THE EVALUATION OF CONVENTIONAL RETTING VERSUS SOLAR BAKING OF *AGAVE AMERICANA* FIBRES IN TERMS OF TEXTILE PROPERTIES

‘Manonyane Albertina ‘Mamthimk’ulo Mafaesa

Dissertation submitted in fulfilment of the requirements for the degree

Master of Science in Home Economics

in the
Faculty of Agricultural and Natural Sciences
Department of Microbial, Biochemical and Food Biotechnology:
Consumer Science

at the
University of Free State, Bloemfontein, South Africa

Promoter: Professor H.J.H. Steyn
November 2006

DEDICATION

This work is dedicated to my son, Mthimk'hulo, my daughter, Mamajoin Mafaesa and my husband who constantly provided assistance and words of encouragement.

ACKNOWLEDGEMENT

I wish to acknowledge the valuable support, encouragement and sound advice of several people who helped me through out the course. I could have not completed this research study without their support and collaboration.

I wish to express gratitude and appreciation to my supervisor professor H.J.H. Steyn, Department of Microbial, Biochemical and Food Biotechnology: Consumer Science, who encouraged me, read the script and made many penetrating comments, constructive criticisms and useful suggestions during the research work. In fact my thesis would have not been possible without the immense assistance I received from the professor.

I wish to express sincere gratitude to the University of the Free State for financial support they gave me to study.

I would like to acknowledge Mrs P.L. Venter who spun and wove the *Agave americana* fibre into fabrics which were used for testing the performance properties.

I also owe a special word of thanks to Mrs. D.M. Riekert, Mrs. P.Z. Swart and Mrs. J.S. van Zyl, from the Consumer Science section of the department of Microbial, Biochemical and Food Biotechnology for their friendly attitude and recommendations, they have been a source of inspiration to me.

Thanks are also due to Mr. P. Neumann, a Peace co-op. volunteer from the USA for taking photographs, and for tireless computer technological assistance and many other people who provided special assistance.

Special thanks to my husband, my son and daughter for their tireless assistance with computer skills and the encouraging words they had for me.

Thanks to the language editor, Mrs. M. Lekunutu for the valuable contribution she offered.

I acknowledge Mrs. A. van der Westhuizen who patiently assisted with technical skills – it was very difficult for me to do it properly.

Above all I thank God Almighty who gave me the strength and chance to experience and go through this hard work.

The author would like to acknowledge and thank every one who has contributed to the finalising of this dissertation.

The author is also grateful to her family, parents, brothers and sisters, friend and colleagues who granted moral support during the study.

TABLE OF CONTENTS

PAGE

LIST OF TABLES

LIST OF FIGURES

PAGE

PAGE

CHAPTER 1

GENERAL INTRODUCTION

1.1 BACKGROUND

A textile is a broad term referring to any material that can be made into fabric by any method of fabric construction. The word textile is derived from a Latin word, *textilis* and a French word, *texere* which mean to weave. Although the term was originally used only to indicate woven fabrics, at present it includes other fabric construction methods (Bartle & O'Connor, 1997:2; Cushing, 2000:4; Hall, 1966:9; Hatch, 1993:128; Mauersberger, 1954:11; Miller, 1968:8; Wingate, 1976:22, 27).

A textile fibre is a unit of matter with an extremely small diameter and a length of at least 100 times longer than its width. There are various fibrous substances. The ones which can be used to make fabrics are categorized as textile fibres, others as non-textile fibres. Textile fibres have a minimum length of about 15 mm and a minimum width of about 10µm. Fibres shorter than 15 mm are generally considered non-textile fibres because it is too difficult to commercially twist them into a yarn of adequate strength and uniform diameter (Hatch, 1993:85; Marsh, 1947:2; Thomson, 1974:9).

Likewise, fibres which are too fine and delicate to process into yarn are also categorized as non-textile fibres. At the other size extreme, fibres exceeding 50 µm. in diameter are generally classified as non clothing textile fibres because they are too coarse and thick to be comfortable, if worn next to the skin. Brittle fibres have very limited application for clothing purposes. All textile fibres are from natural vegetable, animal or mineral matter or man-made from manufacturing processes which utilises natural or fibrous materials or synthetics fibre from chemicals (man-made) (Hatch, 1993:85; Joseph, 1986:8; Marsh, 1947:2; Page, 1968:98; Picton & Mack, 1989:23; Thomson, 1974:9; Wingate, 1976:22, 27).

The textile industry is one of the oldest and largest industries, in the world. Natural fibres have been used to make textiles since prehistoric times. Until the 20th century, all fabrics were made up of fibres from natural plants and animal sources. Wool, flax, cotton and silk were the most important (Ishida, 1991:97; Joseph, 1986:2).

However, these natural fibres were subjected to minimum processing and most early fabrics were probably made by either a simple plain weave or plaiting fibres, grasses or other raw material. Later, the emergence of man-made fibre has dramatically affected the production and the use of the natural fibres. However the natural fibres are still used today because of special performance properties they possess (Asian Textile Business, April 2004:17, 19; Ishida, 1991:98; Joseph, 1986:2, 6).

Fibres are the basic units of most fabrics and fibre properties are determined by the nature of the physical structure, the chemical composition and the molecular arrangement. This provides a better foundation for the fibre performance and a comprehensive understanding of the limitations of the fibre (Cray & Budden, 1996:33; Cushing, 2000:18; Hollen *et al.,* 1988:3, 5; Wynne, 1997:5; Wingate & Mohler, 1984:35).

Fibres contribute to the aesthetic appearance, durability, comfort, appearance retention and safety, suitability and ecological impact of textile products production, processing and utilisation. They determine to a great extent the care and maintenance required for fabrics. Successful textiles must be readily available, constantly in supply and inexpensive. It must have sufficient strength, pliability, length and cohesiveness to be spun into yarns (Cray & Budden, 1996:33; Cushing, 2000:18; Hollen *et. al*.,1988:3, 5; Wingate & Mohler, 1984:35); Wynne, 1997:5).

Textile performance deals with what a textile can do, that is, the need the textile can help to satisfy. Textile fibre performance can be specified on two levels of precision: Performance attributes which are more general and difficult to objectively measure and performance properties which are specific and quantifiable. The end use or ultimate purpose is a primary consideration (Hatch, 1993:3, 4; Smith & Block, 1982:19; Wynne, 1997:5).

Food, shelter and clothing are the basic needs of humankind (Hollen, *et al.,* 1988:2). Most of them are obtained from different kinds of plants. *Agave americana* plant is one essential plant that can furnish the three basic needs of man. The evaluation of the physical structure and performance properties of *Agave americana* fibre can assist one to predict its end uses. The main aims of this research study are: to evaluate solar baking as an accessible, effective, eco-friendly and non-renewable energy-saving empirical method of extracting fibre from *Agave americana* plant leaves; To comparatively evaluate the physical structure and textile performance properties of *Agave americana* fibre obtained by solar baking and convectional retting methods of fibre degradation and extraction.

Agave americana fibre is obtained from the leaves of the monocotyledonous perennial plant, commonly called the century plant or *marginata* and scientifically named *Agave americana L. Agave americana* plants are commonly found in Lesotho and in South Africa. *Agave americana* plant is one of the scientifically identified group of dessert plants belonging to the *Agav*e family – *Agavaceae*. It is of the division; *Magnoliophyta*, class; *Liliopsida*, subclass; *Liliidae*, order; *Liliales*. *Agave* is therefore a genus name, whereas the genus, *Agave* followed by *americana* is the species of the plant of interest (Dahlgren *et al.,* 1985:16; Morse, 2004:1; Nobel, 1994:6; Nobel, 1988:28, 10, 42; Sunset magazine & Sunset Book, 1967:54).

Smith, (2003:4,5) described the century plant as the Mexican *Agave americana* (blougaringboom), and the representative of *Agave* genera which is widely grown in South Africa, especially in the arid, karroid areas and is used for the production of a high quality tequila-like alcoholic drink. *Agave americana* plant differs from *Agave sisalana* plant in that *Agave sisalana* leaves are without spines along the edges while *Agave americana* has spines along the leaves, but they are closely related (Mauerbersger, 1954:393). The Textile Institute (1975) says: "*Agave* plants particularly henequen resemble sisal very closely and indeed are sometimes termed sisal". Mauersberger, (1954:414) regards it to be a Lurida- another *Agav*e specie.

The century plant is a big slow growing succulent plant with curved, grey, 25 cm wide leaves in a basal rosette of about 3 m which have spines along the edges and one at the top as illustrated in Figure 1.1. The plant produces plenty of suckers during its life. It lives for a number of years without flowering but it does not take 100 years to bloom as the name denotes. It takes about 10-15 years in a warm climate, considerably longer in colder ones before flowering. Figure 1.2 shows fleshy leaves of *Agave americana* plant that begins to bloom.

The flower stalk reaches up 6 to 16 m. as illustrated in Figure 1.3. After blooming the clump dies. *Agave americana* plant is the commonest and largest specie readily propagated vegetative by ramets and cultivated in warm parts of the world as ornamental or boarder plants. The picturesque variegated form of *Agave americana* plant has longitudinal yellowish stripes alternating with dark green stripes along its leaves, have become favourite decorative plants in botanical and private gardens around the world (Dahlgren *et al.,* 1985:161; Morse, 2004:1-2; Nobel, 1994:6, 42; Nobel, 1988:28, 10; Sunset magazine & Sunset Book, 1967:54).

Figure 1.1 ***Agave americana*** **plant before blooming**

Figure 1.2 ***Agave americana*** **plant when blooming**

Figure 1.3 Indeterminate inflorescence fully blossomed *Agave americana* plant with its large panicles

1.2 PROBLEM STATEMENT

Agave americana plant is under utilised in Lesotho and other Southern African countries. The extraction of *Agave americana* leaf sap which is highly valued in the cosmetic, pharmaceutical and soap making industries recently became an essential innovative practice in Lesotho. Unfortunately, this industry utilizes a very small percentage of this economic, eco-friendly, fibre productive and renewable plant. The rest of the plant material is disposed off as waste. This waste contains long fibres, which can be used profitably for textiles. Apart from being a useful by-product it can also provide employment opportunities to a number of needy people.

Agave americana plant is a common plant but not yet thoroughly exploited as a potential textile fibre plant. It is therefore ideal to analyse its fibre in order to predict its textile performances.

The *Agave americana* fibres have been used in Lesotho until mid 18th century, when it was replaced by cotton. May be this happened because it is difficult to separate *Agave americana* fibres from the leaf lignocelluloses biomass as is the case with ramie (Carter, 1971:28). Traditionally the leaves are boiled in pure water until they are soft to scrape off the binding extraneous matter to release the fibres. This process takes too long. It consumes a lot of non-renewable fuel and water for several washing and rinsing processes, it therefore lacks practical economy. This requires a high amount of energy and hence adds considerable cost to the overall production of the fibre. It also leads to environmental pollution because the washing is usually done in rivers.

It has been well known for about 100 years, in Lesotho, country wide that the *Agave americana* plant provides long, strong textile fibres but no research has been conducted to widen its scope and improve its performance properties where necessary. People have abandoned the use of this fibre.

The possible reason could be the fact that individual cells of *Agave americana* fibres are stuck firmly together with lignified gum. The difficulties in processing and degumming have kept it from being commercially competitive with other natural cellulosic fibres. The single *Agave americana* fibre consists of overlapping cell bundles which make them coarse, rough and stiff when compared to cotton and wool. This hard texture limits the fibre uses in apparel and household goods, even though these fibres are of good strength. They therefore, have been used only for twine and rope making.

The important textile fibres found in Lesotho are wool and mohair successively. The high rate of stock theft forces individual textile scientist to think about other forms of fibre that have a potential to take over important textile functions of wool and mohair.

Another essential motive to study *Agave americana* fibre is the fact that very little study has been done worldwide on the properties of *Agave americana* fibres. Natural vegetable fibres have been addressed worldwide by other researchers (Easson & Molloy, 1996:245). It therefore worthwhile to investigate the possibilities of *Agave americana* to be an eco-friendly, accessible and economical textile fibre. Generally, the research is done to widen the scope of *Agave americana* fibres.

The recurring incidences of periodic as well as protracted droughts in Lesotho and the Southern African region also challenge researchers to find out the potential significance of a fibre which can survive under such adverse weather conditions. Cultivation and efficient use of this plant can improve the existing life situation because *Agave americana* plant is one of the most drought tolerant plants. It does not need extensive care, during its cultivation.

1.3 JUSTIFICATION OF STUDY

Natural fibres form the basis of textiles. It is worthwhile to do research on *Agave americana* fibre because, it is a natural fibre. Miller, (1992:18) says that it is still appreciated that the natural fibres are an essential source of textile fibres in spite of increasing competition from man-made fibres. The natural cellulosic fibres are likely to increase in importance due to their low price, availability and environmental-friendly, soil erosion preventative and biodegradable character. Frings, 1996:71 considers natural fibres as the most luxurious fibres. It is worthwhile to conduct the research experiments on *Agave americana* plant because it is so abundant in Southern Africa. It is available in both urban and rural areas. It is also available through out the year since it is not affected by seasonal temperature changes.

The *Agave americana* fibre is a natural renewable fibre, according to Ford, (1994:8) and it is among the best bet ecological fibres. The plant is thought to gain popularity and importance because it is abundantly available and almost accessible to individuals because it usually grows wild and there is also a possibility of its easy and cheap cultivation.

It is also good to encourage the use of its fibres as the by-products of medicinal, pharmaceutical and cosmetic manufacturing projects, which are carried out in the country in order to efficiently utilise this valuable *Agave americana* plant. Nobel, (1994:42) emphasised this point by saying that *Agave* fibres are the by products of juices pressed from some *Agaves* for soap making.

Agave americana plant is thought to be an environmental- friendly plant as it does not need large quantities of chemicals to be used as pesticides or fertilizer during its production and cultivation. It also grows well as a wild plant. It cleans the land and the atmosphere. It has a wide variety of uses including that of textiles.

This can be another way of alleviating poverty, because more job opportunities could be created because people would get involved in craft projects and thus use the fibre for individual as well as business to improve their lives. This can encourage innovative and efficient methods of utilizing *Agave americana* fibre as an existing natural resource product which is expected to result in good economic returns.

Agave americana plants provide a good number of fibres per leaf. For obvious economic reasons commercial productivity of *Agaves* should be encouraged. *Agaves* produce about 220 leaves per plant before the emergence of the inflorescence at lifespan of seven to eight years of age under usual plantation conditions. Leaves can be harvested after two to four years of age. The *Agave* fibres are said to be strong, long and absorbent (Cook, 1988:27; Nobel, 1988:201). These are good reasons for one to think that *Agave americana* fibre can also be a potential textile fibre.

This research study is therefore looking for new ways to remove the fibre from the leaf biomass. The research is hoped to provide contribution to the improvement of textile industry through a systematic and orderly evaluation of the physical structure and textiles performance properties of *Agave americana* fibres removed from the biomass by the eco-friendly method of solar-baking.

Cornelissen, (1996:50) strongly encouraged individuals to take initiative to do research in their own practices with locally available materials so that theory generated in such experiences and understanding can assist in bringing changes in that context, so that it can be socially useful and theoretically meaningful. This research is thought to be self-reflective to improve the rationality of local people who can hopefully take its results and apply it.

The textile industry in Lesotho and Southern Africa has made only limited progress in the resolution of its numerous and complicated national problems and its accomplishments have not kept pace with social demands. In order to partly resolve this existing textile problem (so as to obtain a fruitful textile development) the effective dissemination of research projects like this one has to be conducted. It is quite obvious that in order for the textile industry in Lesotho to progress, it needs more research studies for new insights with which to meet some challenges within the textile industry.

The textile consumers are challenged by new developments, to know the relationship between their needs and the available textile resources so as to make wise and thoughtful use of them. The American Home Economics Association, (1974:1) supports this idea when saying: “Today the consumer’s acquaintance with the world of textiles from fibre to finished products is a necessity as well as pleasure”. The research on textile fibre performances contributes to technical innovation of the concerned textile researchers, worldwide (Schoeser & Rufey, 1989:202) it is expected to be so with *Agave americana* fibre as well.

The problem of waste disposal (pollution) and the depletion of resources, especially non-renewable resources are forcing changes that are challenging the textile researchers and manufacturers' innovation and responsive production and processing of fibre. The interest in environmentally friendly products is universal and not restricted to textile researchers and manufacturers; nobody can afford to ignore it.

Solar processing enables the most effective use of resources, because it reduces energy cost, and minimizes waste. John Ford, (1994:8) insists that it is necessary to investigate the capacity of different fibre sources in order to understand changes in supply. He then found it worthwhile to give natural, renewable fibres the first preference because they seem the best bet ecologically (Warrnambool Wollen Co. 1982:5).

It is ideal to study the *Agave americana* fibre because in the recent years there is a rapid revival in the utilization of natural fibres due to the fact that they yield a unique high performance, great versatility and processing advantage of favourable cost and environment as emphasized by Cumberbirch, (1987:47); Ford, (1994:9-11); Joseph *et al.,* (2003:275); Miller, (1992:20); Weaver, (1984:5).

The consumers' ecological consciousness directs their buying and consumption towards more ecological friendly products. This research project is intended to encourage these sentiments. *Agave americana* plant is easily available and cheap to grow. It is worthwhile to conduct the research on effective, efficient and relevant ways to process and release *Agave americana* fibres and to evaluate its performance properties.

1.4 PURPOSE OF RESEACH

1.4.1 Overall goal

The overall goal of the study is to evaluate conventional retting as against solar baking of *Agave americana* fibre in terms of textile properties. The study focused mainly on identification of the most cost effective, efficient and environmental-friendly methods for partial degradation of *Agave americana* leaves to release textile fibre. The focus was also on confirmatory identification of the fibre. Finally, the focus was on comparing physical structures and some textile performance properties of the fibre obtained through those two processes in order to predict its possible end uses in textiles.

This research is therefore intended to open up new possibilities to partially degrade and decorticate *Agave americana* leaves in order to use the fibres for textiles purposes. It is exploring on non-traditional plant fibre to supplement the consumer's demands for textiles. It is also intended to investigate each performance attribute in selected performance properties so as to show how they contribute to *Agave americana* textile product performance.

1.4.2 Specific objectives of this research study are to:

- Manually harvest the mature *Agave americana* plant leaves for fibre extraction and evaluation.
- Determine the two most effective, efficient and eco-friendly methods of degrading the extraneous matter from *Agave americana* leaves so as to release clean, long and strong textile fibres
- Use solar energy to partially degrade *Agave americana* leaves in order to remove *Agave americana* fibres
- Cut the *Agave americana* leaves in ribbon-like structures so as to hasten the natural retting and solar baking processes and to reduce pollution.
- Extract *Agave americana* leaf fibres from the lignocelluloses biomass of the plant leaves with the most accessible means.
- Hand-evaluate the texture and strength of *Agave americana* fibres when dry versus when wet
- Physically evaluate the length, width, and colour of *Agave americana* fibres
- Evaluate microscopic longitudinal appearance of *Agave americana* fibres for confirmation at identification
- Evaluate microscopic cross-sectional shape and appearance of *Agave americana* fibres for confirmation at identification
- Evaluate the tensile strength of *Agave americana* yarns.
- Determine the rigidity of *Agave americana* fabric in order to predict its flexibility as a basic property of a textile fibre
- Evaluate thickness of *Agave americana* fabric.
- Evaluate the crease recovery properties of *Agave americana* fabric.
- Evaluate the dimensional stability of *Agave americana* fabric.
- Determine water absorption of *Agave americana* fibres.

- Determine the moisture regain of *Agave americana* fibres.
- Determine the dyeability performance properties of *Agave americana* fabric.

1.5 HYPOTHESES

A null hypothesis approach was used to describe the expected outcomes of the research project.

H0$_{1}$ Solar baking process is not an effective method of partial degradation for *Agave americana* leaves for fibre extraction.

H0$_{2}$ The physical structure of *Agave americana* fibre is not different from that of other natural cellulosic fibre.

H0$_{3}$ There is no difference between the physical structure of solar-baked and retted *Agave americana* fibres.

H0$_{4}$ *Agave americana* fibre has an adequate length-to-width ratio to quilify to be a textile fibre.

H0$_{5}$ Solar-baked *Agave americana* fibre is not longer than retted *Agave americana* fibre.

H0$_{6}$ *Agave americana* fibre does not have the adequate tensile strength to be regarded as a fibre.

H0$_{7}$ *Agave americana* fibre is not a uniform textile fibre.

H0$_{8}$ Solar-baked *Agave americana* fibre is not as flexible as retted *Agave americana* fibre.

H0$_{9}$ *Agave americana* fibre is not a thick textile fibre.

H0$_{10}$ Solar-baked *Agave americana* fibre has no better breaking elongation property than retted *Agave americana* fibre.

H0$_{11}$ Solar-baked *Agave americana* fibre is not as dimensionally stable as retted *Agave americana* fibre.

H0$_{12}$ *Agave americana* fabric has low crease recovery.

H0$_{13}$ Solar-baked *Agave americana* fabric has no significantly different crease recovery property from retted *Agave americana* fabric.

H0$_{14}$ Solar-baked *Agave americana* fibre has less water absorption property than retted *Agave americana* fabric.

H0$_{15}$ Solar-baked *Agave americana* fibre has less moisture regain property than retted *Agave americana* fabric.

H0$_{15}$ Solar-baked *Agave americana* fibre has less moisture regain property than retted *Agave americana* fabric.

H0$_{16}$ *Agave americana* fibre does not have good dyeability properties.

H0$_{17}$ *Agave americana* fibre is not a potential and useful textile fibre.

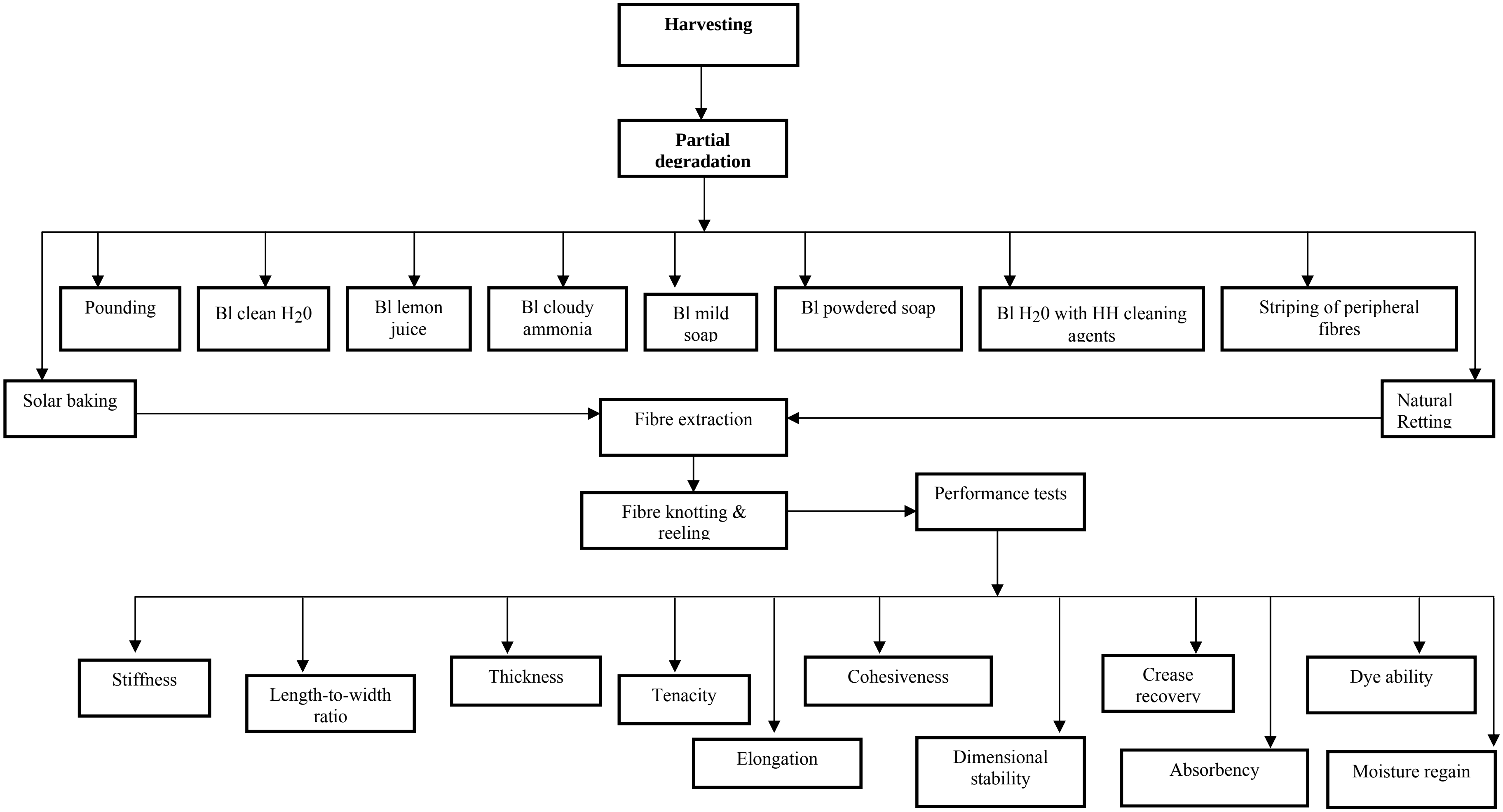
H0$_{18}$ The conventional retting of *Agave americana* fibre has less moisture regain properties than retted *Agave americana* fabric.

1.6 CONCEPTUAL FRAMEWORK

The conceptual framework illustrates the experimental flow in this research study as shown in Figure 1.4.

Figure 1.4: Conceptual Framework

FLOW CHART FOR EXPERIMENTAL PROCEDURE



1.7 OUTLINE OF STUDY

The main objectives of the study are to compare solar baking against conventional retting to identify the most effective, efficient and eco-friendly method to partially degrade *Agave americana* leaves so as to release textile fibre and to compare physical structure and some performance properties of solar baked and retted *Agave americana* fibres.

The dissertation will comprise five chapters organised as follows:
Chapter 1 is the introduction, while Chapter 2 is devoted to the present review of literature. Research procedures are described in Chapter 3 and have Phase 1 on plant harvesting and preliminary fibre extraction of *Agave americana*, while Phase 2 identifies the physical structure of the *Agave americana* and in Phase 3 the textile performance properties of *Agave americana* fibres are evaluated. Chapter 4 presents the results and discussion of the experimental study, while conclusions derived from the analysis of the results of the study and recommendations for further research are provided in Chapter 5.

1.8 LIMITATION OF STUDY

The study focused on natural degradation of non-fibrous leaf constituents, mechanical fibre extraction and the evaluation of some of the performance properties of *Agave americana* fibre. It was limited to the evaluation of the physical structure only. Manual harvesting, and hand fibre decortications are energy and labour-intensive. Retting, spinning and weaving on the other hand are time consuming and restricting factors.

It was therefore difficult to have a proper random sample of leaves from different plants. The leaves for this study were all selected from two plants. The chemical structure and molecular arrangement of the fibre are not covered in this research study. It was difficult to have a clear demarcation within the leaf for the outermost and innermost fibres which is followed but there is a clear trend of the different cellular shapes of the outer fibres and the inner fibres. The evaluation of performance properties was limited to some selected performance properties only because the time span of the study could be too long.

Another limiting factor was the fact that *Agave americana* leaves have sapogenins. Nobel, (1994:41) said that future economic significance of *Agaves* might be affected by their high contents of sapogenins. This fact has been experienced during processing of *Agave americana* leaves in this research study.

It was a time consuming and labour intensive process to decorticate, spin and weave the fibre. In order to make the project feasible in terms of time, all plant material was restricted to one plant. This made the comparison between the methods more reliable but restricted the representative qualities of the research.

1.9 DEFINITION OF TERMS

Cellulose is a naturally occurring polysaccharide which forms linear chains which aggregate into bundles to form micro-fibrils (Anderson & Beardall, 1991:19).

Conventional retting is the fermentation process whereby natural micro-organisms are encouraged to grow on the stem or leaf by sprinkling or soaking it for a period of time in water, so that their enzymes could degrade parenchymatous non-cellulosic biomass so as to release the fibre (Catling, 1990:64; Down, 1999:109; Greenwood, 1991:22; Ossala & Galante, 2003:177).

Decortication is the process whereby the cuticle and other extraneous matter of plant portions are separated from the fibre (Kadolph & Langford, 2002:45**.**

Dimensional change is a generic term for changes in length or width of a fabric specimen subjected to a specific condition. The change is usually expressed as a percentage of the initial dimension of the specimen (AATCC, 1990).

Dimensional residual shrinkage refers to additional shrinkage that may occur after the first care cycle. It is determined after testing for relaxation dimensional change, drying and re-measuring (AATCC, 1990:148).

Inflorescences are the arrangement of flowers into a cluster or clusters and mode of development of the flowers on the floral axis (Rolf et *al.,* 1982:102; Smith, 2003:56).

Lignin according to Kirk, *et al.,* (1980:2, 3) lignin is a generic name for the complex aromatic polymers which are the major components of vascular plant tissue. Raj, (1997:483) further defines it as a group of insoluble complex polymers that hold water. Pearl, (1967:2, 3) defines it as a system of three-dimensional polymers, which permeates membranous polysaccharides and the spaces between the cells, thereby strengthening them.

Pectin's are linear water-soluble polymers of D – galacturonic acid linked with 1–4 alpha glucosidic bonds that form gel and binds water captions (Merkel, 1991:375; Raj, 1997:484).

Relaxation dimensional change refers to the dimensional change that occurs when, fabric is immersed in water for the first time without agitation so that the strains and stress put into fibres, yarns or fabrics during previous processing stages such as spinning, weaving or knitting and finishing are relieved.

Sapogenins are the chemical substances that are found in the leaf juices of some *Agaves* including *Agave americana*, which are poisonous and cause dermatitis (Nobel, 1994:43).

Tenacity is the force required to break the fibre. Strong fibres have a high tenacity value and fabric made from these fibres is very durable (Down, 1999:106).

Textiles is used to describe the wide range of fibres, yarns and fabrics, their functions behaviour, appearance, performance, and maintenance which are largely influenced by the structure and the properties of fibres which make up the yarns, the structure of the yarns, the methods of fabric construction and finishes applied to the fabrics (Ishida, 1991:97).

Textile fibre is a long linear basic building element of textile material, generally characterized by flexibility, fineness and high ratio of length to thickness, which is capable of being spun into yarn or made into fabric by bonding or by interlacing a variety of methods including knitting, weaving, braiding, felting, twisting or webbing. Textile fibre can be available in short staple lengths or as long continuous filament (Bartle & O'Connor, 1997:28; The Textile Institute, 1995 27; Wingate, 1976: 23).

CHAPTER 2

LITERATURE REVIEW

2. 1 INTRODUCTION

Until approximately the beginning of the 18th century the natural textile fibres such as the animal skins, leaves and the bark of trees were the only fibres available as potential raw materials for textile fibre products. The leaves did not last very long and the animal skins were very heavy and hard especially after wetting. Then textile equipment was invented and gradually the hair of animals were twisted together to make yarn. Yarn could then be made into fabric and fabric into textile products. Clothes made of fabric are much more comfortable than clothes made from skins (Cushing, 2000:4).

In spite of increasing competition from man-made fibres, it becomes even more appropriate to appreciate that natural fibres still remain an important and necessary source of the world's textile materials. Natural cellulosic fibres have good possibilities for increasing their market shares. They are likely to increase in importance due to their low price, eco friendly character and technical properties. It is also appreciable and appropriate that natural fibres are still an important and a necessary source of the world's textile fabrics in spite of increasing competition from man-made fibres (Cumberbirch, 1987:46; Ford, 1994:9-11; Miller, 1992:8;). It is important for these reasons alone that the general characteristics of natural fibres like *Agave americana* fibres should be studied.

2.2 HARVESTING OF *AGAVE* PLANT TO EXTRACT FIBRES

Harvesting of *Agave* plant leaves is usually done after some years of planting, starting around 5 to 6 years old, when the outer leaves have attained their full maturity length. Those which have reached maturity form a 45° angle to the ground. This is before they blossom. Approximately 15-20 mature lower leaves which are usually more than 1m long are harvested annually per plant. Commercial–quality leaves are harvested for about ten years after which the production of an inflorescence or bolting signals the end of the plant's life (Nobel, 1994:40).

Harvesting of *Agaves* is usually done by cutting the leaves close to the stalk by hand with a knife (labour intensive small-scale method) starting with the outer ones. Hand harvesting is normally used if the fibre is produced and utilised on a small-scale, otherwise large-scale methods of production uses machinery to harvest which is a capital-intensive method. If not harvested when they have attained their maturity size, the leaves commence to deteriorate (Catling, 1990:64; Mauersberger, 1954:398).

2.3 DEGRADATION OF NON-FIBROUS PLANT BIOMASS AND FIBRE EXTRACTION

The structural fibres grow embedded in the cellular tissue and lignin, hemi-cellulose and pectin's are necessary to free them from this matrix before they can be spun (Easson & Molloy; 1996:236). This is usually done in two stages: The first is a non - fibrous cellular degradation which breaks down and softens the matrix. Its purpose is to break and soften the pectin's and gums (or resinous and glue-like substance) that hold the fibres together and free them from the leaf and fibre bundles from other components. The subsequent mechanical scraping, separates the fibres, consist of connected elementary bundles from the cortical parenchyma (Catling, 1990:65; Ossala & Galante, 2003:177).

These processes however may cause a variety of changes in the fibres, but the main effects are the shortening of the external and internal fibrillation. The increased amount of water in the cell wall makes the fibres more pliable and as a result the fibre becomes more conformable (Young & Rowell, 1986:104). Processing of the fibre bundles requires several steps in order to produce quality textile fibres, yarns and fabrics. Further mechanical treatments are applied before spinning in order to split the fibre bundles into finer structures and to render them parallel, and then acid scouring is applied, followed by alkaline scouring (Ossala & Galante, 2003:178).

2.3.1 Mechanical fibre decortications

After cutting, the leaves are hauled to the plant. If it is possible or done in a factory, the fibres are machine decorticated - machine crushes the leaves, scrapes cellular tissue from the fibre and, leaving the long hard whitish fibre strands then washes the fibre to remove any pieces of pulp remaining on fibre after scraping. After the decortications and washing operations are completed the fibres are dried, either with mechanical driers or in the sun (to dry) and to bleach the chlorophyll. To extract the fibre the thorns on the leaf margins and the spine at the leaf tip are removed. Hand decortications can also be done whereby the leaves are then pounded and the pulp is scraped away with a knife (Mauerbersger, 1954:398-399; Nobel, 1994:39; Young & Rowell, 1986:188-189). However hand-decortication needs a lot of hand labour (Kadolph & Langford, 2002:44).

The operations of fibre removal, washing and drying must be done promptly after the leaves are cut, otherwise the gums in the leaves harden, causing the pulp to adhere to the fibres and making it impossible to clean the fibres properly. *Agave* fibres must be extracted cleanly for an increasingly diverse range of valuable markets (Mauerbersger, 1954:398-399; Hall, A.J. 1969:24; Nobel, 1994:39; Young & Rowell, 1986:188-189).

Mechanical decorticators were crucial for the success of sisal production in Eastern Africa. Some decorticators are fed by hand. The pulp is first rasped from half of a leaf; the leaf is withdrawn; and then the opposite half is inserted for rasping. Those machines in which the leaves enter broadside are more efficient as two raspers act simultaneously or more usually in sequence, to remove the leaf pulp from the proximal (basal) and the distal halves of the leaves. Beautiful tresses of long strong fibres emerge from the decorticators. The fibres are usually washed and then dried for a few hours in the sun (Nobel, 1994:41).

2.3.2 Chemical degradation of non-cellulosic components of the leaves

In chemical operations lignin, that is mainly located in middle lamella and secondary wall of the fibre, is removed by reaction and conversion to a soluble derivative (Young & Rowell, 1986:188-189). Plant leaves are treated with an aqueous solvent mixture and cooked for a period of time at elevated temperatures. Cooking initially releases acetic acid and formic acid from natural esters in the leaves. This then promotes the hydrolysis of hemi-cellulose and lignin to low- molecular-weight. Catalysts such as mineral acids (hydrochloric acid), organic carboxylic acids (acetic, oxalic), sulphuric acid and Lewis acids and bases ($ALCL_3$), Fe_2 (So_4), mg (So_4) 2, $Cacl_2$ etc. are often used to accelerate the hydrolysis process. The literature has indicated that anthraquinone promotes delignification of polymeric lignin too (Young & Rowell, 1986:188-189).

