Developing and Characterizing New Materials Based on Natural Fibres and Waste Plastic

By

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A thesis submitted to the department of Chemical Engineering in conformity with the requirements of the degree of Doctor of Philosophy

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Kingston, Ontario, Canada

December, 2008

Abstract

Natural Fibre Composites (NFCs) offer new opportunities to mitigate negative impact of engineering activities on the environment. Due to their lost cost, light weight and environmental benefits, they find applications in building, furniture and automotive industry. This study seeks to improve mechanical properties of composites made from waste recyclable plastics and natural fibres from agricultural byproduct sources such as *Agave americana* leaves, corn, wheat and seed flax straws. The approach used is a holistic one which includes investigating the availability and properties of natural fibres and their composites with waste plastic for use in Canada and Lesotho, a small country in Southern Africa. The social and environmental implications of using these materials are also investigated.

In both Lesotho and Canada, there are enough raw materials which can be used in NFCs if the necessary environment is developed. The unique microstructural and interfacial behaviour of *Agave americana* fibres were investigated and their possible impact on the composites forecasted. Composites made with a variety of underutilized natural fibres: *Agave americana*, corn, seed flax and wheat were also manufactured and tested. The addition of natural fibres and milled straw to the waste plastic improved mainly the tensile and flexural moduli of the composites. The environmental properties of NFCs were also analyzed through a case study using Life Cycle Assessment (LCA) as tool. The results suggest that NFCs could be seen as a more environmentally friendly alternative than conventional composites.

Co-authorship

All the work in this report was done under the supervision of Professor Caroline Baillie and therefore she is the main coauthor in all the chapters. The author collected the flexural and tensile properties data in chapters 6 and 7 together with the help of the following Queens University Engineering chemistry students whom he supervised in their fourth year projects: Ryan Marien, Christina Wu, Lisa Chong and Andria Bowie. Some of the equations in chapter 5 were reviewed and corrected by Dr Darko Matovic from the department of Mechanical Engineering at Queens University.

Acknowledgements

I am indebted to you my parents, Fusi and ‘Maleboli Thamae who despite your little education, have shown a special interest in providing it for your children. I always remember your hard work and desire to see a better future for your children.

I am very grateful to you, Professor Caroline Baillie for all the support and patience in your supervision. You have made this, “my improbable journey” an interesting one. Your enthusiasm and firm belief in seeking to do be of benefit to the disadvantaged had positively added to my world view.

I thank you my brothers Zachia and Ret’selistsoe Thamae, my sister in law Nkeleli Thamae and my younger sister ‘Makeuna Thamae, you were always there for moral support.

I was blessed to meet and work with you Professor Darko Matovic in your design and building of the hotpress and in helping us through a tough process of grant applications for developing countries; I learned a lot from you.

It has also been a pleasure to work closely with the following people at Queens University, Ryan Marien, Stanley Aghedo, Steven Hodgson, Lauren Sharpe, Kelly Sedore, Andrea Liskova, Charlie Coney, Dr Scott Parent and many other people in and outside the department of Chemical Engineering.

I would also like to thank John Baker, Grant Moorecraft and many other Ontario farmers who supplied waste plastic and fibres from their farmers. We thank Biolin Research Inc in Saskatchewan also for providing us with flax fibres for this work.

Lastly we thank all the organizations without whose financial assistance; this work would be impossible, Queens University, Ontario Ministry of Agriculture and Rural Affairs (OMAFRA), Auto 21, Way Memorial Award and National Sciences and Engineering Research Council (NSERC).

Statement of originality

I, Thimothy Molefi Thamae certify that the work presented in this thesis is original unless otherwise noted.

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Chapter 1: General introduction

1.1 Composite materials and objectives of this study

Composite materials consist of two or more components, at least one of which is reinforcement and another, a matrix. The matrix acts as a binder, which keeps the reinforcement together and transfers load to it. It also contributes toughness (the ability to absorb energy) to the composite which natural fibre alone would not have. The reinforcement bears load and provides stiffness and strength to the composite. Based on the premise of "the whole is better than the sum of its parts," the material is created with properties that are better than those of the components that make it. Natural Fibre Composites (NFCs) are normally made of plastic as a matrix (although cements and other materials can also be used as matrices) and natural fibres as reinforcement. Due to their lost cost, light weight and environmental benefits, these materials are presently replacing glass and other human-made fibres in automotive industry, wood in furniture industry and some structural products in building applications.

