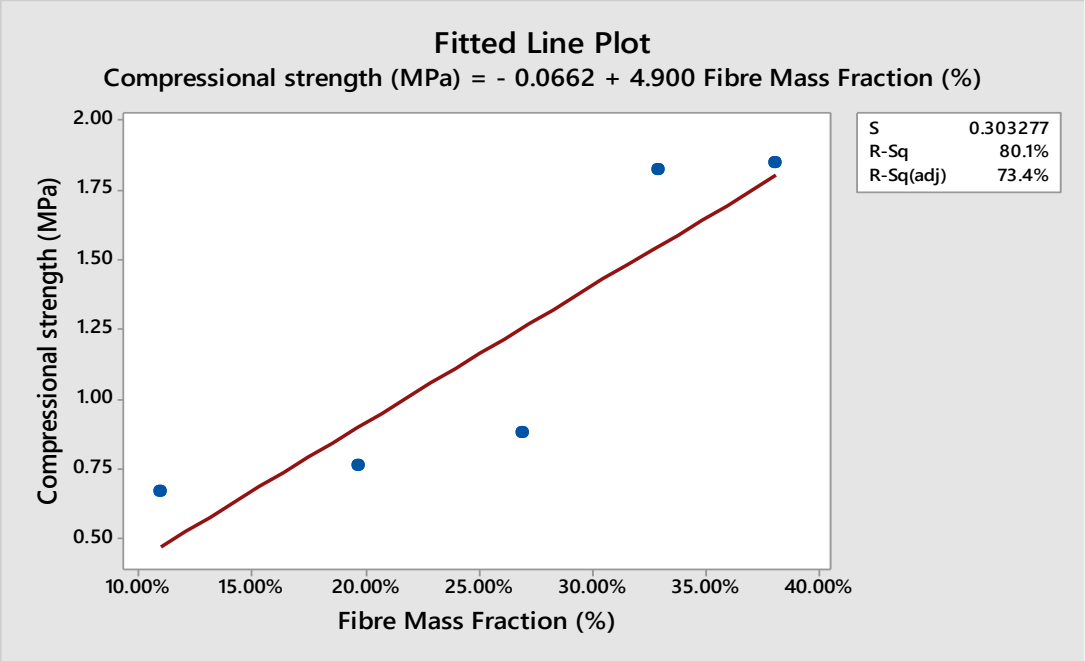

Figure 4-17 – Fibre mass fraction of composite against compressional strength for composite

The compression strength of the composite increases steadily with increase in fibre mass fraction from 11% to 26%. During this stage the compressional strength increases from 0.7MPa to 0.9MPa. From 26% M_f there is a sharp increase in compressional strength to 1.8MPa for fibre mass fraction of 33%. There after the compressional strength becomes almost constant with a very small increase in compressional strength when the mass fraction increases to 38%.

Compression failure is a design limiting feature of fibre composite materials (N.A.Fleck B. a., 1993). The dominant failure mode that was observed for the fibreboard under compression was compressive buckling or kinking. Other failure modes such as fibre crushing also occurred. A significant number of previous experimental results have revealed that material failure (usually at microstructural level) such as fibre micro buckling or kinking in laminae where the fibres are aligned with the loading axis are initiated mechanisms of compressive failure that lead to global instability (Sohi, 1987). This was visible on the tested fibreboard after compression fibre buckling and kinking was visible.

A simple linear regression was calculated to predict compressional strength based on the fibre mass fraction. This analysis was done using Minitab statistical software and the results are attached in the appendix section. Preliminary analyses were performed to ensure that there was no violation of the assumption of normality and linearity. A significant regression equation was found ($F(1, 3) = 12.04$, $p < .0040$), with an R^2 of 0.80 Compressional strength (MPa) is equal to -0.066+4.90 (Fibre mass fraction %). Compressional strength increased 4.90 for each percent change in fibre mass fraction.

4.3.3 Composite flexural strength

Flexural strength test was carried out on the fabricated cotton stalk fibre composite. Flexural strength is defined as the maximum stress in the outermost fibre. Flexural strength is an important parameter that helps determine potential end uses of fibreboards. Attached in appendix V is the raw data for composite flexural testing of the composite showing the ultimate breaking load and the calculated flexural strength in MPa. Figure 4-18 shows the fitted line plot for flexural strength of composite vs the fibre mass fraction. The flexural strength of each of the boards was plotted on a graph against the corresponding fibre mass fraction. The flexural strength increases steadily with increase

in fibre content (Humayun Kabir, 2014). As fibre content increases both the fibre and matrix can distribute and bear the load. The matrix is very brittle and does not have much flexural strength on its own.

The flexural strength is lowest with the minimum fibre mass fraction. With the lowest flexural strength recorded at 46.39Pa. The flexural strength increases gradually with increase in fibre content with 50 gram(19.76% M_f) sample having flexural strength of 78.41MPa which is an increase of 32.02Mpa from composite board with 25 grams (10.98%M_f) fibre mass fraction.

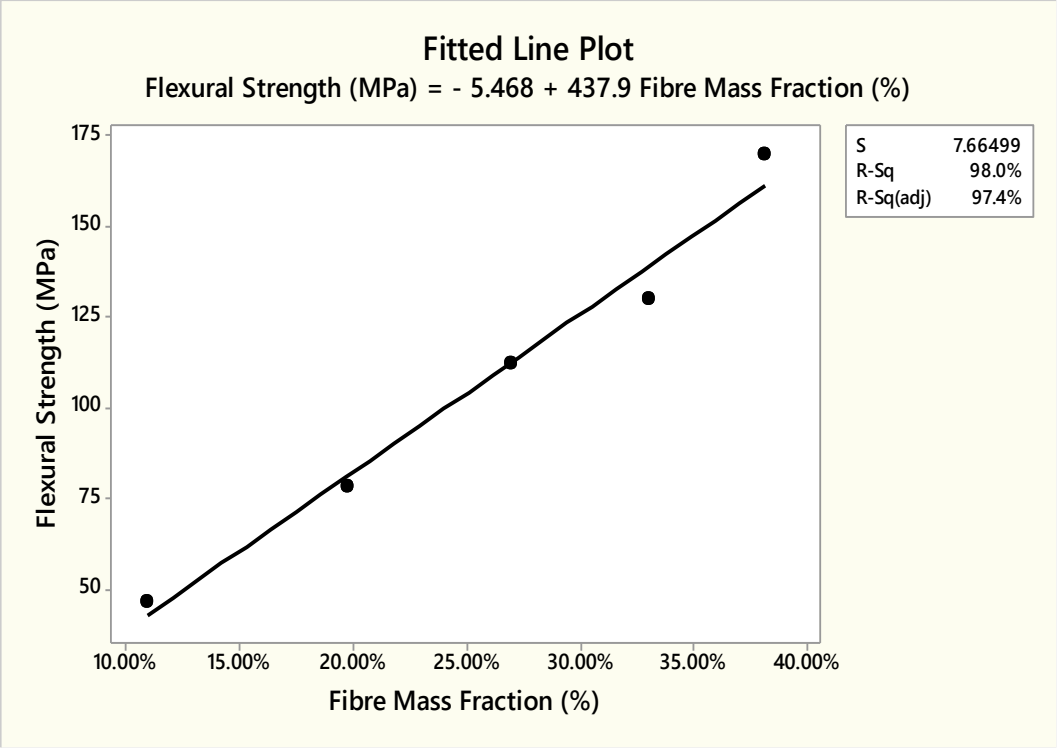

Figure 4-18 – Fitted line plot for flexural strength vs fibre mass fraction

The board with 75 grams (26.98% M_f) fibre mass fraction has strength of 112.01MPa which is a steady increase of 33.6MPa. However from 75 grams (26.98% M_f) to 100 grams (33.00% M_f) there is a small increase in flexural strength then a sharp increase in the board with 125grams (38.11% M_f) fibre content. The general trend is an increase in fibre content increases the composite flexural strength due to the reduction of voids within the composite structure. Joseph et al, (Joseph, 1999) attributed the increase in the flexural

modulus to the increasing fibre to fibre contact when the fibres were impregnated. This suggests that for increase in flexural rigidity, higher fibre mass fraction is desirable. Regression analysis was carried out to come up with the relationship between flexural strength and corresponding flexural strength after checking that no violation of regression principles were present.

A simple linear regression was calculated to predict flexural strength based on the fibre mass fraction. Minitab statistical software was used and the results for the analysis are attached in the appendix section. A significant regression equation was found ($F(1, 3) = 150.45$, $p < .001$), with an R^2 of 0.98.

4.3.4 Composite water absorption

Water absorption is an important parameter of fibreboards that determines where it can be used. The water absorption of fibreboards is the ratio of the difference in weight to the original weight of the specimen expressed as a percentage. The formula that was used for calculation of water absorption was as shown in equation 3.15.

The raw data for the calculation of water absorption for the composite boards is attached in appendix T. Water absorption is used to determine the amount of water absorbed under specified conditions of testing. Factors affecting water absorption include: type of resin, additives used, temperature and length of exposure (M.Sakthivei, 2013). Water absorption affects the physical properties of the composites and could affect the matrix structure and fibre-matrix interface, resulting in changes of bulk properties such as dimensional stability, as well as mechanical and physical properties (C.K.Abdullah, 2012). Figure 4-19 shows the water absorption with time for the fabricated cotton stalk composite.

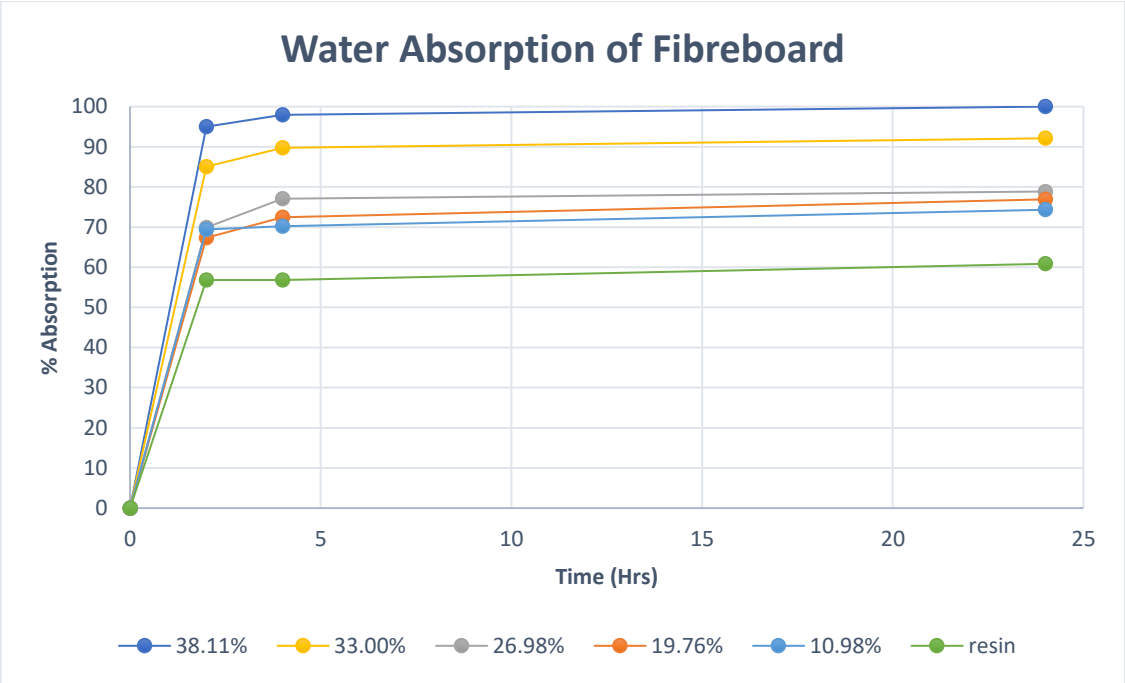

Figure 4-19 – Graph showing water absorption of bio-composite with time

The bio-composite that had the highest fibre mass fraction of 38.11% absorbed water the most of all the boards and in 2 hours the absorption recorded was 94.97% and in the next two hours this absorption increased by 2.96%. In 24hours the total absorption was 100.00%. This high absorption could be attributed to the extremely high fibre content in the composite. The 33% fibre mass fraction composite absorbed less than the 38.11% fibre mass fraction composite and had total absorption of 92.10%. The 26.98% fibre mass fraction composite absorbed 78.85% water due to the lower fibre content. The 10.98% fibre mass fraction composite which had the least fibre content absorbed the least water at 74.31% absorption.

During the first two hours, more than half of the final absorbed water occurred. This was followed by a period of very slow and consistent water uptake this is consistent with most fibre and particle boards (J.Khazaei, 2008). The higher initial water absorption rate can be explained by the diffusion phenomenon, like a fluid migration, where the water spreads itself through the capillaries, vessels and cellular walls of the cotton stalk fibres (Tay Chen Chiang, 2012). Two forms of water up-take patterns were present: interstitial water

and bound water. The interstitial water is contained in the cellular cavities and bound water is retained in the cellular walls. The rate of water absorption depends on the difference between the saturation water content and the water content at a given time, which is called the driving force. The moisture diffusion into the fibres takes place because of moisture gradient between the surface and the centre. As absorption proceeds, the water content increases, diminishing the driving force and consequently the absorption rate. Generally, the interstitial water molecules are relatively weaker than the bound water molecules, thus, water will migrate from the more concentrated medium towards the less concentrated one. The graph in Figure 4-20 shows a fitted line plot for maximum water absorption of fabricated composite against the varying fibre mass fraction.

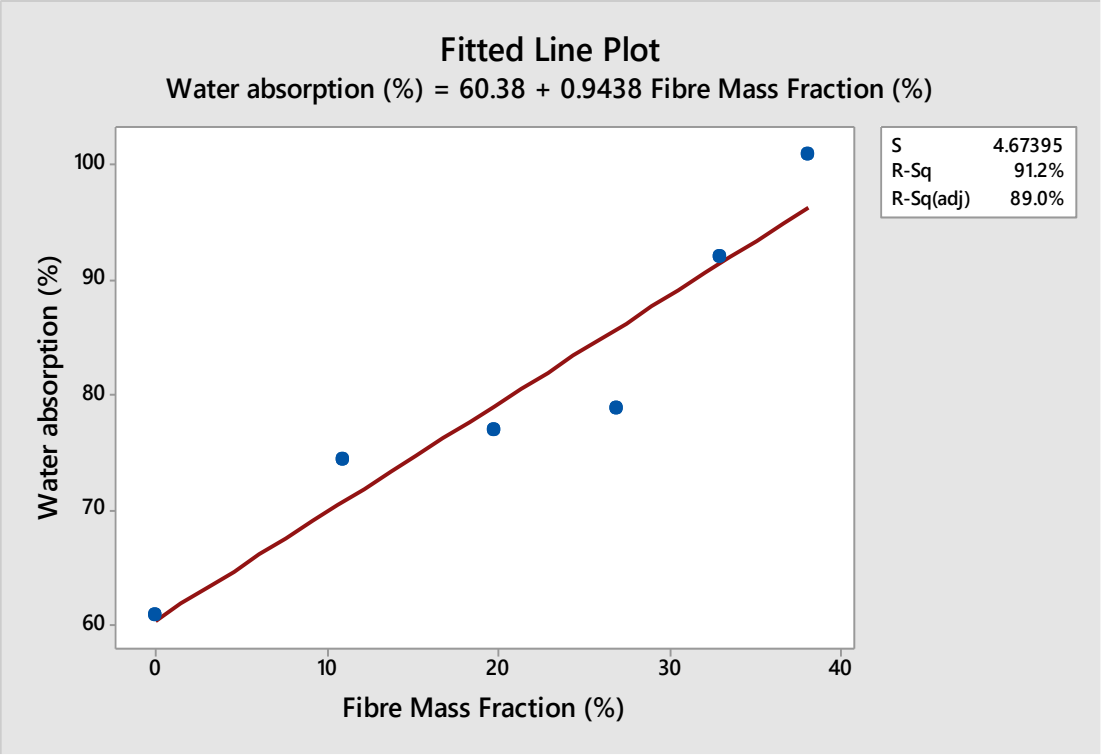

Figure 4-20 – Variation of water absorption with fibre mass fraction (M_f)

The trend line shows that the water absorption decreases with increase in resin content of the composite. Likewise with increase in fibre content the water absorption increases. The water penetration is restricted by the hydrophobic nature of the resin. Natural fibres are

hydrophilic in nature due to the presence of large number of hydroxyl groups and hence tend to absorb a lot of water (Debasish De, 2007). Water absorption increased as the fibre loading increased and this can be explained by the theory of void over volume of the board where the fibres were not fully bound by the phenol formaldehyde resin and hydroxyl properties by the fibre. Higher fibre loaded samples would be expected to contain a greater diffusivity due to higher cellulose content (H.N.Dhakal, 2006).The hydrophilic character of cotton stalk fibres is responsible for the water absorption in the fibreboard, therefore, higher fibre content in turn leads to a higher amount of absorbed water. Generally, water absorption increases with immersion time until equilibrium condition is reached. When the cotton stalk fibre mass fraction is increased in the fibreboard, the number of free OH group of cotton stalk cellulose also increases. Hence, the water absorption increases (Alirezashakeri, 2010). This is attributed to the fact that cotton stalk fibres are extremely hydrophilic in nature due to the presence of the hydrophilic hydroxyl group of cellulose, hemicelluloses and lignin that is responsible for water absorption (TakianFakhruland, 2013). The hydrophilic swelling of the cotton stalk fibres leads to the composite swelling. When the composite swells, micro cracking of the brittle phenol resin occurs. This results in water penetrating deeper into the composite and further fibre absorption due to the micro cracks caused by fibre swelling. The higher the water absorption created swelling stresses which weakened the composite board. The water molecules actively attack the interface, resulting in deboning of fibre and matrix (Tay Chen Chiang, 2012).