Chemical degradation of non-cellulosic polymers found in fibres consists of softening the tissues by boiling it with dilute oxalic acid or alkali either at normal atmospheric conditions or under pressure. After treatment the soluble bodies formed by degradation of less-resistant tissues are washed away. This process is considerably quicker than those relying upon natural fermentation. After degradation by whichever means, the residual tissues are passed between squeeze rollers to remove the excess liquor, and are then well washed in fresh water and dried (Gohl & Vilensky, 1980:277).

2.3.3 Soda processes

Lignin and hemi-celluloses can also be degraded with inorganic reagents (alkalis) (Pearl, 1967:18). For example, the treatment with sodium hydroxide or ammonia swells cellulose fibres and loosens lignin and hemi-celluloses (Young & Rowell, 1986:277-278; Pearl 1967:69). In these processes the plant portions to be treated are heated under pressure with aqueous solutions of the inorganic compounds at temperatures ranging from 130–180 degrees Celsius until ready for fibre extraction. The use of aqueous sodium hydroxide under pressure is a common alkali treatment and it is called the soda process (Pearl, 1967:18-19, 69).

Sulphur dioxide can successfully be used for the degradation of the leaf matrix but the produced fibres are coarser and stronger. A satisfactory retting can be achieved in only 24 hours with a concentration of 1.5 g/ℓ in an enzyme-like chemical called flaxy me sulphur dioxide. Formic acid and propionic acid can be used with success (Easson & Molloy, 1996:240). Ramaswamy *et al.,* (1994:305) conducted bacterial and chemical retting on kenaf fibre. The chemical retting was done by boiling stalks in 7% sodium hydroxide for one hour, after which they were washed, neutralised in 0.2% acetic acid, washed, dried and combed.

2.3.4 Organosolv processes

These are the processes whereby fibre extraction is done through the use of chemical organic solvents such as methanol or ethanol, acetone, dioxane or others in the presence of mild acids. The organosolv processes employ non – acidic, volatile solvents of intermediate to high polarity such as acetone, methanol and ethanol. Since these solvents are not acidic, higher digestion temperatures are needed to auto hydrolyse hemi-cellulose and lignin (Young & Rowell, 1986:189).

Reaction temperatures are usually kept just below the temperature at which pentose begin to decompose to furfural (205-210ºC) to obtain maximum rates without by-products. If furfural forms, it can react with lignin and induce repolymerisation and deposition onto the pulp product. Low degradation rates would incur high capital costs per unit of product.

Acid and Lewis acids used as catalysts in the organosolv processes will attack the cellulose to a limited extent. It is therefore ideal to post- treat the fibres from this process by soaking them in a dilute alkali. The process is referred to as lixification (Young & Rowell, 1986:191).

Ethanol degradation usually uses 1:1 ethanol water mixture. In the presence of SO_2 catalyst, the hemi-cellulose is completely hydrolysed (Young & Rowell, 1986:277-278). In the process, extractives (unwanted substance) are dissolved and some degradations and dissolutions of cellulose and hemicelluloses fractions also occur. The extent of the dissolution of the various constituents depends on the operational conditions such as temperatures, concentrations of active chemicals in the cooking liquor, duration of degradation and type of chemical action such as Kraft or sulphite degradation conditions. Thus depending on the nature of the raw material and the degradation conditions (Pearl, 1967:13-14; Young & Rowell, 1986:188-189).

2.3.5 Natural retting

Retting is the extraction of fibres by a natural microbial process. It is a preferential rotting process to separate the fibre from ligno-cellulosic biomass without damaging the fibre cellulose. Retting is the microbial freeing of plant fibres from their surroundings, usually parenchymatous tissue, which concentrates on the leaf fibre (Easson & Molloy, 1996:240; Gohl & Vilensky, 1980:277; Mignoni, 1999:4; Wilson, 1979:11).

Retting is a well researched method of degrading the extraneous matter which acts as glue between the fibres in woody plant parts and fibres without damaging the fibre cellulose. The process takes up to three weeks if carefully exercised. Retting microbes consume the non–fibrous cementing materials mainly pectin’s and hemi-celluloses. This gradually softens the stems or leaves by the destruction of the less resisting intercellular adhesive substances. When fermentation has reached the appropriate stage, the fibres can be separated quite easily from the debris of the other tissues (Gohl & Vilensky, 1980:277; Kadolph & Langford, 2002:42).

If fermentation is allowed to proceed beyond this point the fibres themselves may become damaged, and to avoid this, the progress of retting must be observed carefully at intervals. The danger of attack extending to the fibre, together with the fact that the operation takes about three weeks, are serious objections, but a compensation advantage is that the cost is negligible (Gohl & Vilensky, 1980:277; Kadolph & Langford, 2002:42).

If the plant fibre is not retted enough, the removal of extraneous matter without injury to the fibre is difficult. Over retting causes degradation of fibre cellulose and weakens some of the bonds between the elemental fibre cells within the fibre bundles, so that finer cells can be produced during scraping of the fibre, thus allowing finer yarn to be spun. Under retting causes incomplete removal of gummy materials such as, pectin substances. Both over retting and under- retting are difficult to control and cause production of low grade fibres. There are two main variants on the technique; dew and water retting (Easson & Molloy, 1996:237 & 240; Gohl & Vilensky, 1980 277; Wilson, 1979:11).

2.3.5.1 Water retting

Retting involves the removal of plant tissue from around the fibres by immersion in water, which causes and promotes microbial growth on the more easily biodegradable material, but to which the tough fibres are resistant. Water retting carried in river causes pollution as retting process is carried out using waterborne bacteria to break down the cellular tissue and gums which surround the fibre (Gohl & Vilensky, 1980:277).

Water retting is an anaerobic process whereby tanks and other stagnant water ret rapidly become depleted of oxygen encouraging the development of an anaerobic flora. The plant retting in this process is brought about by a natural pectinase enzyme produced by bacteria (Kashyap *et al.,* 2001:13-14; Mignoni, 1999:4; Trotman, 1978:63).

Specially constructed tanks are used, to keep the process under control, maintaining the high standards required by the environmentalists. Production and processing methods of natural cellulosic fibres should be more environmentally conscious. The temperature and bacterial content of the leave retted in tanks can be more carefully controlled and eliminate stream or river pollution. The time can be appreciably shortened with consistently good results (Cowan & Jangerman, 1969:58; Easson & Molloy, 1996:237; Greenwood, 1991:22-23; Trotman, 1978:63).

In conventional retting, a huge biomass undergoes decomposition in stagnant water, so retting causes environmental pollution. In “ribbon” retting, “ribbons” are stripped out chemically from the part of mature plants, coiled and allowed to ret under water. Ribbon retting time is almost half in comparison to conventional whole plant retting under normal conditions. This also reduces environmental pollution to a great extent. The use of efficient pectinolytic microbial inoculums improves quality of fibre and further reduces the time of retting of the plant (Banik *et al.,* 2003). However, Andrassy *et al.,* (2005:20) says that retting does not completely degrade the non-fibrous matter from the fibre. They indicated that only 58% of the pectin material in flax stem is destroyed, while the pectin bonding elementary fibres is not decomposed in the process.

2.3.5.2 Dew retting

Dew retting is a variant of water retting and it is done in many areas of the world because it is gentle to the environment (Easson & Molloy, 1996:237). Dew retting is similar in action to water retting, but slower. The plant part to be processed is moistened and allowed to ferment in ambient temperatures. The necessary moisture is supplied either by dew, rain or occasional watering. Sometimes the fermentation is started by water retting and the stalks or leaves of the plant are then taken out and laid on the grass to complete the process. In this way a better colour is obtained (Gohl & Vilensky, 1980:27). Dew retting is an aerobic process whereby plant parts to be retted are exposed to the action of fungi and aerobic bacteria for some time. Retting especially dew retting darkens the fibre giving it natural colour (Kadolph & Langford, 2002:42; Kashyap *et al.,* 2001:13; Mignoni, 1999:4; Trotman, 1978:63).

2.3.6 Enzymatic retting

Enzymatic retting has been a focus of interest in the textile industry, because it results into soft and desized textiles of good performance. It has a potential to simplify and reduce fibre extraction costs. Enzymatic retting in which the pectin materials surrounding the fibre bundles are degraded by industrially- produced enzyme preparations. The process is expected to offer greater process control, increased fibre yield and shorter processing time. The cost- effectiveness of the process is increased by recycling the enzyme solution several times. The use of enzyme extracted from Aspergillus's to digest gum which binds plant debris to the fibres is bio-softening (Enzyme Technical Association 2000:26; Easson & Molloy, 1996:240; Buschle-Diller *et al.,* 1994:270; Gohl & Vilensky, 1980:277).

Ligno-cellulosic polymers with polygalacturonide chains which are insoluble can be broken down by the following enzymes: pectin, polygalacturonase and pectin esterase. For the most effective retting some hemi-cellulase and cellulase activity is also necessary. Pectinases (polygalacturonases) and xylanases enzymes can be used for retting plant portions for fibre release. The advantages of enzyme retting are that there is no accumulation of putrid smelling by-products in the liquor and the same liquor can be reused several times before the activity of the enzyme becomes depleted. The enzyme can be used at higher concentrations to speed up the retting process for example 1.5 g/ℓ or 3.0 g/ℓ water or 5.0 g/ℓ water (Easson & Molloy, 1996: 237, 240; Etters, 1999:34-35; Kundu *et al.,* 1991:720).

Aspergillus-niger can also be used with success. The enzyme cellulase should be avoided in any enzymatic retting process of plant for fibre extraction since this will reduce the strength of the fibres. Enzyme retting is the process in which the pectin materials surrounding the fibre bundles are degraded by industrially-produced enzyme preparations. Enzymatic retting is faster than natural fermentation retting and the quality of fibre improves (Buschle-Diller, 1994:278; Easson & Molloy, 1996:240; Kadolph & Langford, 2002:44; Kashyap *et al.,* 2001:215; Kapdana *et al.,* 2000:381, 386; Ramaswamy *et al.,* 1994:305; Ueda *et al.,* 1994:615; Val *et al.,* 1999:47).

2.4 FIBRE FINISHING PROCESSES

2.4.1 Bleaching

Bleaching is the process of applying oxidizing and reducing chemicals to decolour and remove coloured matter from the fabric. Normally greige fabrics that are composed of natural fibres are of buff to off-white due to natural pigmentation in their fibre and / or the presence of foreign matter in the fabric (Hatch, 1993:388). Bleaching is to whiten the cloth. The natural tan colour of some plant fibres makes bleaching one of the most important processes in the finishing of fibre fabrics (Wingate & Mohler, 1984:154-155). Bleaching completes the effect of scouring and further removes the natural colour of the fibres and renders them white. The bleaching of cellulosic fibres is carried out with oxidising agents, using usually one of the following: hydrogen peroxide (H_2O_2), sodium hypochlorite ($NaOCI$) or sodium chlorite ($NaCIO_2$) (Wynne, 1997:234).

Oxidizing agents convert the cellulose in cellulosic fabric into oxycellulose. Oxycellulose is much weaker than cellulose. Carter, (1972:7) says that scouring and bleaching are processes which are used to remove impurities which occur along with cellulose in vegetable fibres. Bleaching and softening of hard fibres such as jute with polysaccharide degrading enzymes could reduce rigidity of the fibre (Kundu *et al.,* 1993: 453).

2.4.2 Mercerisation

Mercerization is a preparation process which is carried out only on cellulosic fibres, especially cotton. Mercerization changes the chemical and physical properties of the fibre. It renders improved lustre, strength and capacity to accept dye. The fibre is more absorbent, has a softer handle and has more extensibility (Carter, 1971:8; Wynne, 1997:235).

2.4.3 Ammoniating process

Ammoniating process for fabrics has many advantages over mercerisation. This process is less expensive and has little or no negative consequences, results with fewer imperfections, produces greater strength of 40-50% over untreated plant fibre as compared to the 20% increase by mercerization and increases yarn smoothness, thereby improving abrasion resistance like mercerizing. Ammoniating increases lustre, dimensional stability and affinity for dyes. The improved hand, which increases after two or more launderings, contributes toward wrinkle-shedding ability (Corbman, 1985:163).

Fibres that retain their smooth appearance, are more absorptive and therefore more comfortable. They have better heat resistance and will not be quickly degraded by a hot iron. They are non-pilling, do not readily snag and have good dimensional stability and shape retention, have a pleasing lustre and dye well. Ammonizing decreases stiffness in fibre (Corbman, 1985:164; Hatch, 1993:407).

The major problem is safe handling of a chemical that boils at -33°C which forms explosive mixtures with air. It produces severe contact burns and gives off a vapour with extremely pungent (unpleasant) smell. Nevertheless, the process is now considered to be safe and simpler than mercerisation (Hatch, 1993:407).

2.4.4 Dyeability

Dyeing is the process of adding dyes and pigments which are commonly referred to as colourants to the fibres, yarn and fabrics (Hatch, 1993:443). Dyeability is an important performance property of appearance retention. The wise consumer considers in addition to other qualities the element of colour. Dyeability is the textile's receptivity to colouration by dyes and dye affinity.

When a dye colours a fabric directly with one operation of impregnation, without the aid of an affixing agent, the dye is said to be a direct dye for that fibre. Direct dyes are the easiest to produce, the simplest to apply and the cheapest in their initial cost as well as in application limitation – the degree of colourfastness. Direct dyes are water soluble and suitable for a large range of cellulosic textile fibres and products, where high wet fastness is not so essential (Corbman, 1985:201; Needle, 1981:73-77).

Cellulosic fibres have reactive groups which can be attached to the dye as an auxochrome. Cellulosic fibre can be successfully dyed with reactive dyes because reactive dyes form bonds with fibres. The chemical bonds are much stronger than physical attraction, so these dyes are essentially permanent. Reactive dyes were originally developed for use with the cellulosic fibres. They exhibit a good to excellent colourfastness. However they may be damaged by chlorine bleaches and perspiration. Fabric colourfastness refers to its ability to retain its original colour. Dyes that are fast for the purpose for which the fabric is intended are termed fast dyes (Smith & Block, 1982:340, 341).

The fibres of uneven thickness dye somehow unevenly and this fact gives them a natural look of quality. They can be laundered or dry-cleaned, depending upon the dyes used. In general a fabric exhibits acceptable colour fastness toward one destructive agent such as perspiration or chlorine water (bleaches used in laundering or chlorine added in swimming pool water). Natural fibres usually have some natural colour (Hatch, 1993:50; Wynne, 1997:22).

2.4.5 Softening

Handle and performance are central to fabric importance and use. In their quest for the comfort, consumers are more and more attentive to the feel of cloths. Finishing techniques are proving to be increasingly valuable weapons in the marketing of quality fabric collections, adding value and variety (Ishida, 1979: xxv).

In the raw state all native fibres are associated with some oily, fatty or wax substances whose main function appears to be protective. With the exception of silk, the fibres become harsher when the fatty matter is removed and indeed it is very difficult to spin fibres from which all the wax or grease is removed. Softness and suppleness are frequently required in textiles and therefore attempts have been made to add softness to material which has been deprived of its natural lubricant. Softeners therefore, may be applied to impart softness, smoothness, fullness, suppleness and flexibility in them or to modify other finishing materials such as starch (Cook, 1984:306; Cray *et al.,* 1996:33).

2.5 FACTORS AFFECTING SPINNING OF FIBRES INTO A YARN

2.5.1 Lignocelluloses

Plant lignocelluloses adhering to fibres after retting, cause delays in spinning and weaving, reduce the quality rating of the finished products, and may damage machines used in processing methods used to prepare fibres for spinning and weaving. It is ideal that the shive is completely removed from the fibre so that the fibre can be successfully spun into a yarn. The shive will only be completely separated from the fibre, if it is adequately degraded (Easson & Molloy, 1996:237).

2.5.2 Degumming

Degumming process includes both chemical and mechanical techniques used for further purification of cellulosic fibres (Carter, 1971:28). Inadequate degradation of non-fibrous matter may result in fibres consisting of pectin and hemi-cellulose. Hence it is necessary to degum fibres for meeting the requirements of textiles, through the use of hot alkaline (12-20% NaOH solution) with or without pressure. In addition to high energy consumption this process also results in serious environmental pollution. The degumming with microbes and their enzymes is a likely means to solve this problem (Easson & Molloy, 1996:237; Kashyp *et al.,* 2001:227). Kashyp *et al.,* (2001:14) believe that it is necessary to degum structural fibres like ramie of which after decortications contain 20-35% gum and consist mainly of pectin and hemi-celluloses in order to meet the requirements of textiles.

2.5.3 Cohesiveness

A fibre must have good spinnable properties if it is to have commercial value. Spinnability is usually defined as the ability of the fibre to cling so that they can be made into yarn (Lyle, 1977:27). *Agave* fibres are uneven and rigid therefore possess very low cohesion, which is necessary for textile fibres to cling together in a mass. It is assumed that a low degree of frictional resistance contributes greatly in low cohesive behaviour of fibres. However, their non-uniform surface structure on the other hand is expected to improve the fibre cohesiveness and thus increase spinnability (Labarthe, 1975:11; Lyle, 1976:17). Reddy and Yang, (2005:26) believe that convolutions along the length of a fibre especially in natural fibres increase the cohesiveness and surface contact between fibres that is helpful during the processing of the fibres, especially during spinning.

Without adequate cohesiveness, it would be impossible to convert fibres into yarns and yarns into fabrics. Cohesiveness of the fibre may be due to the shape and contour of the individual fibres or the nature of the surface of the fibre. However, long filament fibres by virtue of their length can be twisted together to give stability without true cohesiveness between fibres (Labarthe, 1975:11; Lyle, 1976:17).

The well prepared fibres are twisted together to form a yarn. This is referred to as spinning. Spinning is essentially a simple operation of two steps carried out almost simultaneously. They consist of drawing fibres out of a mass and twisting them into a continuous rope (Cowan & Jangerman, 1969:118). It is absolutely necessary that the raw materials of short fibres are such that they can be spun properly. It can be influenced by the fineness, length, curliness, clinging quality and surface friction coefficient. (Nakamura, 2000:11). Fibres are processed into yarns by means of spinning for spun yarns or twisting for filament yarn. The fabrics are formed by these yarns (Ishida 1979:114; Wingate & Mohler, 1984:269).

2.6 FACTORS AFFECTING THE USE OF FIBRES

The popularity and utilisation of an individual fibre largely depends on its practical significance. Availability, adaptability and versatility determine along with fibre properties the use, value and cost of a fibre (Cook 1984: xvi; Labarthe, 1964:15).

2.6.1 Availability

For a textile fibre to be really important and useful it must be available in large quantities and be reasonably cheap (Corbman, 1985:4; Hall, 1969:79). The initial cost of a fibre depends on its availability in relation to demands. Natural fibres are agricultural products which need the use of land and labour for their production and collection. In highly developed countries land and labour are costly. Production must be good for efficient economic production. The scientific methods used to ensure this, usually produce fibres which are reasonably uniform in quality. If wide demand can be adequately matched with competing production sources, the basic cost of the fibre will be low. If production is inadequately matched to demands due to problems of land, location, transport, labour, climate or artificial restrictions, then the basic cost of the fibre will be high (Cook, 1984:xvi; Labarthe, 1964:15).

2.6.2 Adaptability to processing

The conversion of fibres to yarns and fabrics is a well organised industry in which for majority of textiles, machines are used at every processing stage. Hand production is generally very slow, expensive and limited to textiles which are of high aesthetic and artistic value and therefore not suitable for large production units (Cook, 1984: xvi; Labarthe, 1964:15).

2.6.3 Versatility

Versatility of a fibre is a measure of the extent of variety of textile structures, which can be made from it, and the variety of use and suitability of these structures (Cook, 1984: xvi; Labarthe, 1964:15).

2.7 NATURAL CELLULOSIC FIBRES

Textile fibres are of two main classes namely natural and synthetic fibres (Hongu & Philips, 1990:1; Pomeroy, 1988:15). Natural fibres refer to all fibres that occur in fibre form in nature. Cellulosic fibres have been used for centuries. They get their name from their chemical structure which is cellulose, a carbohydrate similar to starch (Baulch & Oppermann, 1994:4; Cushing, 2000:22). All plants are fibrous. The fibre bundles of plants provide strength to their stems, leaves and roots. Plants provide natural cellulosic textile fibres. They can be classified according to the part of the plant from which they are derived. For example:

- Seed fibres: cotton, kapok, coir
- Bast fibres: flax, ramie, hemp, jute
- Leaf fibres: abaca, henequen, *Agave sisalana*, *Agave americana*

These fibres differ in physical structure but are alike in chemical composition. The arrangement of the molecular chains in fibres, although similar, varies in orientation and length therefore the performance characteristics related to polymer orientation and length will differ. The fabrics from these fibres will thus have different appearance and hand but will react to chemicals in essentially the same way and will require essentially the same care. Cellulose is the raw material for several commercially important derivatives (Hart, 1987:374; Hollen *et al.,* 1988:36; Stout, 1970:41, 43).

2.7.1 Chemical structure and molecular arrangements of cellulosic fibre

The most abundant polysaccharide in plants is cellulose, which is also a very essential textile polymer. Cellulose fibres having considerable physical strength are built up from these fibrils wound spirally in opposite directions around a central axis (Anderson & Beardall, 1991:17; Hart, 1987:374). The presence of binding non-cellulosic substances such as lignin, pectin and hemicelluloses give fibres a rough and irregular surface (Reddy & Yang, 2005:25).

Cellulose is a solid inert substance that is a part of plants. It is the polymer made up from only one kind of monomer residue (ß – D-glucose as illustrated in Figure 2.1) and therefore referred to as homopolysaccharide (homopolymer). Cellulose is a linear homopolymer of the class called glucan, the polymer of D-glucose but the sugar residues are connected by ß (1-4) glycosidic linkages. Two glucose units combine first to form cellobiose; then many cellobiose units combine to form cellulose. Covalent links between the glucose monomers in cellulose are identical and formed by removing a water molecule between the adjoining molecules, leaving glucose residues, forming cellobiose (Anderson & Beardall, 1991:18; Lomax, 1987:76-79; Mathews & van Holder, 1966:299; Merkel, 1991:374).

It is a linear polymer built by combining several thousand anhydroglucose units. These linear molecules containing an average of 5 000 glucose units, aggregate to give fibrils bound together by hydrogen bonds between hydroxyls on adjacent chains. The chemical structure of cellulose is very important in determining the properties of cellulosic fibres. Plant fibres are organic and so are cellulosic fibres, so they contain carbon (C), hydrogen (H) and oxygen (O) with chemically reactive hydroxyl groups (–OH) (Anderson & Beardall, 1991:19; Kadolph & Langford, 2002:38).

This group may undergo substitution reactions in procedures to modify the cellulose fibres or in the application of some finishes and dyestuffs. Substitution occurs when one or more hydroxyl units are removed and other ions or radicals, atoms or groups of atoms attach themselves to the carbon atoms. Modification can occur when the hydrogen of a hydroxyl group is removed by chemical action and other elements or compounds hook to the remaining oxygen (Anderson & Beardall, 1991:16; Chapman, 1974:59; Hatch, 1993:101; Mathews & Van Holde 1996:297, 298, 302; Smith & Block, 1982:73).

Each glucose residue retains three hydroxyl groups which are responsible for several important properties of cellulose fibres, yarns and fabrics. The plurality of hydroxyl groups confers a high degree of intermolecular hydrogen bonding. As a result, cellulose fibres possess good mechanical properties and are heat resistant to the extent that they char and decompose before the melting point is reached (Anderson & Beardall, 1991:18-19; Hatch, 1993:101; Mathews & Van Holde, 1996:297, 298, 302; Smith & Block, 1982:73).

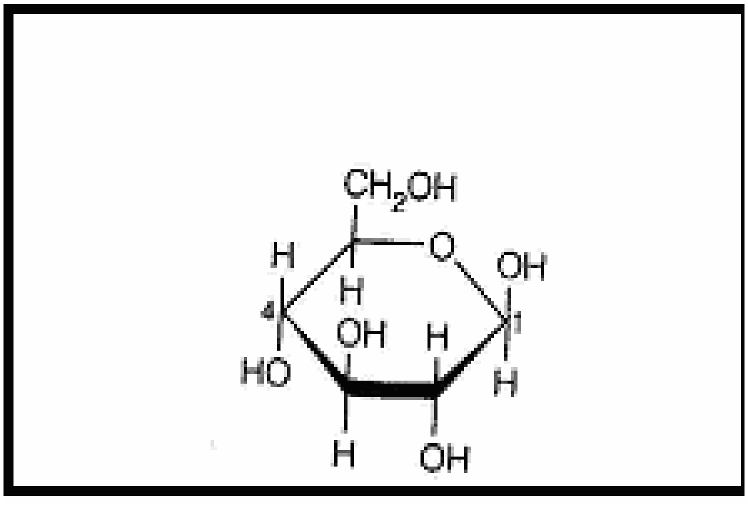


Figure 2.1 Glucose ß – D glucopyranose in hexose rings (Mathews & van Holde, 1996:297)

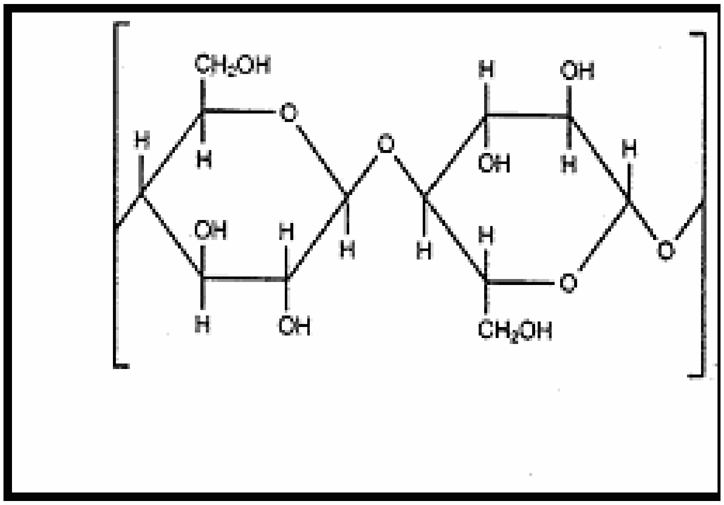


Figure 2.2 **Cellobiose ß – D glucopyranosyl (1 -4) ß – D glucopyranose, the repeat units of cellulose (**Kadolph & Langford, 2002:38)

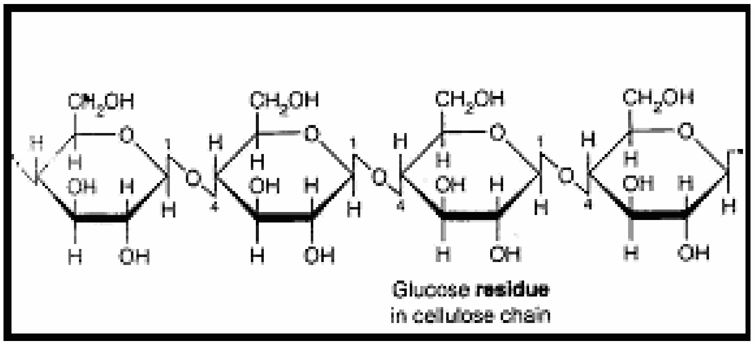


Figure 2.3 **Cellulose ß –D glucopyranosyl ß –D (1-4) glucopyranose** (Mathews & van Holde, 1996:297)

Cellobiose is therefore an oligosaccharide: dimmer of D–glucopyranose. The cellobiose repeat unit is composed of two beta- glucose monomer units linked by an oxygen atom as shown in Figure 2.2. Many cellobiose units combine to form celluloses indicated in Figure 2.3. The regular repeat of cellulose structure results into ordered, crystalline regions that grant natural vegetable fibres strength. It is a high molecular weight polymer, the basic unit of which is cellobiose, the repeating unit of cellulose (Hart, 1987:268; Hatch, 1993:101; Mathews & Van Holde, 1996:297, 298, 302; Smith & Block, 1982:73).

The bonding together of monomers to form a polymer is termed polymerisation (Lomax, 1987:76). Each monomer has a site that is capable of reacting with the second monomer to form a covalent bond. A polymer chain is extended only when two monomer molecules collide at their reactive. The cellulose molecule is made of a number of chemically-linked unit's sites (Hatch, 1993:98).

Each individual cellulose unit is chemically similar to starch, but the difference is in the way in which the glucose units are linked. They are connected by ß (1-4) linkage, which makes the entire polymer insoluble in water. This difference may seem small but it results in major effects on the shape of the molecule. Cellulose is chemically symbolised as formula $(C_6H_{10}O_6)$ n (Gangopadhyay & Ghosh, 2000:1597-1598; Mathews & Van Holde, 1996:302; Smith & Block, 1982:73; Wingate & Mohler, 1984:230).

Cellulose can exist as complete extended chains with each monomer residue flipped by 180° with respect to each other. This structure allows the long molecule (micro fibrils) to be pack together in neat parallel rows with the hydrogen bonds within and between them. (Mathews & Van Holde, 1996:302; Smith & Block, 1982:73; Young & Rowell, 1986:101).

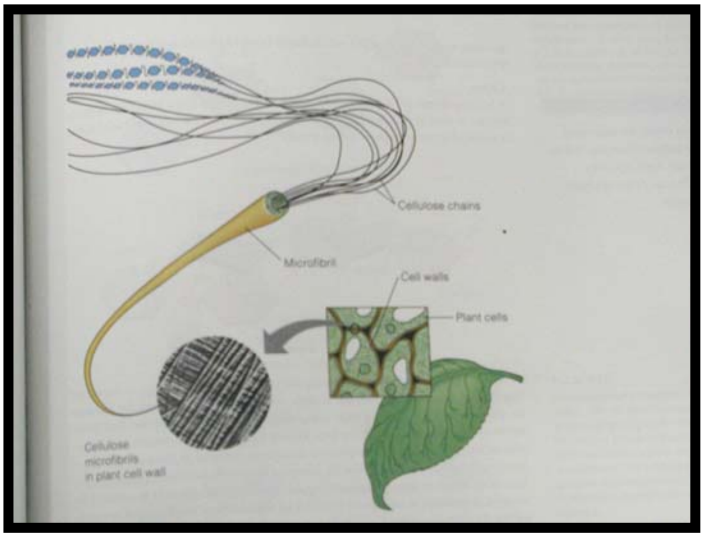


Figure 2:4 Glucose molecules form protofibrils - microfibrils - fibrils - fibres in the leaf (Mathews & van Holde, 1996:303)

Plant fibres are chiefly composed of cellulose micro-fibrils which are embedded in a matrix of other polysaccharides and in some tissues, of non-sugar compounds (Figure 2.4), such as lignin and hemicelluloses, extraneous and mineral constituents, which are concentrated in the space between the micro-fibrils. The chemical nature of each polysaccharide varies from tissue to tissue and from species to species but physically they fall into four classes:

- Unbranched straight chains such as (1-4); linked as xylan or mannan
- Branched chains such as xyloglucan or galactoglucomannan, also (1-4); linked
- Chains of sugar residue that are (1-3); linked and therefore helical.

Chains of pectin, the methyl ester of pectic acid containing galacturonic and residues interrupted by occasional rhamnose residues exist in the fibres (Young & Rowell, 1986:7) Cellulose is the most abundant of all other substances. The fibrils of the cellulose have great mechanical strength but limited extensibility (Anderson & Beardall, 1991:275; Reese, 1963:3).

Cellulosic fibres may be of crystalline material which imparts great strength and rigidity. The ability of a fibre to withstand tensile-, crushing- and bending forces is due to difficulty of forcing molecules within crystals out of their positions. A high level of crystallinity will yield a strong, inflexible fibre with little stretch. In addition, highly crystalline fibres are more resistant to penetration by foreign matter that can cause stains than are more amorphous fibres (Reddy & Yang, 2005; Smith & Block, 1982:56-57).

Maximum level of crystallinity that is achievable in a fibre is dependent upon the chemical nature of the polymer from which the fibre is made and the rate at which the fibre is produced (Smith & Block, 1982:57). Cellulose fibres which are rigid have a high degree of attraction between polymer molecules and form crystals. They are therefore oriented and crystalline and therefore strong and stiff. However oxidation, weathering or other processes, degrade and destroy the -C-O-C- linkages by converting cellulose into sugar which provides food for plants and animals (Kadolph & Langford, 2002:21; Lomax, 1987:78).

According to Carter, (1972:28) sisal and other minor fibres contain 70-76% cellulose with varying quantities of hemicelluloses, pectin and lignin. In addition, the cellulosic fibres contain minor constituents such as fats, waxes, inorganic (mineral) matter, nitrogenous matter and traces of pigments like ß – carotene and xanthophylls. The amount of these associated substances and the ease with which the cellulose fibre can be separated from them determines how useful any vegetable fibre can be as a textile material (Cook, 1988:3; Reese, 1963:5).

The less pure or coarser sources of cellulose are used for non-apparel textiles such as matting, sacks, ropes, cordage and upholstery stuffing or are treated as a raw material for manufacture of man-made cellulosic fibres and cellulose derivatives. Some of these coarse vegetable fibres such as flax, ramie, jute hemp, sisal, kapok and coir which are obtained from the stems, leaves and seed hairs of various plants are of particular importance in the economy of a number of less developed countries (Lomax, 1987:78).

According to Howard, (1981:28) *Agave* fibres are mainly composed of the following chemical constituents:

- Cellulose which ranges between 66-72%
- Lignin 10-14%
- Hemicellulose 12%
- Moisture 10%

- As stated earlier, the cellulose micro fibrils are naturally embedded in a matrix of other polysaccharides and in some tissues of non-sugar compounds such as lignin in wood and in phloem sclerenchyma and cutin and suberin in the outer wall of the epidermis (Reddy & Young, 2005:25).

A number of studies of fibre composition and morphology have found that cellulose content and micro fibril angle tend to control the mechanical properties of cellulosic fibres (Young & Rowell, 1986:7). Hemicelluloses hold water well and bind mineral cations (Raj, 1997:483). Lignin may be defined as a system of tri-dimensional polymers, which permeates membranous polysaccharides and the spaces between the cells, thereby strengthening them. This system is distinct from extractives (soluble in neutral solvents), proteineous materials, inorganic components and polysaccharides (Pearl, 1967:2). Lignin is abundant in terms of weight. It is probably second only to cellulose among renewable organic materials and in terms of energy content it might well be the single most abundant. Lignin comprises 17 to 33% of wood. It has a role in cementing the polysaccharide components in cells as a composite material and it has moderate decay resistance toward micro organism (Kirk *et al.,* 1980:2-3).

Leaf lignin content is expected to increase with age. It is thought to be somewhat higher at lower plant densities than in high ones. It is also thought to be highest in leaf bases and lowest at the top of the leaves (Pearl, 1967:3). Natural cellulose fibres such as abaca, coir, hemp, kenaf, ramie and sisal have very restricted apparel use because they are very stiff. These fibres are examples of the fifth requirement, which has to be overcome. Their polymers are far too well oriented which imparts stiffness to the fibres (Gohl & Vilensky, 1980:23).

2.7.2 Intrafibre or interpolymer forces of attraction

The integrity of fibres is determined by the entanglement of polymers and the forces of attraction between them. The cellulosic molecular chains are held to one another by intermolecular and intramolecular forces called hydrogen or ionic bonds and Van der Waals forces. Polymers also may be cross-linked through covalent bonding. Bonding is essential in determining many fibre properties such as tenacity, elongation, elastic recovery modulus and resilience. Stronger and more numerous bonds strengthen the fibre and lower its elongation. When bonds are broken under stress and reform while the fibre is bent, the fibre remains in the deformed state. The closer the chains are to each other, the stronger are the bonds (Hatch, 1993:95 96).

2.7.2.1 Hydrogen bonding

Hydrogen bonding is the strongest and type of dipole-dipole interaction. Dipole-dipole hydrogen bonding is the attraction of positive hydrogen atoms of one chain for negative oxygen or nitrogen atoms of an adjacent chain. In cellulosic fibres hydrogen bonds occur between hydrogen atoms that are covalently bonded to strongly electronegative oxygen atoms. Hydrogen bonds may form only when the distance is less than 0.5 nanometre between two very slightly polar but oppositely charged atoms. Hydrogen bonding occurs in crystalline regions of the fibres (Hatch, 1993:97-98).