NFCs are not a new idea. Wood, for example, is a complex form of biodegradable natural fibre composite made of natural fibres in a matrix of lignin and hemicelluloses. Artificial composite materials are as old as the known history of humankind. From the traditional mud buildings reinforced with ground pieces of rocks to the modern cement reinforced with concrete and plastics reinforced with glass and carbon fibres for spaceships, examples of composite materials are everywhere.

In the area of plastic composites, major improvements came towards the end of the first half of the 20th century when glass fibres were used to reinforce thermoplastics and thermosets. Other synthetic fibres like carbon and aramid followed. These materials in the form of fibres are preferred not only because of their high strength but also due to the high surface to volume ratio, which provides much area of contact between the matrix and the reinforcement for a more efficient load transfer.

With the growing concern for the impact of human activities on the environment, the idea of using natural instead of synthetic fibres for reinforcement in composites, especially plastic composites developed. The reason behind this research is the perceived environmental benefits of natural fibres and their abundance and low cost compared to synthetic fibres. Whereas most of the initial fabricated composites in this area focused on using thermosets as matrices, partly due to their ease of fabrication, the fact that thermosets are hard to recycle has led to a shift. The focus is now towards the use of more recyclable thermoplastics.

Nevertheless, despite the abundance of waste thermoplastic and underutilized sources of natural fibres, which are normally byproducts of seed production or other plant uses, conventional studies in this area give much attention to the virgin raw materials. The present study seeks to depart from this approach. This study seeks to optimize the mechanical properties of composites made from waste recyclable plastics and natural fibres from byproduct sources such as *Agave americana* leaves, corn, wheat and seed flax (flax grown for seed) straw. It also investigates the availability of the materials, their environmental and even possible social impact of their use in NFCs. In this way, our laboratory investigations are informed by the societal and environmental needs. The emphasis is based on seeking low cost raw materials and processing methods for possible building applications for the benefit of small scale farmers and industries in Canada and cooperatives in Lesotho. Since the aim is to put the results into practice, relevant players in Canada and Lesotho, a small country surrounded by South Africa, have been consulted and interviewed and their views incorporated in these studies. The two countries have been chosen to demonstrate how NFCs can be applied in a developed country (Canada) and a developing country (Lesotho).

1.2 Organization of this thesis

The work is presented in a manuscript format. Therefore a brief literature review for each manuscript is found in the introduction of each chapter. This report is presented in four major sections (Table 1.1). The first section consists of chapters 2 and 3 and it is a survey of raw materials and institutional environment within which NCFs industry could operate in both Canada and Lesotho.

Chapter 4 and 5 in section 2 investigates the interfacial and microstructural properties of the least studied *Agave americana* fibres. In these chapters, investigations seek to understand how the mechanical properties of the composites could be improved by manipulating fibre plastic interface and tensile behaviour of fibres in *Agave americana* plastic composites.

Section 3 investigates the influence of fibre and straw processing parameters and different ways of composite processing on the mechanical properties of their composites. Chapter 5 demonstrates how the availability of raw materials and affordability of processing parameters can be used in decision making for making NFCs. Chapter 6 shows how the nature of wheat straw particle size and shape and their orientation and arrangement in composites could be optimized to improve composite properties.

The last section investigates the life cycle impact of NFCs (chapter 8). This chapter brings the essential concept of Life Cycle Assessment (LCA). Most research reports in this area cite NFCs' environmental benefits as the main reason to develop them. However, what is often missing in most of these assertions is that what is "natural" may not necessarily be "environmentally friendly." An LCA is a tool used to investigate environmental impact of a product from the production of raw materials to the disposal of this product, normally referred to as a "cradle to grave" analysis. Many authors cite a need to replace widely used glass fibres by natural fibres in composites. In this chapter, a life cycle comparison is made between a polypropylene car door panel reinforced with wood fibres and glass fibres. This chapter first takes a critical review of the LCA as a tool but shows how it can shed some light into the environmental impact of products like no other tool.