A simple linear regression was calculated to predict water absorption based on the fibre mass fraction. A significant regression equation was found ($F(1, 4) = 41.35$, $p < .003$), with an R^2 of 91.18%. Water absorption (%) is equal to 60.38 + 0.944 (Fibre mass fraction %). Water absorption increased 0.944 for each percent change in fibre mass fraction.

4.3.5 Resistance to staining

Acetic acid when applied to wood reacts with the natural tannins in the wood producing varying shades of grey to black. The stain created by the pickling solution will sit mostly on the woods surface (Veritas, 2013). The Samples subjected to acetic acid staining did not have any residual staining after cleaning with detergent. The samples were viewed under D65 fluorescent light and there was no evidence of blistering, staining or discolouration of the samples.

4.3.6 Composite density

The actual density of the fibreboard was measured and compared to the calculated density. The weight of the cotton stalk was measured as well as its dimensions to enable calculation of the density in kg/m^3. From the table attached in appendix Y showing raw data used to calculate fibreboard density it can be seen that there are some variations in density of composite boards from the same fibre mass fraction. This can be attributed to dust and waste particles found in the fibres which are removed during composite manufacture. There is also slight variations in thickness of the composite due to the limitations of the tools used and the random nature of the fibres in the composite. Figure 4-21 shows how the density of the composite varies with the increasing fibre mass fraction.

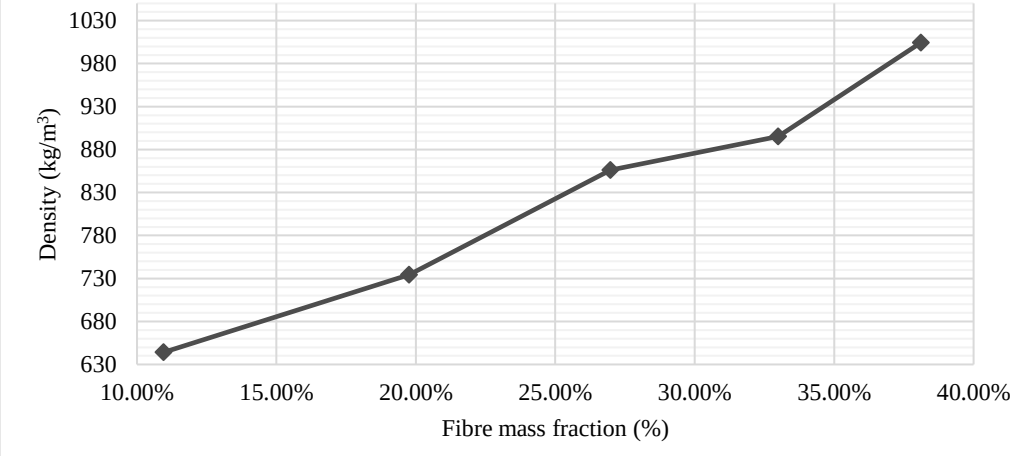

Figure 4-21 – Graph showing variation of fibre mass fraction vs density of fibreboard

The density of the cotton stalk fibreboard varied between 644.16 kg/m^3 for the lowest fibre mass fraction to 1004.34 kg/m^3 for the higher fibre mass fraction of 40%. The results indicate that density value is related to percentage content of fibres. There is a steady rise in the composite density as the fibre content is increased in equal portions of 25grams per sample as fibre mass fraction increases. There is some difference between the calculated and measured density of the composite and the graph in Figure 4-22 shows this variation.

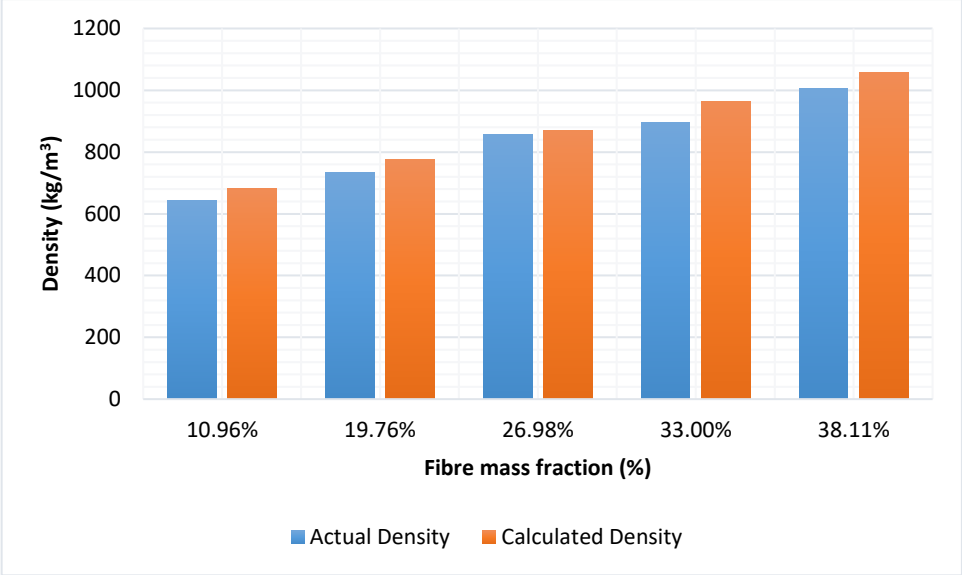

Figure 4-22 – Graph showing actual fibreboard density and calculated density

The actual density is lower than the calculated density. This could be attributed to the small error in experimental work measurement as well as sublimation of the phenolic resin during cure subsequently reducing its weight. This contributes to the lowering of the density of the actual composite. The cotton stalk fibres contain some fluff and dust particles which are removed during composite manufacture by sieving hence the density of the actual board is slightly less than the calculated density. The average difference in the actual from the calculated density is 5%.

4.4 COMPARISON OF PROPERTIES

The produced fibreboard was compared in terms of its mechanical properties and cost to other available fibreboards in the market. This gave an indication of the suitability of the fibreboard in various end uses and its economic viability.

4.4.1 Cost analysis

A financial breakdown was carried out to establish the cost per m^2 of producing the cotton stalk fibreboard. Cost breakdown analysis is the process to build and understand the elements that compose the cost of a product. This helps in assessing the viability of producing the fibre board. The chart shown in Figure 4-23 shows the bill of materials that go into making of the cotton stalk/phenol formaldehyde bio-composite.

Figure 4-23 – Showing bill of materials that go into making of fibreboard

Making of the fibreboard has a number of implements such as the chemicals involved in the process and the overhead costs. These costs were quantified to come up with the cost of making a fibreboard per m^2. The highest fibre mass fraction composite was used for the purposes of costing. Table 4-12 shows the cost breakdown for producing the cotton stalk fibreboard.

Table 4-12 - Costing of cotton stalk fibreboard

Item	**Description**	**Proportion per board**	**Cost per unit**	**Total**
Transport	120 km Umguza - Bulawayo Return @ 16km/ltr	0.25	$1.35/ltr	US$0.01
Retting Water	Water retting	2litres	$0.02/ltr	US$0.04
Release Agent	For coating mould	10ml	$56.58/12kg	US$0.04
Phenol Resin	Resin for Composite	140ml	$1.2/kg	US$0.19
Cotton stalks	Free			
Total cost/504mm^2 (mould size)				**US$0.28**
Cost/m^2				**US$5.56**

Figure 4-24 shows the cost breakdown in terms of ratios for making the fibreboard composites.

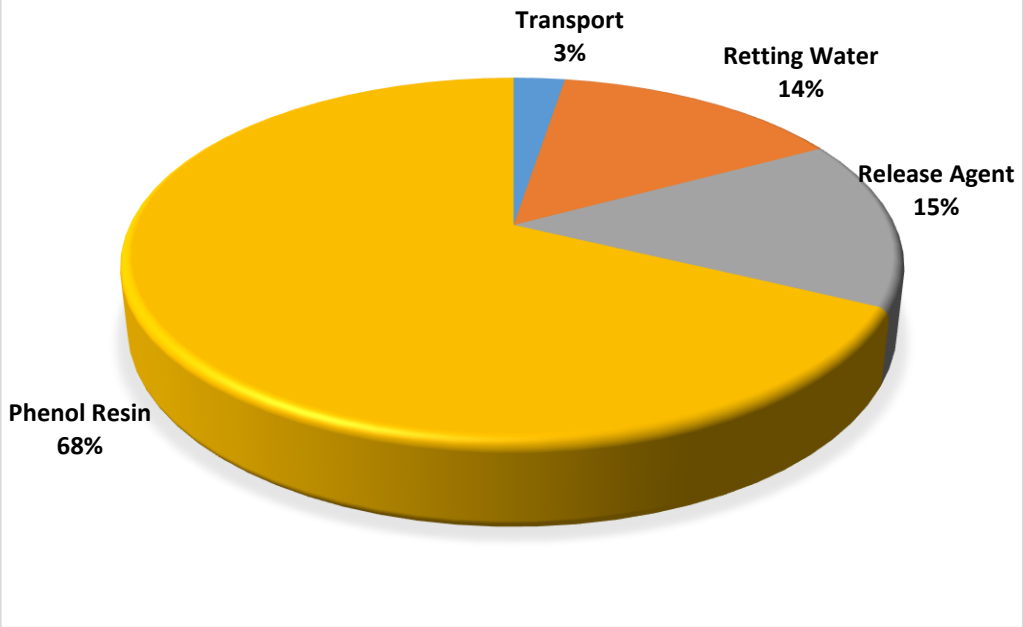

Figure 4-24 – Cost breakdown for fabrication of bio-composite in percentage

The major cost which constitutes 68% of the total cost of the fibreboard is the resin. The resin used was imported from South Africa Resinkem Company at a cost of $1.20/kg. The mould release agent used was also an imported chemical from NCS Company in South Africa which makes the chemically to be a bit expensive. Table 4-13 shows a comparison in the fabricated board cost against the selling price of boards in the market.

Table 4-13 - Comparison of prices of boards

Types of board	**Cost /m^2**
Cotton stalk fibre board	$5.56
Zimtex particleboard	$5.80
Softwood timber partition boards	$16.00

The cotton stalk fibreboard costs approximately $5.56/$m^2$ to manufacture which is cheaper than the locally manufactured Zimtex particleboards which cost $5.80/kg. The fibreboard is far much lower in cost as compared to the softwood which costs $16.00/kg. The cost of producing the cotton stalk fibreboard can be brought down with bulk purchase of the chemicals and raw materials such as the cotton stalks can be transported in bulk. This will bring down the cost due to the economy of scale.

4.4.2 Comparison of fibreboard mechanical properties

The properties of the fabricated cotton stalk fibreboard were compared to the manufactured particleboards currently in the Zimbabwe market manufactured by Zimtex boards. Table 4-14 below shows mechanical properties of fabricated board in comparison to standard used for fibreboards.

Table 4-14 – Comparison of fibreboard mechanical properties

Property	**Cotton stalk board**	**Typical Standard for MDF** (EWPAA, 2008)
Tensile Strength (MPa)	2.25-8.84	1.15
Compressive Strength (MPa)	0.67-1.85	10
Flexural Strength (MPa)	46.39-170.00	44
Density (Kg/m^3)	644-1004	780-860

The cotton stalk fibreboard had tensile strength that varied between 2.25 to 8.84MPa depending on the fibre mass fraction. This tensile strength was well above the standard for MDF which have tensile strength of 1.15MPa. The flexural strength of the cotton stalk fibreboard was well above the standard of 44MPa. The flexural strength ranges from 46.39 to 170.00MPa depending on the fibre mass fraction. The density of the fabricated cotton stalk fibreboard varied from 644-1004 kg/m^3 which is well within the range of the standard MDF of equal thickness (5mm) which has density of between 780-860 kg/m^3.

4.5 CONCLUSION

Cotton stalk fibres were extracted and characterised. The cotton stalk fibres had a yield of 22.50%, 20.76%, 18.28% for the root section, middle section and top section respectively. The fibre yield was 7.04 cm, 8.07 cm, 9.42 cm for the root section, middle section and top section respectively, the fibres from the top section were easier to remove with minimum fibre breakage. The cotton stalk fibres were then used to fabricate a bio-composite which showed to have adequate properties in comparison to medium density fibreboard standards. Making this board suitable for ceiling board and partition boards at a competitive price.

CHAPTER 5 : CONCLUSION AND AREAS OF FURTHER RESEARCH

5.0 CONCLUSION

The project seeks to solve the problem of cotton stalks a wasted resource being burnt polluting the environment. The current study aimed at fabricating a bio-composite from phenol formaldehyde resin and cotton stalk fibres using hand layup process. From the study, the following conclusion can be drawn:

- The cotton stalk fibres were extracted using manual decortication method after 3 weeks of water retting have a light brownish colour similar to that seen on hemp fibres, and an average fibre length of 8.18 cm. The moisture regain of the fibres was higher with those from the root section. The variation was statistically insignificantly. The cotton stalk fibres are hydrophilic in nature.
- The fibre yield of the cotton stalk fibres was approximately 20%. The yield of cotton stalk fibres from the stalk makes the extraction and use of these fibres to be potentially financially feasible. The diameter of the cotton stalk fibres was 0.29 mm, 0.2335 mm, 0.18 mm for the bottom, middle and top section. This diameter is within the range of diameter seen on sisal fibres which have a diameter of between 0.2-0.4mm. The density of the fibres was 1.45 g/cm^3, 1.85 g/cm^3, 1.72 g/cm^3 for the bottom, middle and top sections respectively. These parameters are within the range for common bast fibres such as sisal which has density of 1.45g/cm^3 and hence indicate the suitability of cotton stalk fibres for textile applications.
- The tensile strength of the fibres was highest with fibres from the middle section which had tenacity of 56.3cN/tex. The fibres had an elongation of 1.35% which compared well with elongation of jute fibres which have elongation of 1-2%. The

tensile strength was greatest with fibres from the middle section due to the greater fibre maturity and weaker for the root fibres due to over maturity of the fibres. The strength of the cotton stalk fibres from the middle and top area makes them suitable for composite manufacture as they are comparable to strength of bast fibres used in similar applications.