In plant cell walls cellulose molecule also form intermolecular hydrogen bonds between the oxygen, atom of the glycosidic bond of one cellulose molecule with the C-6 hydroxyl group of another. The hydrogen bonding between cellulose molecules results in the formation of highly ordered, crystalline regions, not readily accessible to water. In higher plants about 50-70 cellulose chains (each comprising up to 5 000-10 000 glycosyl residues) lie parallel to form micro fibrils which impart great strength and rigidity and comprise the single most important structural unit of cell walls. Cellulose is very resistant to both enzyme – mediated hydrolysis and chemical attack (strong acids are required to hydrolyse it). This biological stability is due to the numerous hydrogen bonds between molecules (Anderson & Beardall, 1991:19).

The hydrogen bonds holding together the molecular chains of cellulosic fibres are weak and when fabrics are bent or crushed, the chains move freely to new positions. When pressure removed, these weak, internal forces cannot pull the chains back to their original positions, so the textile remains creased or wrinkled. Crease can be pressed in and wrinkles can be pressed out (Kadolph & Langford, 2002:39).

2.7.2.2 Van der Waals' forces

Van der Waals' forces are extremely weak electrostatic bonds which attract neutral molecules of fibres between atoms which are physically close together. They become intrafibre forces of attraction when two or more polymers lie very close together as occur in crystalline regions of fibres (Hatch 1993:98).

Hydrogen bonding and Van der Waals'forces occur in the crystalline areas and help to make crystalline polymers stronger than amorphous polymers. This is the reason why cellulosic fibres do not stretch easily (Kadolph & Langford, 2002:21).

2.7.3 Polymerisation

Textile fibres consist of polymers. Polymer is technically a poly-molecule that is any molecule composed of more than one monomeric unit or single molecule. Monomers are the smallest molecules from which the large molecules are formed. The process of joining together the monomers is termed polymerisation. In general and in textile science particularly, polymers are the long chain molecules or macromolecules which are required to form fibres. A polymer is described, in part by its degree of polymerisation (DP) which identifies the number or monomer units joined together to each other to form the polymolecule (Corbman, 1985:4; Hall, 1969:79; Hatch, 1993:85; McIntyre, 1971:3, 12; Needles, 1981:4; Smith & Block, 1982:64).

Other important characteristics of a polymer are great strength and stability, a high degree of intramolecular force which prevents easy destruction of polymer and extremely high molecular weight. The most important chemical feature is that fibres consist of polymer-compounds consisting of very large molecules that contain recurring structural units repeated many times within each molecule. Polymers in fibrous form have a well-defined shape (Corbman, 1985:4; Hall, 1969:79; Hatch, 1993:85; McIntyre, 1971:3, 12; Needles, 1981:4; Smith & Block, 1982:64).

The degree of polymerisation of the natural fibres like cellulose is determined by nature during the growth of the plant (Wynne, 1997:35). Cellulose can be considered to be a condensation polymer formed from the glucose units. Initially, two glucose units combine to form a cellobiose molecule with the elimination of water and these polymerise further (Lomax, 1987:76, 77; Wynne, 1997:37).

2.8 LEAF FIBRES

Leaf fibres are those obtained from the leaves of the plants. Leaf fibres are known as a structural or hard-vegetable fibre group in which the fibres occur throughout the leaves of monocotyledonous plants to which they provide rigidity and serves to transport water and plant food from roots to leaves and fruits. Leaf fibres are usually associated with the vascular bundles, usually termed fibro vascular bundles. Here and there, small spiral-shaped bodies can be seen like little springs when looked under a microscope. The leaf fibres are mainly extracted by mechanical methods and the removal of the associated parenchyma cells is thus often less complete than is the case with the bast fibres (Collier, 1974:19-20; Cook, 1984:28; Howard, 1978:22; Kadolph & Langford, 2002:47; Page, 1964:98; The Textile Institute, 1975:19).

Leaf fibres are bundled into strands. These strands are strong and consist of many individual fibres held together by natural gums. Leaf fibres tend to be stiff and rather inflexible. They absorb moisture readily and are weakened by prolong steeping in salty water. Leaf fibres are of limited use. The most important leaf fibres are from the *Agave* family, the banana family, and the bromeliad family (Collier, 1974: 19-20; Cook, 1984:28; Hatch, 1993:179; Kadolph & Langford, 2002:47; Page, 1964:98; The Textile Institute, 1975:19).

There are a number of cells in a typical specimen of the leaf fibre. The fibres are straight and stiff, they are cylindrical, often striated and are broad with characteristic lattice pattern and with small pore-markings. Some cells are cushion-shaped and others are short and rectangular. The average length is about 2.5 mm with tapering ends. Lumens vary in thickness; the cell walls are thick where the lumen is thin and vice versa. The lumen is often packed with tiny granules. Most good quality leaf fibres are obtained from *Agave* or *musa* (Cook, 1984:28; Elwyn, 1963:3).

2.8.1 *Agave* plants for fibre extraction

2.8.1.1 Plant nomenclature

Agave is the genus name that identifies a group of dessert plants belonging to the monocotyledonous family called *Agaveceae*. It is the main genus in this family (Nobel, 1994:3). It is the plant genus characterised by spiny-leaves yielding various types of fibres. It is one of the wild plants, which do not need tender care. They almost take care of themselves. They grow as a rosette with fleshy, juicy leaves which store water in order to withstand periodic drought. They are among those plants which survive in all kinds of hostile environments, from hot dry desserts to snowy mountains (Nobel, 1994:3; Smith 2003:4; Sunset magazine & Sunset Books, 1967:51; The textile Institute, 1995:4).

There are several species of *Agave* (Nobel, 1994:3). The exact number of species in *Agaves* is a very controversial issue. Scientists have not come to an agreement. Mauersberger, (1954:414) says that there are more than 75 *Agave* genuses, which have been classified. Sunset magazine, (1967:54) on the other hand said that there are more than 250 species of *Agave* plant. Nobel, (1994:16) said there are 136 species of *Agave*. Silvertown and Charlesworth, (2001:298) on the other hand said that the genus is made up of about 300 species of plants and *Agave americana* is included in there.

2.8.1.2 Historical background of *Agave* plants

*Agavacea*e comprises chiefly tropical and xerophytic plants with rhizomatous rootstock (Silvertown & Charlesworth, 2001:298). The significance and utility of *Agaves* was recognised in the early 1800 century by European invaders in Mexico. Then the Europeans introduced the *Agave*-fibre industry into their colonies, including Indonesia, the Philippines and Eastern Africa. In these regions, the main specie used was sisal (*Agave sisalana*), which was also cultivated in the Caribbean Islands, in many of the Pacific Islands, Australia and especially Brazil (Flexner & Hauck, 1987:337; Gove *et al.,* 1976:68, 364; Nobel, 1994:3, 38; Smith, 2003:4; World Book, 1969 edition 1969:270-272).

Sisal (*Agave sisalana*) fibres were never popular for fibre-production in Mexico, where henequen (*Agave fourcroydes*) was the main commercial *Agave* fibre being exported during the 19th century. The *Agave* fibre was used, for agricultural products such as baling, twine for hay and sacks for cereal grains (Flexner & Hauck, 1987:337; Gove *et al.,* 1976:68, 364; Nobel, 1994:3, 38; Smith, 2003:4; World Book, 1969 edition 1969:270-272).

The ancient artefacts of clothing and tools in Mexico indicated many uses of *Agaves*. Fibres from Maguey another common name for *Agaves* from Central Mexico, were used prehistorically for weaving and may have been among the earliest fibres used in North America. In addition to remnants of *Agave* leaves in mummified faeces and guilds, Maguey fibres, more than 5 000 years old, have been found in rope, bags, mats, baskets, sandal, clothes and even papers (Nobel, 1994:29). The *Agave* plants were first classified by Clusius in 1575 as aloes, but were recognized or identified as a separate species by Linnaeus in 1748, who gave the genus the name *Agaves*. The confusion of the *Agaves* genus with aloe genus however has persisted into modern times (Flexner, & Hauck, 1987:337; Gove *et al.*, 1976:68, 364; Nobel, 1994:3; Smith, 2003:4; World Book, 1969 edition 1969:270-272).

2.8.1.3 Plant morphology and anatomy

The present-day *Agaves* are apparent homogenous genetically, for instance, all *Agaves* have prominent leaves and single vertical stems that are usually hidden by the leaves. They are characterised by greyish coloured fleshy, ridged, hard surfaced lanceolate, thick, fibrous, linear leaves growing directly out from the central stalk to form a dense rosette maturing and flowering only once in many years (up to ten and more). Commercial quality leaves are harvested for about ten years after which the production of inflorescence signals the end of the plants life (Flexner, & Hauck, 1987:337; Gove *et al,* 1976:68, 364; Hatch, 1993:179; Nobel, 1994:3, 29, 40; Smith, 2003:4; World Book, 1969 edition 1969:270-272).

The lower stalk which sometimes is termed the trunk reaches up to 6 m when the plant flowers. *Agave* leaves are usually wide at the base and 10-18 cm in breadth at the widest part, gradually tapering to a sharp point and have spines along the edges and one on the tip. The spine along the tip of an *Agave* leaf can be removed with an attached string of vascular tissue, creating a needle and a thread combination. (Flexner, & Hauck, 1987:337; Gove *et al.,* 1976:68, 364; Hatch, 1993:179; Nobel, 1994:3, 29, 40; Smith, 2003:4; World Book, 1969 edition 1969:270-272).

They can tolerate long periods without water. The drought tolerance of Agaves is largely influenced by the plants’ morphology and anatomy (Dahlgren, *et al.,* 1985:161; Flexner & Hauck, 1987:337; Gove *et al.,* 1976:68, 364; Jaques, 1975:34; Mauerbersger, 1954:392;

Milne & Milne, 1967:254; Nobel, 1994:3, 42; Nobel, 1988:28; Silvertown & Charlesworth, 2001:298).

The leaves have numerous lengthwise fibres which support the cellular tissue and vascular system of the leaf. These fibres are much, more numerous on the under sides and edges of the leaf. They are relatively strong and constitute the *Agave* fibres of commerce. Most *Agave* leaves are fairly uniformly coloured, such as greyish green (Dahlgren, *et al.,* 1985:161; Flexner & Hauck, 1987:337; Gove *et al.,* 1976:68, 364; Jaques, 1975:34; Mauerbersger, 1954:392).

Agaves flower from 4 to 15 or 20 years after planting. A central flower stalk is sent up to a height usually two to three times greater than the height of the plant and dense clusters of flowers are born on branches growing out from this stalk. The long time needed for the plants to flower gave rise to one of their common names "century plant". After flowering is completed, the parent plant dies. As the flowers begin to wither, buds appear in the axis of the flower stem. These develop into small plants with characteristic leaves and are known as bulbils. When their leaves are a few centimetres long, the bulbils become detached from the plants and fall to the ground where they take roots. New plants also grow from rhizomes sent out by the root system of the parent plant. The leaves are covered with wax (Dahlgren, *et al.,* 1985:161; Flexner & Hauck, 1987:337; Gove *et al.,* 1976:68, 364; Jaques, 1975:34; Mauerbersger, 1954:392; Nobel, 1988:28).

2.8.1.4 Plant sapogenins

A wide range of special chemical compounds can be found in the leaves of *Agaves*. Although, leaf juices from many species were used topically by Indians for relieving itching and sores, the leaf juices of other *Agaves* cause dermatitis especially when not treated. Some are still used as fish poison and an extract of Lechuguilla, was poison for arrow tips. Such toxic compounds in the leaves of *Agaves* may have evolved to repel both insects and larger herbivores. Juices pressed from some *Agaves* are used as soaps. (Nobel, 1994:42-43).

2.8.1.5 Importance of *Agave* plant

Agave plants furnish fibres. The fibres occur in bundles i.e. aggregates of individual cells with the ends over-lapping so as to produce continuous filaments through the length of the leaf (Dahlgren *et al.,* 1985:161; Rolf *et al.,* 1982:90, 102).

Medicinal and decorative functions are currently the most important functions of the plant. *Agave*s are often used for ornamentation especially *Agave americana* plant. *Agave* leaves are uniformly coloured such as greyish green but a popular horticultural variety of *Agave* is also sources of food, because the bases of the fleshy leaves and flower buds are eaten by human beings. They furnish fermented liquors like tequila from the trunk. In Mexico the *Agave* sap is used to make beverages such as Pulque and Mescal (Catling, 1990:65; Mauerbersger, 1954:391; Nobel, 1994:16-19, 41; Nobel, 1988:9).

Mescal is another common name for certain *Agave* plants and also for a distilled alcoholic beverage made from them. The leaves of *Agave* plants have recently served as food/feed for dairy cattle. The residues from the leave retting process make a useful animal feedstuff. The leaves of some *Agave* plants have been used as cattle forage and fodder in Mexico (Catling, 1990:65; Mauerbersger, 1954:391; Nobel, 1994:16-19, 41; Nobel, 1988:9).

Agave spines were used for punishing juvenile delinquents and run away slaves. *Agaves* were also planted as defence against invaders since the leaves are armed spines at the edges and have lateral leaf thorns. *Agaves* have been planted as fences or hedges to separate families and fields. The stalks of the inflorescences have been used for fencing and construction. From a more industrial point of view, *Agaves* have been used in the manufacturing of paper, including that for currency. They are also useful in the manufacturing of cleaning agents. Fermentable sugars of *Agaves* can also be used to produce ethanol for industrial purposes (Nobel, 1994:41; Nobel, 1988:9).

The beautiful geometric symmetry of *Agaves* has endeared them to plant collection worldwide. The future economic importance of *Agaves* may also be influenced by their high content of sapogenins (Nobel, 1994:41; Nobel, 1988:9). *Agave* plant is very easily cultivated and grows wild in the hedge of fields and courtyard premises (Gove *et al.,* 1976:68, 364; Jaques, 1975:34; Milne & Milne, 1967:254; Nobel 1988:10).

Nobel, (1994:16) suggested that the leaves of *Agave* last many years and so might be an ideal thatch for a roof. Necklaces are created from the flat black seed of *Agave*. Sub-simplex, face powder was formed from its cooked stem. The young inflorescence can be tapped for sugar-rich sap, which in large specimen may amount to hundred litres (Dahlgren et *al.,* 1985:161).

Dried leaves of dead *Agave* rosettes burn easily and have been used for household fires, smoke signalling over longer distances and fire associated with cattle herding. The outermost cuticle can be used for wrapping goods. It is believed that construction, utensils and textile purposes are potential functions. The most frequent uses are as fibres, fuel, construction material and medicine. Currently it is often used in the automobile industry in composite structures. Natural fibre textiles are regarded to be especially important where soil surfaces need stabilising and protecting from soil erosion. *Agave sisalana* plant, for example, is biodegradable, retains moisture and yields nutrients upon decomposition. It is also maintenance free. There is therefore the highly considerable potential for expansion of production and a market for it (Nobel, 1994: 31, 43).

The growing concern for the effective utilisation of resources in all countries is providing additional impatiens to completely use the products of this plant. Cellulosic fibres like sisal, ramie, jute, kenaf, coir and cotton have good possibilities for increasing their market shares. They are likely to increase in importance due to their low price, environment-friendly character and technical properties (Nobel, 1994:43).

2.8.1.6 Qualities of A*gave* fibres

Agave fibre is a long natural multicellular fibre produced from the leaves of the *Agave* plant. It is structural fibre which occurs in bundles - aggregates of individual cells with the ends overlapping so as to produce continuous filament through the length of the leaf. *Agave* fibres can be more or less two metres long. Each fibre consists of a number of cells, generally referred to as ultimates or ultimate cells. The overlapping ultimates are held together with a waxy film to form the filament fibres. This implies that an individual fibre is made up of a complete vascular bundle or group of vascular bundles. The vascular bundle consists of transportation tissue vessels surrounded by a thick sheave of fibres cells. Each ultimate is polygonal in shape and has a lumen (Dahlgren *et al.,* 1985:161; Rolf *et al.,* 1982:90, 102).

This clarifies the point that *Agave* fibres in a leaf consist of both xylem and phloem and various ensheafing cells found scattered through a leaf pithy matrix. The cells are lignified to a greater or lesser degree and are hard in comparison with soft fibres found in dicots in which the cellulose is largely associated with pectic materials. The entire fibro-vascular bundle serves as a unit fibre. Hard fibres are usually separated by being mechanically scraped free of the pithy matrix through which they are scattered (Neyn 1954:204). Raphide bundle is an elongated cell of *Agav*e (Dahlgren *et al.,* 1985:161; Rolf *et al.,* 1982:90, 102). The width of *Agave* fibres varies several times along the length. The width of *Agave* fibres therefore depends on how many ultimates are in the cross section (Hatch, 1993:74).

The fibres are strong, hard, coarse and relatively inflexible. *Agave* fibres are smooth, straight and white to yellow and are degraded by salt water. The fibres are long and tough. *Agave* fibres have a dry and crispy hand. They are mostly used for ropes and cords as they are usually too coarse and harsh to make good cloth (Hatch, 1993:179; Nakamura, 2000:26; Rolf *et al.,* 1982:90; Smith & Block, 1982:67).

Agave fibres are very strong and are usually used for better grade ropes, twines, nets, sacks, furniture webbing, mats, cushion stuffing, upholstery padding, saddle pads, carpets, blankets, baskets, bracelets, headbands, sandals, clothing and other woven objects. Armour, brush brittles, fish stringers, musical instruments, ceremonial objects and most recently, construction material, paper pulp, and dart board, papers also have been made from the fibres in the tender inner leaves of certain *Agaves*. They are also useful in the manufacturing of matting, rough hand bags and carpeting (Hatch, 1993:179; Nobel, 1994:38).

The fibre may be expected to have a high density. The fibres are straight and difficult to extend. This means *Agave* fibre is rigid and has low elongation. *Agave* fibres vary greatly with grade and within the same leaf (Cowan & Jangerman, 1969:64; Smith & Block, 1982:67).

2.8.1.6.1 Types of fibres in *Agave sisalana* leaves

Agave sisalana leaves have three types of fibres:

- Mechanical fibres
- Ribbon fibres
- Xylem fibres (Yan Li *et al.,* 2000:2037-2050)

The mechanical fibres are mostly extracted from the periphery of the leaf. They have a roughly thickened horseshoe shape and seldom divide during the extraction processes. They are the most commonly used of the *Agave* fibres. Ribbon fibres occur in association with the conducting tissue in the median line of the leaf. The related conducting tissue structure of the ribbon fibres gives them considerable mechanical strength. They are the longest fibres and when compared to mechanical fibres, they can be easily split longitudinally during processing. Xylem fibres have an irregular shape and occur opposite the ribbon fibres, through the connection of vascular bundles (Yan Li *et al.,* 2000:2037-2050).

There are also three distinct types of tissues in a plant from which the types of fibres are found. Plant phloem (the zone of smaller and darker cells) is the tissue through which the essential mineral salts extracted from the soil pass up to the leaves and flowers. This is where the mechanical fibres are derived. Xylem tissue is composed of very large cells whose walls are composed of a modified form of cellulose known as ligno-cellulose or wood cellulose. The function of these cells is to give strength to the leaves and to conduct water up from the roots. Xylem fibres are obtained in this region. Between the phloem and the xylem is an actively growing tissue known as the cambium. The ribbon fibres grow within this region (Easson & Molloy, 1996:236; Yan Li *et al.,* 2000:2037-2050). *Agave americana* fibres are expected to have the same structure

2.9 PERFORMANCE ATTRIBUTES AND PROPERTIES OF TEXTILE FIBRES

The selection criteria for textile products mainly depend on the following performance attributes: aesthetics, comfort, appearance retention, care and maintenance, durability, and environmental impact. The importance of performance attributes depends entirely on the purpose of the textile product. Although performance attributes provide valuable information about the requirements or needs, which may be fulfilled by textiles, they are difficult to quantify or measure (Smith & Block, 1982:19, 21).

Each performance attribute can be clarified by considering specific performance properties. Performance properties are the specific properties of the product, which are believed to relate to serviceability. Laboratory tests are actually used to check or verify the identity of a product, to determine its nature or construction and to describe it. It is therefore important to evaluate the expected performance of *Agave americana* fibres, in order to judge its performance characteristics (Hatch 1993:4; Merkel, 1991:14).

2.9.1 Essential properties of a textile fibre

Fibre properties are determined by the nature of the physical structure, the chemical composition and molecular arrangement. There are several basic properties of a polymeric material to make an adequate fibre, such as fibre length-to-width ratio, fibre strength and flexibility, fibre extensibility and elasticity and fibre cohesiveness or spinning qualities. For a fibre to be suitable for textile purposes certain qualities are desirable, others are essential. The commercial value of any fibre depends largely on the extent to which it possesses certain properties. (Corbman, 1985:4; Hall, 1969:79; Hatch, 1993:85; McIntyre, 1971:3; Needles, 1981:4; Smith & Block, 1982:64).

Not all fibres are suitable for textile purposes because the primary properties are essential for a textile fibre to be suitable for manufacture into fabric. The useful fibres are characterized by a high length - to diameter ratio, spinning quality, fineness, strength and flexibility (Miller, 1992:10; Smith & Block, 198:69).

2.9.1.1 Fibre length to width ratio

The length of fibre has the effect on the appearance of the yarn into which it is constituted. Filament fibres can be made into yarns with little or no twisting (Tortora, 1978:12). The length of individual fibre is usually expressed in millimeters while the fineness is expressed as a diametre in micrometer units or as a linear density. It reflects the average width along the fibre length. In natural fibres the diametre usually varies from one part of the fibre to another because of irregularities in fibre size. Fineness in natural fibres is often an important aspect of quality. In general, thinner fibres are of higher quality because they are softer, more pliable and have better drapability. Clothing fibres are made in relatively small diameters whereas heavy-duty fibres are for household items or industrial uses made with larger diameters (Hatch, 1993:91; Tortora, 1978:12, 14; Wynne, 1997:15).

Fibres intended for textile use have to exceed a minimum length of about 10 mm to enable them to be processed satisfactorily. Reddy and Yang, (2005:25) said that sisal fibre length ranges between 40 and 100 cm and its ultimate cell length ranges from 0.8-8 mm with the width of 7-47 micrometre. The use of finer fibres produces better uniformity, in yarn in terms of appearance and strength (Morris 1989:8). Fibrous materials must have sufficient length so that they can be twisted into yarns. In addition, the width of the fibre must be much less than the overall length of the fibre and usually the fibre diameter to length should be 1:100 (Cook, 1984: xv; Gohl & Vilensky, 1983:31; Thomson, 1974:9).

2.9.1.2 Durability of a textile fibre

Strength is the ability of textile to withstand the mechanical forces that are encountered for a reasonable period of time (Hatch, 1993:15). Three types of textile strength are breaking, tearing and bursting. Breaking (tensile) strength is the ability of textile to withstand a longitudinal pulling force (a load applied that can cause the textile to break) (Catling, 1985:69; Hatch, 1993:16).

Tensile strength is regarded to be one of the most important textile properties because it provides a comprehensive check of most features of textile product composition and finishing. The tensile strength of a single fibre is called the tenacity, defined as force per unit linear density necessary to break a known unit of that fibre. The breaking tenacity is measured in gram per denier or gram per tex or Newton per tex (1 g per denier, 9 g per tex or Newton per tex). Denier is the mass in gram of 9000 m yarn; tex is the mass in gram of 1000 m (Wynne, 1997:15; Cook, 1984: xvi; McIntyre, 1971:3). Denier is used for filaments while tex is the internationally accepted standard for all yarns and fibres (Kadolph & Longford, 2002:159). The strength of a fibre can be expressed in terms of force per unit area and when expressed in this way the term is tensile strength (Cook, 1984: xvi; Hatch, 1994:41; Needles, 1981:5; Smith & Block, 1982:65).

Tearing strength is the ability of a fabric to resist further rip apart when a sideway-pulling force is applied at a cut or hole in the fabric. Bursting strength of a textile is its ability to maintain physical integrity when subjected to a distending or swelling force; a force applied vertical to the fabric surface (Hatch, 1993:17-18). The strength of a textile article is a crucial property on which its ability to continue to function satisfactorily often depends. A fibre must possess adequate strength to be processed into a textile fabric. In order to fabricate into a textile article, the resulting textile must have sufficient strength to provide adequate durability during end use a durable textile product should last an adequate period of time for its end use (Hollen *et al.,* 1988:12).

A textile which is not durable enough is of little value even if it has other performance attributes (Hatch, 1993:14, 15; Hollen, *et al.,* 1988:12; Nakamura, 2000:8). Many experts consider single fibre strength of 1.0 grams per denier to be necessary for a fibre suitable for textile applications (Cook, 1984: xvi; Marsh, 1947:2; McIntyre, 1971:3; Needles, 1981:5; Slater, 1993:36, 37). Smith and Block, (1982:65) say that fibre tenacity ranges from one g/denier for weak fibres like wool and ten for strong fibres such as glass and aramid. Apparel fibres range from 1 to 7 g/denier. Carpet fibres range in denier; from 15 to 24 g/denier (Hollen *et al.,* 1988:7).

Cellulosic fibres are generally strong and stronger when wet. This may be due to the fact that the polymer in the fibres lie almost parallel to the fibre axis and when a pulling force is applied each polymer takes its share of stress. Cellulosic fibres have high moisture absorption which increases tenacity, modulus and elongation at break and decreases fibre stiffness. They swell in water but are dimensionally stable because they return to their original dimensions as they dry (Hatch, 1993:87, 174).

Strength is an important property for natural fibres, since it can vary from source to source and is heavily dependent on causes such as nutritional or climatic factors that may often be outside human control. Natural cellulosics are the only fibres that increase in tensile strength when wet. The concepts of strength, elongation, elasticity, abrasion resistance and flexibility are of importance to evaluate the durability of fibres. The fine understanding of these performance properties is required to evaluate the durability (Hatch, 1993:15; 16; Slater, 1993:51; Wynne, 1997:22).

- **Abrasion resistance Abrasion** is the wearing away of any part of material by rubbing against another surface. Abrasion resistance is the ability of a fabric to reasonably withstand the rubbing it gets during use and care (Kadolph & Langford, 2002:24). Textile fabrics with excellent abrasion resistance retain their physical integrity. Fabrics with poor abrasion resistance become thin and/or develop holes. Bast and leaf fibres usually have high density and good abrasion resistance because they consist of a number of fibre cells. Heavy textiles are usually more abrasion resistant than thinner ones. Moreover, they are the natural fibres with high molecular orientation and crystallinity. In general, cellulose fibres do have high abrasion resistance and therefore can be expected to have high durability (Hatch, 1993:21; Kadolph & Langford, 2002:39; Merkel, 1991:195; Smith & Block, 1982:313).

Forms of abrasion

- **Flat abrasion**

Flat abrasion occurs when two flat surfaces rub against one another (Merkel, 1991:195). Fibre with high orientation and crystallinity has good flat abrasion resistance (Kadolph & Langford, 2002:44).

- **Flex abrasion**

Flex abrasion is the wear that occurs when a material is bent and straightened, folded and unfolded (Merkel, 1991:197).

- **Edge abrasion**

Edge abrasion occurs along the edge of textile products, which are subjected to great pressure (Merkel, 1991:197).

- **Elasticity**

Elasticity or elastic recovery is the ability of a textile to return to its original dimensions after being stressed or elongated. The more fully a textile can recover from an applied stress, the more likely it will withstand the next stress it encounters. It is measured as the percentage of return to original length. The fibre must be able to almost completely recover from slight fibre deformation. For most uses it is desirable that a textiles article should maintain its size and shape in use and laundering for example, such as clothing. It is essential that any change should be quite small, even after many launderings. A fabric that is dimensionally stable to satisfactory limits can be produced from any fibre in construction. Dimensional stability can either occur in produce as shrinkage degree or stretch (Hatch, 1993:4, 20; Hollen *et al.,* 1988:12-14; Kadolph & Langford, 2002:27, 34; Taylor, 1985:27).

Cellulosic fibres have low resiliency, have no significant elasticity and therefore lack loft; pack well in compact yarns. Fabrics wrinkle badly unless finished for wrinkle recovery. Crease recovery is another aspect of the group of properties which may be classed as appearance retention (Hatch, 1993:4, 20; Hollen *et al.,* 1988:12-14; Kadolph & Langford, 2002:27, 34; Taylor, 1985:27).

- **Fibre elongation**

Elongation is the ability of a textile to extend when subjected to mechanical forces particularly pulling, tearing and bursting forces without breaking it. Elongation therefore refers to the degree to which a fibre may be stretched without breaking rather absorbing the forces attempting to rupture it. An individual fibre must be able to undergo slight extensions of 1-5% in length without breakage of the fibre. In other words, the extension or deformation of the fibre must be nearly elastic. These are often subjected to sudden stress and the textile must be able to give and recover without significant overall deformation of the textiles (Hall, 1969:79; Marsh, 1947:2; McIntyre, 1971:3; Needles, 1981:6; Smith & Block, 1982:65; Thomson, 1974:9).

According to Hatch, 1993:44, fabrics with ≥ 15% elongation are referred to as stretch fabrics, whereas fabrics with ≤ 15% elongation are rigid fabrics. Cellulose fibres have low elongation (Hatch, 1993:19; Kadolph & Langford, 2002:39,44) describe flax as a fibre with very low elongation of approximately 7% and poor elasticity with 65% recovery at an elongation of 2%.

2.9.1.3 Flexibility versus flexural rigidity

Flexibility is perhaps the most important single component of hand and highly relevant to comfort (Merkel, 1991:375). Fibre must be sufficiently flexible to go through repeated bending without significant strength deterioration or breakage. Without adequate flexibility, it would be impossible to convert fibres into yarns and fabrics, since flexing and bending of an individual fibre is a necessary part of this conversion. Fabrics made from fibres of limited flexibility do not drape well and they are not comfortable for apparel. (Ajayi, 1992:52; Cook, 1984:xvi; Hall, 1969:79; Marsh, 1947:2; McIntyre, 1971:3; Needles, 1981:5; Smith & Block, 1982:64; Thomson ,1974:9; Tortora, 1978:11).

Moreover, the fibre must bend or flex often without breaking or splitting. In many end products the textiles are subjected to manipulation that causes them to bend or fold. Textiles with low or no flexibility like stiff coarse textiles can be useful if it is not allowed to bent or twist. The rigidity or flexibility of fibres depends partly on the stiffness of polymers and their degree of orientation and crystallinity. As the degree of crystallinity increases, flexibility tends to decrease and the fibre becomes rigid (Ajayi, 1992:52; Cook, 1984: xvi; Hall, 1969:79; Marsh, 1947:2; McIntyre, 1971:3; Needles, 1981:5; Smith & Block, 1982:64; Thomson, 1974:9; Tortora, 1978:11).

2.9.1.4 Relationship between fibre diameter and flexural rigidity

Fibre diameter has a much greater influence than type of fibre on flexural rigidity. Cross-sectional shape also influences the flexural rigidity of a fibre. Round and "I" shaped fibres have higher values of stiffness than flat fibres. The flexural rigidities of fibres with other cross-sectional shapes lie between these extremes. The ability of a molecule to fold is clearly dependent upon its flexibility and hence chemical structure (Hatch, 1993:114; Lomax, 1987:78).

Some very stiff molecules can be conceived which would not fold or fold only with difficulty and these may be expected to crystallise in an extended molecular conformation-like rods. Stiff molecules introduce fabrication problems because the property contributes to difficulty in spinning the fibres (Chapman, 1974:21). When the flexibility is higher, rigidity is lower and the tenacity is lower. This relationship exists because both properties are linked to the degree of crystallinity. As crystallinity increases tenacity increases and flexibility decreases (Hatch, 1993:114; Lomax, 1987:78).

In their quest for comfort, consumers are more and more attentive to the feel of cloths. Finishing techniques are proving to be increasingly valuable weapons in the marketing of quality fabric collections, adding value and variety (Ishida, 1979: xxv). Stiffness is the major hindrance in the textile potential of the fibre as it becomes difficult to spin it into yarns. Natural cellulose fibres such as abaca, coir, hemp, kenaf, ramie and sisal have very restricted apparel use because they are very stiff. Their polymers are far too well oriented, which imparts stiffness to the fibres (Cook, 1984:xvi; Gohl & Vilensky, 1980:23; Hall, 1969:79; Hatch, 1993:114, 115; Marsh, 1947:2; McIntyre, 1971:3; Needles, 1981:5; Smith & Block, 1982:64; Tortora, 1978:11).

Fibre stiffness is also governed by other two features, the fibre fineness and resistance to stretch. Fine fibres are less stiff than coarse fibres. Fibres which are easier to stretch are also easier to bend. Stiffness of fibre determines the physical and mechanical behaviour and handling of textile products. In the raw state all native fibres are associated with some oily, fatty or waxy substances whose main function appears to be protective (Cook, 1984:306; Taylor, 1972:17).

With the exception of silk, the fibres become harsher when the fatty matter is removed and indeed, it is very difficult to spin fibres from which all the wax or grease is removed or absent. Softness and suppleness are frequently required in textiles and therefore attempts have been made to add softness to material which has been deprived of its natural lubricant. Softeners therefore, may be applied to impart softness, smoothness, fullness, suppleness and flexibility in them or to modify other finishing materials such as starch (Cook, 1984:306; Taylor, 1972:17).

2.9.1.5 Fibre cohesiveness

Fibres must be capable of adhering to one another when spun into a yarn. The cohesiveness of the fibre may be due to the shape and contour of the individual fibres or the nature of the surface of the fibres. However, long filament fibres by virtue of their length can be twisted together to give stability without true cohesiveness between fibres. (Cook, 1984: xv, xvi; Corbman, 1985:4; Hall, 1969:79, Marsh, 1947:2; McIntyre, 1971:3; Needles, 1981:6). A fibre that offers little frictional resistance to motion across its surface and possesses a low coefficient of friction is described as a smooth textile fibre (Ajayi, 1992:52).

2.9.2 Secondary properties of a textile fibre

Fibre properties other than the above mentioned primary properties are secondary properties which increase its value and desirability in intended use rather than being needed to make it a textile. Some secondary properties contribute to making an end product with superior characteristics while others may detract from a textile product end use. The secondary properties of fibres include physical shape, specific gravity, lustre, moisture regain, resilience, thermal behaviour, resistance to biological organisms and resistance to chemical and other environmental conditions (Cook, 1984:xxiv; Corbman, 1985:4; Gohl & Vilensky, 1983:39; Hall, 1969:79; Hollen, *et al.,* 1988:6, 7; Marsh, 1947:2; Needles, 1981:4; Smith & Block, 1982:64).

2.9.2.1 Aesthetic properties

A textile product should be attractive and appropriate for its purpose (Hollen, *el al.,* 1988:9). A textile that pleases the eye and hand has aesthetic appeal. The aesthetic appeal is often the most convincing reason for the selection of a textile. Aesthetic appeal deals with the appearance of the fabric and the feel of the fabric in the hand (Hatch, 1993:45, 54; Taylor, 1985:22-27). Aesthetic properties relate to the way the senses of touch and sight perceive the textile, for example natural cellulosic textiles can resist sunlight well although direct exposure to constant strong sunlight will cause yellowing and eventual degradation of the product. Fibres which have horseshoe shapes and or irregular cross-sections scatter light in all directions and can be perceived dull in appearance with few high lights (Smith & Block, 1982:21, 66).

- **Appearance**

Lustre, texture and drape are the important appearance performance properties. Appearance of the fibre can influence product aesthetic by the way it reflects light-lustre. It is observed by the eye. It may be bright if it has a smooth surface or otherwise dull if it is rough. The high lights and shading are a result of the way light is transmitted through the textile, scattered among its folds. Firmness and crispiness-texture will also affect its appearance. Texture is identified with both visual and tactile senses. Textile product may be smooth or rough to touch. Natural fibres tend to give more texture than synthetics (Corbman, 1985:201; Hollen *et al.,* 1988:12; Kadolph & Langford, 2002; Smith & Block, 1982:66).

Drape is the manner in which textile product hangs or falls over a three-dimensional form (Hatch, 1993:49). Because of high orientation and crystallinity, large fibre diameter and if not properly decorticated, monocotyledonous fibres are usually stiff in drape and harsh in handle (Kadolph & Langford, 2002:39).

- **Appearance retention**

Appearance retention is the ability of textile to remain in the similar condition of cleanliness, dimensions, physical integrity, colour and other desirable attributes as when bought or manufactured, following wear and or use, care and storage procedures, through a reasonable period of time.

Resiliency is the ability of the fabric to return to its original shape after bending, twisting or crushing. Wrinkle resistance is the property of a fabric that enables it to withstand the formation of wrinkles when subjected to folding deformation. Wrinkle recovery is the property of a fabric that enables it to recover from folding deformations; loft, crease retention and shape retention are important aspects of resilience (Hatch, 1993:3; Kadolph & Langford, 2002:28; Merkel, 1991:7).