Table 1.1 Objectives of this study

Objectives and rationale		*Specific questions asked*
Section 1: Material survey and feasibility studies		
Objective 1	To determine the availability of raw materials and other resources and feasibility of composite industry in Ontario, Canada and Lesotho	1. What are the sources of natural fibres and plastic waste in these places and who can provide these materials? 2. Which individuals and organizations can work together to develop NFCs? 3. What are the views and values of these groups and individuals towards possible NFCs projects (see chapters 2 and 3)
Rationale	To guide the choice of materials and methods to be used for making composites in this study based on the situation in each country	
Section 2: Interfacial and microstructural analyses		
Objective 2	To investigate the interfacial and microstructural properties of the fibres and how these may affect the composites properties.	1. What is the effectiveness of mercerization and silane treatment of *Agave americana* fibres in improving the interfacial bond in *Agave americana* composites? 2. What is the impact of the unique microstructural properties of *Agave americana* fibre bundle on its fibre tensile strains? (see chapters 4 and 5)
Rationale	Interfacial and microstructural properties of *Agave americana* fibres, as a new fibre, are still largely unknown. Knowledge of these properties is critical for understanding how the fibres will behave in composites	
Section 3: Processing studies		
Objective 3	To optimize and characterize the mechanical properties of the NFCs by a careful selection of raw materials and manipulation of processing methods and fibre treatment	1. How can flexural properties of composites from waste plastics and fibres be optimized with respect to cost, environment and regional availability? 2. What influence does the size of milled wheat straw particles have on the properties of the wheat waste high density polyethylene (HDPE) composites? (see chapters 6 and 7)
Rationale	The kind of processing and fibre treatment affects the final composite properties. The aim is to find processing and treatment methods that optimize properties without sacrificing environmental and low cost benefits of these composites. Fibre treatment methods such as retting and milling the fibre are selected since they are cheap	
Section 4: Life cycle assessment (LCA)		
Objective 4	To investigate the environmental properties of the NFCs, especially as compared to conventional composites	1. What are the life cycle impact of NFCs vs. conventional composites as used in car door panels? 2. In which environmental areas do both panels have major impact? (see chapter 8)
Rationale	It is important to test the claims that NFCs are environmentally superior to conventional composites at a variety of circumstances	

1.3 Publications coming out of this study

Table 1.2 Publications coming out of this study

Chapter in this report	*Publications*
Chapter 2	Thamae T M and Baillie CA (2005), *Availability of agricultural fibres and agricultural thermoplastic waste for applications in NFCs in Ontario, Canada,* Presented at the 2005 Commerce, Engineering Environmental Conference, Queens University, Kinston, Ontario, Canada. Thamae T M and Baillie CA, A survey of waste plastic and natural fibre for the composite industry in Ontario, *Resource Conservation Recycling,* to be submitted.
Chapter 3	Thamae T M and Baillie CA, The feasibility of establishing a plant fibre industry in Lesotho, *Resource Conservation Recycling,* to be submitted.
Chapter 4	Thamae T M and Baillie CA (2007). Influence of fibre extraction method, alkali and silane treatment on the interface of *Agave americana* waste HDPE composites as possible roof ceilings in Lesotho, *Composite Interfaces*, 14 (7–9), 821–836.
Chapter 5	Thamae T M, Aghedo S and Baillie CA, Matovic D (2009), *Factors influencing tensile properties of* Agave americana *and hemp fibres*, in Bunsell and Schwartz (eds), Tensile failure of fibre Handbook, Woodhead Publishing Ltd., Cambridge, in press.
Chapter 6	Thamae T M, Marien R, Chong L, Wu C, Baillie CA (2008), Developing and characterizing new materials based on waste plastic and agro-fibre, *Journal of materials science*, 43 (12), 4057-4068.
Chapter 7	Thamae T M, Bowie A and Baillie CA, Wheat straw waste plastic composites, *Composites Part A*, submitted for publication.
Chapter 8	Thamae T M and Baillie CA (2007)*, Life cycle assessment of wood based composites: A case study*, in K. Oksman AND. M. Sain (eds), Wood-polymer composites, Woodhead Publishing Ltd., Cambridge. Thamae T M and Baillie CA (2006)*, Life cycle assessment of wood fibre versus glass fibre reinforced car door panel*, Presented at the 'Third International Conference on Science and Technology of Composite Materials' Buenos Aires.