- A bio-composite consisting of cotton stalk fibres and phenol formaldehyde was fabricated and had a tensile strength ranging from 2.3 MPa to 6.8 MPa , flexural strength varied between 46.39-170.00 MPa these mechanical properties of the composite made it suitable for end uses such as flooring, decking, ceiling boards, furniture, door panels and partitioning boards.
- Costing was done for the fabricated bio-composite and it was found to cost \$5.56/m^2 to produce compared to the cost of \$5.80/ m^2 found in the commercially available boards. The cotton stalk fibreboard can be produced at a cheaper price than other available boards due to the fact that they uses a waste resource. The cost can be lowered by economies of scale in transporting the cotton stalks in bulk as well as in sourcing the resin direct from the manufacturer in larger quantities. The cost of manufacture showed potential in the commercialisation of this bio-composite.

5.1 RECOMMENDATIONS

There are some recommendations on this work based on results obtained:

- The results obtained from the cotton stalk fibre testing show their potential use as suitable bast fibres hence instead of burning of these cotton stalks in the field a recommendation is the extraction and use of these fibres in fibreboard manufacture.

- Further characterisation of the developed bio-composite needs to be carried out to study the fracture mechanics as well as stress distribution on load of the composite.
- Critical length of the fibres used in this work needs to be determined to optimise the composite properties.
- More tests need to be carried out to study other bio-composite properties such as impact strength and burning resistance.
- Based on the results of this work there is potential of commercialisation of cotton stalk fibre hence as need to come up with a draft proposal to the cotton research institute in Zimbabwe to request them to allow the collecting of the cotton stalks and their storage off farms in a controlled environment for the purpose of bast fibre extraction. The method of storage used should not encourage the growth of pests or their spread to cotton crops.

5.2 AREAS OF FURTHER RESEARCH

Some further research needs to be carried out in the following areas:

- Use of Steam explosion for fibre extraction (Xiuliang Hou, 2014). This process might be faster and produce better quality fibres.
- More study needs to be carried out to compare fibre properties produced from this natural process to those produced from only mechanical decortication.
- More research needs to be done with natural resins such as corn starch to eliminate the formaldehyde emission from the bio-composite.
- More study also needs to be carried out on non-resin binding of fibres by activation of fibre surface this can create formaldehyde free fibreboards. This is done by applying high pressure to the fibres and the lignin acts as a thermoplastic

adhesive and under pressure fibres can be fused together with covalent bonding also taking place.

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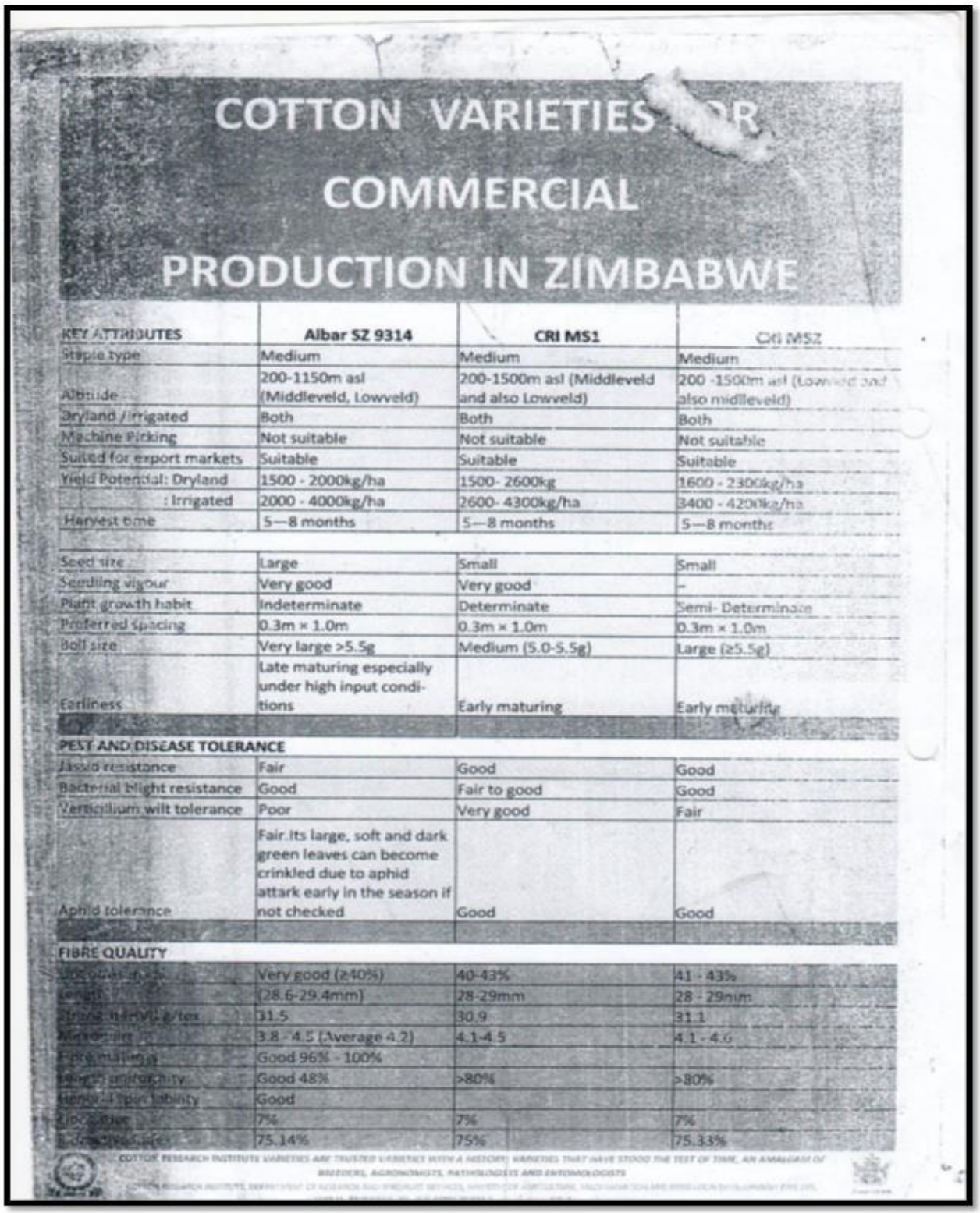
APPENDIX A: TABLE SHOWING COTTON SPECIES IN ZIMBABWE

Table 5-1 - Table showing cotton species farmed in Zimbabwe



COTTON VARIETIES FOR COMMERCIAL PRODUCTION IN ZIMBABWE

KEY ATTRIBUTES	Albar SZ 9314	CRI MS1	Cri MSZ
Staple type	Medium	Medium	Medium
Altitude	200-1150m asl (Middleveld, Lowveld)	200-1500m asl (Middleveld and also Lowveld)	200 -1500m asl (Lowveld and also midleveld)
Dryland / Irrigated	Both	Both	Both
Machine Picking	Not suitable	Not suitable	Not suitable
Suited for export markets	Suitable	Suitable	Suitable
Yield Potential: Dryland	1500 - 2000kg/ha	1500- 2600kg	1600 - 2300kg/ha
: Irrigated	2000 - 4000kg/ha	2600- 4300kg/ha	3400 - 4200kg/ha
Harvest time	5—8 months	5—8 months	5—8 months
Seed size	Large	Small	Small
Seedling vigour	Very good	Very good	–
Plant growth habit	Indeterminate	Determinate	Semi- Determinate
Preferred spacing	0.3m × 1.0m	0.3m × 1.0m	0.3m × 1.0m
Boll size	Very large >5.5g	Medium (5.0-5.5g)	Large (≥5.5g)
Earliness	Late maturing especially under high input conditions	Early maturing	Early maturity
PEST AND DISEASE TOLERANCE			
Jassid resistance	Fair	Good	Good
Bacterial blight resistance	Good	Fair to good	Good
Verticillium wilt tolerance	Poor	Very good	Fair
Aphid tolerance	Fair.Its large, soft and dark green leaves can become crinkled due to aphid attark early in the season if not checked	Good	Good
FIBRE QUALITY			
[illegible]	Very good (≥40%)	40-43%	41 - 43%
[illegible]	(28.6-29.4mm)	28-29mm	28 - 29mm
[illegible]	31.5	30.9	31.1
[illegible]	3.8 - 4.5 (Average 4.2)	4.1-4.5	4.1 - 4.6
[illegible]	Good 96% - 100%		
[illegible]	Good 48%	>80%	>80%
[illegible]	Good		
[illegible]	7%	7%	7%
[illegible]	75.14%	75%	75.33%

COTTON RESEARCH INSTITUTE VARIETIES ARE TRUSTED VARIETIES WITH A HISTORY. VARIETIES THAT HAVE STOOD THE TEST OF TIME, AN AMALGAM OF BREEDERS, AGRONOMISTS, PATHOLOGISTS AND ENTOMOLOGISTS

APPENDIX B: WATER RETTING OF COTTON STALK

Table 5-2 - Retting efficiency test in terms of weight loss for drum (a)

Sample Stalks	Initial oven dry weight (g) (T_0)	Week 1 oven dry weight (g) (T_1)	Week 2 Oven dry weight (g) (T_2)	Week 3 Oven dry weight (g) (T_3)
W_1	8.5792	6.4186	38.0033	37.6308
W_2	10.6841	8.8367	7.0948	14.5318
W_3	4.7371	23.1572	12.8534	17.5226
W_4	7.6202	2.5563	21.6036	5.9364
W_5	26.0830	7.5240	10.4190	21.7044
W_6	20.2981	7.4806	8.4100	8.2001
W_7	10.5348	3.8822	4.8327	6.3878
W_8	8.5818	10.9716	17.8386	12.5900
W_9	6.8398	8.6601	2.4674	5.5345
W_{10}	10.5165	7.1727	14.8597	6.8631
W_{11}	12.0071	18.4257	9.4922	4.6354
W_{12}	6.0804	13.2549	6.1493	8.2038
W_{13}	3.0669	25.5956	6.7774	24.0503
W_{14}	15.1099	9.7740	7.1687	9.4031
W_{15}	8.5561	5.1208	8.1311	5.8964
W_{16}	24.0715	6.0639	23.6611	7.0095
W_{17}	16.3118	15.5106	5.7073	3.5683
W_{18}	38.8636	38.3033	3.6566	2.3859
Total	238.5419	218.7088	209.1262	202.0542
% Change	---	8.31	4.38	3.38

Table 5-3 - Retting efficiency test in terms of weight loss for drum (b)

Sample Stalks	Initial oven dry weight (g) (T_0)	Week 1 oven dry weight (g) (T_1)	Week 2 Oven dry weight (g) (T_2)	Week 3 Oven dry weight (g) (T_3)
W_1	17.3032	11.1498	23.5348	10.0798
W_2	2.7968	16.3823	21.9813	20.5202
W_3	4.6738	16.1012	9.7240	18.4728
W_4	12.6253	24.6178	7.6990	7.9016
W_5	8.5022	18.6209	16.6453	6.1492
W_6	7.8000	11.4245	20.3115	4.0688
W_7	7.3925	16.8017	12.5001	6.3080
W_8	8.1234	6.4418	28.0742	15.8478
W_9	21.5886	7.9696	14.2343	6.0694
W_{10}	26.0928	20.9575	2.3380	20.6393
W_{11}	17.4969	29.7869	6.7676	12.3919
W_{12}	22.8019	20.5752	17.2709	16.8892
W_{13}	7.2948	4.2782	9.6540	29.8960
W_{14}	4.8931	7.3156	13.0608	10.6440
W_{15}	15.7434	12.4468	15.3733	11.0324
W_{16}	31.5190	6.4108	5.1700	13.1315
W_{17}	13.1371	10.2811	4.5471	24.5311
W_{18}	17.6765	0.8464	12.3484	16.2720
W_{19}	11.1530	1.4034	18.6682	2.0968
W_{20}	12.0680	4.1742		
Total	**270.6823**	**247.9860**	**259.9028**	**252.9418**
% Change	---	**8.39**	**4.81**	**2.68**

APPENDIX C: YIELD OF COTTON STALK FIBRES FROM THE DIFFERENT SECTIONS OF THE COTTON STALK

Table 5-4 - Yield of cotton stalk fibres root area

Sample No.	Location on Stalk	Initial Oven dry Weight (g)	Weight of extracted Bark with fibres (g)	Weight of Shive (g)	Percentage Fibres (%)
1	Root Area	35.1230	8.7756	15.9414	24.99%
2	Root Area	64.6640	14.6820	49.9820	22.71%
3	Root Area	36.2121	6.2908	29.9213	17.37%
4	Root Area	15.0321	3.6776	11.3545	24.46%
5	Root Area	24.0511	5.4632	18.5879	22.71%
Mean +/- sd					**22.45% +/-3.02**

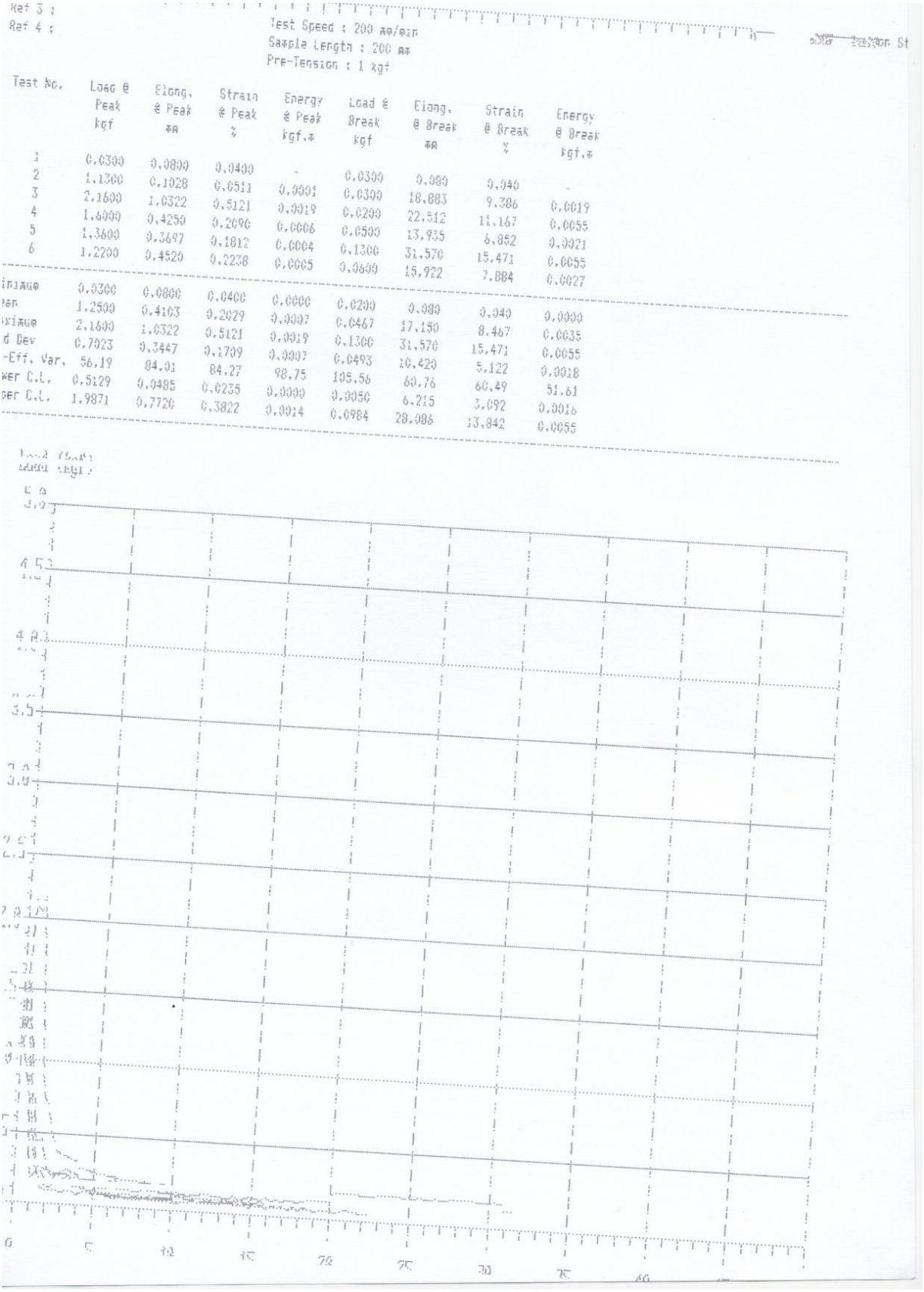
Table 5-5 - Yield of cotton stalk fibres bottom area