Cellulosic fibres may have poor resiliency and lack good appearance retention property because they do not resist deformation as a result they crease and wrinkle badly. They have low resiliency because the hydrogen bonds holding the molecular chains together are weak and when fabrics are bent or crushed, particularly in the presence of moisture the chains move freely to new positions. When pressure is removed, these weak internal forces cannot pull the chains back to their original positions, so the textile stay wrinkled (Corbman, 1985:180; Kadolph & Langford, 2002:39; Lyle, 1977:123; Wingate & Mohler, 1984:269, 167).

Creases can be pressed in and wrinkles can be pressed out at cellulosic fabrics but wrinkling during use and care remain a problem, unless they are finished for crease resistance, they need frequent pressing. It is best to sprinkle the fabrics or iron them while still damp because they are more plastic and iron smoothly when damp. A crease is a fold or deformation of a fabric intentionally formed by pressing while a wrinkle is formed unintentionally by washing or wearing (Corbman, 1985:180; Kadolph & Langford, 2002:39; Lyle, 1977:123; Wingate & Mohler, 1984:269, 167).

Their low resilience and low wrinkle resistance somewhat offset their otherwise excellent qualities as a fabric for summer apparel. Deep repeated folds as in tablecloths should be avoided when using such fabrics because these creases eventually cause the otherwise strong yarns to crack and break long before they ordinarily would (Corbman, 1985:263; Hatch, 1993:87; Smith & Block, 1982:306).

2.9.2.2 Dimensional stability

Dimensional stability is the ability to retain a given size and shape through use and care. It includes properties of shrinkage resistance and elasticity (Kadolph & Langford, 2002:26).

Dimensional stability ensures that the garment will continue to fit comfort and aesthetics properties. For most uses it is desirable that a textile article should maintain its size and shape. For some purposes such as clothing it is essential that any change should be quite small (Taylor, 1985:27). Very low dimensional change that is below 2% is highly desirable. Maximum acceptable shrinkage of almost all fabrics ranges from 2-5% (Merkel, 1991:232; Smith & Block, 1982:304).

Shrinkage resistance is the ability of a fabric to retain its original dimensions throughout care. It is related to the fabric's reaction to moisture or heat. Items which shrink may no longer be attractive and suitable for their end use. There are three well-known forms of shrinkage: Relaxation shrinkage, progressive shrinkage and felting shrinkage (Merkel, 1991:232; Smith & Block, 1982:306).

- **Relaxation shrinkage**

Relaxation shrinkage is that shrinkage which occurs during the wet cleaning of the cloth after it has been stretched and distorted during manufacturing. It is mainly associated with fabrics made from cellulosic fibres and to a lesser extend when compared to other fibres like wool. This type of shrinkage is usually encountered in laundering but it can occur in dry-cleaning if a wet process is used. Relaxation shrinkage results from two processes: (a) The release of the temporary set due to stretching of the wet cloth and drying it in the stretched or extended state during manufacturing and general finishing and (b) The swelling of fibres in warp and weft yarns upon wetting (Smith & Block, 1982:306; Tortora, 1978:14).

- **Progressive (residual) shrinkage**

Progressive shrinkage refers to additional shrinkage which occurs upon repeated laundering or cleaning and drying of the fabric, after first care cycle. This type of shrinkage occurs in most types of fabrics except those made from animal fibres. As in relaxation shrinkage progressive shrinkage is mostly associated with cellulosic fibres and is often encountered in laundering (Kadolph & Langford, 2002:27; Smith & Block, 1982:307).

- **Felting shrinkage**

Felting shrinkage is the characteristic of fabrics made from animal hair fibres more especially wool and occurs as a result of the unique felting properties of these fibres.

Felting shrinkage occurs because the rough, scaly surface of animal hair fibres causes them to become entangled when they are washed. Felting shrinkage occurs due to the presence of heat, moisture, agitation, and soap or other cleaning agent and pressure during wringing or spin-drying which compel the fibre together (Smith & Block, 1982:307).

- **Relationship of dimensional stability to shape retention**

Dimensional stability and shape retention are both related to the ability of the fabric to retain its original size or dimension. The major difference between them is what causes the textile fabric to change dimensions. Dimensional stability generally refers to the dimensional change that can occur when a fabric is exposed to wetting, steaming or variations in humidity. Shape retention usually deals with the potential change in size of fabric that can be induced by mechanical forces (Hatch, 1993:62).

- **Colourfastness**

Fabric colourfastness refers to its ability to retain its original colour. Dyes that are fast for the purpose for which the fabric is intended are termed fast dyes. Different dyes of different colours have different degrees of fastness to various conditions. For example, a colour which may have good fastness to laundering may have poor fastness to light. Colourfastness may be affected by such factors as perspiration, dry-cleaning, bleaching, salt water, swimming pool additives, atmospheric gases or air pollutants. Also certain dyes may bleed or run when wet and may cause discolouration of other fabrics (Corbman, 1985: 201-202; Wingate & Mohler, 1984:249, 264).

Some dyes can crock or rub off due to the friction of wear. Consequently, selection of the proper dye is crucial to its ultimate use. Fastness to light is important in draperies, as they must stand strong light daily but do not need to be washed frequently. Fastness to washing is important in dress fabrics and household linens because they must undergo frequent washings. Therefore, both the kind of fibre to be dyed and intended use for the fabric should be considered. Cellulosic fibres are expected to be good in resistance of fading by perspiration (Corbman, 1985:201-202; Wingate & Mohler, 1984:249, 264).

2.9.2.3 Fibre uniformity

Fibres suitable for processing into yarns and fabrics must be fairly uniform in shape and size. Without sufficient uniformity of dimensions and properties in a given set of fibres to be twisted into yarn, the actual formation of the yarn may be impossible or resulting yarn may be weak, rough and irregular in size and shape and unsuitable for textile usage. In the rural situations which occur in most developing countries where garments are made up locally in small batches or even made up singly for individual, high standards of uniformity are not important (Catling, 1990:64; Hall, 1969:79; Marsh, 1947:2; McIntyre, 1971:3; Needles, 1981:4)

However in most modern countries the absolute conformity to very precise technical specifications, large-scale methods of production have advantage and this is important where goods are intended for mass production of garments (Catling, 1990:64; Hall, 1969:79; Marsh, 1947:2; McIntyre, 1971:3; Needles, 1981:4). Kadolph and Langford, (2002:43) when describing fabrics from bast fibres say that they have uneven thickness because fibre bundles are never completely separated into individual fibres.

2.9.2.4 Comfort

Comfort is the ability of textile to provide the body with freedom from pain and or discomfort. It is the ability to maintain a neutral state. Hatch, (1993:2, 27) believes that people are comfortable in their garments when they are not aware of them, both psychologically and physiologically. A textile product should be comfortable as it is worn or used. The comfort of a textile is also determined by how well it permits air and water vapour to pass through permeability, its feel against the skin - hand, its ability to stretch with the movement of the wearer and to return to its original shape after stretching and its thermal and electrical properties (Cray & Budden, 1996:33; Smith & Block, 1982:22).

It is believed that most people find sensation of liquid against the skin distasteful. The fabric that allows water or sweat to wick away from the skin may be perceived as relatively comfortable. Skin irritation that arises from apparel apart from allergic reaction (dermatitis) is related to fibre stiffness and denier. The coarser the fibre the more wiry it becomes (Merkel, 1991:325). The cellulosic fibres usually are comfortable because they do not generate static electricity, which is another important comfort property (Planning & Managing Projects, 1996:6.8). The following are the textile performance properties of comfort: Hand, absorbency, thermal and electrical retention, density and elongation (Hollen *et al.*, 1988:13; Kadolph, 2002:25)

- **Hand**

Hand is the manner in which a textile product feels to the skin. A textile product may be warm or cool to touch, may be bulky or thin, slick or soft (Kadolph & Langford, 2002:24). Hand is a very important part of fabric comfort. Most people prefer a soft hand especially in body- contact garments. Harsh and scratchy hand may be excellent in some furnishings but not for the apparel worn next to the skin (Merkel, 1991:5). Comfort in a garment involves a number of properties, depending on whether body contact is a factor (Merkel, 1991:5).

Softness and suppleness are also important factors and lack of these properties may make a fibre a textile failure as with horsehair, quite apart from difficulties of manufacture into thread and fabric. Softness is therefore one of the properties which are necessary to add value to a textile fibre. It is a desired property in a textile fibre. Fine fibres give softness and pliability. Softness of the fibre is determined by factors such as its surface lubricity, flexibility, compressibility and elastic recovery. Natural oils and waxes provide some degree of softness which is normally removed during fabrication processing (Burdett, 1984:45; Cray *et al.,* 1996:33; Hollen *et al.,* 1988:6; Marsh, 1947:13; Taylor, 1985).

For tapestry, upholstery and other purposes, it is an advantage that the textile fibre used shall be stiff and resilient but for garments and especially underwear, it is a good thing for a fibre to be naturally soft. In natural fibres, fineness is a major factor in determining quality. Fine fibres are considered of better a quality (Hall, 1969:83; Hollen *et al.,* 1988:6; Labarthe, 1964:15; Marsh, 1947:33; Miller, 1992:8).

- **Absorbency**

Absorbency is the ability of fibre to take up moisture from the body or from the environment. The ability of bone-dry fibre to absorb moisture under a standard atmosphere which is defined as one of 65 per cent relative humidity at a temperature of 20°C ± 1 is called moisture regain. Moisture regain gives an indication of a fibre's absorbency where the moisture in the material is expressed as percentage of the weight of moisture free material. On the other hand moisture content is not necessarily determined from a bone dry fabric, yarn or fibre. The initial weight of a sample includes any moisture it may contain (Joseph, 1986:22; Needles, 1981:6; Wynne, 1997:21). Some cellulosic fibres have high moisture regain; for instance, flax has 12% (Kadolph & Langford, 2002:29). Water or moisture absorption is often used to indicate the moisture content at either 95 or 100 percent relative humidity (Joseph, 1986:22).

Absorbency is one of several factors that determine the suitability of a fibre for a particular purpose. It is important in fibres or fabrics that are to be dyed, since the completeness and uniformity of the dyeing are dependent upon absorbency (AATCC, 1990:112; Hollen *et al.,* 1988:13; Kadolph & Langford, 2002:25, 26; Tortora, 1978:16).

The fibres which absorb moisture readily are referred to as hydrophilic fibres, whereas those which do not absorb moisture or absorb very little moisture are referred to as hydrophobic fibres. Hygroscopic fibres absorb moisture without feeling damp. Cellulosic fibres are hygroscopic, because cellulose is a hydrophilic glucan, a polymer consisting of linear chain of 1-ß bonded anhydroglucose units. This large number of hydroxyl group (-OH) attracts water and gives fibre hydrophilic properties. This leads to a very poor interface between fibre and the hydrophobic matrix and very poor moisture absorption resistance (Catling, 1985:73; Gangopadhyay & Ghosh, 2000:1597, 1598).

The wicking ability of a textile product is desirable in garment, worn next to the skin in hot weather where high temperatures cause sweating and is even more important in fabrics intended for vigorous exercise. Wicking of moisture through a fabric essentially draws moisture away from the skin surface keeping it as dry as possible and therefore provides comfort.

Absorbency is related to static build up. Absorbent fibres are apt to be more comfortable and less prone to problems of cling, crackle and static build up than hydrophobic synthetics (Hatch, 1993:33; Hollen *et al.,* 1988:13; Kadolph & Langford, 2002:25, 26, 39; Lomax, 1987:78; Smith & Block, 1982:67, 70; Tortora, 1978:16; Wingate & Mohler, 1984:34).

Cellulosic fibres are hygroscopic and hydrophilic. That is the moisture spread through the fibre quickly. This means they have high a degree of wicking properties, so they absorb perspiration. They are therefore comfortable for summer wear. They then provide excellent comfort properties. Hydrophilic fibres absorb dyestuff and finishes well as it is usually applied from the aqueous medium (Lomax, 1987:78).

- **Thermal retention**

Heat or thermal retention is the ability of the textile product to hold heat. A low level of thermal retention is ideal for hot weather and a high level in cold weather. This property can be affected by the type of fibre, yarn and fabric structure and layering of fabrics (Hollen *et al.,* 1988:13; Kadolph & Langford, 2002:26; Taylor 1985:25). Natural cellulosic fibres are good conductors of heat and electricity. As a result they transmit warmth away from the body and are favoured for use in hot weather and warm climates. Since they conduct electricity, cellulosic fibres neither build up static electricity nor produce shocks when worn (Kadolph & Langford, 2002:34, 44).

- **Heat sensitivity**

Heat sensitivity denotes fibre reaction to heat. Some fibres soften and melt and others are heat resistant. These properties identify safe pressing temperatures. Natural cellulosic fibres have low heat sensitivity and can be pressed and ironed with high temperatures, they can also be boiled for sterility (Kadolph & Langford, 2002:26, 34).

- **Density**

Density or specific gravity is a measure of fibre weight per unit volume. Lower density fibres can be made into thick fabrics which are more comfortable than high density fibres made into heavy fabrics. Cellulosic fibres from the monocotyledonous plants are usually of high density because a number of fibre ultimates have naturally aggregated to form fibres (Kadolph & Langford, 2002:26).

2.9.2.5 Care and maintenance

Improper care can result in items which are unattractive, not as durable as expected, uncomfortable or unusable. Smoothness of fibre, absorbency, influences of chemicals on fibre and dimensional stability all have impact on care and maintenance of textile fibre products. The ease of maintenance of textile products depend upon a number of factors; such as how resistant it is to soiling and staining and how readily dirt and stains can be removed, what its wrinkle resistance is and ease of wrinkle removal, and how well it withstands shrinkage. Long smooth filament fibres resist soiling and assist in its release during washing (Smith & Block, 1982:22).

- **Resistance to mildew and insects**

Cellulosic fibre is subject to mildew, damage which is caused by fungi. Untreated cellulosic textiles will be stained, malodorous and eventually deteriorated by fungus, if allowed to remain in moist conditions for a long period. Heat and moisture accelerate mildew action on cellulosic fibres. Research has revealed that a chemical component produced by fungi has the power of changing cellulose in plant fibres to sugar, unless they are treated fungal resistant. The fungi feed on the sugar. Unless they are treated for mildew resistance, fabric of cellulose fibre should not be folded and kept on shelves where there is dampness. Cellulosic fibres are also subject to insect damage caused by crickets and silverfish. Moths however will not affect them (Corbman, 1985:195; Cushing 2000:45; Kadolph & Langford, 2002:34; Wingate & Mohler, 1984:231, 249; Wynne, 1997:96).

- **Hygiene quality and launder ability**

The smooth surfaced fibres produce fabrics that are easy to launder and therefore hygienic. They give up stains readily and harbour little adhering surface for particles of dirt. Bacteria do not thrive easily on the smooth surfaced fabric. Dirt and germs do not collect in them easily. They are expected to be highly resistant to most organic solvents including those used in normal care and stain removal (Corbman, 1985:475; Hatch, 1993:168; Wingate & Mohler, 1984:263).

Cellulosic fibres can be laundered easily because they can withstand high temperatures well. Boiling does not harm the fibres. They can be ironed with a hot iron because they do not scorch easily since their scorching point is high. Cellulosic fibres absorb moisture and dry more slowly. This property assists in the increase of strength and hygienic characteristics of such fabrics. Cellulosic fibres are organic, so they contain carbon (C), hydrogen (H) and oxygen (O) with reactive hydroxyl groups (–OH). These groups react readily with moisture, dyes and many finishes. Chemicals such as chlorine bleach damage cellulose by attacking the oxygen atom between the two ring units or within the rings, rupturing the chain or ring (Corbman 1985:263, 474; Kadolph & Langford 2002:38; Wingate & Mohler 1984:231, 248).

- **Resistance to chemicals**

Some chemicals, used or encountered at home cause damage to specific textile fibres, others are quite safe. Those often in contact with fabrics are acids such as acetic acid and salts, fruit juices, weak alkalis such as ammonia, borax, perspiration, oxidizing bleaches such as chlorine bleaches, hydrogen peroxide and sodium per borate and reducing bleaches such as sulphur bleaches. Boiling water, alkalis (weak or strong) chlorine and other bleaches do not harm cellulosic fibres (Hollen *et al.,* 1988:14; Kadolph & Langford, 2002:27).

Different fibres react differently to chemicals. Some are quite resistant to chemicals, others are resistant to a certain class of chemicals but easily damaged by others. Resistance to chemicals determine appropriateness of care procedures, end uses and finishes (Hollen *et al.,* 1988:14; Kadolph & Langford, 2002:27).

Cellulosic fibres are very sensitive to the action of acids. Weak organic acids such as acetic acid have mild effect on cellulose. Cold dilute solutions of acids may be used on cellulose with safety, provided they are not allowed to concentrate by drying in solution for prolonged period. Concentrated mineral acids such as sulphuric, hydrochloric and nitric acids destroy cellulosic fibres even if they are soaked in them for a few minutes (Cook, 1984:102; Hatch, 1993:67; Kadolph & Langford, 2002:34; Wingate & Mohler, 1984:263).

Cellulosic fibres are not easily attacked by alkalis. They resist boiling solutions of mild alkalis such as sodium carbonate, caustic alkalis such as sodium hydroxide. With the latter, care must be taken completely to submerge the goods for the combined action of caustic alkali and the oxygen of the air accelerates the oxidation of the cellulose with corresponding damage. Weak alkalis such as ammonia, borax, silicate soda and cold dilute bleaching agents such as hypochlorite or chlorine bleach are not detrimental to the cellulosic fibres during laundering (Cook, 1984:100; Corbman, 1985:477, 481; Cowan & Jangerman, 1969:61; Wingate & Mohler, 1984:231).

Bleaching agents must be used only under controlled conditions since too high temperatures and concentrations destroy the fibre. Cellulosic textiles may be safely bleached, by using normal care with the ordinary sodium hypochlorite. For treatment, that is gentler, sodium perborate and hydrogen peroxide bleaches may be used. The treatment with sodium hydroxide solution is the basis of mercerisation. Detergent solutions and laundering bleaches are usually alkaline, (Cook, 1984:100; Corbman, 1985:477, 481; Cowan & Jangerman, 1969:61; Hatch, 1993:68; Wingate & Mohler, 1984:231).

- **Resistance to Sunlight**

Cellulosic fibres have good sunlight resistance but the prolonged exposure to intense sunlight causes a physical break down and loss strength to them. The energy in light especially in the ultraviolet region of the spectrum causes irreversible damage to the chemical structure of the fibre (Hatch, 1993:64).

The damage may appear yellow or colour change, a slight weakening of the fabric or eventually the complete disintegration of the fabric. It will start by turning the fibres yellow and will gradually cause degradation. The degrading effect may not be evident until the textile is cleaned. The friction and stress on the textile may then be sufficient to cause disintegration to it. The amount of light resistance required, depends on the end use of the fibre (Kadolph & Langford, 2002:27; Hatch, 1993:64).

2.10 ENVIRONMENTAL IMPACT OF TEXTILES

Environmental impact refers to the way the production, uses, care and disposal of a fibre of a textile product affects the environment. Emphasis on energy conservation, environmental quality, noise abatement, health and safety influences the production and processing of textiles. Hollen (1988:3) stated that energy conservation is achieved by using less water. Danger of pollution-noise, air, land and water has long been a problem in the textile industry, particularly in fabric manufacturing. New technological protective devices have already been implemented in some industries to try and reduce noise pollution. Pollution of the air and water has reserved considerable attention and will continue to be a concern (Etters, 1999:33; Joseph, 1986:4; Kundu *et al.,* 1991:720).

Pollution of outside air through exhausts of fumes and smoke has been controlled in some developed countries but is still a problem in most under-developed countries. Pollution of inside air has been and is still responsible for a variety of illnesses among employees. Although synthetic fibres currently account for the largest percentage of textiles in the global market natural cellulosic fibres have good possibility for increasing their market shares. They are likely to increase in importance due to their low price, eco friendly character and technical properties when compared to synthetic fibres which use more chemicals which cause pollution. Many chemicals used in the production of textile products are potential carcinogens or toxic in some way or the other (Joseph, 1986:4; Weaver, 1984:5).

The problem is increased by the evidence that a micro-amount of certain elements may accumulate in living systems and have serious long-term effects. Traces of certain compounds have been shown to act as mutagens and teratogens as well as nerve poison (Joseph, 1986:4; Weaver, 1984:5). It is also appreciable and appropriate that natural fibres are still an important and necessary source of world's textile fabrics in spite of increasing competition from man-made fibres (Miller, 1992:8). If a fibre requires few agricultural chemicals and irrigation is seldom required, it is regarded as environmental friendly to some extend (Kadolph & Langford, 2002:44).

Most textiles are subject to moist treatments during their processing. The treatments involve the use of large amounts of water since it is the most convenient, readily available and economic medium for applying a large variety of agents to textiles. Water is also used in the removal of unwanted substances originating from the textile fibre and excess chemicals. The water bearing all these process residues constitutes textile effluent. The drawback with this use is that its ultimate destiny, after use, is the very water courses from which it originated and this leads to their contamination by various substances introduced during textile processing (Hatch, 1993:174; Kadolph & Langford, 2002:27-28; Reed, 1982:50).

The recent awakened concern with textiles polluting the environment has focused attention to these by-products of textile processing (Tortora, 1978:348). The general public is more mindful about dangers to the natural environment from textile production. The relationship of the production of modern textiles to ecological problems becomes an issue of the public (Tortora, 1978:346). Conservation of non-renewable resources such as energy and raw materials is of great concern in the production and processing of textiles. Textile manufacturers and or researchers must search for production and processing methods that use a minimum amount of energy-rich resources and the renewable raw resources (Joseph, 1986:3, 4).

The environmentally clean or friendly is the key word in textile production, processing and utilization at the beginning of the 21st century (Asian textile Business, November 2003:19, 20). Cellulosic fibres have continuously been gaining momentum to meet the new demands in connection with the start of the 21st century (Asian Textile Business April 2003).

In order to respond positively to an increasing number of environment-friendly and human-friendly oriented consumers, textile researchers and producers must actively accelerate the development of fibres made from specialty vegetable materials. These fibres are filled with a sense of nature, are biodegradable, help to global environmental protection and therefore attract public interest (Asian Textile Business, April 2004:14; (Asian textile Business, November 2003:18).). Natural cellulosic fibres which make them ecologically sound to be studied. Natural cellulosic fibres are responding to the need existing subconsciously among consumers because of their biodegradable performance (Asian Textile Business, 2004:14

2.11 SAFETY IN TEXTILES

It has been recognised that textile materials particularly in apparel or home furnishings can be a potential fire hazard. Flammability of textile materials is also almost entirely dependent upon fibre properties. These are in turn determined by the microstructure of fibre (Smith & Block, 1982:68).

CHAPTER 3

RESEARCH PROCEDURE

3.1 PHASE 1: PLANT HARVESTING AND PRELIMINARY FIBRE EXTRACTION OF *AGAVE AMERICANA*

3.1.1 Section 1: Pilot study

3.1.1.1 Harvesting and pre-treatment

Harvesting and ten fibre extraction experiments were conducted to find which two methods show potential to extract fibres for phase two where fibre extraction and the evaluation of the performance properties of *Agave americana* fabric would be done. The leaves which form a 45° angle to the ground were chosen for harvesting, as suggested in the literature. Fresh and fleshy leaves were cut close to the stalk to keep the fibres as long as possible, by hand with a knife.

The cut leaves were hauled from the plant. The thorns on the leaf margins and the spines at the tip of the leaf were removed with a knife at the harvest area. The leaves were then transported to the fibre extraction facility. Each leaf was measured lengthwise and weighed. The outer cuticle of the leaf was then stripped off prior to the treatment so as to hasten the extraction processes. One leaf was cut lengthwise four times to equal parts which were separated into innermost and outermost sections for fibre extraction.

3.1.1.2 Partial degradation of leaf for fibre decortication

Before the fibre was mechanically extracted the plant tissues must undergo a partial degradation. This allows the fibre bundles to be separated from the other plant material easily and cleanly. This was done in a number of ways:

Experiment 1: Pounding with a wooden mallet

One portion of the prepared leaves was placed on a 2 x 230 cm plastic sheet and pounded gently with a wooden mallet, to turn the soft non-fibre tissue into amorphous mush which was scraped away immediately from the leaf fibres with the blunt side of a knife. The fibres were then hand washed in warm soapy water to remove remaining pulp after decortication. Washed fibres were then rinsed in clean cold water. If some traces of gums remain attached to the fibres, further pounding was done. The fibres were rewashed, rinsed and dried under the shade.

Experiment 2: Stripping of the peripheral fibres

The leaf cuticle was cut, thinly, in lengthwise direction with a knife for a short distance ± 10cm. With gloves on, the outer leaf cuticle was stripped off starting from the lower and thick end of the leaf towards the tip. The peripheral fibres were obtained simply by pulling them from the inside of the outer leaf cuticle. They were then washed and some dried in the sunlight while others were dried under shade.

Experiment 3: Boiling in clean water

Another leaf portion was put in 20 ℓ tin and 10 ℓ clean water was measured and added into the tin to cover the leaf portion. The leaf portion was boiled until soft to scrape off the pulp (the Basotho traditional way of removing *Agave americana* leaf fibres). The processing time was recorded. The ligno-cellulosic gum was then scraped off. The fibres were washed and rinsed in clean water.

Experiment 4: Boiling in water with lemon juice

Another leaf portion was put in a 20 ℓ tin and 6 ℓ of cold water was measured and poured in the tin. One litre lemon juice was poured into the tin. The contents in the tin were then boiled until the extraneous matter of the leaf was soft and ready for fibre extraction. The processing time was recorded. When cool, the fibres were extracted by squeezing out the non-cellulosic biomass. They were then, washed, rinsed and dried.

Experiment 5: Boiling in water with cloudy ammonia

Another leaf portion was put in a 20 ℓ tin. Six litres of cold water was measured and poured in the tin. Five millilitres cloudy ammonia was added into the tin. The contents in the tin were boiled until the extraneous matter of the leaf was soft and ready to be removed. The processing time was recorded. When cool, the fibres were extracted by squeezing out the non-cellulosic biomass. They were then, washed, rinsed and dried.

Experiment 6: Boiling in water with mild soap

Another leaf portion was put in a 20 ℓ tin. Six litres of cold water was measured and added in the tin. A bar soap weighing 250 g was shredded on a grater and added into the tin. The contents in the tin were then boiled until the extraneous matter of the leaf was soft and ready for fibre extraction. The processing time was recorded. When cool, the fibres were extracted, washed, rinsed and dried.

Experiment 7: Boiling in water with powdered soap-less detergent

Another leaf portion was put in a 20 ℓ tin and 6 ℓ of cold water was measured and poured in the tin. Two grams of a powdered soap-less detergent was measured and added into the tin. Contents in the tin were then boiled until the extraneous matter of the leaf was soft and ready for fibre extraction. The boiling time was recorded. When cool, the fibres were extracted, washed, rinsed and dried.

Experiment 8: Boiling in water with a solution of a mixture of liquid household cleaning agents

Another leaf portion was put in a 20 ℓ tin and 6 ℓ of water was poured in the tin. Three liquid household cleaning agents were mixed in equal parts in a 750 ml glass jar: (the first one composed of 0.5% m/m germicide and glutaraldehyde, the second one contained less than 5% non-ionic surfactant, soap, 4.8% chlorine based bleaching agent, sodium hypochlorite and the third one consists of more than 13% but less than 30% anionic surfactants and preservatives) mixed in equal proportions was added in the tin and boiled until the leaf matrix is soft enough to scrape off to extract fibre. The processing time was recorded. Fibre was then extracted, washed, rinsed and dried under shade.

Experiment 9: Solar baking

Another leaf portion was placed on a lightly greased baking tin and baked in a solar oven for one day, until soft enough to separate the fibre from the matrix. The temperature in the oven was measured in one-hour intervals, starting from 9:00-16:00 hours. The blunt side of the knife was used to mechanically scrape off the non-fibrous and extraneous matter. The fibres were ready to be knotted and wound on the spool.

Experiment 10: Natural Retting of *Agave americana* leaf

The outer cuticle of another leaf was stripped off in order to hasten the degradation of non-cellulose components of the leaves. The leaves were also stripped lengthwise, coiled, immersed and soaked in water in a plastic basin for 14 days at ambient temperature, to decompose and loosen the gum that binds the fibres to the leaves. When they were nearly ready, the decomposing water was spilt off so as to introduce dew retting for another seven days.

Dew retting assists the fibre to develop a light colour. It was left until ready, that is when it was easy to remove the fibres from the leaf biomass and when shiny slippery residue was easy to remove from the fibres. The fibres were extracted by mechanical decortication that is the blunt side of the knife was used to scrape off the gum or the associated parenchyma cells from the fibre. The fibres were hung in air to dry. The fibres were then ready to be knotted and wound on the spool.

3.1.2 Section 2: Solar baking and natural retting for partial degradation of *Agave americana* leaves

After conducting the ten preliminary experiments, the procedure and the results were visually and hand evaluated. This was employed to check colour, length and texture properties of fibre by naked eyes and feel. Out of the ten methods the two most eco-friendly, cost- effective and efficient methods that provided the best fibres in terms of colour, productivity, hand and appearance were selected. Natural retting and solar baking were the ones chosen for Phase 2 to extract more fibre to determine the physical structure, spinning and weaving properties, and to examine the fabric performance properties of *Agave americana* fibre.

3.1.2.1 Natural retting for partial biodegradation of *Agave americana* leaves

Harvesting of the *Agave americana* leaves was the same as for the preliminary procedures for both natural retting and solar baking. The leaves were measured and weighed. The leaf sheaths were mechanically stripped out (split) lengthwise into ribbon-like structures as shown in Figure 3.1. Stripping hastens the partial degradation process and reduces time of conventional whole leaf retting. Moreover requirements of water for stripped natural retting are almost half in comparison to conventional whole leaf retting, under normal conditions. This reduces the depletion of natural resources and the environmental pollution to a certain extent. The modified conventional “ribbon” retting of *Agave americana* leaves can therefore promise a more eco-friendly method.

Figure 3.1 Strips of the split leaf sheath of the *Agave americana* plant

The structures were coiled and put into a big open plastic basin of about 60 ℓ. Water of ambient temperature was poured to immerse all the coils of *Agave americana* leaves as indicated in Figure 3.2. The structures were then retted for 14 to 21 days in the basin so that the binding tissue (gum surrounding the hair-like *Agave americana* fibre decomposed) thus loosening the gum that binds the fibre to the leaf. As the fermentation progressed, the fibres were closely watched to minimize over-retting. When the leaf contents start to disintegrate with ease: in ± 14 days, the decomposing water was spilt off. The remaining plant materials were then spread on a clear patch of grass for dew retting for seven more days.

Figure 3.2 Retting *Agave americana* leaves

After seven days it was easy to remove the fibres from the extraneous, shiny and slippery matter. The fibres were then extracted by hand decortications. Each fibre was pulled between the knife and the thumb to scrape off the gum or the associated parenchyma cells from the fibre. The fibres were simultaneously air-dried. The fibre was then ready to be knotted and wound on the spool.

3.1.2.2 Solar baking for partial degradation of *Agave americana* leaves

Solar baking process was selected for Phase 2 because the processing is an eco-friendly and non-polluting process that utilizes the sun (solar energy) which is a renewable resource instead of non renewable fuels. There is no water used even for washing and rinsing the fibre after extraction process. It is a non-toxic environmentally benign process. It is also quicker than natural retting.

Apparatus: Solar oven

This is an outdoor cooking device. It is produced by Solarsoft business organisation in Mohale's hoek Lesotho. It is a three dimensional device of 73 cm × 63 cm × 33 cm. the frame is made up of metal rods and flat sheets of iron. The frame is made up of double layer of iron sheets and in between the layers; it is stuffed with the insulating fibre. The racks and the base, inside the oven are painted black so as to absorb sunlight heat. The oven door is fitted on the top side.

The door is 65 cm × 55 cm. It is made up of a double layer of a glass so as to retain heat inside the oven. It ha s a T-shaped handle made up of a metal iron. The glass door is protected by an outward curved cover of iron rods and flat iron sheet that is coated with the tinfoil that collects and reflects sunlight rays into the oven when cooking. The bottom of the oven is fitted with 10 cm and 15 cm iron poles at different levels for different angles of sunlight. One pole is inserted into a 50 cm long iron pole that is fixed onto a wheel outside on sunny place. The oven can then be rotated to any direction of the sun as illustrated in Figure 3.3.

Test procedure

The leaf was stripped lengthwise as shown in Figure 3.1, into sections, coiled and placed on a lightly greased baking tin and baked in a solar oven until soft enough to separate the fibre from the matrix (Figure 3.3). The temperatures were recorded throughout the day. Each fibre was pulled between the back of the knife and the thumb to scrape off the slippery, non-fibrous, extraneous matter from the fibre. The fibres were simultaneously air-dried. The fibre was then ready to be knotted and wound on the spool. This method is eco-friendly, not wasting water and making use of solar energy and no air pollution is caused.

Figure 3.3 Solar baking process for partial degradation of *Agave americana* leaf

The *Agave americana* fibres were categorized according to the method of matrix degradation and their positions in the leaf. Those which were obtained toward the outer layer of the leaf were termed the outermost fibres and the innermost ones were found toward the centre of the leaf. The groups were as follows: Retted outermost (RO), retted innermost (RI), solar baked outermost (SO) and solar baked innermost (SI).

3.2 FIBRE DECORTICATION

Materials and apparatus: Partial degraded *Agave americana* leaves and a small hand knife

Test Procedures

After retting and solar baking the pulpy material was removed, thus freeing the fibre-strands generally termed simply fibres from the matrix by picking one or two fibres at a time and mechanically scraping them against the blunt edges of knife held in hand and the thumb thus pushes off the extraneous matter and cleans the fibre. The operation is termed hand stripping (hand decortication). The fibres were air dried and ready to be knotted and wound on the spools.

3.3 KNOTTING AND REELING OF *AGAVE AMRICANA* FIBRE

The four sets of fibres, RO, RI, SO and SI were decorticated, and then knotted using a weaver's knot. A weaver's knot was used with the aim to minimise the warp breaks so as to increase loom efficiency and to improve cloth quality. Garnsworthy and Plate, (1981:26) reports that knots are the cause of all warp breaks, not simply because knots slip undone but also because they jam between reed wires. Weaver's knot is strong to support the full weaving stress (Hower, 1976:131). The fibre strands knot together to form a long strand of fibre.

Knotting procedure for *Agave americana* fibre

The yarn that is shown with bold in Figure 3.4 towards the hand forming the left. The other yarn formed the right loop. The left loop was first made and held toward the hand by thumb. The right yarn was then looped around the left loop and at the back of the left loop the right loop was twisted and its shorter end went through the left loop, the longer end moved under the left loop at the back. The left loop then went through the right loop towards front. Finally the shorter ends were pulled to tighten the knot.

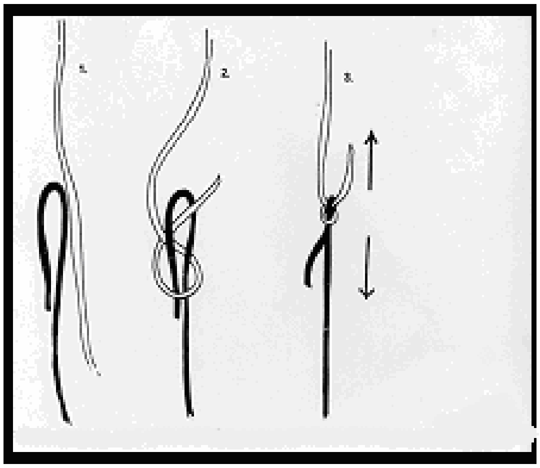


Figure 3.4 Weaver's knot as illustrated by Hower, 1976:131

The knotted fibre sets were then reeled on the paper rolls as illustrated in Figure 3.5.

The labelled spools of fibre were then transported to the weaving facility to be hand spun in yarns and hand woven into four sets of fabrics (The spinning and weaving research study was conducted outside the boundaries of this research study). The woven fabrics were then collected and used to test for some textiles performance properties in this research study.