1.4 List of symbols and their units as used in each chapter

Symbol	*Property*	*Units*
	Chapter 3	
M_g	Annual grain production per year	Metric tonnes (t)
M_s	Total mass of straw available for use in composites annually	Metric tonnes (t)
M_m	Mass of available kind of waste plastic	Metric tonnes (t)
HI	Harvest index	No units
A_h	Roof area needing insulation	Square meters (m^2)
A_c	Roof area each ceiling panel could cover	Square meters (m^2)
V_c	Volume of each ceiling panel	Cubic metres (m^3)
ρ_f	Density of straw	Metric tonnes / cubic metres (t/ m^3)
ρ_m	Density of waste plastic	Metric tonnes / cubic metres (t/ m^3)
ρ_c	Density of a composite	Metric tonnes / cubic metres (t/ m^3)
m_f	Straw mass fraction	No units
v_f	Straw volume fraction	No units
a_f	Fraction of available straw to the total straw produced annually	No units
C_f,	Cost of straw per unit mass	Maloti/kilogram (M/kg) (M is Lesotho currency)
C_m	Cost of waste plastic per unit mass	Maloti/kilogram (M/kg)
C_p	Cost of composite processing per panel	Maloti/panel (M/panel)
C_c	Cost of producing each panel	Maloti/panel (M/panel)
C_{ct}	Total cost of making composites that would insulate a known number of houses	Maloti (M)
N_h	Number of houses that can be roofed by the composite panels	Houses
n_c	Total number of panels that can be made from available straw and unlimited waste plastic in the country annually	Panels
M_{ct}	Total mass of all the composite material that can be made from all the annual available straw and unlimited waste plastic	Metric tonnes (t)
M_c	Mass of each composite ceiling panel	Metric tonnes (t) & Kilograms (Kg)
	Chapter 4	
D	Fibre diameter	Millimetres (mm)
σ	Tensile stress applied on a fibre	Megapascals (MPa)
τ	Interfacial shear stress	Megapascals (MPa)
l_e	Embedded length of fibre in a matrix	Millimetres (mm)
σ_m	Maximum stress at fibre detachment from the matrix	Megapascals (MPa)
P	Maximum force at fibre detachment from the matrix	Newtons (N)

L	Gauge length in tensile testing	Millimetres (mm)
$P_f(\sigma)$	The probability of failure of a fibre of length L at an applied stress σ	No units
L_0	Length of elementary units of a fibre	Millimetres (mm)
σ_u	The lowest value of strength in Weibull distribution normally set to zero	Megapascals (MPa)
σ_0	Characteristic strength	Megapascals (MPa)
m	Shape parameter called Weibull modulus	No units
n	Number of tested samples (for use in probability estimators)	Samples
N	Number of tested samples (for general use)	Samples
	Chapter 5	
$\bar{\sigma}$	Weibull average strengths	Megapascals (MPa)
Γ	Gamma function	N/A
σ	Tensile stress applied on a fibre or its standard deviation	Megapascals (MPa)
m	Shape parameter called Weibull modulus	No units
L	Gauge length in tensile testing of fibres for Weibull analysis	Millimetres (mm)
N	Number of tested samples for general use	Samples
σ_0	Characteristic strength	Megapascals (MPa)
A_d	Cross-sectional area of a fibre bundle	Square microns (μm^2)
A_s	Cross-sectional area of a single fibre	Square microns (μm^2)
n_s	Number of single fibres in a fibre bundle	Fibres
F	Force used to extend a fibre	Newtons (N)
Z	Length of a fully unravelled *Agave americana* single fibre during tensile testing	Millimetres (mm)
l_0	Length of *Agave americana* single fibre before tensile testing (equivalent to gauge length)	Millimetres (mm)
$\o$	*Agave americana* single fibre angle	Degrees (º)
ε_b	*Agave americana* fibre bundle strain	No units
ε_f	*Agave americana* single fibre strain	No units
E_b	Modulus of *Agave americana* fibre bundle	Megapascals (MPa)
U_b	Toughness of *Agave americana* fibre bundle	Joules/cubic metres (J/m^3)
σ_b	Stress on *Agave americana* fibre bundle	Megapascals (MPa)
	Chapter 6	
R	The rate of crosshead motion in flexural testing of composites	Millimiters/minute (mm/min)
L	Support span in a three point bend test	Millimetres (mm)
b	Width of the beam in a three point bend test	Millimetres (mm)
d	Thickness of the beam in a three point bend test	Millimetres (mm)
Z	Rate of straining of the outer fibre	Millimiters/millimetres/minute (mm/mm/min)
P	Load applied on a beam in a three point bend test	Newtons (N)