Sample No.	Location on Stalk	Initial Oven dry Weight (g)	Weight of extracted Bark with fibres (g)	Weight of Shive (g)	Percentage Fibres (%)
1	Bottom Area	17.8783	4.2944	13.5839	24.02%
2	Bottom Area	22.1420	4.0000	18.1420	18.07%
3	Bottom Area	13.4250	2.2646	11.1604	16.87%
4	Bottom Area	9.8931	2.3119	7.5812	23.37%
5	Bottom Area	8.7258	1.8747	6.8511	21.48%
Mean +/- sd					**20.76%+/-3.18**

Table 5-6 - Yield of cotton stalk fibres top area

Sample No.	Location on Stalk	Initial Oven dry Weight (g)	Weight of extracted Bark with fibres (g)	Weight of Shive (g)	Percentage Fibres (%)
1	Top Area	14.7106	2.9239	11.7867	19.88%
2	Top Area	17.8110	14.4193	3.3917	19.74%
3	Top Area	7.2172	1.0783	6.1389	14.94%
4	Top Area	5.7628	1.1725	4.5903	20.35%
5	Top Area	6.2599	1.0317	5.2282	16.48%
Mean +/- sd					**18.28% +/- 2.42**

APPENDIX D: TOP SECTION COTTON STALK FIBRES TENSILE TEST PRINTOUT



Ref 3 :
Ref 4 :

Test Speed : 200 mm/min
Sample Length : 200 mm
Pre-Tension : 1 kgf

Test No.	Load @ Peak kgf	Elong. @ Peak mm	Strain @ Peak %	Energy @ Peak kgf.m	Load @ Break kgf	Elong. @ Break mm	Strain @ Break %	Energy @ Break kgf.m
1	0.0300	0.0800	0.0400	-	-	-	-	-
2	1.1300	0.1028	0.0511	0.0001	0.0300	0.080	0.040	-
3	2.1600	1.0322	0.5121	0.0019	0.0200	18.883	9.386	0.0019
4	1.6000	0.4250	0.2090	0.0006	0.0500	22.512	11.167	0.0055
5	1.3600	0.3697	0.1812	0.0004	0.1300	13.935	6.852	0.0021
6	1.2200	0.4520	0.2238	0.0005	0.0600	31.570	15.471	0.0055
inimum	0.0300	0.0800	0.0400	0.0000	0.0200	15.922	7.884	0.0027
ean	1.2500	0.4163	0.2029	0.0007	0.0467	0.080	0.040	0.0000
ximum	2.1600	1.0322	0.5121	0.0019	0.1300	17.150	8.467	0.0035
d Dev	0.7923	0.3447	0.1709	0.0007	0.0493	31.570	15.471	0.0055
-Eff. Var.	56.19	84.01	84.27	98.75	105.56	10.420	5.122	0.0018
wer C.L.	0.5129	0.0485	0.0235	0.0000	0.0050	60.76	60.49	51.61
per C.L.	1.9871	0.7720	0.3822	0.0014	0.0984	6.215	3.092	0.0016
						28.086	13.842	0.0055

Figure 5-1 – Tensile strength printout for top section cotton stalk fibres

APPENDIX E: MIDDLE SECTION COTTON STALK FIBRES TENSILE TEST PRINTOUT

Ref 2 :
Ref 3 :
Ref 4 :

File : C:\TNREAD\TST0102.DAT
Test Speed : 200 mm/min
Sample Length : 200 mm
Pre-Tension : 1 kgf

Comments : Bottom Section Fibres
: Stronger than root section fibres

Test No.	Load @ Peak kgf	Elong. @ Peak mm	Strain @ Peak %	Energy @ Peak kgf.s	Load @ Break kgf	Elong. @ Break mm	Strain @ Break %	Energy @ Break kgf.s
1	2.0100	0.4808	0.2387	0.0007	-	21.811	10.828	0.0016
2	2.1800	0.2739	0.1362	0.0004	-	18.014	8.961	0.0014
3	2.1800	0.5785	0.2874	0.0009	0.0200	18.709	9.292	0.0028
4	2.7100	0.5604	0.2789	0.0011	0.0200	21.319	10.606	0.0021
Minimum	2.0100	0.2739	0.1362	0.0004	0.0200	18.014	8.961	0.0014
Mean	2.2600	0.4734	0.2353	0.0008	0.0200	19.961	9.922	0.0020
Maximum	2.7100	0.5785	0.2874	0.0011	0.0200	21.811	10.828	0.0028
Std Dev	0.3082	0.1396	0.0694	0.0003	0.0283	1.880	0.933	0.0006
Co-Eff. Var.	13.64	29.49	29.48	36.14	0.00	9.42	9.40	32.56
Lower C.L.	1.7696	0.2512	0.1249	0.0003	0.0450	16.970	8.438	0.0010
Upper C.L.	2.7504	0.6956	0.3457	0.0013	0.0459	22.952	11.406	0.0030

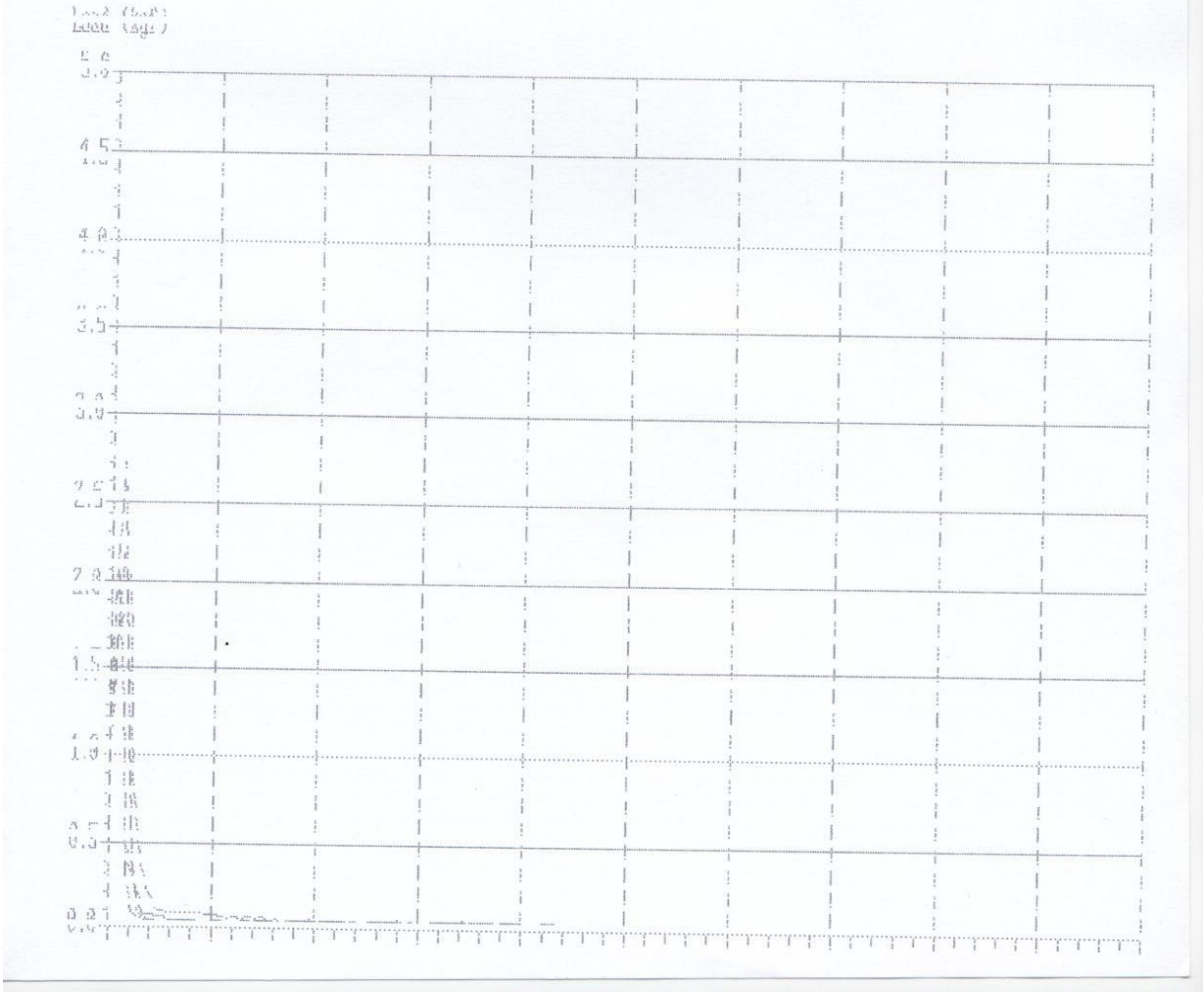
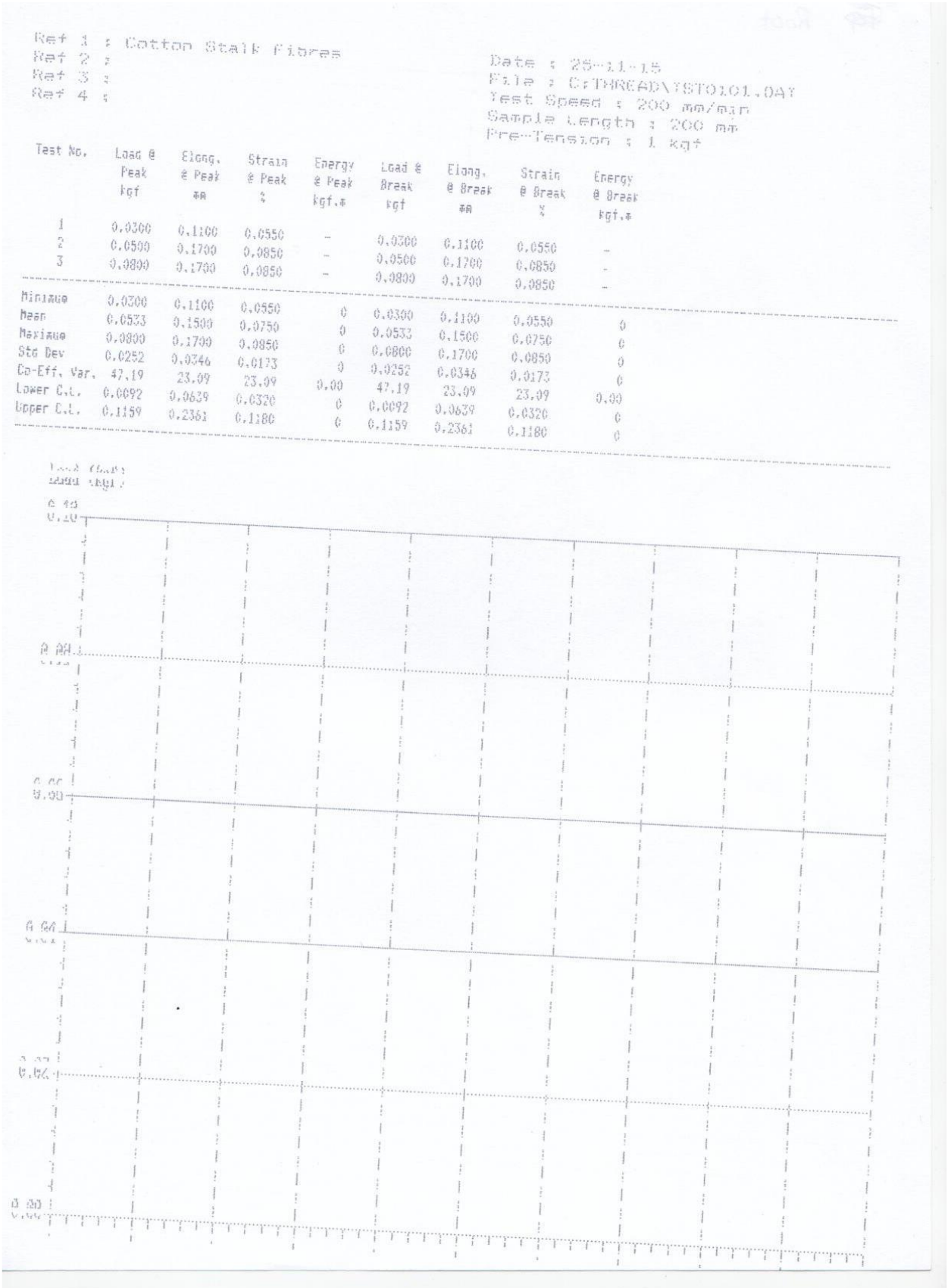


Figure 5-2 – Tensile strength results from fibres in the middle section

APPENDIX F: ROOT SECTION COTTON STALK FIBRES TENSILE TEST PRINTOUT



Ref 1 : Cotton Stalk Fibres
Ref 2 :
Ref 3 :
Ref 4 :

Date : 26-11-15
File : C:\THREAD\YST0101.0AY
Test Speed : 200 mm/min
Sample Length : 200 mm
Pre-Tension : 1 kgf

Test No.	Load @ Peak kgf	Elong. @ Peak mm	Strain @ Peak %	Energy @ Peak kgf.s	Load @ Break kgf	Elong. @ Break mm	Strain @ Break %	Energy @ Break kgf.s
1	0.0300	0.1100	0.0550	-	0.0300	0.1100	0.0550	-
2	0.0500	0.1700	0.0850	-	0.0500	0.1700	0.0850	-
3	0.0800	0.1700	0.0850	-	0.0800	0.1700	0.0850	-
Minimum	0.0300	0.1100	0.0550	0	0.0300	0.1100	0.0550	0
Mean	0.0533	0.1500	0.0750	0	0.0533	0.1500	0.0750	0
Maximum	0.0800	0.1700	0.0850	0	0.0800	0.1700	0.0850	0
Std Dev	0.0252	0.0346	0.0173	0	0.0252	0.0346	0.0173	0
Co-Eff. Var.	47.19	23.09	23.09	0.00	47.19	23.09	23.09	0.00
Lower C.L.	0.0092	0.0639	0.0320	0	0.0092	0.0639	0.0320	0
Upper C.L.	0.1159	0.2361	0.1180	0	0.1159	0.2361	0.1180	0