Figure 3.5 Reeled decorticated *Agave americana* fibres

3.4 PHASE 2 IDENTIFICATION OF THE PHYSICAL STRUCTURE OF THE *AGAVE AMERICANA*

3.4.1 Microscopic examination: (AATCC test method 20-1985)

Microscopic examination was used to identify and describe the cross sectional structure and the longitudinal view of *Agave americana* fibre. The fibre structure was identified by observing the fibre through the light microscope (Figure 3.6). The photomicrographs were taken by light microscope at 250 x magnification.

3.4.1.1 Fibre longitudinal view

Needed material: Glass slide, glycerine drops, cover glass, optical microscope and a bunch of *Agave americana* fibres

Test procedure

A small drop of glycerine was poured on the glass slide. One *Agave americana* fibre was assembled on the glass slide and covered with a cover glass. The glass slide was mounted on the microscope. Lower magnification was used first and the appearance of the fibre noted. Then without moving the slide, the higher magnification was used and the general appearance was noted and photographed at 250 x magnification (AATCC, 1990:52; Weaver, 1984:29-32).

3.4.1.2 Fibre cross-sectional view

Plate method

Equipment needed by plate method: Perforated plate (Shirley Institute kit) of about the size of a microscope slide, a sharp razor blade, nylon pull through thread, a tuft of white acetate floss for background, a tuft of *Agave americana* fibres to test, microscope and microscope slide.

Test procedure

A small, perforated metal plate (Shirley Institute kit) of about the size of a microscope slide was used to identify the cross–section of *Agave americana* fibres. A tuft consists of white acetate fibre for background and one or two *Agave americana* fibres were pulled into a hole in the plate though the use of a loop of tough nylon to pull the thread through so as to ensure that a tuft slice remains in the hole after cutting the background and test fibres must be packed tightly. The top and bottom of the tufts were then cut off the plate using the razor blade as illustrated on Figure 3.2.1. A drop of oil was poured over the slide plate with the slice of threads in the hole and covered with the cover slide and the results were viewed with the microscope and photographed (AATCC, 1990:53).

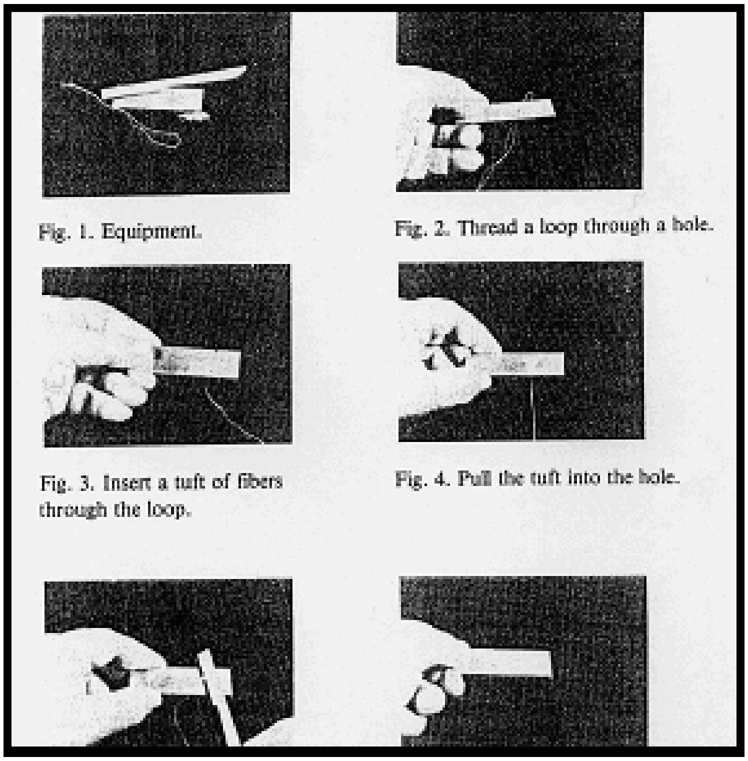


Fig. 1. Equipment.

Fig. 2. Thread a loop through a hole.

Fig. 3. Insert a tuft of fibers through the loop.

Fig. 4. Pull the tuft into the hole.

Figure 3.6 Microscopic plate preparations for cross-sectional view

3.5 PHASE 3: EVALUATION OF THE TEXTILE PERFORMANCE PROPERTIES OF *AGAVE AMERICANA* FIBRES

It is ideal to analyse the fibre in order to predict its performance. Knowledge of the fibre's properties will help to anticipate the fibre's contribution to the performance of a fabric and the products made from it. A number of experiments were carried out to evaluate the performance properties of *Agave americana* fibre and fabric. The fibres were evaluated by different techniques, ranging from simple non-technical test methods such as naked eye observation to more complicated analytical techniques. The non-technical test methods do not require any special equipment for textile testing. Although these methods have certain limitations, they are useful because they are simple to perform and under certain circumstances provide necessary information (Wingate & Mohler, 1984:553).

Preconditioning

All *Agave americana* fibres, yarns and fabrics were preconditioned at 21 ± 1° and 65 ± 5% relative humidity for at least 48 hours prior to testing.

Experimental fabric

The retted outermost (RO), retted innermost (RI), solar-baked outermost (SO) and solar-baked innermost (SI) fibres of *Agave americana* were woven with a plain weave of 9 warp and 13 weft yarn per 100 square mm.

3.5.1 Essential properties for a fibre to be a textile fibre

The following tests were done to determine to which extend *Agave americana* fibre, yarn and fabric meet the recommended standards to be classified as textiles.

3.5.1.1 Length-to-width ratio of *Agave americana* fibre

3.5.1.1.1 Length of *Agave americana* fibre

Sample selection

Twenty two fibre strands were selected on random from each of the following groups of specimens: retted outermost (RO), retted innermost (RI) solar-baked outermost (SO) and solar-baked innermost (SI) of *Agave americana* fibre.

Test procedure

Each fibre strand was held firmly at one end, straightened flat on a table and measured using a tape measure along its entire length starting from the end that was held firmly. Measurements were recorded and grouped for t-test analysis.

3.5.1.1.2 Width of *Agave americana* fibre

The width of the fibre was determined from the microscopic evaluation of the cross-section.

3.5.1.2 Tenacity and elongation at break test according to the International Standards ISO 2062

Principle: A specimen of yarn is extended until rupture by a suitable mechanical device and the breaking force and elongation at break are recorded. A constant rate of specimen extension of 100% per minute (based on the initial specimen length of 200 mm) is used.

Apparatus and materials: An Instron tester which complies with the following requirements:

(a) The constant rate of displacement of the moving clamp of 250 mm/min. to an accuracy of ± 2% with higher rates being permitted for automatic testers on agreement.
(b) Maximum error which does not exceed 2% of the true force.

The tester was equipped with autographic force or elongation recording device of sufficiently fast response, and with a system directly recording the breaking force and elongation at break. The tester was capable of setting a pretension either by means of a set of the force-measuring device.

Sampling

Samples of the retted outermost (RO), retted innermost (RI), solar-baked outermost (SO) and solar-baked innermost (SI) fibre yarns were randomly taken as the representatives of the lot to be tested. There were 12 samples of the RO, 14 of the RI, 12 of the SO and 12 of the SI fibres.

Test procedure

The non-dyed and non-bleached *Agave americana* fibre yarns were taken from the warp ends of the fabrics woven from retted outermost, retted innermost, solar-baked outermost, and solar innermost fibres respectively. They were slightly straightened between the palms of the hands. The jaws were checked that for correct alignment and parallel so that the force applied produce no angular deviation. Each specimen set was placed in the clamp of 0.5 k N/tex ±0.1, kN/tex loaded Instron tensile testing machine, for conditioned specimens, one set at a time. Finally the specimens were secured in the clamps and the test was conducted. During the test the specimens were checked regularly so that they might not slip between the jaws by more than 2 mm. The sketching and recording of the breaking force and elongation at break were done automatically by the tester.

3.5.1 3 Stiffness of the *Agave americana* fabric

Principle: Rectangular specimens are gripped at one end as a cantilever and the bending length, flexural rigidity and bending modulus are calculated from the dimensions of the specimen, and the degree to which it bends under its own or added weight.

Apparatus: The Shirley stiffness tester which is a fixed angle flexometer was used to determine the stiffness of the woven *Agave americana* fabric.

The Shirley stiffness tester has the following essential features: the slide S which is graduated in bending length in centimetres and when the front edge of the slide is coincident with the front edge of the horizontal platform P the zero of the scale coincides with a datum line D on the instrument. On each of the transparent plastic side pieces of the instrument are ascribed two sighting lines L_1 L_2 seen by reflection in the mirror M. both these lines pass through the line of the upper forward edge of the platform and lie 41.5°C below the horizontal**.** The under surface edge of S is covered with rubber so that when it lies on a cloth specimen resting on a cloth the polished surface of P, movement of S carries the specimen.

Specimens

The fabrics to be used were first conditioned for 24 hours at 21± 1°C and 65% ± 5% relative humidity (RH). The twenty four specimens were tested for stiffness. There were six specimens cut from each the following type of the fabrics; RO, RI, SO, and SI with the pair of scissors, using the slide as a template. The specimens were cut parallel to the warp or weft, a clean cut was made with a sharp pair of scissors. In cutting the specimens, care was taken to avoid selvedges, end pieces and creased and folded places and the specimens were handled as little as possible.

Test procedure

The specimens were conditioned and the tests are carried out at 21 ± 1°C and 65 ± 5%, relative humidity (RH). The apparatus was placed on a level table with the mirror towards the observer. The specimen was placed lengthwise on the platform P with one end coincident with the front upper edge of the platform. The slide S was placed on the specimen so that the zero of the scale was in line with the mark D. The slide was then pushed forward, carrying the specimen with it, until by looking in the mirror M is seen that the end edge of the specimen is in line with the two ascribed lines L_1 and L_2. This was possible because the observer had to adopt a viewing position in such that the reflections of L_1 and L_2 coincide.

The same process was repeated with the other side of the specimen up and again at the end of the specimen first with the original face up and then with the specimen turned over. The observation to be recorded in each case was the reading of the scale S when the described adjustment has been made. An observation was not made immediately as the specimen had been adjusted but after an interval during which the previous observation was recorded on the test sheet. A minor readjustment was made before reading S to ensure that all specimens hang for about the same length of time (6-8 sec.) before an observation was made

Expression of results: Since the scale S is calibrated directly in bending length in centimetres, the mean of the four readings gave the bending length of the specimen. The bending lengths of the specimens were averaged to give cloth bending lengths of the specimens. Using these figures, the Flexural Rigidity (G) and the bending modulus q are calculated using the following formulae:

$G == 0.10w_2c^3$ mgm.cm.

$q = 12G /g_2^3 *10^{-6}$ kg. /cm.^{2}

w_2 is the cloth weight in gm.per sq. metre

and

g_2 is the cloth thickness in cm measured at a pressure of 1 gram per centimetre by British Standard 2544:1954.

3.5.2 Secondary textile performance properties of *Agave americana* fibre

3.5.2.1 Dimensional stability tests: Adoption of AATCC test method 99-1988

3.5.2.1.1 Relaxation shrinkage in cold water

Purpose and scope: This test method is intended to determine the dimensional relaxation changes of the woven *Agave americana* fabric, after it has been immersed in water for the first time after fabric construction.

Principle: Fabric specimens were totally immersed in water and dried in the air in the laboratory. The distances between marks on the specimen in warp and weft directions were measured before immersion and after drying. The changes in dimensions were calculated from those measurements. The dimensional changes of woven fabric specimens subjected to steeping, drying and restoration produced are measured using marks done by laundry marker and a template applied to the fabric before immersion in water.

Apparatus and materials: *Agave americana* fabrics (40 by 20 cm) woven from retted innermost fibres, retted outermost fibres, solar baked outermost fibres and solar baked innermost fibres, square template marked in millimetres, laundry marker, laundry basin, specimen: full strip size of ± 40 cm long and 15 cm wide

Test specimen sampling and preparation

Marking: A template with a 10x10 cm square marked in millimeters was prepared. A freshly woven *Agave americana* fabric was placed over the marked template matching the dots which form a square and leaving at least 3 cm from the top edge the first 10 cm square is marked on the fabric using laundry marker. Leaving at least 3 cm from the first 10 cm square the second 10 cm square was marked in the same way as the first. Within the same interval and in the same manner the third 10 cm square was marked. All marks were to start and end at the same warp threads. Each mark was at least 3 cm from all edges of the test specimen. To improve accuracy and precision of the dimensional change, calculation based on the marks applied as above, the distance between marks was measured with the template and recorded.

Test procedure

The specimen was placed in wash basin half-filled with cold water and padded and shaken in the water with hands. The specimen was removed from the washbasin, padded gently by hand to squeeze out the excess water, but never wrung. The specimen was then spread on a horizontal screen, removing wrinkles but not distorting or stretching and is allowed to dry in still air at room temperature. When dry, the test specimen was placed without tension on a smooth horizontal surface, one by one over the template to observe the differences. The differences were measured and recorded. Dimensional changes were calculated based on the average of the three marks.

Calculation: % Relaxation Dimensional change = R – A / A × 100
Where
A = original dimensions
R = dimensions after relaxation

3.5.2.1.2 Residual shrinkage in warm water (65°C)

Purpose and scope: This test method is intended to determine the residual dimensional changes of *Agave americana* fabric, when immersed and gently padded in warm water.

Principle: The dimensional changes of marked woven *Agave americana* fabric specimens immersed and padded in warm water, dried and re-measured.

Apparatus and materials: *Agave americana* fabric (40 by 20 cm), laundry marker, laundry basin, measuring devices: ruler calibrated in millimetres and centimetres, template with rule calibrated directly in percent dimensional change, electric steam iron, specimen used for dimensional relaxation shrinkage.

Test procedure

The dimensional changes of the woven *Agave americana* fabric of the specimen which was previously washed (only once for relaxation shrinkage treatment) to shrink was measured, marked and steeped for two minutes in a wash basin half-filled with warm water (65°C), padded and shaken with hands. Specimen was removed from washbasin, padded gently by hand to squeeze out the excess water, but never wrung. The specimen was then spread on a horizontal screen. The wrinkles were removed by spreading and padding the fabric gently without distorting or stretching it. The fabric was allowed to dry in still air at room temperature. When dry, the test specimens were placed without tension on a smooth horizontal surface, one by one over the template to observe the differences. The differences are measured and recorded. Dimensional changes are calculated based on the average of the three marks.

Calculation: % Residual Dimensional change = R – A / A × 100
where
A = original dimensions
R = dimensions after the second dimensional change.

3.5.2.2 Crease recovery test: IWS – International Wool Secretariat test method no.175

Purpose: To determine recovery of the woven *Agave americana* fabric from creasing. The creasing took place with the fabric in dry conditions. The crease recovery angle of a specimen is defined as the angle between the two arms of the test specimen after loading and recovery. It is measured in degrees. A crease recovery angle of 180 degrees signifies 100 percent recovery from creasing.

Principle: Test specimens were taken free from creases and wrinkles and were creased and compressed under controlled conditions of time and load was suspended in the test instrument for a controlled period, after which the recovery angles were measured in degrees and analysed.

Apparatus: Forceps with flat jaws, stopwatch, and 2 by 2 kg cylindrical weight of 60 mm diameter, Thermo bench smooth base with 2 kg weights, an optical protractor, and a transparent protractor graduated at intervals of 1^0 and in which the radial lines extend nearly to the centre and light projector

Test procedure

Cutting: Three test specimens of 25 mm long by 17 mm wide and three specimens 17 mm long by 25 mm wide were cut randomly on each of the *Agave americana* test fabrics woven from retted innermost - (RI), retted outermost - (RO), solar baked innermost - (SI) and solar baked outermost - (SO) fibres.

This means that three specimens were cut with their long edges parallel to the warp direction and three with their long edges parallel to the weft direction. No two or more specimens contained the same warp or weft threads. Avoiding creases or folds in the materials, the specimens were labelled, steam pressed for one second and preconditioned for 16 hours in relatively humidity 65% ± 5 and the temperature of 21°C ± 1 °C.

Dry creasing

The Thermobench smooth base was set to the temperature of 37°C. Specimens were immediately folded exactly in half to bring the two longer edges together, gripped with the forceps and slided under the middle of one side of rectangular or pentagon plate. The long edges of the specimens were in line with the slide plate. Three more specimens were folded and placed under the remaining sides of the pentagon plate in a similar manner and place a 4 kg load (made from 2 by 2 kg weights) centrally over each specimen. They were then left under loads for 90 minutes, removed thereafter and allowed on the base to recover for 30 minutes.

Each specimen was transferred in turn to the platform of the optical projector, crease uppermost using forceps and taking care not to disturb the existing crease formation. The position of the platform was slightly adjusted until a clear image of the crease profile is obtained on the screen. The protractor was placed over the image, read off and recorded, the crease recovery angle to the nearest degree. Measurements were taken from the convex face of the specimen as the image of the platform was turned round, the crease recovery angle measured and recorded at the other end of the specimen in a similar manner. The mean values for each fabric were calculated and recorded to the nearest degree; this is the crease recovery angle of the test specimens.

3.5.2.3 Water absorption of *Agave americana* fabrics

Requirements: *Agave americana* fabric samples, large beaker, glass rod, watch- glasses, stop watch, sheet of glass, absorbent blotting paper, sensitive balance, forceps with flat jaws, and a pair of scissors.

Test procedure

Five 4 by 4 cm samples were cut from each of the four fabrics, that is fabric made out of retted outermost (RO) fibres, retted innermost (RI) fibres, solar baked outermost (SO) fibres and solar baked innermost (SI) fibres. Each sample was weighed on a sensitive balance and their dry masses were recorded. The six pieces of the same fabric were placed each in a separate glass jar of 500 ml. The water was poured into the jar to cover the fabric and samples were left immersed for 20 minutes at ambient temperature before extracting each of them.

The glass rod was used occasionally to push the fabric under the surface to avoid floating. At the end of the test time each fabric was removed with the forceps with flat jaws and placed between two pieces of blotter paper padded until no signs of free water was seen. The blotting paper removes any excess water from the fabric. The moist fabric was then weighed, the weights were recorded and water absorbency values were determined from the gain in weight after soaking. Water absorbency was calculated from gain in weight (Meirowitz, 2003:20-21).

Calculation: $W = A - B / A \times 100$

Where:

W = water absorption, percent
A = dry weight of sample
B = moist weight of sample after it has been immersed in water

3.5.2.4 Moisture regain test

Purpose: This method presents procedure for the quantitative determination of moisture content of *Agave americana* fabric.

Principle: The specimens to be tested are dried in a weighed container and the moisture regain is calculated from the weight loss normally referred to as the dry weight of the specimens.

Test procedure

Agave americana fabrics were conditioned at 65% ± 5% relative humidity and the temperature of 21°C ± 1°C. The smallest container was selected for use in this research study. The four conditioned *Agave americana* specimens of about 1 g (smallest) each were cut from RO, RI, SO and SI fabrics respectively. The empty container with a single solid cap was weighed on an analytical balance and the results were recorded. One specimen was put into the weighed container. Then the container with the single cap on and the specimen inside was re-weighed, the results were once more recorded.

The solid cap was then replaced with a perforated one. The container was then inserted into the apparatus. The motor and the heater were switched on respectively. The air stream temperature was adjusted as indicated by the thermometer on the top of the apparatus, by turning the thermostat control knob until it reached 140°C. The specimen was dried for approximately 10 minutes.

The container was then removed from the machine, the perforated cap was removed and replaced with the solid cap and the container with the dried sample inside was weighed. The solid cap was then removed and the perforated cap replaced and the container with the sample inside was inserted into the apparatus again and dried for 5 minutes and re-weighed. The weighing and drying for 5 minutes were repeated until the weight was constant. The same procedure was repeated with each specimen. The percent moisture regain was then calculated as the ratio of the amount of water absorbed to the dry weight of the sample.

Calculation: $R = A - B / B \times 100$
Where:
R = moisture regain, percent
A = weight of sample before drying
B = weight of sample after drying

3.5.2.5 Dye ability

Apparatus and materials: Urn (L) kettle with perforated rack with a handle, Tingecor guarany purple direct dye, 15 by 20 cm unbleached *Agave americana* fabric, multi-fibre content fabric and stirring stick.

Test procedure

Dry fabrics were measured and put in the kettle inside the rack. Ten litres of water was added into the kettle. The kettle was plugged on and the heat regulated to 70°C. Using a 250 ml beaker, 20 g dye was dissolved in cold water and then added into the kettle. The solution was shaken with a rack, to distribute the dye evenly. Previously washed *Agave americana* and multi-fibre content fabrics were immersed into the hot dye-bath, while still wet. The kettle contents were then brought to 85°C. The kettle contents were then kept at 85°C for approximately 30 minutes and stirred after every 10 minutes interval. The fabrics were the removed from the dye- bath and rinsed thoroughly. They were let to dry in the shade. The visual evaluation of the dye quality was done.

3.5.2.6 Thickness of *Agave americana* fabric

Materials: Fabrics made from RO (retted outermost), RI (retted innermost), SO (solar baked outermost) and SI (solar baked innermost) *Agave americana* fibre.

Apparatus: Essdiel thickness gauge

Test procedure

The thickness gauge was set up as appropriate and with the presser foot resting on the reference plate. The knurled screw was screwed down until the lamp just lit up. The dial reading was recorded. To allow for insertion of the sample under test the knurled screw was unscrewed and the sample was clamped on the reference plate. The presser foot was raised with one hand and the sample placed in position with the other; the foot was gently lowered onto the sample. The presser foot was let to rest on the sample for half a minute. The knurled screw was then screwed down until the lamp lighted. The dial reading was recorded. This reading minus the zero reading gave the thickness measurement at 20 gm/cm^2 (2.0kPa) pressure (i.e. this was the pressure applied by loading shaft assembly without weights. The same operation was repeated with all the other samples.

3.6 STATISTICAL ANALYSIS

The analysis of variance was used to support the interpretation of the results of the tensile strength and elongation at break of *Agave americana* fibre yarn because many independent variables were studied simultaneously.

The statistical t-test analysis was used on technical and quantitative results except those of stiffness and flexural modulus to determine whether there were significant differences between the results obtained from the two groups (Compton & Hall, 1972:352): retted and solar-baked *Agave americana* fibre.

CHAPTER 4

RESULTS AND DISCUSSIONS

The underlying problem in this research study was that *Agave americana* plant leaves were under utilised in cosmetics and pharmaceutical projects that are common in Lesotho. The projects extract and use *Agave americana* leaf juice only. The rest of the leaf ligno-cellulosic biomass which contains lot of fibre that can be useful in textiles is discarded as a by-product. The non-cellulosic biomass is firmly adhered to the cellulosic fibre and it is difficult to extract the fibre.

The feasibility preliminary experiments of *Agave americana* fibre extraction showed that conventional or natural retting and solar baking were the two comparative eco-friendly, cost-effective and efficient processes that can be used to degrade the leaf extraneous matter so as to release *Agave americana* fibre. These two processes were chosen to be used for fibre extraction in phase two. The identification confirmation properties, physical structure and textile performance properties of *Agave americana* fibre that was extracted by the two processes were evaluated.

In this chapter a brief overview is given of the experimental design used indicating phases undergone during the research study. The results obtained from the experiments were presented photographically, graphically and numerically were discussed according to predetermined objectives outlined in Chapter 1, where applicable references will be made to previous research findings.

4.1 OVERVIEW OF EXPERIMENTAL DESIGN

The variables used in this study are the position of a fibre in a leaf, conventional retting and solar baking of *Agave americana* fibre. The following selected properties were evaluated to determine the quality of solar-baked and conventional retting of *Agave americana* fibre.

Natural retting and solar baking were evaluated in terms of the time taken to degrade the leaves, identification confirmation properties, fibre length, diameter, fibre yarn tensile strength, elongation at break, fabric thickness, stiffness, dimensional stability, crease recovery, moisture regain, water absorption and dye ability. The results showed that conventional retting and solar baking can successfully be used to degrade leaf biomass.

Research study showed clear that *Agave americana* leaves can also be used for production of fibre that can be useful in textiles even though it has some limitations in apparel.

4.2 SECTION 1: PILOT STUDY

4.2.1 Harvesting and fibre extraction

Agave americana plant leaves are not pulled out when harvested so they assist to reduce soil erosion. *Agave americana* fibres have minimal environmental impact. The production does not need agricultural chemicals. Its harvesting is eco-friendly. It does not cause soil erosion. It is biodegradable. Depending on the type of partial degradation method used it can be very safe to the environment.

4.2.2 Partial degradation of leaf components and fibre decortication

Experiment 1: Pounding with a wooden mallet

The process was not so successful, because it was difficult to pound the leaf without having the sap spilt all over and it causes dermatitis which is the case with other *Agaves* which have high content of sapogenins (as stated by Nobel 1994:41; Nobel 1988:9). It was also difficult to remove pithy from the fibres since the pithy strongly adhered to the fibres. It took a long time and a lot of energy to process a few fibres. It also resulted into a high percentage of fibres wasted because there was a lot of fibre fracture experienced when further beating was done in order to further crush the matrix to ease fibre decortication. The decortication required fewer operations but resulted into low production. There is a lot of waste matter and dirt left with the fibres. The extraneous matter was not easy to completely remove from the surface of the fibre so degumming before spinning would be necessary.

Experiment 2: Stripping of the peripheral fibres

This was a very quick and easy method but the problems were that once the leaf contents especially the juice came in contact with human skin caused dermatitis. This is the typical behaviour of most *Agaves* (Nobel, 1994:41; Nobel, 1988:9). It was also wasteful since it worked for the fibre just underneath the cuticle. It was not easy to pull out those embedded inside the pithy. These fibres did not easily divide during processing as it is the case with the *Agave sisalana*. The peripheral fibres were thinner than the ones embedded in the thick white matrix in the middle of the leaf. They seldom divide during the extraction process. This property is similar to that of *Agave sisalana* mechanical fibres (Yan Li *et al.,* 2000:3).

Experiment 3: Boiling in clean water

It was more difficult to decorticate fibre than with retting. It resulted into the increase in proportions of fibre fractions. The innermost fibres even though longer and thicker than the outermost fibres, seemed to be less strong because they easily divided lengthwise during processing and become shorter.

Experiment 4: Boiling in water with lemon juice

There was no obvious injurious effect to the fibre. *Agave americana* fibre withstands high temperatures and boiling water, for this reason it is considered as the most hygienic fibre, being practical for household articles that are laundered.

Experiment 5: Boiling in water with cloudy ammonia

The leaf extraneous matter was easy to remove from the cellulosic fibres and a rough fibre surface topography was produced.

Experiment 6: Boiling in water with mild soap

Stiff and slightly rust fibres were produced. There was no significant change on fibre length.

Experiment 7: Boiling in water with powdered detergent

The fibres were very easy to remove they showed desirable effects of removal of surface fibres. Fibres were softer, finer, fluffier and brighter in colour than the fibres degraded with other methods. The use of the detergent for this purpose might be seen as a threat to the environment. Detergent contains ingredients that contaminate the water (Lyle, 1977:197) and is therefore seen as unfriendly to the environment.

Experiment 8: Boiling in water with a mixture of liquid household cleaning agents

The non-cellulosic leaf components were very soft and easy to remove from the cellulosic fibres. The fibres were long and cream white in colour. They looked strong and stiff. The ingredients are unfriendly to the environment.

Experiment 9: Solar baking

Solar baking was a cost-effective process because the renewable and naturally available resource, the sunlight was used. It is a very quick process when compared to natural retting. Processed fibres were ready for fibre decortication within one day if it is a sunny day. The fibres were more lustrous than the retted ones. The advantages of solar processing of *Agave americana* fibre are that one works within mild operating conditions.

It is safe to handle and has a low environmental impact, since there is no need for washing and repeated rinses although there is a high energy requirement of elevated temperatures (up to 110°C in the oven) but it is renewable. In general the one by one fibre hand decortication process was time consuming even though it was effective and energy saving in that each fibre was well cleaned without any use of water. It also produced long fibres.

Experiment 10: Natural Retting

Retting in water in June took 21-23 days. The natural retted *Agave americana* fibres were strong with improved colour and finer texture compared to other methods of leaf partial degradation. Natural retting whereby the leaf was first stripped into ribbon like structures has a greater promise to produce high quality *Agave americana* fibres and it is also a more eco-friendly measure when compared to whole leaf retting. Prolonged retting after readiness led to significant fibre bundle separation which resulted into short fibre bundles.

Natural retting resulted in fibre with a natural look in terms of colour and texture. The fibre felt and looked cleaner than the fibre obtained by most methods of fibre extraction. These results confirm previous research that claim that natural retting give the best results (Ramaswamy *et al.,* 1994:306).

The cooking time to degrade the non-cellulosic components of *Agave americana* leaves, so as to release fibre was recorded and the results are shown in Figure 4.1.

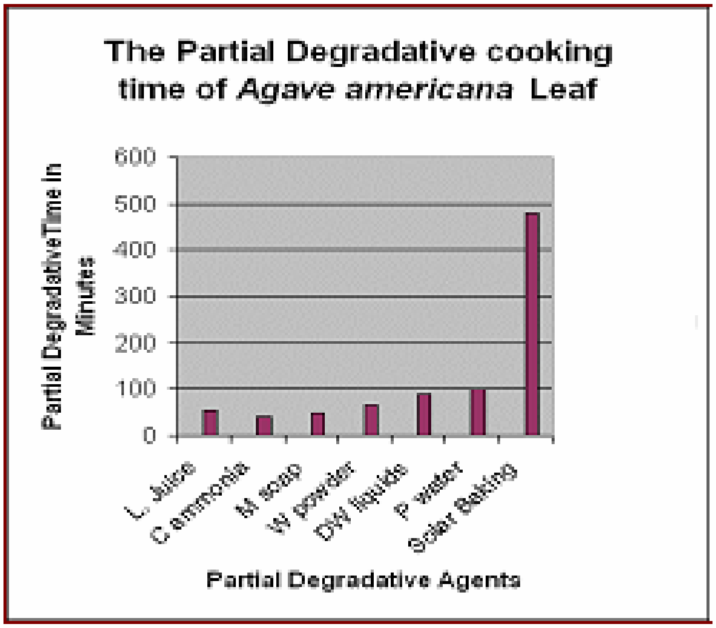


Figure 4.1 **Partial degradation heating time of *Agave americana* leaves in different experimental processes**

4.2.3 Visual and hand evaluation of *Agave americana* fibre

Visual inspection of the fibre for appearance and hand was done first to evaluate the physical properties of *Agave americana* fibre. The observation of the colour, shape, surface texture, flexibility and length of the fibre were visually evaluated.

Colour of the fibre

The colour of the *Agave americana* fibre ranges from off-white to rust depending upon the processing technique used for fibre extraction and the processing time. The retted fibre was darkened and discoloured with a naturally looking light brown colour of which Storey, (1978:15) believed is due to bacterial action. Solar baked *Agave americana* fibre develops the light brown to rust colour (Figure 3.4) if left for more than two days in pithy after partial-degradation processing. Reddy and Yang, (2005:25) blame the colour on the presence of lignin and other noncellulosic substances which give the fibre a yellow colour.

Lustre

The fibres are dull in appearance and one has a reason to believe that this is due to the fact that they have the uneven surface shown by Figure 4.6a. Another possible reason may be the fact that under the microscope it has irregular cross-sectional shape. A fibre with an irregular cross-section scatters light in all directions, resulting in a dull appearance with few high lights (Smith & Block, 1982:66). No difference was seen between the shape of solar baked and retted fibres.

Texture of the fibre

The dry *Agave americana* fibre is stiff, harsh, coarse and hard-surfaced; the typical characteristic of a dry leaf fibres but they are flexible, smooth and slippery only when wet. *Agave americana* fibre is expected to irritate the skin and is uncomfortable because of the fact that it is rough when dry. The fibre feels strong and durable. It has a natural look and the textured appearance when it is dry, the property that gives it a unique quality. The fibre has an uneven surface. No difference was seen between the texture of solar baked and retted fibres.

Physical shape of *Agave americana*

The fibre is long, round and generally taper to a point, having one side thicker, especially from the lower side of the leaf.

4.3 SECTION 2: FIBRE EXTRACTION OF NATURALLY RETTED AND SOLAR BAKED *AGAVE AMERICANA* LEAVES

Section one described the pilot study and visual evaluation of the results. This section reports on the technical evaluation of retting and solar baking as fibre extraction methods. These two empirical procedures were found most efficient, effective, accessible and eco-friendly methods of leave partial degradation and fibre decortication.

4.3.1 Natural retting of *Agave americana* leaves to release fibre

Preliminary retting was done in June. It took 21 days for the leave ribbons to be ready for fibre decortication. Retting in August took 17 days for leaves to be ready for fibre decortication. Another retting experiment was carried out in December and satisfactory results were obtained after 14 days as illustrated in Figure 4.2. This implies that the ambient temperature of the time of the year has an impact on the natural retting rate. During cold weather conditions natural retting occurs slower than during in hot summer times as it is obvious in Figure 4.2.

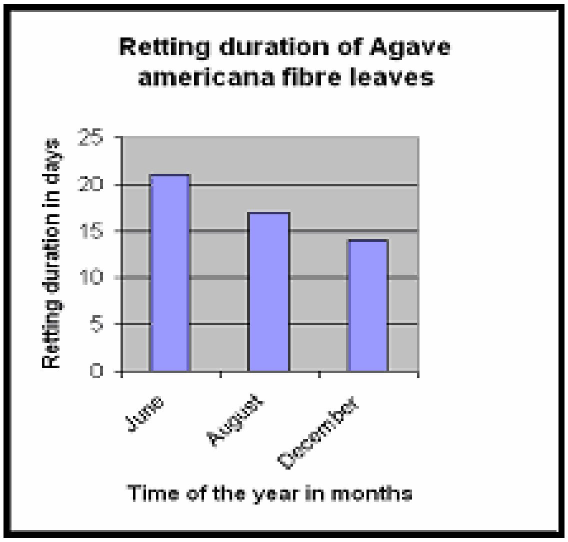


Figure 4.2 **Natural conventional retting duration of *Agave americana* fibre leaves**

4.3 2 Solar baking of *Agave americana* leaves for fibre extraction

Solar baking experiments of the results presented in Figure 4.3 were conducted in three successive days in December. The experiments started at 07h00 and ended at 16h00.

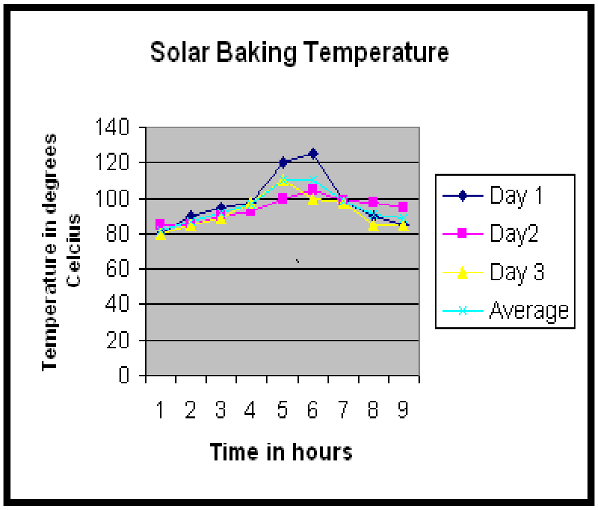


Figure 4.3 **Temperatures achieved in the solar baking oven through out the day**

Figure 4.3 illustrates the solar baking temperatures in three different days in December. It took nine hours for the *Agave americana* leaf strips to soften the matrix for fibre decortication on a clear sunny day. Day one seems to be the hottest day because it reached the highest temperature of 125°C. On average, the temperature of about 110°C is needed to partially degrade *Agave americana* leaves for fibre extraction. Solar baking is faster than natural retting. It took one day compared to natural retting which took fourteen days.

4.4 IDENTIFICATION OF THE PHYSICAL STRUCTURE OF *AGAVE AMERICANA* FIBRE

4.4.1 Microscopic examination: AATCC test method 20-1985

It is important that microscopic evaluation has been carried out in this research study because it is the simplest and best way to differentiate between different natural fibres (Kadolph & Langford, 2002:30).

4.4.1.1 Longitudinal view of *Agave americana* fibre

Figures 4.4(a-c): Microscopic. Longitudinal appearance of the *Agave americana* fibre.