σ	Stress in the outer fibres at mid span, or flexural strength	Megapascals (MPa)
E	Flexural modulus	Megapascals (MPa)
m	Slope of the tangent to the initial straight line portion of the load-deflection curve in a three point bend test	Newtons/millimetres (N/mm)
	Chapter 7	
F_{max}	Maximum load from the load-extension curve in a tensile testing of composites	Newtons (N)
A	Original cross-sectional area of a specimen in a tensile testing of composites	Square millimetres (mm^2)
σ	Tensile strength of a composite	Megapascals (MPa)
ε	Tensile strain of a composite	No units
L	Average length of a cuboidal wheat particles before being divided into smaller particles	Microns (µm)
W	Average width of cuboidal wheat particles before being divided into smaller particles	Microns (µm)
t	Average thickness of cuboidal wheat particles	Microns (µm)
l	Average length of smaller cuboidal wheat particles cut from bigger cuboidal wheat particles	Microns (µm)
w	Average width of smaller cuboidal wheat particles cut from bigger cuboidal wheat particles	Microns (µm)
A_{EP}	Average epidermal surface area of cuboidal wheat particles before being divided into smaller particles	Square microns (μm^2)
A_{ep}	Average epidermal surface area of a cuboidal wheat particles cut from a bigger cuboidal wheat particles	Square microns (μm^2)
A_{PA}	Average parenchymal surface area of cuboidal wheat particles before being divided into smaller particles	Square microns (μm^2)
A_{pa}	Average parenchymal surface area of a cuboidal wheat particles cut from a bigger cuboidal wheat particles	Square microns (μm^2)
A_{TOT}	Average total surface area of cuboidal wheat particles before being divided into smaller particles	Square microns (μm^2)
A_{tot}	Average total surface area of cuboidal wheat particles cut from a bigger cuboidal wheat particles	Square microns (μm^2)
$Ø_i$	Orientation of a particle number *i*	Degrees (^{o})
n	Number of particle orientations in a measured sample	Orientations
N	Number of tested samples for general use	Samples
E_c	Tensile modulus of a composite	Megapascals (MPa)
v_f is	Volume fraction of fibre in a composite	No units
E_f	Modulus of a fibre in a composite	Megapascals (MPa)
E_m	Modulus of a matrix in a composite	Megapascals (MPa)
	Chapter 8	
F	Fuel consumed over the life of a panel as a car travels	Litres (L)
L	Life of a door panel which is assumed to be the same as life of a car	Kilometres (km)
FE	Fuel economy	Litres /kilometres (L/ km)

FE_{city}	City fuel economy	Litres /kilometres (L/ km)
FE_{hwy}	Highway fuel economy	Litres /kilometres (L/ km)
FE_{comb}	Combined Fuel economy	Litres /kilometres (L/ km)

Chapter 2: A survey of waste plastic and natural fibre for the composite industry in Ontario

Abstract

This study investigates the availability of the present sources of agricultural fibre and agricultural waste plastic for the establishment of a natural fibre composite industry in Ontario. It focuses on hemp, flax, corn, wheat and agricultural waste plastic as sources of raw materials for the fibre composite industry. The information for this study was found mainly through email interviews of representatives of relevant institutions in Ontario and throughout Canada.

Though present production of hemp and flax fibre is low, past experiences show that Ontario farmers have a capacity to grow these products in abundance provided there is a reliable processing technology and markets for them. Corn straw and wheat straw are possible sources of abundant, cheap and consistent supply of fibre. There are also abundant sources of waste plastic for use in NFCs in Ontario. However, a success of NFCs industry in the province will depend on how well the whole chain of industries from the raw material suppliers to the product distributors is organized to work as a team.

2.1 Introduction

According to recent estimations, the world is currently consuming petroleum at an estimated rate of 100 000 times faster than it can be recreated naturally (Netravali and Chabba, 2003). It is of interest to note that petroleum-based plastics have also found their application in various sectors of agriculture. They can be used as bale wrap films, containers for seedlings, silage covers and so on (Markarian, 2005). Ontario Ministry of Agriculture and Food, (2004) reported that almost half of Ontario’s greenhouse area was plastic.

Agricultural plastics degrade if exposed to solar radiation, wind, rain, high temperatures and relative humidity. This may reduce their lifetime ranging from a few months to a few years depending on combinations of different factors (Scarascia-Mugnozza, 2004). Regardless of their rates of degradation they all end up as waste and cause environmental problems. Some abandoned agricultural plastics can release toxic substances to the environment (e.g. release of tricresyl phosphate (TCP) from agricultural plastic films into the rivers) (Okada, 1996).