Figure 5-3 – Tensile strength results from root section fibres

APPENDIX G: SHOWING RAW DATA FOR LINEAR DENSITY MEASUREMENT

Table 5-7 - Linear density of cotton stalk fibres

No.	Root Area (mm)	Bottom Half (mm)	Top Half (mm)
1	10.70	12.40	7.60
2	8.00	8.40	18.65
3	6.60	6.50	7.85
4	9.80	6.55	10.20
5	6.00	7.40	10.70
6	12.00	10.55	14.90
7	14.60	5.10	20.30
8	7.30	7.90	16.20
9	3.50	5.20	5.70
10	6.80	7.20	9.40
11	7.70	11.70	13.40
12	10.50	6.00	19.10
13	6.60	10.00	13.60
14	9.10	7.70	12.40
15	6.10	7.10	7.60
16	7.70	9.30	10.60
17	5.50	10.90	5.95
18	9.00	5.25	6.70
19	7.00	9.95	6.30
20	8.50	4.50	8.20
21	6.90	8.40	9.40
22	3.30	6.50	5.10
23	8.55	10.10	5.75
24	4.60	6.70	7.50
25	6.70	10.70	6.55
26	7.00	11.70	4.80
27	4.55	15.70	6.50
28	7.00	6.05	12.30
29	4.40	4.60	8.40
30	5.75	6.10	7.30
31	5.20	8.95	14.20
32	5.10	3.70	5.40
33	4.95	5.45	7.95
34	5.60	7.10	5.50
35	9.40	14.10	10.60
36	5.00	3.80	6.30
37	6.80	8.40	4.80
38	5.65	3.30	4.50
39	6.60	4.20	9.40
40	5.60	17.90	9.35
Total (mm)	281.65	323.05	376.95
Mass (g)	0.0269	0.0514	0.0561
Linear Density (tex)	2.364	3.938	3.683

APPENDIX H: RAW DATA FOR MEASUREMENT OF MOISTURE REGAIN OF COTTON STALK FIBRES

Table 5-8 - Moisture regain of top half cotton stalk fibres

No.	Position on Stalk	Initial Weight	W(g)	Moisture Regain (%)
1	Top Half	0.0810	0.0737	9.01
2	Top Half	0.0202	0.0181	10.40
3	Top Half	0.0141	0.0125	11.34
4	Top Half	0.0956	0.0853	10.77
5	Top Half	0.0647	0.0585	9.58
6	Top Half	0.0369	0.0333	9.76
7	Top Half	0.1090	0.0979	10.18
8	Top Half	0.0445	0.0408	8.31
9	Top Half	0.0725	0.0655	9.66
10	Top Half	0.0953	0.0837	12.17
11	Top Half	0.0457	0.0408	10.722
12	Top Half	0.0565	0.0512	9.20
13	Top Half	0.0616	0.0554	10.06
14	Top Half	0.0544	0.0489	10.11
15	Top Half	0.0343	0.0302	11.95
16	Top Half	0.0889	0.0789	11.25
17	Top Half	0.0414	0.0364	12.07
18	Top Half	0.0541	0.0481	11.09
19	Top Half	0.1065	0.0937	12.02
20	Top Half	0.0575	0.0495	13.91
Mean				**10.68**
Std. Deviation				**1.33**
Variance				**1.772**

Table 5-9 - Moisture regain of bottom half cotton stalk fibres

No.	Position on Stalk	Initial Weight	W_1 (g)	Moisture Regain (%)
1	Bottom Half	0.0468	0.0418	**10.68**
2	Bottom Half	0.0525	0.0483	**9.33**
3	Bottom Half	0.0422	0.0379	**10.19**
4	Bottom Half	0.0461	0.0423	**8.24**
5	Bottom Half	0.0670	0.0607	**9.40**
6	Bottom Half	0.2693	0.2418	**10.21**
7	Bottom Half	0.0907	0.0822	**9.37**
8	Bottom Half	0.0943	0.0847	**10.18**
9	Bottom Half	0.0462	0.0414	**10.39**
10	Bottom Half	0.0813	0.0735	**9.60**
11	Bottom Half	0.1073	0.0963	**10.25**
12	Bottom Half	0.0742	0.0655	**11.73**
13	Bottom Half	0.0721	0.0642	**10.96**
14	Bottom Half	0.0542	0.0480	**11.44**
15	Bottom Half	0.0878	0.0788	**10.25**
16	Bottom Half	0.1024	0.0913	**10.84**
17	Bottom Half	0.0301	0.0267	**11.30**
18	Bottom Half	0.0493	0.0444	**9.94**
19	Bottom Half	0.0649	0.0583	**10.17**
20	Bottom Half	0.0230	0.0208	**9.57**
Mean				**10.20%**
Std. Deviation				**0.83036**
Variance				**0.690**

Table 5-10 - Moisture regain of root area cotton stalk fibres

No.	Position on Stalk	Initial Weight	W_1 (g)	Moisture Regain (%)
1	Root Area	0.0267	0.0370	**10.86**
2	Root Area	0.1153	0.1014	**12.06**
3	Root Area	0.2143	0.1877	**12.41**
4	Root Area	0.1167	0.1030	**11.74**
5	Root Area	0.0988	0.0873	**11.64**
6	Root Area	0.0803	0.0711	**11.46**
7	Root Area	0.1337	0.1186	**11.29**
8	Root Area	0.0593	0.0526	**11.30**
9	Root Area	0.0832	0.0738	**11.30**
10	Root Area	0.0737	0.0647	**12.21**
11	Root Area	0.0519	0.0463	**10.79**
12	Root Area	0.0715	0.0630	**11.89**
13	Root Area	0.0857	0.0769	**10.27**
14	Root Area	0.0570	0.0506	**11.23**
15	Root Area	0.0509	0.0456	**10.41**
16	Root Area	0.0732	0.0660	**9.84**
17	Root Area	0.0928	0.0828	**10.78**
18	Root Area	0.0703	0.0631	**10.24**
19	Root Area	0.0697	0.0629	**9.76**
20	Root Area	0.1430	0.1268	**11.33**
Mean				**11.14%**
Standard Deviation				**0.76164**
Variance				**0.580**

APPENDIX I: SHOWING RAW DATA FOR COTTON STALK FIBRE DIAMETER

Table 5-11 - Cotton stalk fibre diameter raw data

Sample	Diameter (mm)		
	Root Area	**Bottom Half**	**Top Half**
1	0.21	0.18	0.19
2	0.28	0.19	0.18
3	0.22	0.17	0.19
4	0.22	0.18	0.14
5	0.21	0.18	0.11
6	0.19	0.20	0.14
7	0.21	0.18	0.19
8	0.28	0.18	0.23
9	0.21	0.22	0.19
10	0.28	0.17	0.14
11	0.72	0.18	0.11
12	0.22	0.17	0.14
13	0.21	0.19	0.19
14	0.19	0.17	0.13
15	0.21	0.18	0.19
16	0.28	0.18	0.14
17	0.21	0.19	0.11
18	0.28	0.18	0.14
19	0.22	0.16	0.19
20	0.22	0.22	0.13
21	0.21	0.17	0.19
22	0.19	0.18	0.14
23	0.21	0.18	0.11
24	0.28	0.19	0.14
25	0.21	0.17	0.19
26	0.28	0.18	0.13
27	0.22	0.18	0.19
28	0.22	0.2	0.14
29	0.21	0.18	0.17
30	0.19	0.18	0.14
31	0.21	0.22	0.19
32	0.28	0.17	0.33
33	0.21	0.18	0.13
34	0.28	0.18	0.14
35	0.22	0.19	0.11
36	0.22	0.17	0.14
37	0.21	1.19	0.15
38	0.19	0.18	0.14
39	0.21	0.2	0.13
40	0.28	0.18	0.18
Mean Diameter (mm)	**0.2900**	**0.2335**	**0.1800**
St Dev	**0.1676**	**0.2192**	**0.0693**
Minimum	**0.1900**	**0.1700**	**0.1100**
Maximum	**0.7200**	**1.1900**	**0.3300**
Variance	**0.0281**	**0.0480**	**0.0048**
CoefVar	**57.81**	**93.86**	**38.51**

APPENDIX J: SHOWING RAW DATA FOR COTTON STALK FIBRE LENGTH MEASUREMENT

Table 5-12 - Cotton stalk fibre length raw data

No.	Root Area (cm)	Bottom Half (cm)	Top Half (cm)
1	10.70	12.40	7.60
2	8.00	8.40	18.65
3	6.60	6.50	7.85
4	9.80	6.55	10.20
5	6.00	7.40	10.70
6	12.00	10.55	14.90
7	14.60	5.10	20.30
8	7.30	7.90	16.20
9	3.50	5.20	5.70
10	6.80	7.20	9.40
11	7.70	11.70	13.40
12	10.50	6.00	19.10
13	6.60	10.00	13.60
14	9.10	7.70	12.40
15	6.10	7.10	7.60
16	7.70	9.30	10.60
17	5.50	10.90	5.95
18	9.00	5.25	6.70
19	7.00	9.95	6.30
20	8.50	4.50	8.20
21	6.90	8.40	9.40
22	3.30	6.50	5.10
23	8.55	10.10	5.75
24	4.60	6.70	7.50
25	6.70	10.70	6.55
26	7.00	11.70	4.80
27	4.55	15.70	6.50
28	7.00	6.05	12.30
29	4.40	4.60	8.40
30	5.75	6.10	7.30
31	5.20	8.95	14.20
32	5.10	3.70	5.40
33	4.95	5.45	7.95
34	5.60	7.10	5.50
35	9.40	14.10	10.60
36	5.00	3.80	6.30
37	6.80	8.40	4.80
38	5.65	3.30	4.50
39	6.60	4.20	9.40
40	5.60	17.90	9.35
Total (cm)	281.65	323.05	376.95
Mean Length (cm)	7.04	8.08	9.42
St Dev	2.314	3.312	4.156
Minimum	3.300	3.300	4.5
Maximum	14.6	17.900	20.300
Variance	5.357	10.967	17.273
Coef Var	32.87	41.00	44.10

APPENDIX K: MANOVA ANALYSIS TABLES FROM SPSS SOFTWARE

Table 5-13 – Showing between subject factors

Between-Subjects Factors

		Value Label	N
Location	1	Top	40
	2	Bottom	40
	3	Root	40

Table 5-14 - Descriptive statistics for cotton stalk fibre Manova statistical analysis

Parameters	Location on stalk	Mean	Std. Deviation	N
Tensile strength (MPa)	Middle	56.3	0	40
	Root	2.21	0	40
	Top	39.79	0	40
	Total	32.7667	22.72861	120
Elongation (%)	Middle	0.4734	0	40
	Root	0.15	0	40
	Top	0.4103	0	40
	Total	0.3446	0.14056	120
Fibre Density (g/mm^3)	Middle	1.72	0	40
	Root	1.45	0	40
	Top	1.85	0	40
	Total	3.6733	1.80413	120
Fibre Diameter (mm)	Middle	0.1835	0.01369	40
	Root	0.2275	0.03193	40
	Top	0.1538	0.03094	40
	Total	0.1882	0.04043	120
Moisture Regain (%)	Middle	10.202	0.81965	40
	Root	11.1405	0.75181	40
	Top	10.6781	1.31388	40
	Total	10.6735	1.05793	120
Fibre length (mm)	Middle	7.9012	2.94373	40
	Root	6.9162	2.01082	40
	Top	9.0488	3.46947	40
	Total	7.9554	2.97924	120
Linear density (tex)	Middle	3.938	0	40
	Root	2.364	0	40
	Top	3.683	0	40
	Total	3.3283	0.69268	120

APPENDIX L: BETWEEN SUBJECT TEST RESULTS FOR MANOVA CALCULATIONS FOR COTTON STALK FIBRES

Table 5-15 – Tests of between subject effects

Tests of Between-Subjects Effects									
Source	**Dependent Variable**	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**	**Partial Eta Squared**	**Noncent. Parameter**	**Observed Powerb**
Corrected Model	Tensile strength (MPa)	61474.195a	2	30737.097	.	.	1	.	.
	Elongation (%)	2.351a	2	1.176	.	.	1	.	.
	Fibre Density (g/mm^3)	387.331a	2	193.665	.	.	1	.	.
	Fibre Diameter (mm)	.110c	2	0.055	76.34	0	0.566	152.68	1
	Moisture Regain (%)	17.617d	2	8.808	8.917	0	0.132	17.835	0.97
	Fibre length (mm)	91.127e	2	45.564	5.524	0.005	0.086	11.047	0.845
	Linear density (tex)	57.097a	2	28.548	.	.	1	.	.
Intercept	Tensile strength (MPa)	128838.533	1	128838.533	.	.	1	.	.
	Elongation (%)	14.247	1	14.247	.	.	1	.	.
	Fibre Density (g/mm^3)	1619.205	1	1619.205	.	.	1	.	.
	Fibre Diameter (mm)	4.253	1	4.253	5.90E+03	0	0.981	5895.322	1
	Moisture Regain (%)	13670.918	1	13670.918	1.38E+04	0	0.992	13840.096	1
	Fibre length (mm)	7594.639	1	7594.639	920.704	0	0.887	920.704	1
	Linear density (tex)	1329.336	1	1329.336	.	.	1	.	.
Location	Tensile strength (MPa)	61474.195	2	30737.097	.	.	1	.	.
	Elongation (%)	2.351	2	1.176	.	.	1	.	.
	Fibre Density (g/mm^3)	387.331	2	193.665	.	.	1	.	.
	Fibre Diameter (mm)	0.11	2	0.055	76.34	0	0.566	152.68	1
	Moisture Regain (%)	17.617	2	8.808	8.917	0	0.132	17.835	0.97
	Fibre length (mm)	91.127	2	45.564	5.524	0.005	0.086	11.047	0.845
	Linear density (tex)	57.097	2	28.548	.	.	1	.	.
Error	Tensile strength (MPa)	0	117	0					
	Elongation (%)	0	117	0					
	Fibre Density (g/mm^3)	0	117	0					
	Fibre Diameter (mm)	0.084	117	0.001					
	Moisture Regain (%)	115.57	117	0.988					
	Fibre length (mm)	965.102	117	8.249					
	Linear density (tex)	0	117	0					
Total	Tensile strength (MPa)	190312.728	120						
	Elongation (%)	16.598	120						
	Fibre Density (g/mm^3)	2006.536	120						
	Fibre Diameter (mm)	4.447	120						
	Moisture Regain (%)	13804.104	120						
	Fibre length (mm)	8650.868	120						
	Linear density (tex)	1386.433	120						
Corrected Total	Tensile strength (MPa)	61474.195	119						
	Elongation (%)	2.351	119						
	Fibre Density (g/mm^3)	387.331	119						

	Fibre Diameter (mm)	0.195	119						
	Moisture Regain (%)	133.187	119						
	Fibre length (mm)	1056.229	119						
	Linear density (tex)	57.097	119						

a. R Squared = 1.000 (Adjusted R Squared = 1.000)
b. Computed using alpha = .05
c. R Squared = .566 (Adjusted R Squared = .559)
d. R Squared = .132 (Adjusted R Squared = .117)
e. R Squared = .086 (Adjusted R Squared = .071)