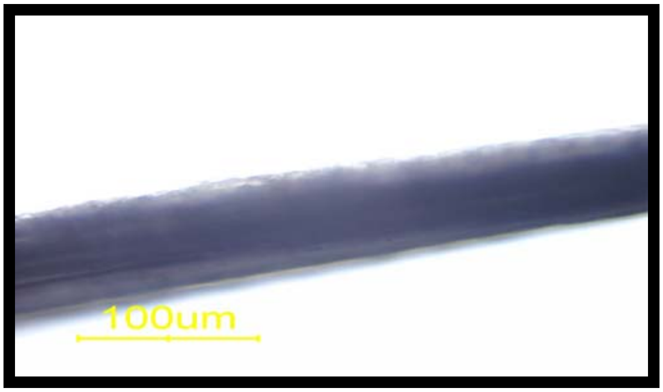


Figure 4.4(a) Longitudinal view of *Agave americana* fibre

Figure 4.4(a) shows that under the microscope *Agave americana* fibre has the appearance of a straight tube, which is slightly round or cylindrical in shape. The fibre surface contour is rough and uneven. Reddy and Yang, (2005:25) found that the roughness and irregularity of cornhusk fibre was due to the presence of an encrusting substance. The roughness and irregularity of *Agave americana* can probably be explained in the same way. The outer edge of the cross section views Figure 4.4(a-h) clearly shows the uneven surface. The fibre diameter seems to gradually vary in size along the length. The fibre size tapers to a point.

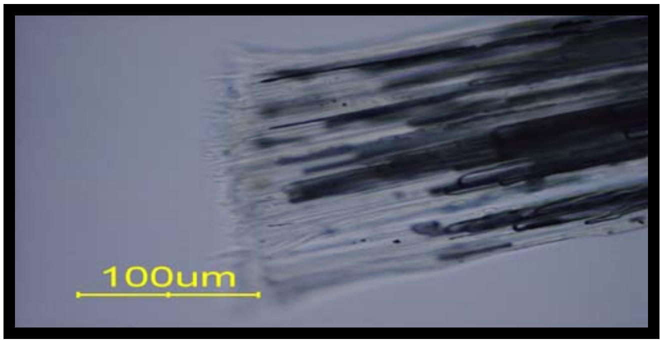


Figure 4.4(b) Longitudinal broken end of *Agave americana* fibre

The longitudinal broken end of a fibre shows that a single fibre strand consists of numerous, minute individual fibrils which overlap each other to form a long continuous fibre.

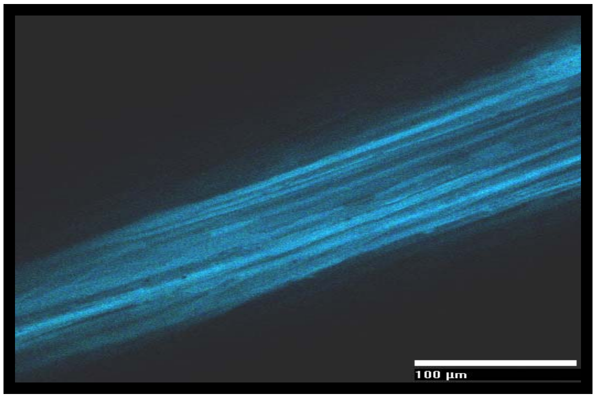


Figure 4.4(c) Longitudinal view showing fibre striations within *Agave americana* fibre

The longitudinal striations (horizontal lines) are visible. There are no apparent nodes as is the case with linen fibres (Hatch, 1993:174). It seems that fibrils overlap to join end to end.

4.4.1.2 Cross-sectional view of *Agave americana* fibre

Figures 4.5(a-h) show the microscopic cross sectional appearance of *Agave americana* fibre

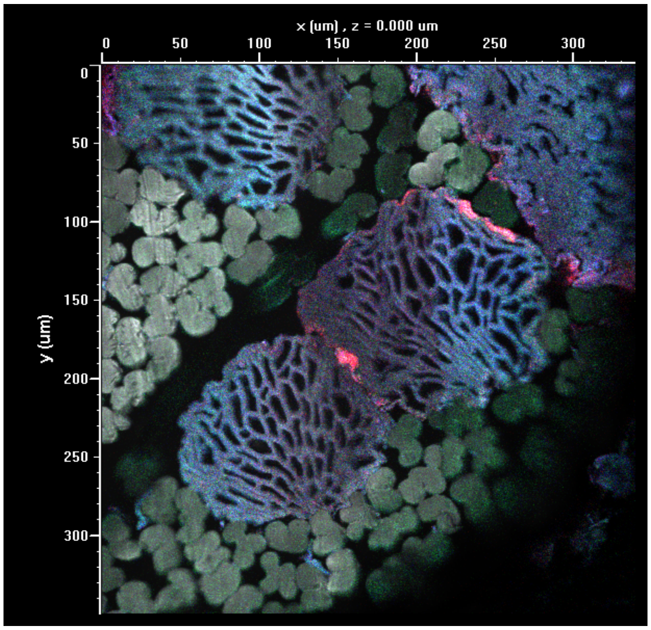


Figure 4.5(a) Cross-section of retted outermost A*gave americana* fibre showing the distribution of cells of different sizes and shapes

Figure 4.5(a-h) shows the lace like cross-sectional view of *Agave americana* fibre. It shows that one fibre consists of several flat irregular polygonal shaped cells (ultimates) with well-defined central hollow regions, lumens - the typical characteristic of natural cellulosic fibres (Herrera-Franco & Valedez-Gonzales, 2003:1; Reddy & Yang, 2005:26) which vary in sizes as indicated in the photograph in Figures 4.5(a-h) as is the case with *Agave sisalana* fibres (Joseph *et al.,* 2003:277; Yan Li *et al.,* 2000:3).

The natural lumens of the individual cells of *Agave americana* fibre may render it warm (Herrera-Franco & Valedez-Gonzalez, 2003:1). The cell walls of ultimates look thinner with larger lumens than those of *Agave sisalana* fibre. Figure 4.5(a) clearly indicates that the diameter of a single strand ranges between 100 and 150 μm, the range found within that of a sisal fibre of 100-300 μm (Yan Li *et al.,* 2000:3). This indicates that *Agave americana* fibre strand is often finer than sisal fibre.

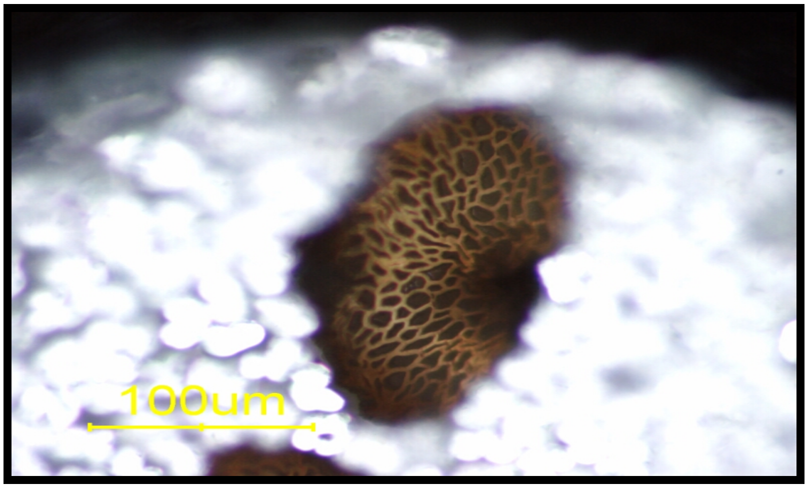


Figure 4.5(b) Cross sectional structure of solar-baked outermost A*gave americana* fibre

The shape of *Agave americana* fibre in Figure 4.5(b) has a lima bean shape with the outer edge serrated with several irregular polygonal cells. The cell walls of its ultimate cell look thinner than those of *Agave sisalana* ultimate cells as shown by The Textile Institute, 1975:84; Figure 70.

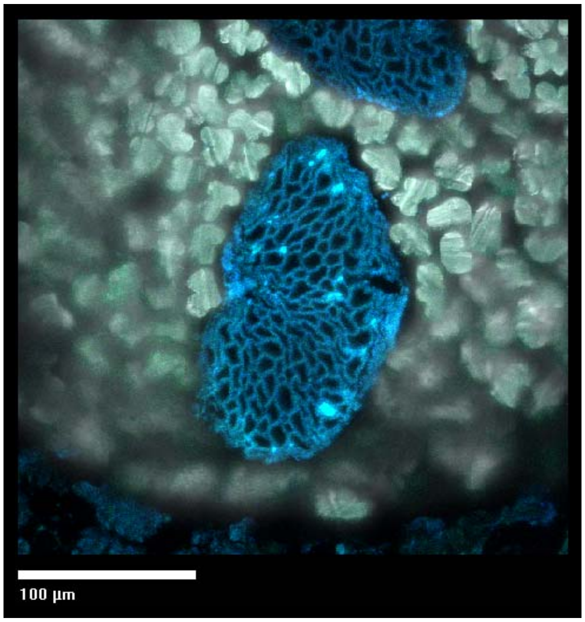


Figure 4.5(c) Solar-baked outermost *Agave americana* fibre cross sectional structure

Figure 4.5(c) Solar outermost fibres more or less looks like Figure 4.5(b). Each fibre strand consists of numerous irregular polygonal sub-fibres which have well defined cell wall surrounding a large wide open hole

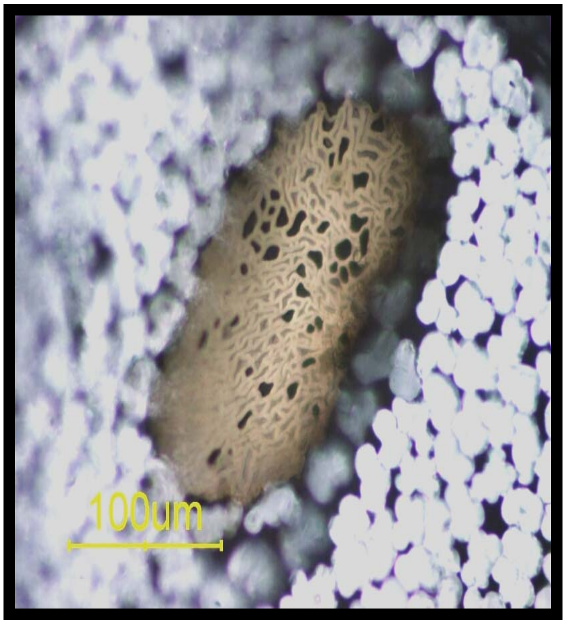


Figure 4.5(d) Retted innermost A*gave americana* fibre cross sectional structure

Figure 4.5(d) shows that the ultimates of the inner fibre are more dense and oblong than the outer ones. Most of the ultimates are filled with a semi-transparent substance of which one has a good reason to think that it is a natural, non-cellulosic extraneous matter which binds individual fibre cells together. This can be explained by the fact that the extraneous matter is highly concentrated at the centre most of the leaf.

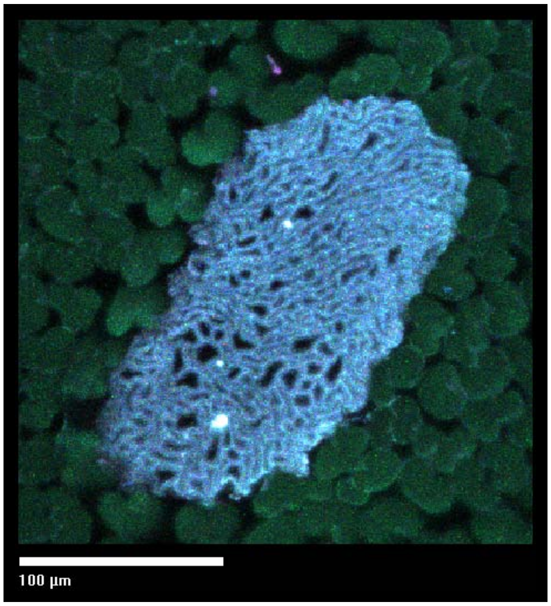


Figure 4.5(e) Retted innermost *Agave americana* fibre cross sectional structure

Figure 4.5(e) shows the fibre structure with sharp and irregular outlines. The cells are irregular in shapes and sizes. Most of the cells are densely packed with small and somehow invisible lumen in each cell.

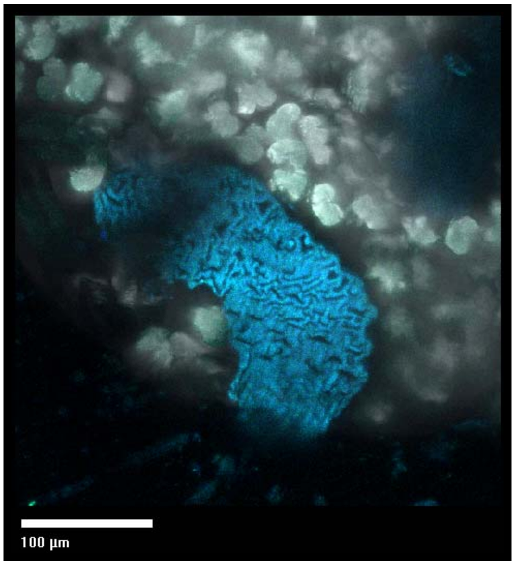


Figure 4.5(f) Solar-baked innermost *Agave americana* fibre cross sectional structure

Figure 4.5(f) shows the solar-baked innermost fibre which has sharp outer edges. It has a more curved horseshoe shape with the cells which are closely packed. The individual cells are collapsed to the extent that the lumens are some times not visible. The crescent shape outline is obvious in this figure.

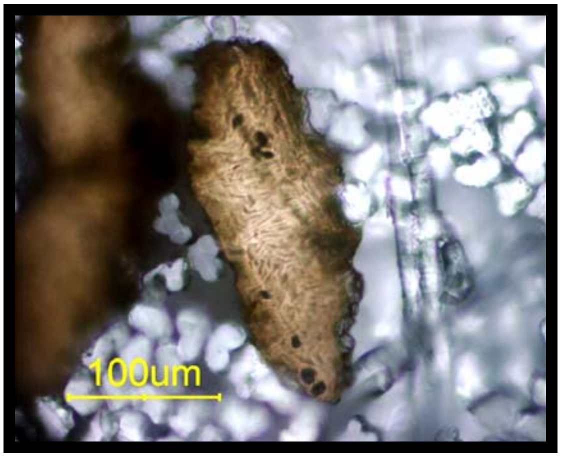


Figure 4.5(g) Retted innermost *Agave americana* fibre cross sectional structure

Figure 4.5(g) shows a unique shape of *Agave americana* fibre. The cells are more oblong and denser than those of the outermost fibres. They seem to be filled with a transparent natural gum. There are very few cells with large well-defined lumens.

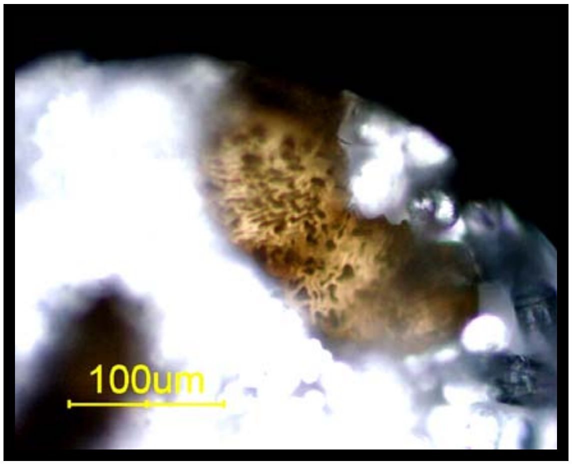


Figure 4.5(h) Solar-baked innermost *Agave americana* fibre cross sectional structure

Figure 4.5(h) shows another unique horseshoe shaped fibre. The fibre may be expected to have a high density because of many ultimates within a single fibre strand and the fact the innermost fibre are expected to have even higher density because their individual cell structures are denser with less hollow structures. These cross section images show a prominent difference between the innermost and outermost fibres. The innermost fibres are more densely packed and the cross section is oblong or slightly curved oblong. The outermost fibres are much less dense and slightly less oblong.

4.5 TEXTILES PERFORMANCE PROPERTIES OF *AGAVE AMERICANA* FIBRE

4.5.1 Essential properties for a fibre to be a textile fibre

Textile performance evaluation is often done for various specific reasons that contribute toward the general goal of ensuring serviceability (Merkel, 1991:14). But some properties are essential for a fibre to be classified as a textile fibre (Joseph, 1986:22)

4.5.1.1 Length-to-width ratio of *Agave americana* fibre

4.5.1.1.1 Length of *Agave americana* fibre

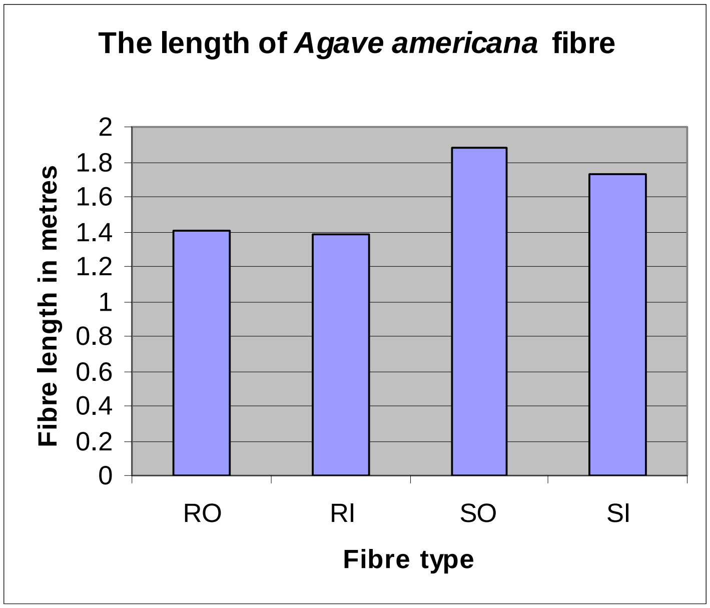


Figure 4.6 **Fibre length of retted and solar-baked outer- and innermost fibre strands of *Agave americana***

Figure 4.6 compares the fibre length of retted and solar baked *Agave americana* fibre strands. Solar baked fibres are longer than retted fibres. On average it shows that solar-baked fibre is longer than retted fibre. Solar-baked outermost fibre is longer than retted outermost, retted innermost and solar-baked innermost fibre. Solar-baked innermost fibre on the other hand is longer than retted outermost and retted innermost fibres.

The retted fibres might be shorter as a result of damage to the ends during the retting process which result in a shorter fibre retrieved from the process.

Figure 4.7 ***Agave americana*** **fibre strands draped over a chair to show the length of the fibre**

Agave americana fibres are aesthetically long and have a natural look as illustrated by Figure 4.7. The bundles have a long effective length that ranges from 1 to 2.8 m. This clearly shows that the fibre length goes beyond the boundaries of a typical fibre. This fibre is somehow longer than sisal fibre which ranges between 100 and 150 cm. The length of the fibre strands depends not only upon the length of the leaf sheath but also on the method used for removing fibre sheath. If fibre is removed from the full length of sheaths as in hand stripping the strands from the middle sheaths may run as long as 2.8 m. The strand length range is longer than 1.27 cm the minimum length of cotton fibre usable as textiles and it can therefore be used as textile fibre in this regard.

Table 4.1 shows that there was a highly significant difference in the length of retted and solar-baked *Agave americana* fibre, $P < 0.01$. Table 4.2 shows the significant difference in the length of outermost and innermost *Agave americana* fibre, $P < 0.05$. Table 4.3 shows the highly significant difference in the length of retted outermost and solar-baked outermost *Agave americana* fibre, $P < 0.01$. Table 4.4 also shows the highly significant difference in the length of retted innermost and solar-baked innermost *Agave americana* fibre, $P < 0.01$.

Table 4.1 T-test analysis of the length of retted and solar-baked *Agave americana* fibre

T-test group	N	Mean	Std. Deviation	Std. Error Mean	P- Value
1	40	140.535	22.4243	3.5456	0.000
2	40	178.380	27.6426	4.3707	

Table 4.2 T-test analysis of the length of outer- and innermost *Agave americana* fibre

T-test group	N	Mean	Std. Deviation	Std. Error Mean	P- Value
3	40	162.360	33.1723	5.2450	0.331
4	41	155.480	30.0461	4.6924	

Table 4.3 T-test analysis of the length of retted and solar-baked outermost Agave americana fibre

T-test group	N	Mean	Std. Deviation	Std. Error Mean	P- Value
5	20	140.750	23.7312	5.3064	0.000
6	20	188.570	28.2136	6.3087	

Table 4.4 T-test analysis of the length of retted and solar-baked innermost *Agave americana* fibre

T-test group	N	Mean	Std. Deviation	Std. Error Mean	P- Value
7	20	138.070	21.0583	4.7088	0.000
8	20	173.175	28.4600	6.3639	

4.5.1.1.2 Width of *Agave americana* fibre

The thickness of the fibre was determined from the microscopic evaluation of the fibre cross-section, as between 100-150 µm as shown in Figures 4.5(a-h). *Agave americana* is a relative thick fibre as a result of the numerous cell ultimates that form the fibre bundle, as can be seen in Figures 4.5(a-h). This property is determinant to the success of *Agave americana* as a textile fibre. Figure 4.5 measured the diameter of *Agave americana* fibres ranging between 100-150 µm.

The fibres above 30-40 µm. feel course, they do not deflect easily, and tend to scratch or stick into the skin. This implies that it is not suitable for clothing manufacture because clothing fibres should be relatively small in diameter (≤ 30µm.). It is a heavy-duty fibre for household items or industrial uses, made with larger diameters ≥ 30-40 µm. (Morris, 1989:2). *Agave americana* fibre is at least 100 µm. thick, which indicate that it would not be suitable for clothes but other household items like carpets can be considered because, Hollen *et al.,* (1988:6) said that large fibres resist crushing-a property that is important in carpets.

4.5.1.2 Tenacity of the experimental *Agave americana* fibre measured according to International standard ISO 2062

The Yarn Tensile strength of *Agave americana* fibre was determined as an indication of the durability of the fibre.

The results of yarn tensile strength and elongation at break of *Agave americana* fibre are reported in Figures 4.8, 4.10 and in Tables 4.5 to 4.8.

A textile fibre, fabric and or fabric which is not durable enough to resist the mechanical forces is of little value, no matter what other performance attributes it may have (Hatch, 1993: 15).

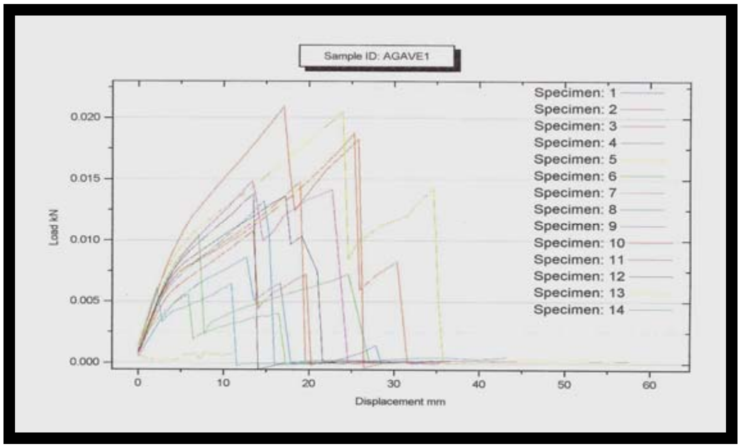


Figure 4.8(a) Load-elongation curve of the innermost *Agave americana* yarns decorticated by retting

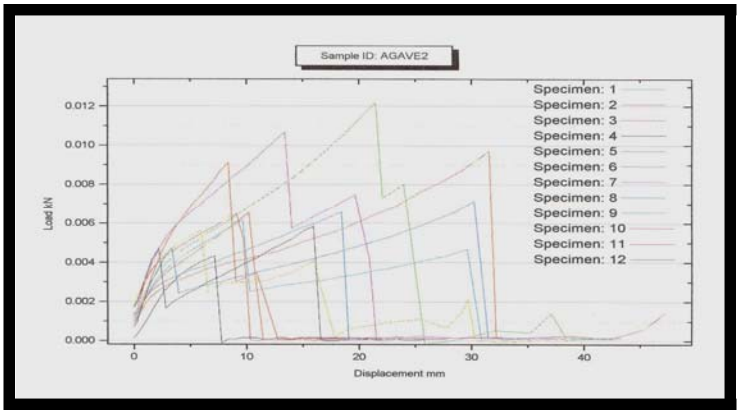


Figure 4.8(b) Load-elongation curve of the outermost *Agave americana* yarns decorticated by retting

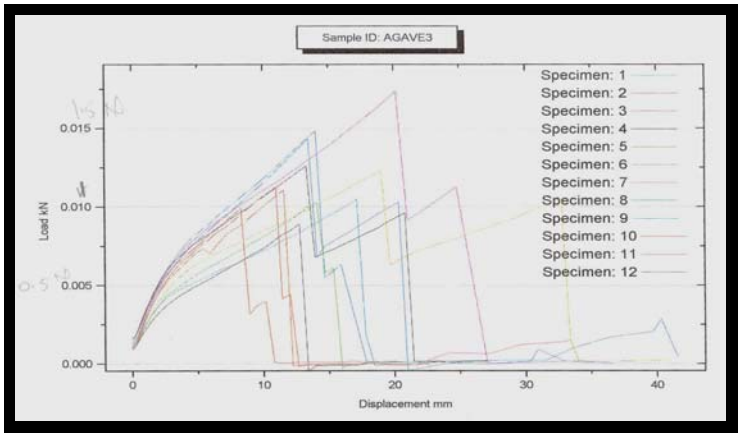


Figure 4.8(c) **Load-elongation curves of the innermost *Agave americana* yarns decorticated by solar baking**

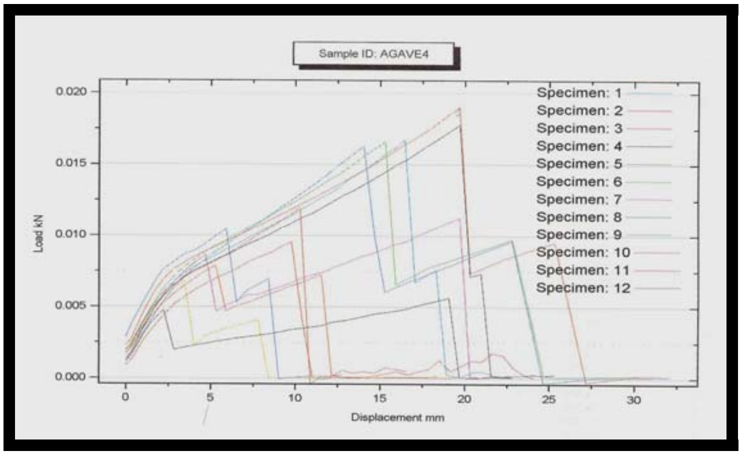


Figure 4.8(d) **Load-elongation curve of the outermost *Agave americana* yarns decorticated by solar baking**

The results presented in Figures 4.8 illustrate the behaviour of the *Agave americana* yarn specimens from zero load and elongation at break up to the breaking point. All the yarns exhibit the same peculiar shaped load-elongation curve with a wide range of values. The shape of the curves resembles a typical strain stress curve but they show a unique second curve. This can be explained by the structure of the yarns.

Each yarn consisted of two fibres. The yarn resisted the external forces, until it reached the maximum breaking strength and broke as seen in the first curve and when the first fibre of the yarn broke the other fibre remained resistant to the external forces in a typical way for a while and continued to elongate for a while and form the second curve as illustrated in the above four tensile strength and elongation at break curves.

The graphs also show that *Agave americana* fibre has a wide range of tenacity deviation. The tensile properties of *Agave americana* fibre are not uniform. This can be explained by the fact that it is a natural fibre and natural fibres are subject to growth irregularities to the extent that fibres from the same plant are not uniform in size (Hollen *et al.,* 1988; Yan Li *et al.,* 2000:2041) and properties. The Analysis of variance tests for *Agave americana* fibre is presented in Tables 4.5 to 4.8.

Table 4.5 Analysis of variance results of yarn tensile strength and elongation at break of retted innermost *Agave americana* fibre

Agave 1	**Max. load (N)**	**Displacement at max. load (mm)**
Mean (m)	12.514	14.151
S.D.	5.790	6.415
C.V.	46.268	45.337
Median	13.610	13.700
Mean + 2.00 SD	24.095	26.982
Mean - 2.00 SD	0.934	1.320
Minimum	0.910	2.370
Maximum	21.310	25.310

Table 4.6 Analysis of variance results of yarn tensile strength and elongation at break of retted outermost *Agave americana* fibre

Agave 2	**Max. load (N)**	**Displacement at max. load (mm)**
Mean (m)	7.596	15.294
S.D.	2.310	8.716
C.V.	30.405	56.987
Median	6.705	12.030
Mean + 2.00 SD	12.215	32.726
Mean - 2.00 SD	2.977	-2.137
Minimum	4.400	6.160
Maximum	12.180	31.580

Table 4.7 **Analysis of variance results of the tensile strength and elongation at break of solar-baked innermost *Agave americana* yarn**

Agave 3	**Max. load (N)**	**Displacement at max. load (mm)**
Mean (m)	11.185	13.028
S.D.	4.241	5.262
C.V.	37.921	40.390
Median	11.165	13.510
Mean + 2.00 SD	19.668	23.553
Mean - 2.00 SD	2.702	2.504
Minimum	0.160	0.180
Maximum	17.500	20.390

Table 4.8 **Analysis of variance results of tensile strength and elongation at break of solar-baked outermost *Agave americana* yarn**

Agave 4	**Max. load (N)**	**Displacement at max. load (mm)**
Mean (m)	13.639	13.398
Median	4.596	6.002
S.D	36.363	44.794
C.V	11.675	14.865
Mean + 2.00 SD	21.831	25.402
Mean - 2.00 SD	3.447	1.395
Minimum	5.630	3.620
Maximum	19.000	19.900

The results in Tables 4.5 to 4.8 exhibited that *Agave americana* fibre has significantly high yarn breaking tenacity.

The tensile strength is the breaking load of a textile. It is the characteristic that provides a general evaluation on quality of a textile (Taylor, 1985:230).

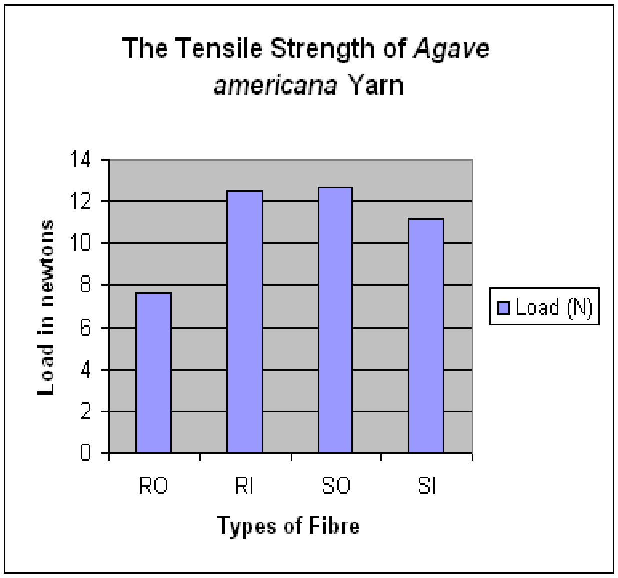


Figure 4.9 Yarn tensile strength of retted and solar-baked *Agave americana* fibre yarn

Figure 4.9 shows the tensile strength of both retted and solar-baked *Agave americana* fibre. It shows that an average load of 10.9835 Newton was necessary to break the yarn. This implies that *Agave americana* yarn can perform well where instantaneous forces act on the yarn either during fabric manufacturing or during the use of the fabric. The solar baked fibres have higher rupture strain which means they are stronger than the retted fibres. The innermost fibres have a high fracture strain while the peripheral fibres have lower tensile strength.

This graph clearly shows that *Agave americana* fibres vary in tensile strength. Some are extremely strong while others are weak. However, the high load it carried before it broke indicated that it is strong enough to be a textile fibre. It is thought that its strength is due to high degree of cellulose polymerization and crystallization processes that may be due to many years of growth. This tensile strength implies that *Agave americana* fibre can function well for furnishing fabrics, placemats, carpets, floor mats and rugs and upholstery fabrics.

According to Mauersberger, (1954:380) the outer leaf sheaths produce the strongest fibres while the inner sheaths produce the weakest fibres, but this is not the case with these results because retted outermost fibres have been the weakest, may be they were over retted since it is difficult to control the process. This fact applied to solar outermost fibres because they are the strongest of all. This figure makes it obvious that the method of leaf partial degradation has an important bearing on fibre strength. Solar baked fibre from both inner and outer is on average stronger than retted fibre. The statistical analysis though put it in perspective.

The results in Table 4.9 indicate that there was no significant difference in the tensile strength of retted and solar baked *Agave americana* fibre yarns since $P > 0.05$. Table 4.10 shows that there was no significant difference in the tensile strength of the outermost and the innermost yarns of *Agave americana* fibre, $P > 0.05$. Table 4.11 shows that there was a highly significant difference in the tensile strength of the retted outermost and the solar-baked outermost yarns of *Agave americana* fibre, $P < 0.05$. The results in Table 4.12 show that there was no significant difference in the tensile strength of the retted innermost and the solar baked innermost yarns of *Agave americana* fibre, $P > 0.05$. In general, the tensile strength of *Agave americana* fibre did not differ significantly.

Tenacity t-test analysis

The t-test analysis was also used to statistically compare the tensile strength of *Agave americana* fibre yarns. The criteria is the term significant at alpha < 0.05 and highly significant difference when $P < 0.01$.

Table 4.9 T-test analysis of the tensile strength of the retted and solar-baked *Agave americana* fibre yarns

T-test group	N	Mean	Std. Deviation	Std. Error Mean	P- Value
1	26	10.24423	5.102235	1.000631	0.223
2	24	11.91208	4.388365	0.895771	

Table 4.10 T-test analysis of the tensile strength of the outer- and innermost *Agave americana* fibre yarns

T-test group	N	Mean	Std. Deviation	Std. Error Mean	P- Value
3	24	10.11750	4.391849	0.896483	0.192
4	26	11.90077	5.079942	0.996259	

Table 4.11 T-test analysis of the tensile strength of the retted solar-baked outermost yarns of *Agave americana* fibre

T-test group	N	Mean	Std. Deviation	Std. Error Mean	P- Value
5	12	7.59583	2.309512	0.666699	0.003
6	12	12.63917	4.595930	1.326731	

Table 4.12 **T-test analysis of the tensile strength of the retted and solar-baked innermost of *Agave americana* fibre yarns**

T-test group	N	Mean	Std. Deviation	Std. Error Mean	P- Value
7	14	12.51429	5.790148	1.547482	0.517
8	12	11.18550	4.241373	1.224379	

4.5.1 3 Elongation at break of *Agave americana* fibre yarn

Elongation is an indication of the ability of a textile to absorb energy. If elongation at break of warp yarns is extremely low, weaving becomes difficult or even impossible. On the other hand, low elongation yarns have greater dimensional stability (ASTM, 1978:20).

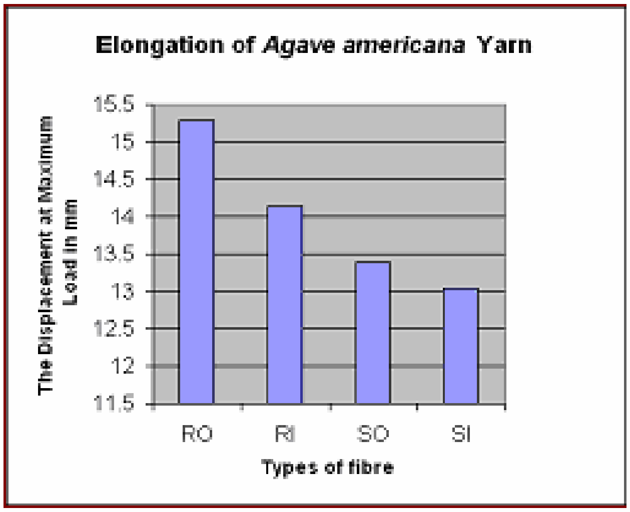


Figure 4.10 **Elongation at break of retted and solar-baked *Agave americana* fibre yarn**

Figure 4.10 shows the elongation at break of both retted and solar-baked *Agave Americana* fibre yarn. Retted fibres have more elongation than solar baked fibres. On the other hand the outermost fibres showed more elongation before break than inner fibres. The fibres are difficult to extend. This means *Agave americana* fibre is rigid and has low elongation. The fibre has low elongation of 6.699% before breaking. It is therefore a rigid fabric. Hatch, (1993:49) says that fabrics with ≥15% elongation are referred to as stretch fabrics while fabrics with ≤15% elongation are rigid fabrics. Hatch, (1993:19) suggests that the minimum breaking elongation for a useful textile fibre should at least be 1%. Although the *Agave americana* fibre is rigid it does qualify to be a textile fibre in terms of elongation.