APPENDIX M: MANOVA MULTI COMPARISON TABLE WITH RESULTS FROM TUSKEYS HSD POST HOC TESTS

Table 5-16 - Manova multiple comparisons

Multiple Comparisons								
Dependent Variable		**(I) Location on stalk**	**(J) Location on stalk**	**Mean Difference (I-J)**	**Std. Error**	**Sig.**	**95% Confidence Interval Lower Bound**	**Upper Bound**
Fibre Diameter (mm)	Tukey HSD	Mid	Roo	-.0440*	0.00601	0	-0.0583	-0.0297
			Top	.0297*	0.00601	0	0.0155	0.044
		Roo	Mid	.0440*	0.00601	0	0.0297	0.0583
			Top	.0738*	0.00601	0	0.0595	0.088
		Top	Mid	-.0297*	0.00601	0	-0.044	-0.0155
			Roo	-.0738*	0.00601	0	-0.088	-0.0595
	LSD	Mid	Roo	-.0440*	0.00601	0	-0.0559	-0.0321
			Top	.0297*	0.00601	0	0.0179	0.0416
		Roo	Mid	.0440*	0.00601	0	0.0321	0.0559
			Top	.0738*	0.00601	0	0.0619	0.0856
		Top	Mid	-.0297*	0.00601	0	-0.0416	-0.0179
			Roo	-.0738*	0.00601	0	-0.0856	-0.0619
Moisture Regain (%)	Tukey HSD	Mid	Roo	-.9385*	0.22224	0	-1.4661	-0.4109
			Top	-0.4761	0.22224	0.086	-1.0037	0.0515
		Roo	Mid	.9385*	0.22224	0	0.4109	1.4661
			Top	0.4624	0.22224	0.098	-0.0652	0.99
		Top	Mid	0.4761	0.22224	0.086	-0.0515	1.0037
			Roo	-0.4624	0.22224	0.098	-0.99	0.0652
	LSD	Mid	Roo	-.9385*	0.22224	0	-1.3786	-0.4984
			Top	-.4761*	0.22224	0.034	-0.9162	-0.036

		Roo	Mid	.9385*	0.22224	0	0.4984	1.3786
			Top	.4624*	0.22224	0.04	0.0223	0.9025
		Top	Mid	.4761*	0.22224	0.034	0.036	0.9162
			Roo	-.4624*	0.22224	0.04	-0.9025	-0.0223
Fibre length (mm)	Tukey HSD	Mid	Roo	0.985	0.64221	0.279	-0.5396	2.5096
			Top	-1.1475	0.64221	0.178	-2.6721	0.3771
		Roo	Mid	-0.985	0.64221	0.279	-2.5096	0.5396
			Top	-2.1325*	0.64221	0.003	-3.6571	-0.6079
		Top	Mid	1.1475	0.64221	0.178	-0.3771	2.6721
			Roo	2.1325*	0.64221	0.003	0.6079	3.6571
	LSD	Mid	Roo	0.985	0.64221	0.128	-0.2869	2.2569
			Top	-1.1475	0.64221	0.077	-2.4194	0.1244
		Roo	Mid	-0.985	0.64221	0.128	-2.2569	0.2869
			Top	-2.1325*	0.64221	0.001	-3.4044	-0.8606
		Top	Mid	1.1475	0.64221	0.077	-0.1244	2.4194
			Roo	2.1325*	0.64221	0.001	0.8606	3.4044

Based on observed means.
The error term is Mean Square (Error) = .000.
*. The mean difference is significant at the .05 level.

APPENDIX N: TENSILE TEST 25GRAMS FIBREBOARD

Ref 1 : Fibreboard
Ref 2 : 25grams fibre
Ref 3 : test 1
Ref 4 : phenol resin 140ml

Date : 16-03-16
File : C:\FABRIC\TST0602.DAT
Test Speed : 200 mm/min
Sample Length : 200 mm
Pre-Tension : 1 kgf

Comments : 25 grams and 140ml phenol resin composite tests

Test No.	Load @ Peak kgf	Elong. @ Peak mm	Strain @ Peak %	Energy @ Peak kgf.m	Load @ Break kgf	Elong. @ Break mm	Strain @ Break %	Load @ 100% kgf	Load @ 100 % kgf	Elong. @ 100 kgf mm
1	38.970	4.5733	2.2848	0.1114	34.700	5.113	2.555	-	-	-
2	27.940	3.9270	1.9622	0.0647	23.100	4.867	2.432	-	-	-
3	23.020	1.4451	0.7213	0.0183	1.550	17.805	8.888	-	-	-
4	24.750	2.2553	1.1257	0.0304	1.550	20.475	10.220	-	-	-
Minimum	23.020	1.4451	0.7213	0.0183	1.550	4.867	2.432	0	0	0
Mean	28.670	3.0502	1.5235	0.0562	15.225	12.065	6.023	0	0	0
Maximum	38.970	4.5733	2.2848	0.1114	34.700	20.475	10.220	0	0	0
Std Dev	7.163	1.4488	0.7243	0.0417	16.485	8.243	4.113	0	0	0
Co-Eff. Var.	24.98	47.50	47.54	74.24	108.28	68.32	68.28	0.00	0.00	0.00
Lower C.L.	17.273	0.7449	0.3710	0.0102	11.007	-1.050	-0.521	0	0	0
Upper C.L.	40.067	5.3555	2.6759	0.1226	41.457	25.181	12.568	0	0	0

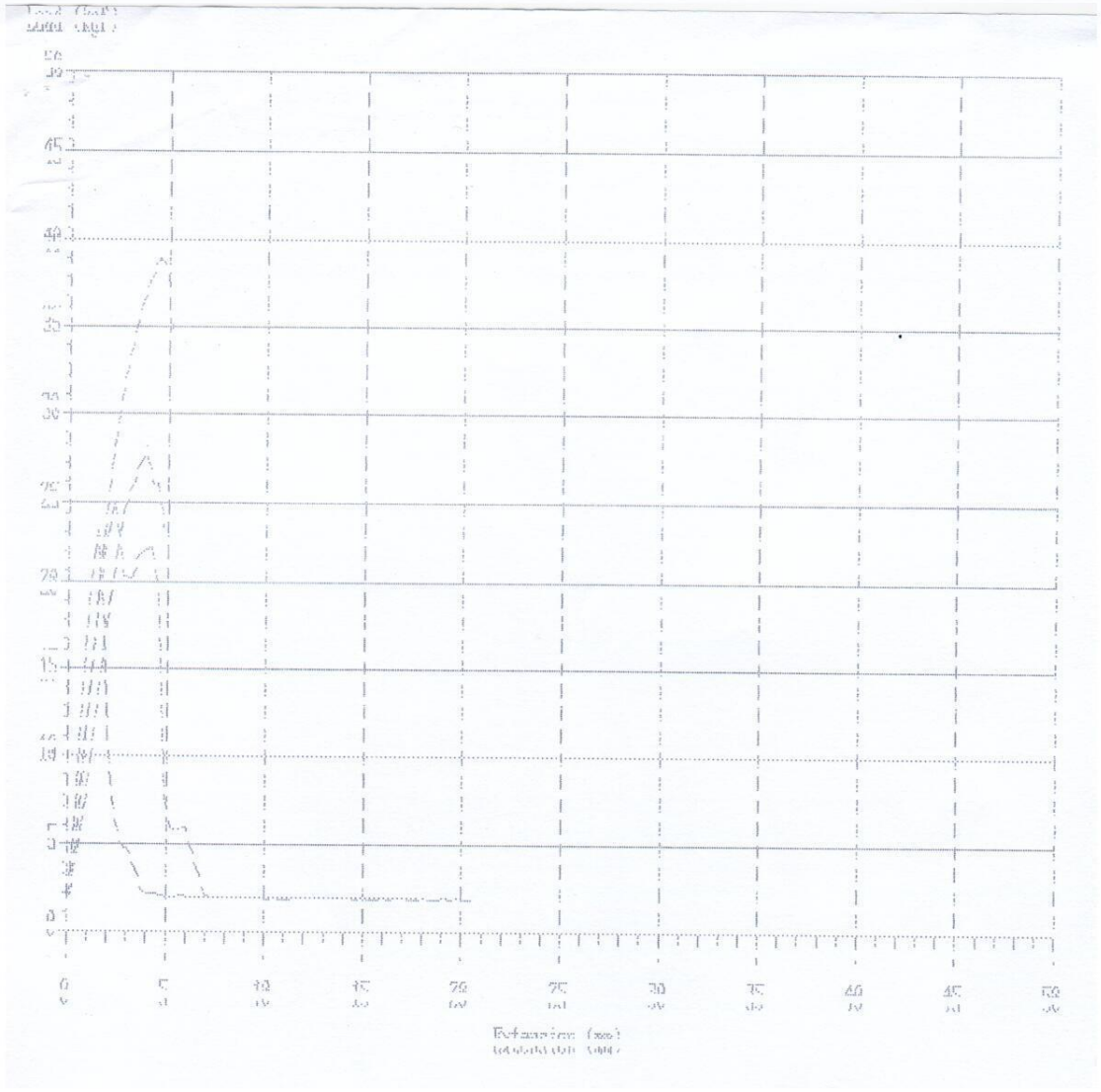


Figure 5-4 – Tensile test results for 25 grams fibreboard

APPENDIX O: TENSILE TEST RESULTS FOR 50GRAMS FIBREBOARD

Ref 1 : 50 grams 140ml resin
Ref 2 : Fibreboard
Ref 3 : Sample set 2
Ref 4 :

Comments : 50 grams and 140ml resin test
:

Date : 16-03-16
File : C:\STRAPPIN\TST0050.DAT
Test Speed : 200 mm/min
Sample Length : 200 mm
Pre-Tension : 1 kgf

Test No.	Load @ Peak kgf	Strain @ Peak %	Elong. @ Peak mm	Energy @ Peak kgf.m	Load @ Break kgf	Elong. @ Break mm	Strain @ Break %	Energy @ Break kgf.m
1	36.290	2.2808	4.5671	0.0978	22.260	6.527	3.2596	0.1491
2	22.960	2.1529	4.3232	0.0571	0.330	11.773	5.8630	0.0653
3	28.510	0.8378	1.6786	0.0267	4.900	8.199	4.0921	0.0992
4	54.350	1.4250	2.8552	0.0931	34.050	4.085	2.0389	0.1499
Minimum	22.960	0.8378	1.6786	0.0267	0.330	4.085	2.0389	0.0653
Mean	35.528	1.6741	3.3561	0.0687	15.385	7.646	3.8134	0.1159
Maximum	54.350	2.2808	4.5671	0.0978	34.050	11.773	5.8630	0.1499
Std Dev	13.688	0.6730	1.3499	0.0334	15.623	3.229	1.6056	0.0412
Co-Eff. Var.	38.53	40.20	40.22	48.56	101.55	42.22	42.10	35.58
Lower C.L.	13.748	0.6033	1.2081	0.0156	-9.474	2.509	1.2586	0.0503
Upper C.L.	57.307	2.7450	5.5040	0.1218	40.244	12.783	6.3682	0.1815

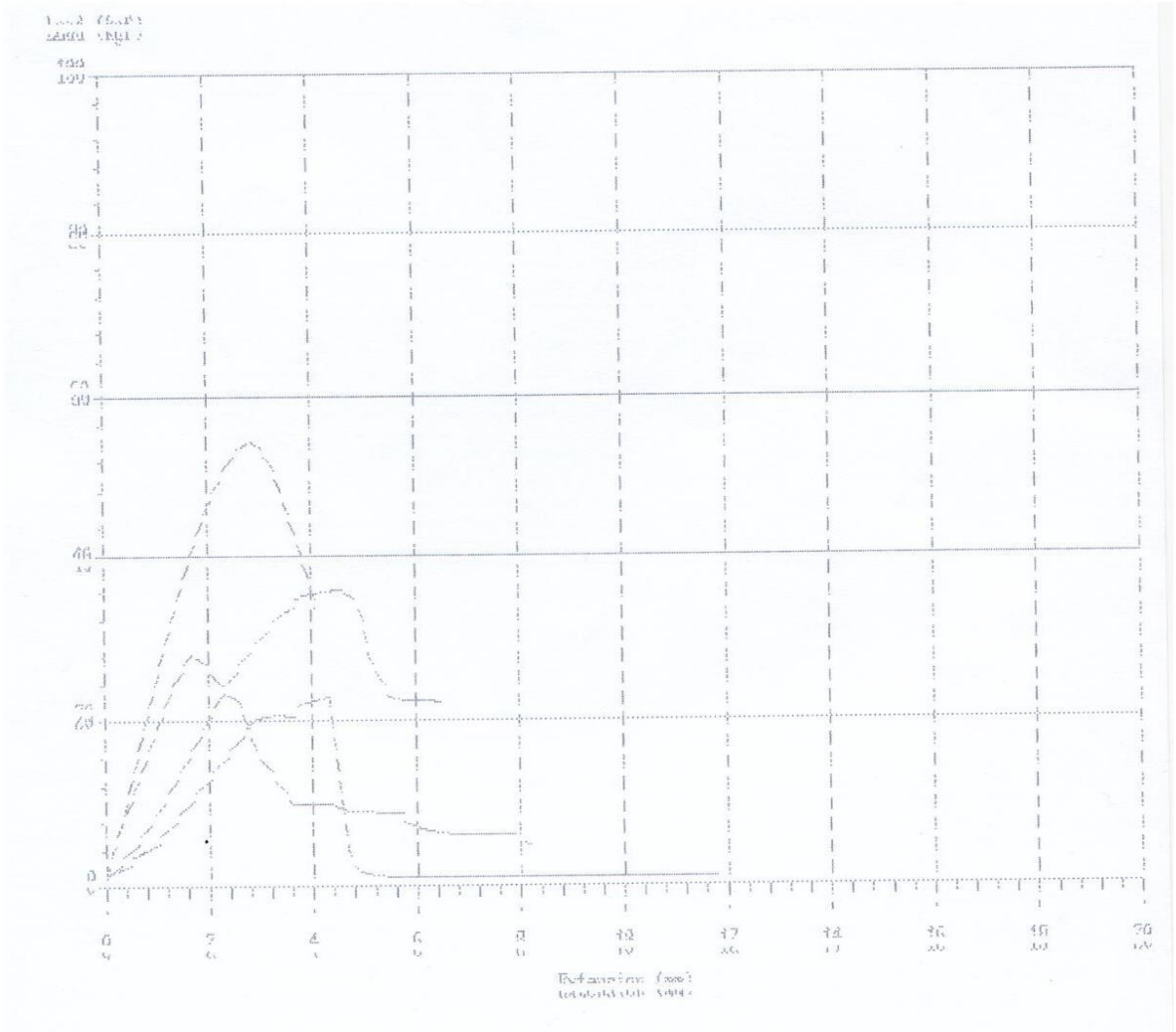
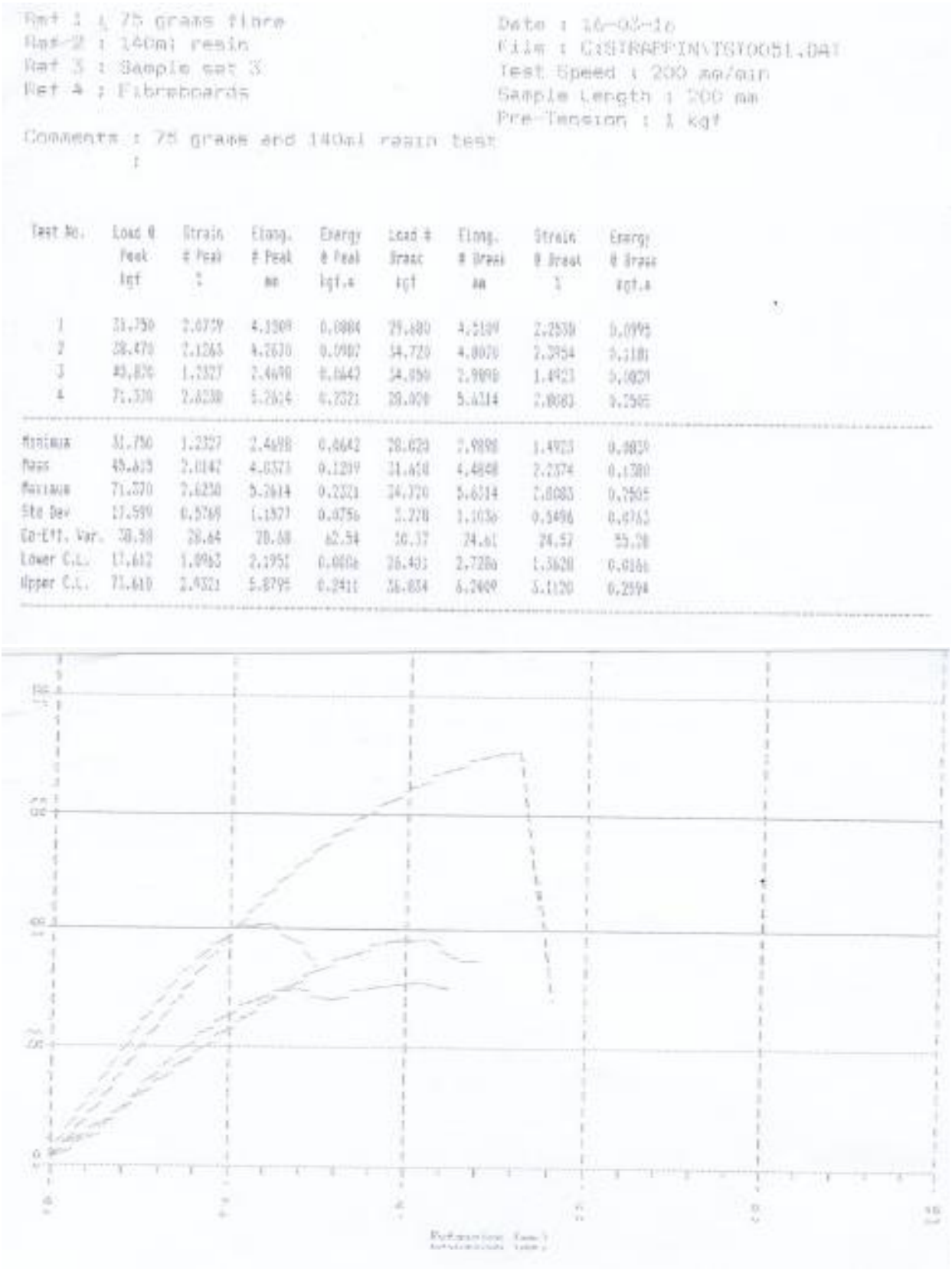