Morris, (1989:2) prefers elongation above 5% in order to avoid brittleness and give toughness to a fabric. The low elongation-at-break implies that weaving becomes difficult even though not impossible. On the other hand low elongation yarns (and fabrics made from them) have greater stability and durability because rigid fibres usually need more force to break and so give higher product life (Kadolph & Langford, 2002:21). The elongation percentage (6.699%) of *Agave americana* fibre is comparable to that of sisal which ranges from 3.0-7.0% as reported by Reddy and Yang, (2005:26).

In general the elongation of all yarns was in range of 13-15.3 mm. Thus shows low stretch properties. This may be advantageous since it is likely that it has better stretch recovery and shape retention than those fibres that stretch easily like wool but the disadvantageous factor of less elongation may be seen at a time of high speed fabric construction like weaving (Ingle & Doke, 2005:12).

Table 4.13 indicates that there was no significant difference in elongation at break when comparing the retted and solar baked yarns of *Agave americana* fibre, $P > 0.05$. Table 4.14 shows that there was no significant difference in elongation at break of the outer- and innermost yarns of *Agave americana* fibre, $P > 0.05$. Table 4.15 shows that there was no significant difference in elongation at break of the retted and the solar baked outermost yarns of *Agave americana* fibre, $P > 0.05$. Table 4.16 shows that there was no significant difference in elongation at break of the retted and the solar baked innermost yarns of *Agave americana* fibre, $P > 0.05$.

Table 4.13 T-test analysis of elongation at break of the retted and solar-baked yarns of *Agave americana* fibre

T-test group	N	Mean	Std. Deviation	Std. Error Mean	P- Value
1	26	14.67846	7.427288	1.456611	0.436
2	24	13.21333	5.523161	1.127411	

Table 4.14 T-test analysis of elongation at break of the outer- and innermost yarns of *Agave americana* fibre

T-test group	N	Mean	Std. Deviation	Std. Error Mean	P- Value
3	24	14.34625	7.382076	1.506860	0.705
4	26	13.63269	5.823354	1.142054	

Table 4.15 T-test analysis of elongation at break of retted and solar-baked outermost yarns of *Agave americana* fibre

T-test group	N	Mean	Std. Deviation	Std. Error Mean	P- Value
5	12	15.29417	8.715754	2.516022	0.541
6	12	13.39833	6.001613	1.732516	

Table 4.16 T-test analysis of elongation at break of the retted and solar-baked innermost yarns of *Agave americana* fibre

T-test group	N	Mean	Std. Deviation	Std. Error Mean	P- Value
7	14	14.15071	6.415478	1.714609	0.634
8	12	13.02833	5.262110	1.519040	

4.5.1.4 Flexural Rigidity of *Agave americana* fabric

4.5.1.4.1 Bending length as indication of stiffness

Comfort varies from critical as in bed linen to almost unimportant as in wall hangings depending on whether body contact is a factor of interest. Comfort is one of the factors which are evaluated by the evidence of senses (Merkel, 1991:5).

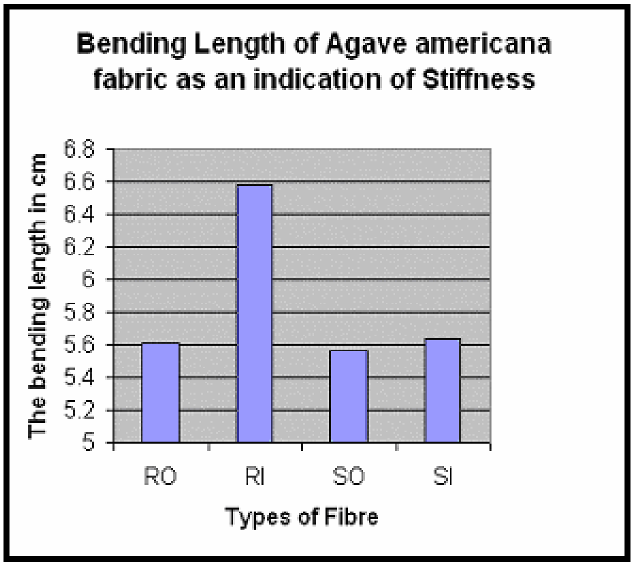


Figure 4.11 Bending length of retted and solar-baked *Agave americana* fabric

Figure 4.11 shows the bending length of *Agave americana* fibre. The bending length *of Agave americana* fibre is high. This indicates that it is a relatively stiff fibre, so it lacks sufficient drape and flexibility. The stiffness is shown in Figure 4.12.

Table 4.17 shows that there was no significant difference in bending length of retted and solar baked *Agave americana* fabric, P > 0.05. Table 4.18 shows that there was no significant difference in bending length of the outer- and innermost *Agave americana* fabric, P > 0.05. Table 4.19 shows that there was no significant difference in bending length of the retted and the solar baked outermost *Agave americana* fabric, P > 0.05. Table 4.20 shows that there was a highly significant difference in the bending length of the retted and the solar baked innermost yarns of *Agave americana* fibre, P < 0.01.

Table 4.17 T-test analysis of the bending length of the retted and solar-baked *Agave americana* fabric

T-test group	N	Mean	Std. Deviation	Std. Error Mean	P- Value
1	12	6.0950	0.65201	0.18822	0.071
2	12	5.6017	0.61987	0.17894	

Table 4.18 T-test analysis of bending length of the outer- and innermost *Agave americana* fabric

T-test group	N	Mean	Std. Deviation	Std. Error Mean	P- Value
3	12	5.5875	0.59328	0.17127	0.55
4	12	6.1092	0.66459	19185	

Table 4.19 T-test analysis of bending length of the retted and solar-baked outermost *Agave americana* fabric

T-test group	N	Mean	Std. Deviation	Std. Error Mean	P- Value
5	6	5.6083	0.41849	0.17085	0.910
6	6	5.5667	0.77343	0.31575	

Table 4.20 T-test analysis of bending length of the retted and solar-baked innermost yarns of *Agave americana* fibre

T-test group	N	Mean	Std. Deviation	Std. Error Mean	P- Value
7	6	6.5817	0.43783	0.17874	0.006
8	6	5.6367	0.49415	0.20174	

4.5.1.4.2 Stiffness of *Agave americana* fabric

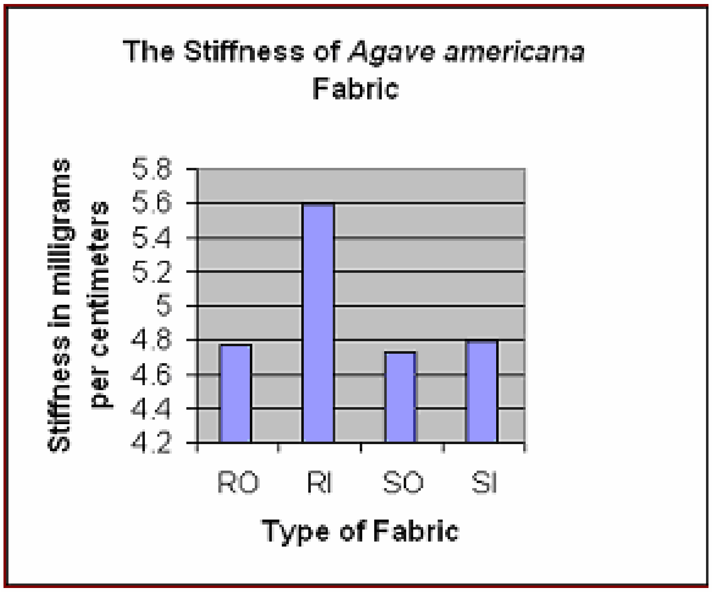


Figure 4.12 Stiffness of retted and solar-baked *Agave americana* fabric

The results on Figure 4.12 agree with those in Figure 4.11. Retted innermost fibre was the stiffest of all and solar-baked the least stiff fibre fabric. In general, *Agave americana* fibre is relatively stiff and should, like linen not have creases pressed firmly into them. Corbman, (1985:263) recommended that deep repeated folds as in tablecloths should be avoided on fabrics made out of rigid textile fibres because these creases eventually cause the otherwise strong yarns to crack and break long before they ordinarily would.

This stiffness may be due to the fact that it is a thick fibre with many fibre ultimates within a single fibre strand. Perhaps it has high lignin content which makes the fibre very stiff and difficult to be spun as it is the case with sunnhemp (*Crotolaria juncea L.*) (Nilesh & Doke, 2005:225). Rigidity also may be explained in terms of the time taken for fibre formation and the manner in which molecules are arranged within a fibre.

The fact that the *Agave americana* plant grows very slowly and the rate at which the fibre is formed may be slow too and in general a high degree of attraction between polymer molecules and slow rate of fibre formation favour the growth of crystals. The crystals also have a long time to align themselves to achieve the most stable orientation during the time natural fibre plant takes to grow and the crystals must be oriented with respect to the fibre axis (Kadolph & Langford, 2002:21; Reddy & Yang, 2005; Smith & Block, 1982:56-57).

The ability of fibre to withstand the bending forces is due to the difficulty in forcing molecules with crystals out of their positions. The fibre with crystalline molecular arrangement is inflexible, strong and with little stretch. This can further be explained by the fact that fibres consist of large hollow sections and hollow sections usually give higher shape factor and hence greater flexural rigidity than solid cross sections.

The flexural rigidity of *Agave americana* may depend partly on the stiffness of polymers and their degree of orientation and crystallinity. The more crystalline the fibre the stiffer they tend to be. Fibre diameter has a much greater influence than type of fibre on flexural rigidity. Cross-sectional shape also influences the flexural rigidity of a fibre. According to Hatch, (1993:114), round and "I" shaped fibres have higher values of stiffness than flat fibres. The flexural rigidities of fibres with other cross-sectional shapes lie between these extremes.

They are relatively stiff and have little resilience. *Agave americana* fibre is rigid and rigidity is the major factor in durability because such fibres require more force to break and so fabrics containing them have higher abrasion resistance and giving a higher product-wear life (Merkel, 1991:195; Smith & Block, 1982:313; Hatch, 1993:21; Kadolph & Langford, 2002:39).

It is possible that the fabric made out of *Agave americana* fibre is difficult to extend and therefore not comfortable for wearing apparel. Its rigidity and stiffness still hamper it from being useful as a versatile clothing textile fibre. Because it is appealing to the eye it is possible to be used satisfactorily for decorative apparel fabrics with loose styles that do not need frequent bending.

4.5.2 Secondary textile properties of *Agave americana* fibre

4.5.2.1 Dimensional stability of *Agave americana* fabric in cold water, in warp and weft directions

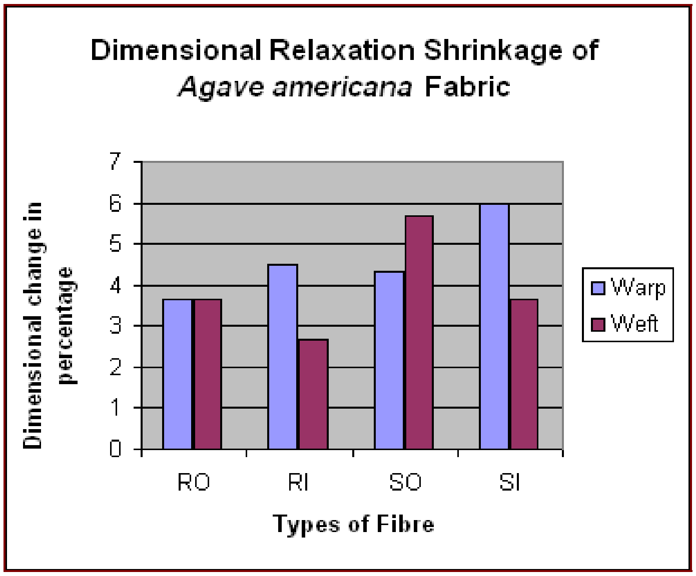


Figure 4.13 Relaxation shrinkage of fabric made of retted and solar-baked *Agave americana* fibre

The mean values for shrinkage in the warp and weft directions of the *Agave americana* fabric are shown in Figure 4.13. According to Figure 4.13 the *Agave americana* fabric exhibited warp and weft relaxation shrinkage of 4.6 and 3.9% respectively with no residual (progressive) shrinkage. Fibres exhibited more relaxation shrinkage lengthwise than crosswise. This can be explained by the fact that warp threads experience more tension than weft during weaving and as a result they shrink more when coming in contact with water for the first time after fabric construction. This is typical behaviour of cellulosic fibres such as cotton and linen (Hollen *et al.*, 1988:318; Smith & Block, 1982:318). This implies that *Agave americana* fabric is dimensionally stable because the fabric will neither shrink nor stretch during use and care after the initial wash cycle. Solar baked fibres showed greater shrinkage than retted fibres.

Table 4.21 shows that there was a highly significant difference in the relaxation shrinkage of the retted and solar baked *Agave americana* fabric, $P < 0.01$. Table 4.22 shows that there was a highly significant difference in the relaxation shrinkage of the outer and inner warp of *Agave americana* fabric, $P = 0.01$. Table 4.23 shows that there was a significant difference in the relaxation shrinkage of the retted and solar baked warp yarns of *Agave* *americana* fabric, $P < 0.05$. Table 4.24 shows that there was a significant difference in the relaxation shrinkage of the retted and the solar baked weft yarns of *Agave americana* fabric, $P < 0.05$. Table 4.25 shows that there was a significant difference in the relaxation shrinkage of the warp fibres and the weft yarns of *Agave americana* fabric, $P < 0.05$.

Table 4.21 T-test analysis of the relaxation shrinkage of the retted and solar-baked *Agave americana* fabric

T-test group	N	Mean	Std. Deviation	Std. Error Mean	P- Value
1	24	3.46	1.351	0.276	0.000
2	24	4.88	1.191	0.243	

Table 4.22 T-test analysis of the relaxation shrinkage of the outer- and inner warp of *Agave americana* fabric

T-test group	N	Mean	Std. Deviation	Std. Error Mean	P- Value
3	12	4.00	0.853	0.246	0.010
4	12	5.25	1.288	0.372	

Table 4.23 T-test analysis of the relaxation shrinkage of the retted and solar-baked warp yarns of *Agave americana* fabric

T-test group	N	Mean	Std. Deviation	Std. Error Mean	P- Value
5	12	4.08	1.084	0.313	0.047
6	12	5.08	1.240	0.358	

Table 4.24 T-test analysis of the relaxation shrinkage of the retted and solar-baked weft yarns of *Agave americana* fabric

T-test group	N	Mean	Std. Deviation	Std. Error Mean	P- Value
7	12	2.83	1.337	0.386	0.002
8	12	4.67	1.155	0.333	

Table 4.25 T-test analysis of the relaxation shrinkage of the waft and weft yarns of *Agave americana* fabric

T-test group	N	Mean	Std. Deviation	Std. Error Mean	P- Value
9	24	4.58	1.248	0.255	0.045
10	24	3.75	1.539	0.314	

4.5.2.2 Crease recovery test: IWS – International Wool Secretariat Test Method No.175

Purpose: To determine recovery of the dry, woven *Agave americana* fabric from creasing.

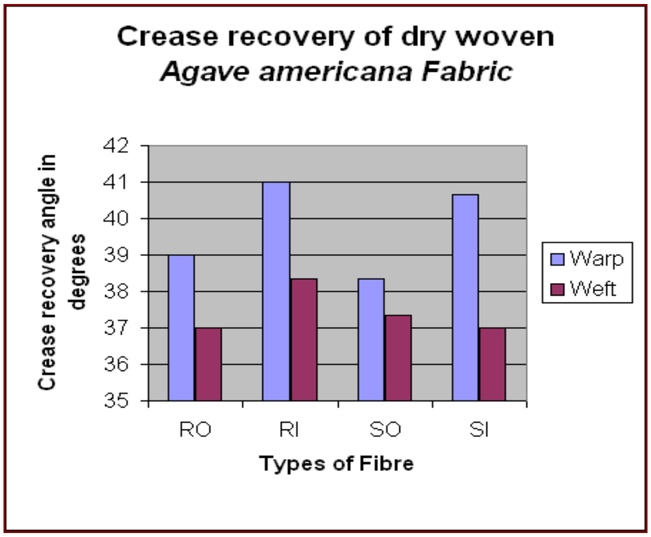


Figure 4.14 Crease recovery of retted and solar-baked dry *Agave americana* fabric

The crease recovery results, shown in Figure 4.14 shows clearly that the warp had a better crease recovery than the weft. The innermost warp fibres had better crease recovery than the outermost warp fibres. The results show that in general, *Agave americana* fabric has low recovery properties, since its mean recovery angle 40° lengthwise and 37° crosswise with the grand total mean angle was 39°. A recovery angle of 0 degrees signifies no recovery from creasing and a crease recovery angle of 180° signifies 100% recovery from creasing.

This is a clear indication that *Agave americana* fibres have low resiliency and wrinkles badly. This is typical behaviour of cellulosic fibre (Kadolph & Langford, 2002:34; Hollen *et al.,* 1988:37). This can be explained by the fact that cellulose fibres have hydrogen bonds holding together the molecular chains and such bonds are weak. When cellulosic fabrics are bent or crushed, the molecular chains move freely to new positions. When pressure is removed these weak internal forces cannot pull the chains back to their original positions so textile remains creased or wrinkled (Corbman, 1985:263; Smith & Block, 1982:75-76).

The *Agave americana* fibre like other natural cellulosic fibres does not have natural cross-links, which strongly hold adjacent molecular chains together and pull them back into position after the fibre bent, thus preventing the formation of wrinkles or creases. *Agave americana* fabrics would require frequent pressing to remove wrinkles, unless the fabric has been treated for crease resistance (Bartle & O'Connor, 1997:60; Corbman, 1985:263; Smith & Block, 1982:75-76).

Table 4.26 shows that there was no significant difference in the crease recovery of the retted fibres and the solar-baked fibres of *Agave americana* fabric, P > 0.05. Table 4.27 shows that there was no significant difference in the crease recovery of the outer and the inner warp fibres of *Agave americana* fabric, P > 0.05. Table 4.28 shows that there was no significant difference in the crease recovery of the retted and the solar-baked warp fibres of *Agave americana* fabric, P > 0.05. Table 4.29 shows that there was no significant difference in the crease recovery of the retted and solar-baked weft of *Agave americana* fabric, P > 0.05. Table 4.30 shows that there was a highly significant difference in the crease recovery of the warp fibres and the weft fibres of *Agave americana* fabric, P = 0.010.

Table 4.26 The t-test analysis of the crease recovery of the retted and solar-baked fibres of *Agave americana* fabric

T-test group	N	Mean	Std. Deviation	Std. Error Mean	P- Value
1	12	39.00	2.730	0.788	0.547
2	12	38.33	2.605	0.752	

Table 4.27 T-test analysis of the crease recovery of the outer- and inner warp fibres of *Agave americana* fabric

T-test group	N	Mean	Std. Deviation	Std. Error Mean	P- Value
3	6	38.67	1.033	0.422	0.126
4	6	41.33	3.777	0.542	

Table 4.28 T-test analysis of the crease recovery of the retted and solar-baked warp fibres of *Agave americana* fabric

T-test group	N	Mean	Std. Deviation	Std. Error Mean	P- Value
5	6	40.50	2.811	1.147	0.587
6	6	39.50	3.332	1.360	

Table 4.29 T-test analysis of the crease recovery of the retted and solar-baked weft fibres of *Agave americana* fabric

T-test group	N	Mean	Std. Deviation	Std. Error Mean	P- Value
7	6	37.50	1.761	0.719	0.679
8	6	37.17	0.753	0.307	

Table 4.30 T-test analysis of the crease recovery of the warp and weft of *Agave americana* fabric

T-test group	N	Mean	Std. Deviation	Std. Error Mean	P- Value
9	12	40.00	2.985	0.862	0.010
10	12	37.33	1.303	0.376	

4.5.2.3 Water absorption of *Agave americana* fabrics

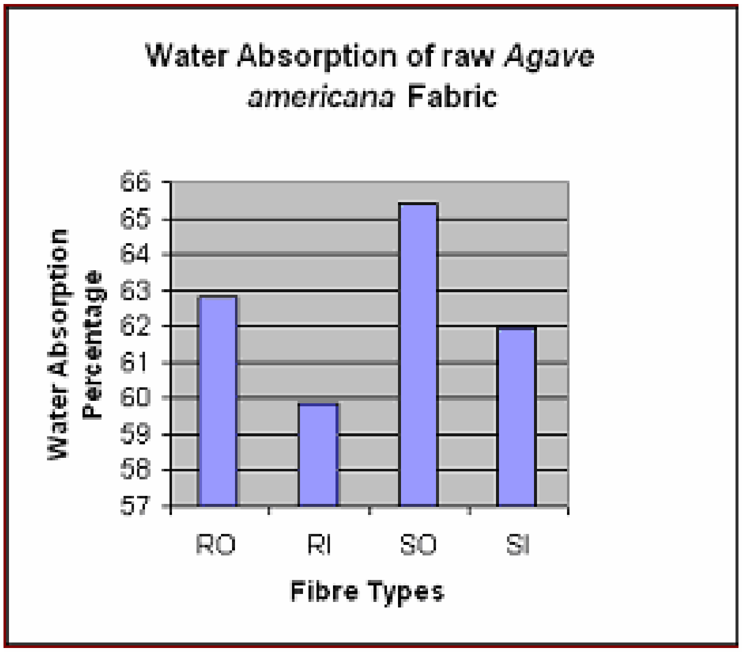


Figure 4.15 Water absorption of retted and solar-baked Agave americana fabric

The results in Figure 4.15 indicate that the outer most fibres have more absorbing properties than the innermost fibres. Solar-baked outermost fibres have the highest water absorbing properties. This can be an indication that they were highly dehydrated because there is less plant water towards the outside of the plant leaf and baking further dried them up. These results are obvious though not significant. Table 4.31 shows that there was no significant difference in the water absorption of the retted and solar-baked fibres of *Agave americana* fabric, P > 0.05.

Table 4.32 shows that there was no significant difference in the water absorption of the outer- and innermost fibres of *Agave americana* fabric, P > 0.05.

Table 4.33 shows that there was no significant difference in the water absorption of the retted and solar-baked outermost fibres of *Agave americana* fabric, P > 0.05. Table 4.34 shows that there was no significant difference in the water absorption of the retted and solar-baked innermost fibres of *Agave americana* fabric, P > 0.05.

The fabrics absorbed much water, (mean value of 65.46%). This is can be explained by the fact that it is a natural, cellulosic fibre and therefore hydrophilic. Cellulose is a hydrophilic glucan polymer with large hydroxyl groups which give the fibre hydrophilic properties (Herrera-Franco & Valadez-Gonzalez, 2003:1; Lyle, 1977:29). The high absorption values can also be explained in terms of the internal structure of the fibre. The cellulosic fibres have hollow regions and these regions give access to water penetration so the fibre absorbs moisture readily (Corbman, 1985:253). It is obvious from the microscopic cross-sections that *Agave american's* outermost fibres have cell ultimates with wider opened hollow regions than those of the innermost fibres which are denser and oblong with small openings as indicated in Figure 4.5.

Table 4.31 **T-test analysis of the water absorption of the retted and solar-baked fibres of *Agave americana* fabric**

T-test group	N	Mean	Std. Deviation	Std. Error Mean	P- Value
1	12	61.3218100	8.9297589	2.57779560	0.600
2	12	64.1788417	16.34534368	4.7i849429	

Table 4.32 **T-test analysis of the water absorption of the outer- and innermost fibres of *Agave americana* fabric**

T-test group	N	Mean	Std. Deviation	Std. Error Mean	P- Value
3	12	65.1665017	12.3703242	3.57100500	0.430
4	12	60.9011725	12.56823568	3.91681226	

Table 4.33 **T-test analysis of the water absorption of retted and solar-baked outermost fibres of *Agave americana* fabric**

T-test group	N	Mean	Std. Deviation	Std. Error Mean	P- Value
5	6	62.8042833	11.51852821	4.70241945	0.750
6	6	65.3946833	15.55982470	6.35227183	

Table 4.34 T-test analysis of the water absorption of the retted and solar-baked innermost fibres of *Agave americana* fabric

T-test group	N	Mean	Std. Deviation	Std. Error Mean	P- Value
7	6	59.8393450	6.12190488	2.49925720	0.801
8	6	61.9630000	19.1005177	7.79775371	

4.5.2.4 Moisture regain of *Agave americana* fabric

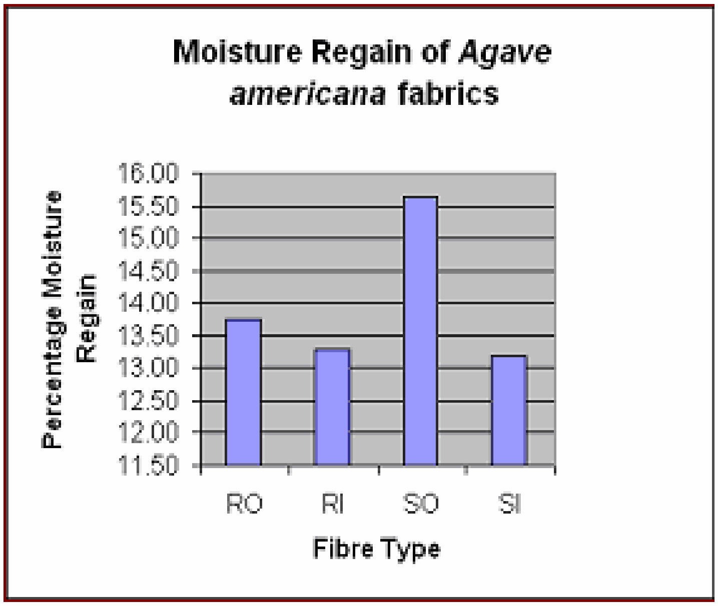


Figure 4.16 Moisture regain of retted and solar-baked fibres of *Agave americana* fabric

Figure 4.16 illustrates the moisture regain of *Agave americana* fabric. The overall percentage moisture regain is 14%. It is comparable to the moisture regain of other natural cellulosic fibres for example, sisal 11%; hemp 12%; jute 13.75%; ramie 8.5%; corn 5.5-9.5%; cotton 8% and linen 12% (Kadolph & Langford, 2002:25; Nakamura, 2000:10; Reddy & Yang, 2005:26; Yan Li *et al.,* 2000:7). The fibre showed hydrophilic properties. This implies that it absorbs enough water to prevent noticeable static build up, except when humidity is very low, another useful property for household textiles.

It takes 30 minutes at 150°C to scorch the *Agave americana* fabric. This clearly indicates that *Agave americana* fibre can be safely washed and ironed with hot temperatures, though too long exposure to high dry heat will scorch it and turn it to light brown. It has a relatively high degree of heat resistance like other natural cellulosic fibres.

The results in Table 4.35 show that there was no significant difference in the moisture regain of the retted and solar-baked fibres of *Agave americana* fabric, $P > 0.05$. Table 4.36 shows that there was no significant difference in the moisture regain of the outer- and innermost fibres of *Agave americana* fabric, $P > 0.05$. Table 4.37 shows that there was no significant difference in the moisture regain of the retted and solar-baked outermost fibres of *Agave americana* fabric, $P > 0.05$. Table 4.38 shows that there was no significant difference in the moisture regain of the retted and solar-baked innermost fibres of *Agave americana* fabric, $P > 0.05$.

Table 4.35 T-test analysis of the moisture regain of the retted and solar-baked fibres of *Agave americana* fabric

T-test group	N	Mean	Std. Deviation	Std. Error Mean	P- Value
1	6	13.5133	1.35951	0.55502	0.458
2	6	14.4067	2.48836	1.01587	

Table 4.36 T-test analysis of the moisture regain of the outer- and innermost fibres of *Agave americana* fabric

T-test group	N	Mean	Std. Deviation	Std. Error Mean	P- Value
3	6	14.6883	2.20809	0.90145	0.214
4	6	13.2317	1.53956	0.62852	

Table 4.37 T-test analysis of the moisture regain of the retted and solar-baked outermost fibres of *Agave americana* fabric

T-test group	N	Mean	Std. Deviation	Std. Error Mean	P- Value
5	3	13.7467	2.02219	1.16751	0.350
6	3	15.6300	2.33232	1.34656	

Table 4.38 T-test analysis of the moisture regain of the retted and solar-baked innermost fibres of *Agave americana* fabric

T-test group	N	Mean	Std. Deviation	Std. Error Mean	P- Value
7	3	13.2800	0.60671	0.35029	0.948
8	3	13.1833	2.35596	1.36021	

4.5.2.5 Dye ability of *Agave americana* fabric

Agave americana fibres dyed satisfactorily with direct dyes without any preliminary bleaching processes. The dyestuff coloured the *Agave americana* fabric with one operation of impregnation, without the aid of an affixing agent. This was expected results, as direct dyes are recommended for cellulosic fibres. This can be explained by the fact that *Agave americana* fibre is a natural cellulosic fibre, which have high moisture absorption, and therefore have good dye ability.

4.5.2.6 Thickness of *Agave americana* fabric

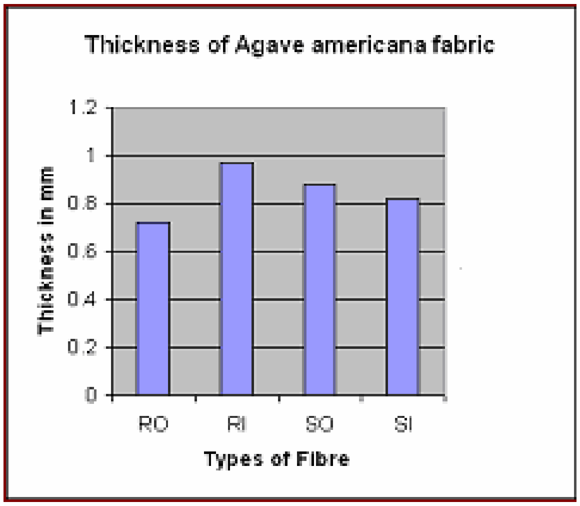


Figure 4.17 Thickness of retted and solar-baked outer- and innermost fibre 9x13 yarn count *Agave americana* fabric

Figure 4.17 shows the little difference in the thickness of the retted outermost and the retted innermost and the solar baked outermost and the solar baked innermost fibres of *Agave americana* fabrics. This indicates that processing method has no significant difference on the thickness of the fibre. In general, fabric made from *Agave americana* fibres had thick-and-thin texture variations in their appearance. This variable thicknesses and texture lend a fibre and its products a natural look. This can be explained by the fact that fibre bundles are never separated into individual fibres and they are subject to growth irregularities and are not uniform in size. This irregularity property is typical of natural leaf cellulosic fibres (Coward & Jangerman, 1969; Hatch, 1993:74, 91; Kadolph & Langford, 2002:47; Miller, 1992:20; Smith & Block, 1982:76).

They vary greatly with grade and within the same leaf. Thin-and-thick areas indicate yarn diameter irregularities which are mostly influenced by fibre heterogeneity which is in turn influenced by growth irregularities of natural fibres. *Agave americana* fabric is thick with a mean value of 0.8479 mm. It is coarse with limited useful properties. The limited useful range relies on the thickness and rigidity of fibre. Morris, (1989:2) says that some thick natural fibres are not suitable for making into clothes and other textiles because of their stiffness.

Table 4.39 shows that there was no significant difference in thickness of retted and solar baked fibres of *Agave americana* fabric, P > 0.05. Table 4.40 shows that there was no significant difference in the thickness of the outermost and the innermost *Agave americana* fabric, P > 0.05. Table 4.41 shows that there was a significant difference in the thickness of the retted and the solar baked outermost *Agave americana* fabric, P < 0.05. Table 4.42 shows that there was a significant difference in the thickness of the retted innermost and the solar baked *Agave americana* fabric, P < 0.05.

Table 4.39 T-test analysis of the thickness of the retted and solar-baked *Agave americana* fabric

T-test group	N	Mean	Std. Deviation	Std. Error Mean	P- Value
1	12	0.84958	0.140380	0.040524	0.988
2	12	0.85042	0.119743	0.034567	

Table 4.40 T-test analysis of the thickness of the outer- and innermost *Agave americana* fabric

T-test group	N	Mean	Std. Deviation	Std. Error Mean	P- Value
3	12	0.81792	0.123757	0.035725	0.226
4	12	0.88208	0.128390	0.037063	

Table 4.41 T-test analysis of the thickness of the retted and solar-baked outermost *Agave americana* fabric

T-test group	N	Mean	Std. Deviation	Std. Error Mean	P- Value
5	6	0.73250	0.052512	0.021438	0.008
6	6	0.90333	0.115873	0.047305	

Table 4.42 T-test analysis of the thickness of the retted and solar-baked innermost *Agave americana* fabric

T-test group	N	Mean	Std. Deviation	Std. Error Mean	P- Value
7	6	0.96667	0.087731	0.035816	0.013
8	6	0.79750	0.106759	0.043584	

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

The first aim of the study was to find an eco-friendly, effective and affordable way to extract *Agave americana* fibre. The second aim was to evaluate the physical structure and the performance properties of the *Agave americana* fibre extracted by selected methods so as to conclude whether it qualifies to be a textile fibre or not. The third aim was to indicate the performance properties which add its value and desirability to consumers and to recommend the end uses of the fibre on basis of its performance attributes and properties. Ribbon retting and solar baking met the first aim and was further used for fibre extraction and the physical structure and performance properties of those fibres were evaluated.

The conclusions reached, were based on the results obtained from selected empirical procedures for fibre extraction and evaluation of performance properties of solar-baked *Agave americana* fibre against retted *Agave americana* fibre.

H0$_1$ Solar baking process is not an effective and efficient method of partial degradation for *Agave americana* leaves for fibre extraction

The hypothesis is rejected because the solar baking is a new, successful, environment-friendly and recently discovered method for degradation of *Agave americana* leaves for fibre extraction. Like the natural retting, it is a great promise to produce high quality *Agave americana* fibres. Solar baking for fibre extraction would help to satisfy future energy and environmental requirements because mild temperatures are required and it has the capacity to replace harsh organic and inorganic chemicals. It is a potential eco-friendly and clean method of partially degrading the leaves for fibre extraction. It is faster and produces longer fibre than the conventional retting.

H0$_2$ The physical structure of *Agave americana* fibre will not be different from that of other natural cellulosic fibres

This hypothesis is rejected because microscopic results indicated that the fibre has a clearly identifiable, unique and specific physical structure.

$H0_3$ There is no significant difference between the physical structure of solar-baked and retted *Agave americana* fibres

The hypothesis is accepted because the results showed no structural difference between solar-baked and retted fibres. The outermost fibres of both solar-baked and retted fibres are more convex shaped with open cells that have well-defined lumens while the innermost fibres different shapes with more collapsed lumens. They both consist of irregular polygonal ultimate cells as shown by Figures 4.5(a-h).

$H0_4$ *Agave americana* fibre has inadequate length-to-width ratio to qualify to be a textile fibre

The hypothesis is rejected because the results indicated that the length-to-width ratio of *Agave americana* fibre is more than 100, the minimum ratio which is recommended for a fibre to qualify to be a textile fibre. The fibres are exceptionally long but also very thick.

$H0_5$ Solar-baked *Agave americana* fibre is not longer than retted *Agave americana* fibre

This hypothesis is rejected because results showed that there was a highly significant difference between the fibre length of retted and solar-baked *Agave americana* fibre strands. Solar-baked fibre was longer than retted fibre. Even though retted fibre was shorter than solar baked fibre, they both exceed one metre. This is an indication that an *Agave americana* fibre strand is a long fibre that is measured in metres.

$H0_6$ *Agave americana* fibre does not have the adequate tensile strength in order to be regarded as a textile fibre

The hypothesis is rejected because results showed that *Agave americana* fibre yarn carries adequate load before breaking. This is an indication that it has adequate tensile strength to be a textile fibre.

$H0_7$ *Agave americana* fibre is not a uniform textile fibre

The hypothesis is accepted because *Agave americana* fibre is not uniform. The results showed that it is not uniform in diameter along the fibre length. The fabric thickness varied because the fibre had irregular thickness, however the thickness difference between solar-baked and retted *Agave Americana* fabric is not statistically significant. It is also not uniform in terms of strength.

$H0_8$ Solar-baked *Agave americana* fibre is not as flexible as retted *Agave americana* fibre

The hypothesis is rejected. The flexural rigidity difference of solar-baked and retted *Agave americana* fibre is not statistically significant. In general *Agave americana* fibre is stiff and therefore lacks flexibility, the characteristic typical of leaf fibres. Its flexural rigidity is not to the extent that it cannot qualify to be a textile fibre. It is possible that it can function as a textile fibre for textile products that require less or no repeated bending like curtains, rugs and table- mats. It does have shortcomings but it is a potential textile fibre.

$H0_9$ *Agave americana* fibre is not a thick textile fibre

The hypothesis is rejected since its diameter ranges within the figures of textile fibres which are classified thick fibres. The *Agave americana* fibre diameter ranged between 100-150 µm. This size range is however thicker than the diameter size range of apparel fibres so it qualifies to be a textile fibre that can be used for household furnishing and rugs. One has a good reason to conclude that *Agave americana* fibre is one of the leaf fibre genera of which Mauersberger, (1954:361) said that are awaiting more efficient cultivation and processing methods that their full potential may be realised.

$H0_{10}$ Solar-baked *Agave americana* fibre has no better elongation property than retted *Agave americana* fibre

The hypothesis is accepted. *Agave americana* is classified as a fibre with low elongation but exceeds the minimum amount of elongation of 1%. This implies that it can withstand the stress placed on it during yarn and or fabric manufacture. The difference illustrated between the retted and solar baked fibre, in the results is statistically insignificant.

$H0_{11}$ *Agave americana* fibre is not a dimensionally stable textile fibre

The hypothesis is rejected because the results clearly indicated that the fibre exhibited the relaxation shrinkage with no residual shrinkage .This implies that it is dimensionally stable.

$H0_{12}$ Solar-baked *Agave americana* fabric is not as dimensionally stable as retted *Agave americana* fabric

The hypothesis is accepted because the results indicated that there were significant and highly significant differences in relaxation shrinkage of solar-baked and retted *Agave americana* fabrics. Solar baked *Agave americana* fabrics resulted in greater relaxation shrinkage than retted *Agave americana* fabrics. The warp of *Agave americana* fabric also exhibited more relaxation shrinkage than its weft.

H0$_{13}$ *Agave americana* fabric has low crease recovery

The hypothesis is accepted, because the results showed that the fabric has limited crease recovery. This property is similar to that of other cellulosic fibres and does not exclude it from functioning as a textile fibre.

H0$_{14}$ Solar-baked *Agave americana* fabric has a significantly different crease recovery property from that of retted *Agave americana* fabric

The hypothesis is rejected. There is no statistically significant difference between the crease recovery of solar-baked and retted *Agave americana* fabric. A highly significant difference is found between the warp and weft of *Agave americana* fabric. Warp has a higher crease recovery than weft. In general *Agave americana* fabric has limited crease recovery.

H0$_{15}$ Solar-baked *Agave americana* fibre has less water absorption property than retted *Agave americana* fibre

The hypothesis is rejected because the difference in water absorption property of solar-baked and retted *Agave americana* fibre is not statistically significant. In general *Agave americana* fibre has good water absorption properties. It makes it possible to dye it and to apply other water based finishes.

H0$_{16}$ Solar-baked *Agave americana* fibre has less moisture regain than retted *Agave americana* fibre

The hypothesis is rejected because the results indicated that moisture regain difference between solar-baked and retted *Agave americana* fibre is of no statistical significance. However, *Agave americana* fibre generally has high moisture regain which is higher than that of cotton, linen, and *Agave sisalana* fibres.

H0$_{17}$ *Agave americana* fibre does not have good dye ability property

The hypothesis is rejected because results showed that the fibre exhibited good dyeing properties with direct dye, even without bleaching. This property adds to its value and desirability in household textiles.

H0$_{18}$ *Agave americana* fibre is not a potential and useful textile fibre

The hypothesis is rejected because the results indicated that the fibre qualifies to be a textile fibre. However, it does not satisfy the softness and flexibility requirements for apparel fibres since it is coarse and stiff. It can successfully be made into hard wearing, elegant fabrics with homey character although the fabrics may lack typical appearance of materials made from other commonly used cellulosic fibres because of its stiffness.

Had it not been for the fact that it is coarse and harsh it could be excellent fibre for linen and towels since, it is absorbent. *Agave americana* fibre has a high tensile strength and low elongation at break (but adequate for it to function as a textile fibre), it might therefore be used for blending the less durable, non-absorbent but soft and pliable fibres in order to produce fabrics of high quality. *Agave americana* fibre in its natural conditions is a large, crispy, rough, bulky, stiff and viable textile fibre that can be used for hard wearing household and recreational items.

Agave americana fibre can be considered a hygienic textile fibre because it can be laundered frequently since it is ideal to think that it can withstand friction due to the fact that it is strong like other natural cellulosic fibres (Down, 1999:107; Tortora, 1978:16). It also withstands high temperatures so can be boiled, washed in hot water and ironed with a hot iron for sterilisation.

H0$_{19}$ The conventional retting of *Agave americana* fibre produces a better quality textile fibre than solar baking process

The hypothesis is rejected because the general trends observed in all the tests indicated that solar baking process produced a better quality fibre than the conventional retting process of non-cellulosic components of leaf. However the results show no significant difference between the fibres of the two processes except for fibre length and relaxation shrinkage where solar-baked fibre exhibited the longer length and a more shrinkage properties than retted fibres. This new process could provide significant economical advantage through shorter treatment time or and better performance properties as against the conventional retting.

RECOMMENDATIONS

Agave americana plant is a potentially useful plant in Southern African countries. *Agave americana* fibre is a viable fibre for household textile products. It is recommended that further research should be carried out on the structure of *Agave americana* fibre. It is also recommended that further research should be done on softening of the *Agave americana* fibre conducted so as to improve its usefulness in apparel. The use of enzymatic processing to improve softness is recommended

.

Agave americana fibres can be used like *Agave sisalana* fibre to provide a complementary texture, carpet backing and background for many furnishing styles because it is very strong and coarse (Goodwin, 1994:16). Its strength implies that it can be used satisfactorily in heavy-duty commercial applications. It is rough so it can be blended with softer fibres such as wool, cotton or synthetic fibres for a softer hand. *Agave americana* fibre has adequate tensile strength so it is reasonable for one to recommend it as a potential textile fibre that can be used in composites. It is also suggested that *Agave americana* fibre be bleached in environmentally friendly ways in order to improve its appeal to consumers.

REFERENCES

Anderson, J.W. & Beardall, J. 1991. *Molecular activities of plant cells. An introduction to plant biochemistry*. London: Blackwell Scientific Publications.

Andrassy, M., Pezelj, E. & Cunko, R. 2005. Single-bath bleaching and fibre bundle size reduction of flax using ultrasound. *American Association of Textile Chemists and Colorists Review*, 20-23.

AATCC. 1990. AATCC Technical Manual**,** *American Association of Textile Chemists and Colorists*, (65). New York.

AATCC. 1978. AATCC Technical Manual. *American Association of Textile Chemists and Colorists* (54). New York.

Ajayi, O.J. 1992. Fabric Smoothness, Friction and Handle. *Textile Research Journal,* 62(1):52-59.

ASTM. 1978. Annual book of ASTM standards part 32. Textiles - yarn, fabrics and general test methods. American Society for Testing and Materials. Philadelphia.

ASTM. 1978. Annual book of ASTM standards part 33. Textiles - yarn, fabrics and general test methods. American Society for Testing and Materials. Philadelphia.

Asian Textile Business. 2002. Addressing environmental issues. Developing and enhancing systems and materials. *Asian Textile Business,* August, 13-15.

Asian Textile Business. 2003. Cellulosic fibres and textiles. Changing for new demand structure. *Asian Textile Business,* April, 22-27.

Asian Textile Business. 2003. Cellulosic fibres and textiles. Creating originality in function and feel. *Asian Textile Business,* November, 18-25.

Asian Textile Business. 2004. “Ingeo” The Crème of the corn crop. *Asian Textile Business,* April, 22-23.

Asian Textile Business. 2004. Cellulosic fibres. Fashion fibre for sustainable society. *Asian Textile Business,* October, 12-15.

Asian Textile Business. 2004. Cellulosic fibres utilize specialty materials for sophistication. *Asian Textile Business,* April, 14-21.

Bagshaw, M. 1982. *Science in Home Economics.* Hong Kong: Oliver and Boyd.

Banik, S., Basak, M.K., Paul, D., Nayak, P., Sardersil, S.C., Sampui, B.C., Ghosh, A. 2003. Ribbon retting of jute, a prospective and eco-friendly method for improvement of fibre quality. National Institute of research on Jute and Allied Fibre Technology. *Indian Council of Agricultural Research* (ICAR), 17(3):183-190.

Bartle, A. & O’Connor, B. 1997. *Textile technology. GCSE design and technology.* Orms Kirk: Causeway.

Baulch, K. & Oppermann, K. 1994. *Textiles and technology* (Australian Technology studies). London: Cambridge.

Booth, J.E. 1968. *Principles of textile testing. An Introduction to Physical methods of testing textile fibres, yarns and fabrics.* Third edition. London: Newness-Butterworth.

Burdett, B.C. 1984. Chemical testing of textiles. *Textiles,* 13(1):44-50.

Buschle-Diller G., Zeronian S.H., Pan N. & Yoon, M.Y. 1994. Enzymatic hydrolysis of cotton, linen, ramie and viscose rayon fabrics. *Textile Research Journal,* 64(5):270-279.

Carter, M.E. 1971. *Essential fibre chemistry*. New York: Marcel Dekker.

Catling, H. 1990. Appropriate technology. *Textiles*, 19(3): 64-66, 71.

Catling, H. 1985. History of measurements of basic yarn properties, Part 2. *Textiles,*14(3):69-73.

Chapman, C.B. 1974. *Chemistry in modern industry series*. Textile book (The book company for the textile world) services.

Collier, A.C. 1974. *A Handbook of Textiles*. Second edition. Oxford:Pergamon.

Compton, N.H. & Hall, O.A. 1972. *Foundations of home economics research. A human ecology approach.* Minneapolis: Burgess.

Cook, J.G. 1984. *Handbook of textile fibres*. Natural fibres. Great Britain: Merrow.

Cornelissen, J.J. 1996. Action research as a mode of teacher. *Journal of Dietetics and Home Economics,* Cape Town.

Corbman, B.P. 1985. *Textile fibre to fabric*. Sixth edition. McGraw-Hill International editions. Home Economics series.

Cowan, M.L. & Jangerman, M.E. 1969. *Introduction to textiles*. Second edition. New-York: Appleton Century – Crafts.

Crawford, R. 1981. *Lignin biodegradation and transformation*. Toronto: Wiley-Interscience Publications.

Cray, S. & Budden, G. 1996. Chemical route to the feel good factor. *Textile Month,* March, 33-37. Dow Corning Ltd.

Cushing, S. 2000. *Textiles technology. Design in the making*. England: Longman.

Dahlgren, R.M.T., Clifford, H.T. & Yeo, P.F. 1985. *The families of monocotyledons: Structure, evolution and taxonomy.* Springer-Verlag. Berlin and Heidelberg.

David, N.S. 1982. *Graft copolymerisation of ligno-cellulosic fibres*. Washington DC: American Chemical Society.

Down, J. 1999. *Textiles technology to GCSE*. Oxford: Oxford University Press.

Easson, D.L. & Molloy, R. 1996. Retting – A key process in production of high value fibre from flax. *Outlook on Agriculture*, 25(4):235-242.

Eiryl, I. 1979. *Practical textile studies. A modern approach to teaching*. London: Heinemann Educational Books.

Etters, J.N. 1999. Cotton preparation with alkaline pectinase: An environmental advance. *Textile Chemist and Colorist & American Dyestuff Reporter*, November, 1(3):33-36.

Flexner, S.B. & Hauck, L.C. 1987. *The random house dictionary of the english language.* Second edition, unabridged. New York: Random House.

Ford, J. 1994. The fibre position. *Textiles Magazine,* autumn 18-11.

Frings, G.S. 1996. *Fashion from concept to consumer.* Englewood Cliffs, New Jersey: Prentice-Hall.

Gay, L.R. 1987. *Educational research competencies for analysis and application.* Fourth edition. Maxwell: Macmillan International Publishing Company.

Gale, E. 1971. *From fibre to fabric.* London: Allman.

Ganggopadhyay, R. & Ghosh, P. 2000. Uncatalysed photografting of poly (methyl metacrylate) from photofunctionalised sisal fibre. Elsevier. *European Polymer Journal,* 36:1597-1606.

Garnsworthy, R.K. & Plate, D.E.A. 1981. The fisherman' knot, *Journal Textile Instute*, (1):26-33.

Greenwood, P.F. 1991. How green are cotton and linen. *Textiles*, (3):22-23.

Gohl, E.P.G. & Vilensky, L.D. 1980. *Investigations in textile science.* Hong Kong: Blackie and Sons.

Gohl, E.P.G. & Vilensky, L.D. 1983. *Textile science: An explanation of fibre properties.* Second edition. Australia: Longman Cheshire.

Goodwin, J. 1994. Hemp – A fibre for future. *Textile Magazine*. Autumn 15-17.

Gove, P.B.C. & The Merriam-Webster Editorial staff. 1976. Webster's third new international dictionary. Springfield Massachusetts, USA: G and C Merriam Company Publisher.

Hall, A.J. 1969. *The standard handbook of textiles*. London: Heywood.

Hall, A.J. 1966. *Textile finishing*. London: Heywood.

Hart, H. 1987. *Organic chemistry. A short course*. Seventh edition. Dallas Geneva: Houghton Mifflin Company.

Hatch, K.L. 1993. *Textile Science*. Minneapolis: West Publishing Company.

Herrera-Franco, P.J. & Valadez-Gozalez. 2003. *Mechanical properties of continuous natural fibre-reinforced polymer composites. Composites*. Part A. Applied Science and Manufacturing, Elsevier Science Ltd .

Hollen, N., Saddler, J., Langford, A.L. & Kadolph, S.J. 1988. *Textiles*. New York: Macmillan Publishing Company.

Hollen, N. & Saddler, J. 1973. *Textiles*. Fourth edition. New York: Macmillan Company.

Hongu, T.P. & Glyn, O. 1990. New fibres. London: Ellis Horwood.

Hoon, J.H. 1994. Die benutting van *Agave americana L.* (Garingboom) as voedingsbron vir skape. (Abstract). Universiteit Oranje-Vrystaat, Bloemfontein.

Howard, C. 1978. *Textile crafts*. London: Pitman.

Hower, G.V. 1976. *Weaving, spinning and dyeing. A beginner' manual*. Englewood Cliffs, New Jersey: Prentice-Hall.

Ishida, T. 1991. *An introduction to textile technology*. Revised edition. JTN Osaka Senken.

Jang, K.O. & Yeh, K. 1993. Effects of silicone softeners and silane coupling agents on performance properties of cotton fabrics. *Textile Research Journal*, 63(10):557-565.

Jaques, H.E. 1975. *Plants we eat and wear*. Second edition. New York: Dover.

Jones, G. 1990. *Finding out about textiles*. Cheltenham, England: Stanley Thornes.

Joseph, M.L. 1981. *Introductory textile science*. Fourth edition. California State University. New York: North Ridge.

Joseph, M.L. 1986. *Introductory textile science*. Fifth edition. California State University. New York: North Ridge.

Joseph, P.V., Mathew, G., Joseph, G., Groeninck, G. & Thomas, S., 2003. *Dynamic mechanical properties of short sisal fibre reinforced polypropylene composites.* Elsevier Science Ltd, 34(3):276-290.

Judy, D.T. Harmon, H. & Ramey, J.R. 1994. Relationship between cotton fibre strength and molecular weight distributions: HIV Calibration standards. *Textile Research Journal* 64(10):557-562.

Kapdan, I.K., Kargi, F., McMullan & Marchant, R. 2000. Effect of environmental conditions on biological decolorization of textile dyestuff by C versicolor. *Enzyme and Microbial Technology,* 26:381-387.

Kashyap, D.R., Vohra, P.K., Chopra, S. & Tewari, R. 2001. Application of pectinases in commercial sector: a review. *Bioresource Technology*, 77(3):215-227. Elsevier Science.

Kilgour, O.F. 1976. *At home with science*. London: Heinemann.

Kadolph, S.J. & Langford, A.L. 2002. *Textiles*. New Jersey: Prentice Hall.

Kirk, T.K., Higuchi, T. & Chang, H. 1980. *Lignin Biodegradation: Microbiology and chemistry and potential application V I.* Florida: CRC Press Inc.

Kundu, A.B., Ghosh, B.S. & Chakrabarti, S.K. 1993. Advanced bleaching and softening of jute pre-treated with polysaccharide degrading enzymes. *Textile Research Journal,* 63(8):451-454.

Kundu, A.B., Ghosh, B.S., Chakrabarti, S.K. & Ghosh, B.L. 1991. Enhanced bleaching and softening of jute by pre-treatment with polysaccharide degrading enzymes. *Textile Research Journal,* 61(12):720-723.

Kutzer, W. 2001. *Framework for secondary curriculum in family and consumer science*. State Board for Vocational and Technical Education. Bismarck.

Labarthe, J. 1975. *Elements of textiles*. New York: Macmillan.

Lomax, G.R. 1987. The polymerization reaction. Part 2 – Natural textile polymer. *Textiles,* 16(3):76-83.

Lyle, D.S. 1976. *Modern textiles*. New York: John Wiley and Sons.

Lyle, D.S. 1977. *Performance of textiles*. New York: John Wiley and Sons.

Mairet, E. 1942. *Hand weaving and education*. R.I.D. London: Faber and Faber.

Maloney, T.G. 1978. Chemicals from pulp and wood waste production and application *Chemical Technology Review*, no.101. ndc.

Marsh, J.T. 1947. Textile *science: An introductory manual.* London: Chapman and Hall

Mathews, K.C. & Van Holde, K.E. 1996. *Biochemistry*. Second edition. Menlo Park, California: Benjamin Cummings.

Mauersberger, H.R. 1954. *Mathew's textile fibres, their physical, microscopic and chemical properties.* Sixth edition. New York: John Wiley and Sons.

McIntyre, J.E. 1971. *The chemistry of fibres. Studies in chemistry.* Great Britain: Edward Arnold.

Meirowitz, R. 2003. Water proosistance. *American Association of Textile Chemists and Colorists Review,* March, 3(1):19-22.

Merkel, R.S. 1991. *Textile product serviceability.* New York: Macmillan.

Mignoni, G. 1999. *Cannabis as a licit crop: Recent developments in Europe*. Kenaf Eco-fibre, Rome.

McIntyre, J.E. 1995. *Textile terms and definitions*. Tenth edition. The Textile Institute, Great Britain.

Miller, E. 1992. *Textiles properties and behaviour.* London: B.T. Batsford.

Miller, E. 1968. *Textiles properties and behaviour*. London: B.T. Batsford.

Milne, L. & Milne, M. 1967. *Living plants of the world*. London: Thomas Nelson and sons.

Morris, W.J. 1989. *Fibre shape and fabric properties. Textiles,* (18):1, 2-9.

Morse, C. 2004. *Ecology and evolutionary biology*: Conservatory & Gardens. Storrs. University of Connecticut. 1-2.

Mouly, J.G. 1970. *The science of educational research.* Second edition. New York: D. Van Nostrand Company.

Nakamura, A. 2000. *Fibre science and technology.* Plymouth: USA: Science Publishers Inc.

Needle, H. L. 1981. *Handbook of textile fibres, dyes and finishes*. New York: Davis Garland STPM press.

Neuman, W. L. 1997. *Social research methods. Qualitative and quantitative approaches*. London: Allyn and Bacon.

Newton, A. 1993. *Small scale textiles. Fabric manufacture. A handbook.* United Kingdom: Intermediate Technology Publications.

Nobel, P.S. 1994. *Remarkable Agaves and Cacti*. New York: Oxford.

Nobel, P.S. 1988. *Environmental biology of Agaves and Cacti*. New York: Cambridge.

Ossala, M. & Galante, Y.M. 2003. Enzyme, microbial technology. Elsevier, *Science Direct,* October (34):177-186.

Page, C.E. 1964. *Textiles*. London: Fredrick Muller.

Pearl, I.A. 1967. *The chemistry of Lignin library of congress.* USA.

Picton, J. & Mack, J. 1989. *African textiles*. Second edition. Britain: British Museum.

Planning and Managing Projects Pty. Ltd 1996. *Pre-feasibility studies of hemp products prepared for the rural industries.* Australia: Research and Development Corporation.

Pomero E. & Pomro, J. 1988. *Textiles for you*. London: Hutchinson.

Praff, B. & Loiza, P. 1992. Choosing research methods. Data collection for development worker. *Development Guidelines no.7*. Netherlands: Oxfam.

Ramaswamy, G.N., Ruff, C.G. & Boyd, C.R. 1994. Effect of bacterial and chemical retting on kenaf fibre quality. *Textile Research Journal,* 64(5):305-308.

Reddy, N. & Yang, Y. 2005. Long natural cellulosic fibres from cornhusks: Structure and Properties. *American Association of Textile Chemists and Colorists* Review, July 24-27.

Reese, E.T. 1963. *Enzymatic hydrolysis of cellulose and related materials*. Symposium publications division. Oxford: Pergamon.

Ridley, A. & Williams. 1974. *Simple experiments in textile science*. London: Heinemann.

Rolf, M.T., Dahlgren, R.M.T. & Clifford, H.T. 1982. *The monocotyledons. A comparative study*. London: Academic Press Inc.

Schoeser, M. & Rufey, C. 1989. *English and American textiles from 1790 to the present*. Thames and Hudson.

Schubert, W.J. 1965. *Lignin biochemistry*. New York: Academic Press.

Silvertown, J. & Charlesworth, D. 2001. *Introduction to plant population biology*. Fourth edition. London: Blackwell Science.

Smith, B.F. & Block, I. 1982. *Textiles in perspective*. Englewood Cliffs, London: Prentice-Hall.

Smith, G. 2003. *Sasol first field guide to Aloes of Southern Africa*. Cape Town: Struik Publishers.

Spencer, D.J. 1989. *Knitting technology*. Second edition. Oxford: Pergamon.

Steward, D., Azzini, A., Hall, A.T. & Morrison, I.M. 1997. Sisal fibres and their constituent non-cellulosic polymers. Elsevier. Industrial Crops and Products. *An International Journal,* (6):17-26.

Stout, E.E. 1970. *Introduction to textile*. London: John Wiley & Sons.

Sunset Magazine and Sunset Books. 1967. *Dessert gardening*: Menlo Park, California.

Svedova, J. 1990. Industrial textiles. *Textile science and technology*. Elsevier.

Taylor, H.M. 1985. Physical testing of textiles. *Textiles*, 14(1):21-28.

Taylor, M.A. 1972. *Technology of textile properties***.** London: Forbes.

Textile Institute and International Textiles. 1991. World review of textile design. *Textile Institute and International textiles*. New York.

The American Home Economics Association. 1974. *Textiles and clothing section*. *Textile Handbook*. Library of Congress Cataloguing in publication data. New York.

The Mechanical Age Library. 1964. *Textiles*. London: Muller Frederick.

The Northern India Textile Research Association. 1995. Indigenous technology for textile effluent treatment. Textile and the environment. *Textile Month,* (6):37.

The Textile Institute 1958. *Identification of textile materials*. Fourth edition. The Textile Institute, Manchester.

The World Book Encyclopaedia. 1969. Volume 13. London : Field Enterprises Educational Corporation.

Thomson, H. 1974. *Fibres and fabrics of today*. London: Heinemann.

Torston, H. & Boalt, G. 1967. *Educational research and educational change. The case of Sweden.* London: John Wiley and sons.

Tortora P.G. 1978. *Understanding textiles*. New York: Macmillan.

Trotman, E.R. 1964. *Dyeing and chemical technology of textile fibres*. Third edition. London: Griffin.

Ueda, M. 1994. Cellulase treatment of cotton fabrics. Part II: Inhibitory effect of surfactants on cellulase catalytic reaction. *Textile Research Journal* 64, (10):615-618.

Warrnambool Wollen Co. 1982. First solar installation for wool scouring now in operation at Warrnambool Woollen. *Textile Journal,* April/May, 5-6.

Weaver, W.J. 1984. Analytical methods for a textile laboratory. Third edition. *American Association of Textile Chemists and Colorists*, Research Triangle park, N.C

Western Michigan University. 2002. Family and consumer sciences. *Textile and apparel studies*. Kalamazoo, College of Education.

Wilson, K. 1979. *A history of textiles.* Coloranda: Westview.

Wingate, I.B. 1976. *Textile fabrics and their selection.* Seventh edition. Library of congress in publication data. Prentice-Hall: New Jersey.

Wingate, B. & Mohler, F. 1984. *Textile fabrics and their selection*. Eigth edition. Prentice-Hall : New Jersey.

World Book. 1969. *The world book encyclopaedia*. Volume 13. London: Field Enterprises Educational Corporation.

Wynne, A. 1997. *Textiles*. The motive series. London: Macmillan texts for industrial, vocational and technical education.

Yachmenev, G.V. Blanchard, J.E. & Lambert, H.A. 1999. Study of the influence of ultrasound enzymatic treatment of cotton fabric. *Textile Chemist and colourist & American Dyestuff Reporter,* 1(1):47-51.

Yan, Li, Yin-Wing Mai & Lin Ye. 2000. Fibre and its composites: A Review of resent developments: Composites science and technology. *Elsevier Science Ltd,* Vol. 60 no. 11, 8, 2037-2055.

Young, R.A. & Rowell, R.M. 1986. *Cellulose structure, modification and hydrolysis*. New York: Wiley-Interscience Publication.

APPENDIX

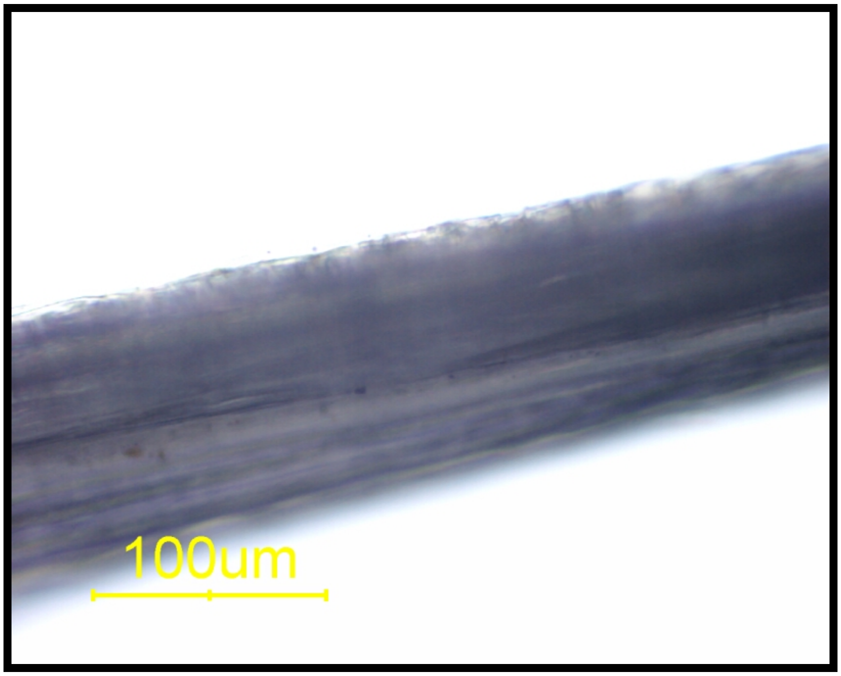
The ready to harvest xeromorphic and stiff *Agave americana* plant leaves forming a 90°angle

***Agave americana* plant with its spine edged, boat-shaped leaves arranged in a rosette**

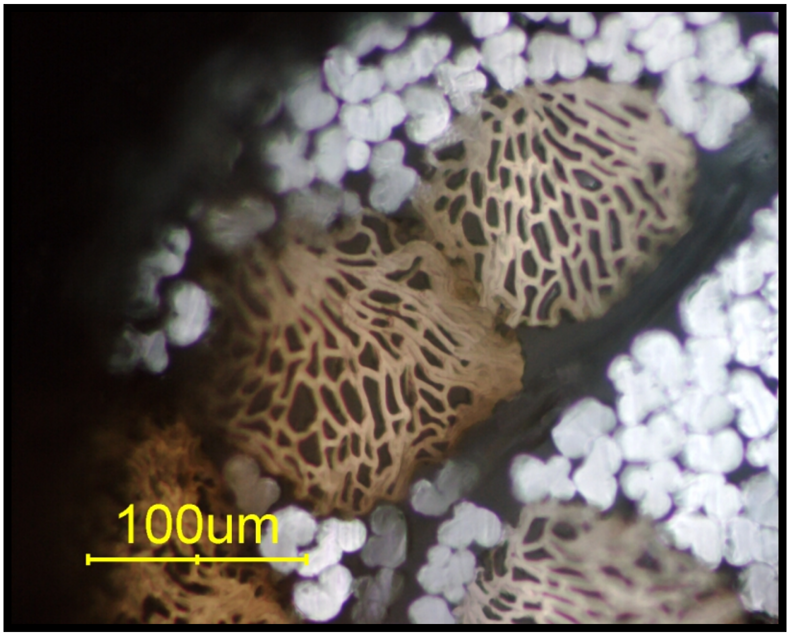
Open yellow inflorescences developed on the upper position of central flower stalks of *Agave americana* plants

The leaves of *Agave americana* plant start withering after blossoming

After blooming the plant dies



Cross-sectional view of retted outermost fibre structure



In comparison to the structure of cotton and linen, *Agave americana* fibres have unique big hollow structures

ABSTRACT

The overall goal of the study was to evaluate solar baking against conventional retting as decortication methods of *Agave americana* fibre in terms of textile properties.

The study focused mainly on:

- Identification of the most cost-effective, efficient and eco-friendly methods of partial degradation of *Agave americana* leaves to release the textile fibre.
- Evaluating the physical structure of *Agave americana* fibre decorticated by solar baking and conventional retting.
- Evaluating the essential textile properties and some secondary textile properties of *Agave americana* fibre fabric to predict its possible end uses in textiles.

Preliminary comparison of ten different leaf partial degradation methods, suggested the feasibility of investigation of solar baking as a partial degradative method for fibre extraction. Conventional retting was chosen to be the control method. The solar baking process was found successful, energy saving, more eco-friendly and faster than conventional retting of the *Agave americana* leaves.

Fibre decortication was entirely done by hand after the leaves were partially degraded. After hand decortication the fibres were then knotted, twined and woven into fabric. Long beautiful fibre with natural look was obtained from *Agave americana* leaves. *Agave americana* fibre in its natural condition is coarse, harsh and stiff when dry. Fibre identification tests confirmed that *Agave americana* react like all other natural cellulosic fibres in burning behaviour, solubility and Shirlastain C identification tests. Microscopic evaluation indicated that the fibre consisted of a number of irregularly sized and shaped individual cells, each with a lumen. The Shirlastain C colour reaction and the cross-sectional view of the *Agave americana* fibre are unique and would be useful to distinguish *Agave americana* from other natural cellulosic fibres.

The physical structure and the length of *Agave americana* fibre were evaluated while the fibre was in a fibre form. The retted and solar baked *Agave americana* fibre yarn was

evaluated for tensile strength and elongation at break. The thickness, stiffness, dimensional stability, crease recovery, dye ability, moisture regain and water absorption of the *Agave americana* fabric of the solar baked and retted fibres were evaluated.

Agave americana fibre showed adequate tensile strength and elongation at break to be a useful textile fibre. No significant differences were found between the tensile strength of the retted and the solar baked fibre. *Agave americana* exhibited excellent dimensional stability; it showed relaxation shrinkage with no residual shrinkage. *Agave americana* showed good water absorption and moisture regain properties. *Agave americana* accepted the direct dye easily even without bleaching. The *Agave americana* fibre fabric was found to be relatively stiff. *Agave americana* exhibited poor crease recovery no significant difference in crease recovery were found between retted and solar baked fibre fabrics, but the warp yarns recovered significantly better from creases than the weft yarns. *Agave americana* fibre is a promising speciality cellulosic fibre which has a potential of being valuable for current as well as future applications. The research proved that solar baking is an efficient, fast and environment friendly alternative to conventional retting as a partial degradation method for *Agave americana* fibre decortication.

KEY WORDS

Conventional retting, solar baking, leaf partial degradation, fibre decortication, *Agave americana* textile fibre, tensile strength, stiffness, dimensional stability, crease recovery, microscopic view.

OPSOMMING

Die oorkoepelende doel van die studie was om son-oond-bak teenoor konvensionele roting as ontveselings metode van *Agave americana*-vesels in terme van tekstieleienskappe te evalueer. Die fokus van die studie was op:

- Identifisering van die mees koste-effektiewe, doeltreffende en omgewingsvriendelike metodes vir gedeeltelike afbreking van *Agave americana*-blare vir ontveseling om tekstielvesels vry te stel.
- Evaluering van die fisiese struktuur van son-oond-en konvensionele roting ontveselde *Agave americana* vesel.
- Evaluering van die essensiële tekstieleienskappe en sommige sekondêre tekstiel-eienskappe van *Agave americana* tekstielstowwe om die moontlike tekstielgebruike daarvan te voorspel.

Voorlopige toetse met tien verskillende gedeeltelike blaar-ontveselingmetodes het uitgewys dat dit wenslik sou wees om son-oond-bak te gebruik vir die afbreking van die *Agave americana* blaar om dit te ontvesel. Konvensionele roting is as kontrole-metode gebruik. Daar is gevind dat die son-oond-bak proses suksesvol, energiebesparend, meer omgewings-vriendelik en vinniger is om *Agave americana*-blare te ontvesel as konvensionele roting.

Die ontveseling is na die son-oond-bak proses volledig met die hand gedoen. Die vesels is daarna geknoop, getwyn en in tekstielstof geweef. Die *Agave americana*-vesels is mooi lank met 'n natuurlike voorkoms. *Agave americana*-vesel is in sy natuurlike vorm grof, hard en styf terwyl dit droog is.

Veselidentifikasie-toetse het bevestig *Agave americana* soos alle ander natuurlike sellulose-vesels reageer in brandtoetse en oplossing-toetse. Mikroskopiese ondersoek van die lengte en dwarsdeursnit van die vesel en die Shirlastain-kleurreaksie het aangetoon dat die dwarsdeursnit-vorm van die vesel uniek is, en dat die twee eienskappe gebruik sal kan word om *Agave americana*-vesels van ander natuurlike sellulose-vesels te onderskei. Die dwarsdeursnit van die vesels toon 'n hele aantal onegalig gevormde individuele selle van verskillende dikte, elkeen met 'n lumen.

Die fisiese struktuur van die *Agave americana*-vesel is bepaal. Die roting en son-oond ontveselde *Agave americana*-garing is gebruik om die treksterkte en breekverlenging van die vesel te bepaal. Die dikte, styfheid, dimensionele stabiliteit, kreukelherstel, kleurbaarheid, vogbyslag en vogabsorpsie van die son-oond- en roting-ontveselde *Agave americana*- tekstielstof is geëvalueer.

Die *Agave americana*-vesels het voldoende treksterkte en breekverlenging om suksesvol as tekstielvesels gebruik te word en daar was geen betekenisvolle verskil tussen die treksterkte en breekverlenging van die son-oond- en die roting- behandelde vesels nie.

Die *Agave americana*-vesels het uitstekende dimensionele stabiliteit getoon, daar was normale verslapping-krimping maar geen progressiewe krimping nie. Dit het goeie vogabsorpsie en vogbyslag-eienskappe ge-openbaar. Dit het direkte kleurstof goed ge-absorbeer, selfs sonder ‘n bleikmiddel.

Die tekstielstof van *Agave americana*-vesel was styf met hoë buigstyfheid. Dit het ook swak van kreukels herstel en daar was ook geen betekenisvolle verskil in kreukelherstel van tekstielstofvesels deur die son-oond verwyder en diè deur roting verwyder nie.

Agave americana-vesel is ‘n spesialiteits-sellulosevesel met die potensiaal om huidig en in die toekoms toepassing in tekstielprodukte te hê. Die navorsing het bewys dat die son-oond proses vir Agave *americana*-ontveseling ‘n doeltreffende, vinnige en omgewings-vriendelike alternatief vir konvensionele roting is.

KERNWOORDE

Konvensionele roting, son-oond-bak, gedeeltelike blaar afbreking, ontveseling, *Agave americana*-vesel, treksterkte, styfheid, dimensionele stabiliteit, kreukelherstel, mikroskopiese voorkoms.