Figure 5-5 – Tensile test results for 50 grams fibreboard

APPENDIX P: TENSILE TEST RESULTS FOR 75 GRAMS FIBREBOARD



Ref 1 : 75 grams fibre
Ref 2 : 140ml resin
Ref 3 : Sample set 3
Ref 4 : Fibreboards

Date : 16-03-10
File : C:\STRAFFIN\TST0051.DAT
Test Speed : 200 mm/min
Sample Length : 200 mm
Pre-Tension : 1 kgf

Comments : 75 grams and 140ml resin test

Test No.	Load @ Peak kgf	Strain @ Peak %	Elong. @ Peak mm	Energy @ Peak kgf.s	Load @ Break kgf	Elong. @ Break mm	Strain @ Break %	Energy @ Break kgf.s
1	31.750	2.0729	4.1509	0.0804	29.680	4.5109	2.2559	0.0995
2	38.470	2.1263	4.2630	0.0982	34.720	4.8070	2.3954	0.1181
3	49.826	1.2327	2.4698	0.0642	28.030	2.9898	1.4923	0.0829
4	71.330	2.6230	5.2614	0.2221	28.020	5.6214	2.8083	0.2505
Minimum	31.750	1.2327	2.4698	0.0642	28.020	2.9898	1.4923	0.0829
Mean	47.844	2.0137	4.0363	0.1209	31.612	4.4818	2.2374	0.1380
Maximum	71.330	2.6230	5.2614	0.2221	34.720	5.6214	2.8083	0.2505
Std Dev	17.599	0.5769	1.1571	0.0756	3.228	1.1036	0.5496	0.0763
Co-Eff. Var.	36.78	28.64	28.68	62.54	10.17	24.61	24.57	55.28
Lower C.L.	17.612	1.0963	2.1951	0.0606	26.403	2.7286	1.3628	0.0166
Upper C.L.	77.610	2.9321	5.8795	0.2411	36.834	6.2469	3.1120	0.2594

Figure 5-6 – Tensile test results for 75 grams fibreboard

APPENDIX Q: TENSILE TEST RESULT FOR 100GRAMS FIBREBOARD

Set 1 : 100grams
Set 2 : 140ml resin
Set 3 : Fibreboard
Set 4 : Specimen 4

Comments : 100 grams

Date : 16-03-10
File : C:STRAPPIN\IST0052.DAT
Test Speed : 200 mm/min
Sample Length : 200 mm
Pre-Tension : 1 kgf

Test No.	Load @ Peak kgf	Strain @ Peak %	Elong. @ Peak mm	Energy @ Peak kgf.m	Load @ Break kgf	Elong. @ Break mm	Strain @ Break %	Energy @ Break kgf.m
1	40.740	1.4004	2.8125	0.0698	3.480	11.602	5.8766	0.1648
2	44.170	1.9313	3.8886	0.1073	5.800	8.919	4.4296	0.2092
3	66.190	2.2813	4.5732	0.1927	25.790	7.893	3.9374	0.3488
4	61.870	1.5195	3.0467	0.1067	43.570	4.307	2.1479	0.1798
Minimum	40.740	1.4004	2.8125	0.0698	3.480	4.307	2.1479	0.1648
Mean	53.243	1.7831	3.5802	0.1191	19.660	8.230	4.0979	0.2757
Maximum	66.190	2.2813	4.5732	0.1927	43.570	11.602	5.8766	0.3488
Std Dev	12.658	0.4025	0.8073	0.0521	18.825	3.095	1.5386	0.0842
Co-Eff. Var.	23.77	22.58	22.55	43.77	95.75	37.61	37.55	30.56
Lower C.L.	32.101	1.1426	2.2956	0.0362	10.295	3.305	1.6496	0.0914
Upper C.L.	73.384	2.4237	4.8648	0.2021	49.615	13.155	6.5461	0.3594

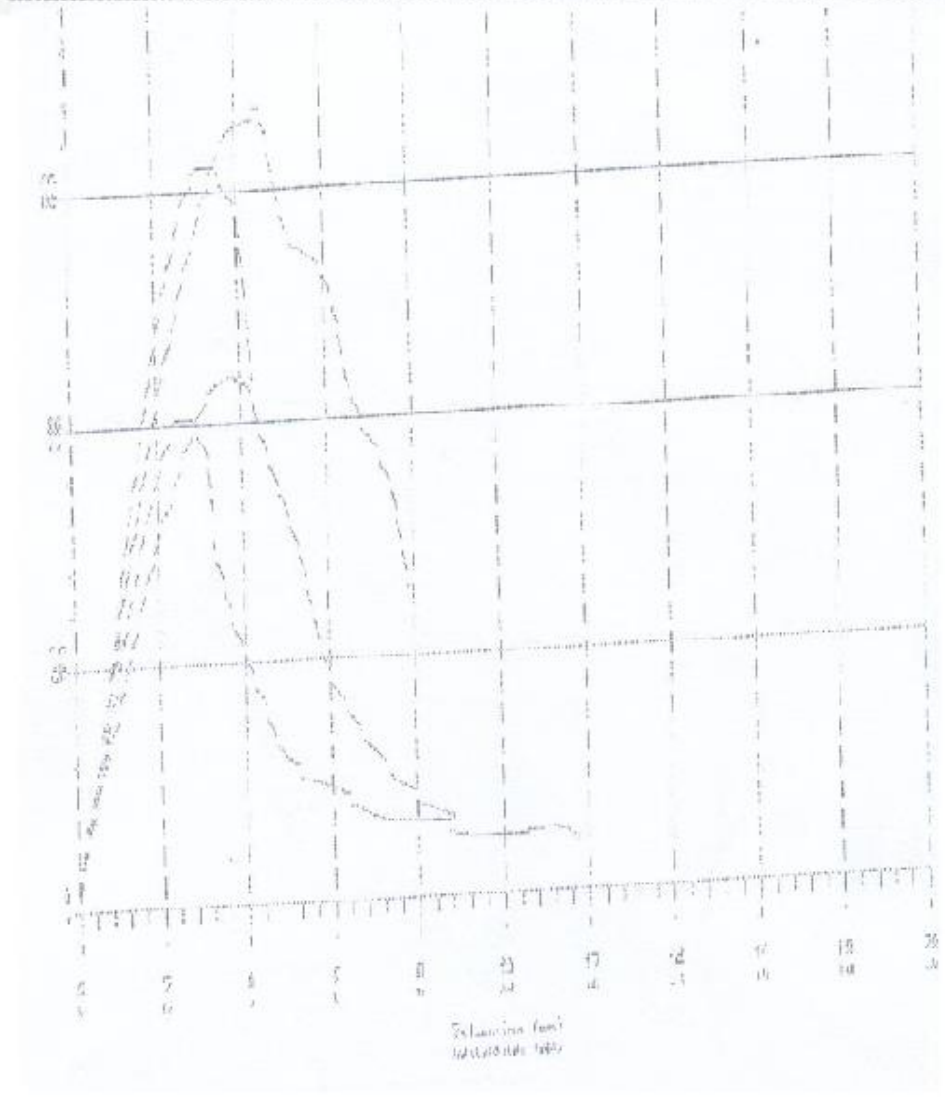
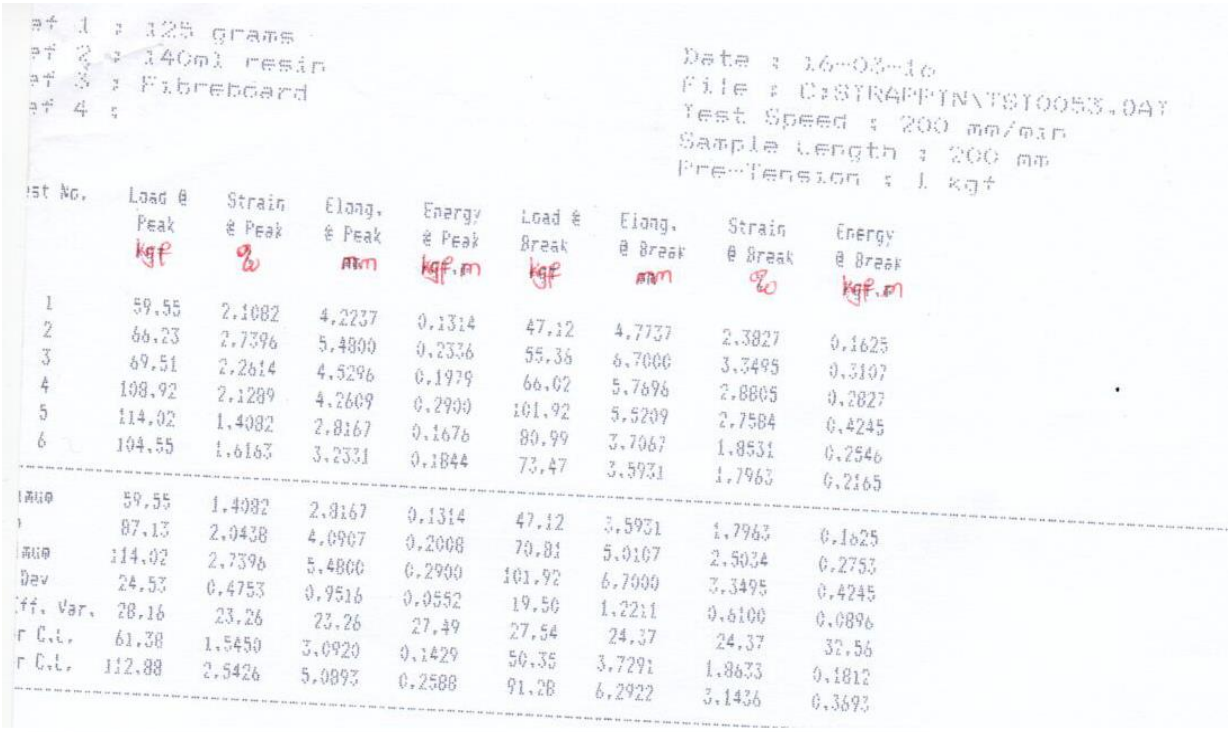


Figure 5-7 – Tensile test results for 100 grams fibreboard

APPENDIX R: TENSILE TEST 125GRAMS FIBREBOARD



af 1 : 125 grams
af 2 : 140ml resin
af 3 : Fibreboard
af 4 :

Date : 16-03-10
File : C:\STRAPPIN\TST0053.DAT
Test Speed : 200 mm/min
Sample Length : 200 mm
Pre-Tension : 1 kgf

st No.	Load @ Peak kgf	Strain @ Peak %	Elong. @ Peak mm	Energy @ Peak kgf.m	Load @ Break kgf	Elong. @ Break mm	Strain @ Break %	Energy @ Break kgf.m
1	59,55	2,1082	4,2237	0,1314	47,12	4,7737	2,3827	0,1625
2	66,23	2,7396	5,4800	0,2336	55,36	6,7000	3,3495	0,3197
3	69,51	2,2614	4,5296	0,1979	66,02	5,7696	2,8805	0,2827
4	108,92	2,1289	4,2609	0,2900	101,92	5,5209	2,7584	0,4245
5	114,02	1,4082	2,8167	0,1676	80,99	3,7067	1,8531	0,2546
6	104,55	1,6163	3,2331	0,1844	73,47	3,5931	1,7963	0,2165
ıaıe	59,55	1,4082	2,8167	0,1314	47,12	3,5931	1,7963	0,1625
	87,13	2,0438	4,0907	0,2008	70,81	5,0167	2,5034	0,2753
ıaıe	114,02	2,7396	5,4800	0,2900	101,92	6,7000	3,3495	0,4245
Dev	24,53	0,4753	0,9516	0,0552	19,50	1,2211	0,6100	0,0896
ff. Var.	28,16	23,26	23,26	27,49	27,54	24,37	24,37	32,56
r C.L.	61,38	1,5450	3,0920	0,1429	50,35	3,7291	1,8633	0,1812
r C.L.	112,88	2,5426	5,0893	0,2588	91,28	6,2922	3,1436	0,3693

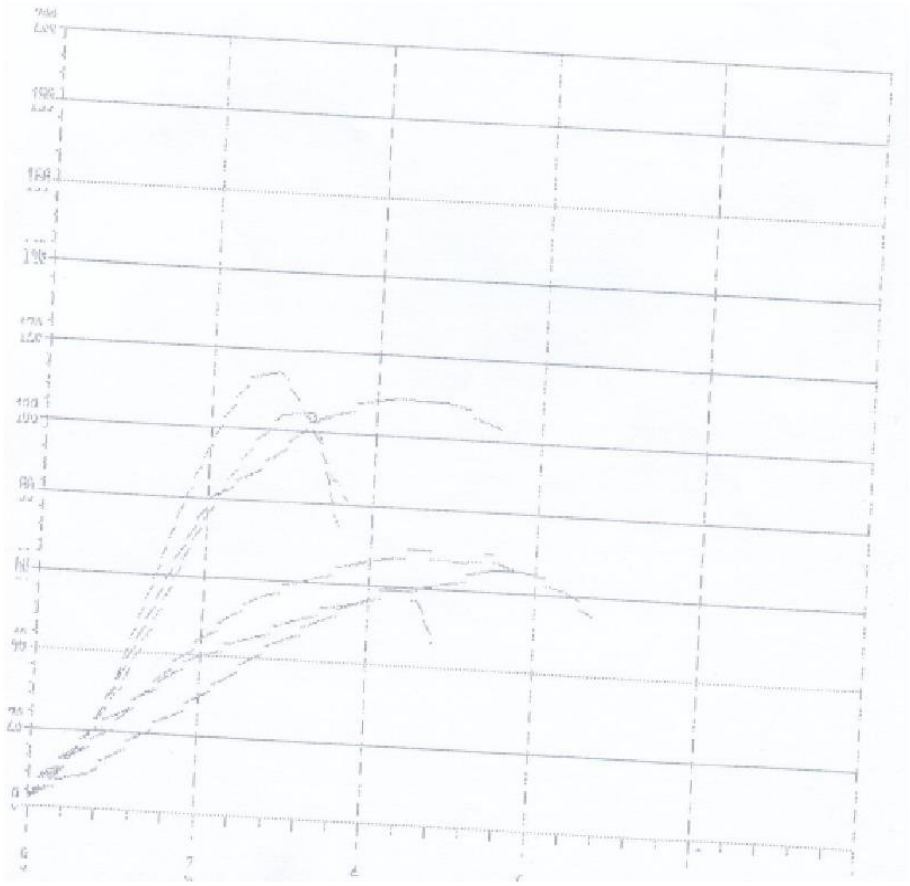


Figure 5-8 – Tensile test results for 125grams fibreboard

APPENDIX S: RESULTS FOR COMPRESSIONAL STRENGTH TEST OF FIBREBOARD

Table 5-17 - Compressional test results for fibreboard

10.96% M_f						
Weight (g)	**Length (mm)**	**Width (mm)**	**Volume (mm^2)**	**Density (g/mm^2)**	**Ultimate compressional load (kN)**	**Compressive strength (MPa)**
5.54	100	25	2500	0.00222	1.4	0.56
5.7	100	25	2500	0.00228	2.2	0.88
5.34	100	25	2500	0.00214	1.6	0.64
5.4	100	25	2500	0.00216	1.5	0.6
Mean				**0.000032**	**1.68**	**0.67**
Std				**0.000064**	**0.359**	**0.1438**
Variance				**0**	**0.129**	**0.0207**
Co-Eff Va.				**2.92**	**21.46**	**21.46**
19.76% M_f						
Weight (g)			**Volume (mm^2)**	**Density (g/mm^2)**	**Ultimate compressional load (kN)**	**Compressive strength (MPa)**
9.13	100	25	2500	0.003652	1.00	0.40
8.63	100	25	2500	0.003452	3.00	1.20
9.8	100	25	2500	0.00392	1.80	0.72
5.86	100	25	2500	0.002344	1.80	0.72
Mean				**0.003342**	**1.90**	**0.76**
Standard deviation				**0.000692**	**0.825**	**0.33**
Variance				**0**	**0.68**	**0.109**
Co-Eff Va.				**20.72**	**43.4**	**43.4**
26.98% M_f						
Weight (g)			**Volume (mm^2)**	**Density (g/mm^2)**	**Ultimate compressional load (kN)**	**Compressive strength (MPa)**
16.25	100	25	2500	0.0065	1.00	0.40
13.86	100	25	2500	0.005544	3.00	1.20
14.37	100	25	2500	0.005748	1.80	0.72
11.93	100	25	2500	0.004772	1.80	0.72
11.89	100	25	2500	0.004756	3.40	1.36
Mean				**0.005464**	**2.20**	**0.88**
Standard deviation				**0.00732**	**0.98**	**0.392**
Variance				**0.000001**	**0.96**	**0.154**
Co-Eff Va.				**13.39**	**44.54**	**44.54**
33.00% M_f						
Weight (g)			**Volume (mm^2)**	**Density (g/mm^2)**	**Ultimate compressional load (kN)**	**Compressive strength (MPa)**
16.02	100	25	2500	0.006408	5.00	2.00
20.12	100	25	2500	0.008048	3.40	1.36
7.93	100	25	2500	0.003172	5.00	2.00
9.86	100	25	2500	0.003944	4.80	1.92
Mean				**0.005393**	**4.55**	**1.82**
Standard deviation				**0.00224**	**0.772**	**0.309**
Variance				**0.00001**	**0.579**	**0.095**

Co-Eff Va.				**41.62**	**16.98**	**16.98**
38.11% M_f						
Weight (g)			**Volume (mm^2)**	**Density (g/mm^2)**	**Ultimate compressional load (kN)**	**Compressive strength (MPa)**
16.47	100	25	2500	0.006588	5.60	2.24
18.63	100	25	2500	0.007452	4.80	1.92
13.36	100	25	2500	0.005344	3.80	1.52
14.12	100	25	2500	0.005648	4.30	1.72
Mean				**0.006258**	**4.63**	**1.85**
Standard deviation				**0.000956**	**0.768**	**0.307**
Variance				**0.000001**	**0.589**	**0.094**
Co-Eff Va.				**15.28**	**16.6**	**16.6**

APPENDIX T: WATER ABSORPTION RAW DATA MEASUREMENTS FOR COMPOSITE SAMPLE

Table 5-18 - Water absorption of cotton stalk fibre/phenol resin composite

Phenol Formaldehyde Resin 100%							
Sample	**Initial**	**2 hours**	**Water absorbed (%)**	**4 hours**	**Water absorbed (%)**	**24 hours**	**Water absorption (%)**
1	6.9595	10.4943	50.79			11.07	5.46
2	6.4489	10.4312	61.75			10.64	2.03
3	5.2507	8.2870	57.83			8.67	4.66
Mean			**56.79**				**4.05**
Standard Deviation			**5.55**				**1.80**
Variance			**30.84**				**3.23**
Coefficient of Variation			**9.78**				**44.36**
25grams (10.98%) Fibre Mass Content							
Sample	**Initial**	**2 hours**	**Water absorbed (%)**	**4 hours**	**Water absorbed (%)**	**24 hours**	**Water absorption (%)**
1	10.6781	17.6553	65.34	18.9710	7.45	19.6683	3.68
2	5.7262	9.0215	57.55	9.4000	4.20	9.8600	4.89
3	11.2268	19.1025	70.15	19.5826	2.51	20.6155	5.27
4	15.8047	26.3471	66.70	28.1478	6.83	28.8877	2.63
Mean			**64.94**		**5.25**		**4.12**
Standard Deviation			**5.33**		**2.31**		**1.21**
Variance			**28.36**		**5.32**		**1.45**
Coefficient of Variation			**8.20**		**43.95**		**29.25**
50 grams (19.76%) Fibre Mass Content							
Sample	**Initial**	**2 hours**	**Water absorbed (%)**	**4 hours**	**Water absorbed (%)**	**24 hours**	**Water Absorption (%)**
1	8.2180	13.8544	68.59	14.8	6.83	15.2317	2.92
2	5.9986	9.8552	64.29	10.2	3.50	10.9321	7.18
3	7.6972	12.5127	62.56	13.069	4.45	14.2061	8.70
4	5.1160	8.9016	74.00	9.4051	5.66	9.3006	-1.11
Mean			**67.36**		**5.11**		**4.42**
Standard Deviation			**5.10**		**1.45**		**4.43**
Variance			**25.99**		**2.09**		**19.59**
Coefficient of Variation			**7.57**		**28.33**		**100.12**
75 grams (26.98%) Fibre Mass Content							

Sample	Initial	2 hours	Water absorbed (%)	4 hours	Water absorbed (%)	24 hours	Water absorption (%)
1	9.2484	15.4536	67.09	15.8660	2.67	16.9945	7.11
2	14.6675	23.4490	59.87	25.3054	7.92	25.985	2.69
3	10.5738	18.0232	70.45	20.0385	11.18	19.3074	-3.65
4	7.6679	13.9547	81.99	14.9498	7.13	15.0967	0.98
Mean			**69.85**		**7.22**		**1.78**
Standard Deviation			**9.22**		**3.51**		**4.45**
Variance			**84.96**		**12.30**		**19.79**
Coefficient of Variation			**13.2**		**48.55**		**249.47**
100 grams (33%) Fibre Mass Content							
Sample	**Initial**	**2 hours**	**Water absorbed (%)**	**4 hours**	**Water absorbed (%)**	**24 hours**	**Water absorbed (%)**
1	12.6780	26.2780	107.27	26.855	2.20	27.5860	2.72
2	10.6813	20.6280	93.12	22.151	7.38	22.1360	-0.07
3	13.4674	20.0010	48.51	21.12	5.59	21.8001	3.22
4	6.8464	13.1013	91.36	13.5649	3.54	14.0430	3.52
Mean			**85.07**		**4.68**		**2.35**
Standard Deviation			**25.40**		**2.28**		**1.65**
Variance			**644.60**		**5.21**		**2.71**
Coefficient of Variation			**29.84**		**48.77**		**70.02**
125 grams (38.11%) Fibre Mass Content							
Sample	**Initial**	**2 hours**	**Water absorbed (%)**	**4 hours**	**Water absorbed (%)**	**24 hours**	**Water Absorbed (%)**
1	12.9644	27.0340	108.52	28.9124	6.95	27.9140	-3.45
2	17.4875	33.7381	92.93	34.2146	1.41	36.4318	6.48
3	16.5558	31.6832	91.37	32.1750	1.55	33.0521	2.73
4	20.3770	38.1188	87.07	38.8517	1.92	39.8654	2.61
Mean			**94.97**		**2.96**		**2.09**
Standard Deviation			**9.37**		**2.67**		**4.11**
Variance			**87.77**		**7.12**		**16.89**
Coefficient of Variation			**9.86**		**90.18**		**196.6**

APPENDIX U: SHOWING RAW DATA RESULTS FOR CALCULATION OF COMPOSITE BOARD DENSITY

Table 5-19 - Density of cotton stalk fibreboards

10.96% M_f						
V_f %	**Weight (Kg)**	**Length (mm)**	**Width (mm)**	**Thickness (mm)**	**Volume (mm^3)**	**Density (Kg/m^3)**
10.98	163.0125	24	21	0.48	0.24192	673.828125
10.98	150.234	24	21	0.45	0.2268	662.4074074
10.98	150.254	24	21	0.5	0.252	596.2460317
Mean	**172.76**			**0.48**	**0.24024**	**644.16**
Standard Deviation	**2.47**			**0.0577**	**0.0291**	**98.3**
Variance	**6.1**			**0.0033**	**0.008**	**9671**
Co-Eff Va.	**1.43**			**13.32**	**13.32**	**12.3**
19.76% M_f						
V_f %	**Weight (Kg)**	**Length (mm)**	**Width (mm)**	**Thickness (mm)**	**Volume (mm^3)**	**Density (Kg/m^3)**
10.98	190	24	21	0.52	0.26208	724.969475
10.98	172.2157	24	21	0.5	0.252	683.3956349
10.98	180.1476	24	21	0.45	0.2268	794.3015873
Mean	**180.7877667**			**0.49**	**0.24696**	**734.22**
Standard Deviation	**2.42**			**0.03**	**0.01512**	**58.3**
Variance	**5.86**			**0.0009**	**0.00023**	**3398.7**
Co-Eff Va.	**1.26**			**6.3**	**6.38**	**7.14**
26.98% M_f						
V_f %	**Weight (Kg)**	**Length (mm)**	**Width (mm)**	**Thickness (mm)**	**Volume (mm^3)**	**Density (Kg/m^3)**
10.98	215.0087	24	21	0.48	0.24192	888.7595073
10.98	218.0273	24	21	0.49	0.24696	882.8445902
10.98	200.8642	24	21	0.5	0.252	797.0801587
Mean	**211.3000667**			**0.49**	**0.24696**	**856.23**
Standard Deviation	**2.87**			**0.01**	**0.00504**	**19.4**
Variance	**8.24**			**0.0001**	**0.00003**	**376.7**
Co-Eff Va.	**1.32**			**2.04**	**2.04**	**2.21**
33.00% M_f						
V_f %	**Weight (Kg)**	**Length (mm)**	**Width (mm)**	**Thickness (mm)**	**Volume (mm^3)**	**Density (Kg/m^3)**
10.98	220.8465	24	21	0.48	0.24192	912.890625
10.98	225.1475	24	21	0.5	0.252	893.4424603
10.98	226.0006	24	21	0.51	0.25704	879.2429194
Mean	**223.9982**			**0.50**	**0.25032**	**895.19**
Standard Deviation	**2.35**			**0.01528**	**0.0077**	**26.2**
Variance	**5.52**			**0.00023**	**0.00006**	**688.4**
Co-Eff Va.	**0.97**			**3.08**	**3.08**	**2.71**
38.11% M_f						
V_f %	**Weight (Kg)**	**Length (mm)**	**Width (mm)**	**Thickness (mm)**	**Volume (mm^3)**	**Density (Kg/m^3)**
10.98	250.155	24	21	0.5	0.252	992.6785714
10.98	255.1589	24	21	0.52	0.26208	973.5916514
10.98	263.7822	24	21	0.5	0.252	1046.754762
Mean	**256.3653667**			**0.51**	**0.25536**	**1004.34**

Standard Deviation	**2.47**			**0.01155**	**0.00582**	**32.5**
Variance	**6.09**			**0.00013**	**0.00003**	**1054.9**
Co-Eff Va.	**0.94**			**2.28**	**2.28**	**3.15**

APPENDIX V: SHOWING REGRESSION ANALYSIS RESULTS FOR TENSILE STRENGTH (MPA) VS M_F (%)

Table 5-20 - Regression Analysis: Tensile Strength (MPa) versus Fibre Mass Fraction (%)

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	10.313	10.3131	12.66	0.038
Fibre Mass Fraction (%)	1	10.313	10.3131	12.66	0.038
Error	3	2.445	0.8149		
Total	4	12.758			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.902710	80.84%	74.45%	22.77%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	0.07	1.16	0.06	0.955	
Fibre Mass Fraction (%)	0.1496	0.0420	3.56	0.038	1.00

Regression Equation

Tensile Strength (MPa) = 0.07 + 0.1496 Fibre Mass Fraction (%)

APPENDIX W: SHOWING REGRESSION ANALYSIS FOR COMPRESSIONAL STRENGTH (MPA) VERSUS V_F (%)

Table 5-21 - Regression Analysis: Compressional strength (MPa) versus Fibre Mass fraction (%)

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	1.1078	1.10779	12.04	0.040
Fibre Mass fraction (%)	1	1.1078	1.10779	12.04	0.040
Error	3	0.2759	0.09198		
Total	4	1.3837			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.303277	80.06%	73.41%	42.10%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	-0.066	0.388	-0.17	0.875	
Fibre Mass fraction (%)	4.90	1.41	3.47	0.040	1.00

Regression Equation

Compressional strength (MPa) = -0.066 + 4.90 Fibre Mass fraction (%)

APPENDIX X: SHOWING REGRESSION ANALYSIS FOR FLEXURAL STRENGTH (MPA) VERSUS M_F (%)

Table 5-22 - Regression Analysis: Flexural Strength (MPa) versus Fibre Mass Fraction (%)

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	1666585	1666585	26.55	0.014
Fibre Mass Fraction (%)	1	1666585	1666585	26.55	0.014
Error	3	188295	62765		
Total	4	1854880			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
250.530	89.85%	86.46%	64.17%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	-177	321	-0.55	0.619	
Fibre Mass Fraction (%)	6013	1167	5.15	0.014	1.00

Regression Equation

Flexural Strength (MPa) = -177 + 6013 Fibre Mass Fraction (%)

APPENDIX Y: REGRESSION ANALYSIS RESULTS FOR WATER ABSORPTION (%) VS V_F (%)

Table 5-23 - Regression Analysis: Water Absorption (%) versus Fibre Mass Fraction (%)

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	903.39	903.39	41.35	0.003
Fibre Mass Fraction (%)	1	903.39	903.39	41.35	0.003
Error	4	87.38	21.85		
Total	5	990.77			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
4.67395	91.18%	88.98%	82.39%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	60.38	3.68	16.39	0.000	
Fibre Mass Fraction (%)	0.944	0.147	6.43	0.003	1.00

Regression Equation

Water Absorption (%) = 60.38 + 0.944 Fibre Mass Fraction (%)