Additionally, much of the potentially useful agricultural crop residues may also be dumped due to lack of alternative uses. For instance, Canada currently produces tonnes of unused wheat straw residues every year (Sain and Panthapulakkal, 2005). In the Western Canada, flax straw has become an environmental problem due to lack of alternative uses (Ulrich and Marleau, 2005).

Consequently, most governments have reacted to some of these challenges by encouraging increased use of renewable resources and recycling of non-renewable ones, (Netravali and Chabba, 2003). In Canada, the Ontario Ministry of the Environment has introduced the 3Rs program (Reduce, Reuse, and Recycle) in an attempt to challenge the problem of waste disposal. With this initiative, Ontario has increased its waste diversion from 804 million tonnes in 1994 to 1381 million tonnes in 2001 (Ontario Ministry of the Environment, 2005). In mid 2004, Ontario Ministry of the Environment announced its intention to divert 60% of Ontario's waste from landfills by 2008.

What remains as a challenge is the development of effective mechanisms to achieve these goals of waste reduction. One of the best ways to treat agricultural residues is not only to mitigate their polluting effects but to turn them into valuable products. Reinforcement of thermoplastics with natural fibres is a rapidly growing field. This field of NFCs offers opportunities for the use of crop fibres and recyclable agricultural plastics, some of which would otherwise become a waste.

However, if these raw materials are to be used in NFCs, it is important to know how much of them is available and to understand the nature of the factors affecting this availability such as the identification of various players in this area and their location , and the present ways of handling and using these raw materials. This important aspect is lacking in literature. Therefore the main aim of this study is to investigate the availability of present sources of agricultural fibre and agricultural waste plastic for establishment of natural fibre composite industry in with focus in Ontario, Canada.

2.2 Methodology

2.2.1 Data collection

A questionnaire was developed to solicit information about selected crops and agricultural plastic waste for use in NFCs industry (Appendix 1). This questionnaire was then sent by email to members of relevant Canadian institutions (Appendix 2). The information was collected over a period from the 23rd of March 2005 to 27th of April 2005.

Attempted telephone interviews always resulted in interviewees opting to get more information and send it by emails. There was only one occasion where a direct personal interview was made with a hemp farmer. While some interviewees were predetermined by the researcher on the bases of their positions within relevant organizations, others were found during data collection as new possible sources of information emerged. The other important complementary data was found on internet sources.

Out of the 47 attempted interviews made, 15 (31%) of them were successful. The information sought is not meant to characterize the views of individuals or organizations but the scale of production and use of the raw materials. Therefore the response level cannot be viewed as adequate or not adequate in terms of the percentage of responses to the number of requests made (e.g. one respondent can provide information that is worth 10 responses from others). The unsuccessful interviews were partly due to the respondents having no knowledge to answer the questions or not responding at all.

Nevertheless, this exercise revealed the scarcity of information related to the relevant raw materials, especially hemp and flax fibre. Little is known in Ontario concerning production and sales of the agricultural fibres, perhaps because they are of little economic importance at the moment.

2.3 Results and discussion

Although the main focus of this study is on the province of Ontario, discussion is often extended to the rest of Canada and beyond to put the larger picture in perspective. Reflections are made at the end of each sub-section, discussing the implications of the findings. Interviews with Hempline Inc. are more often quoted since it is currently the only company processing hemp fibre in Ontario and they have a direct experience with hemp production and sales. Paraphrased quotations of the interviewees are referenced by their numbers in Appendix 2 for simplicity.

2.3.1 Hemp fibres

Production of hemp fibres

Statistics showing amounts of hemp fibres produced and sold in Ontario were not found. Statistics Canada has no official hemp statistics so far (Appendix 2, 38). There is not yet any solid hemp fibre industry in Canada (Appendix 2, 30). However, some information exists that can shed some light into the scale of hemp industry from 1998 and the years that followed in Ontario and other provinces.

In 1998, just after hemp had been legalized for commercial purposes, approximately 5,300 acres of hemp had been contracted in Ontario (Pinfold and White, 1999). Some of the main companies who contracted land for hemp cultivation in Ontario are shown in Table 2.1. Between the period 1998 to 2000, Hempline Ltd. had increased its total acreage contracted from 500 in 1998 to 1500 by 2000 (Appendix 2, 37).

The average licensed hemp acres planted in Canada from 1998 to 2000 are shown in Table 2.2. In the beginning, Ontario used more area to plant hemp than any other Canadian province. In 1998, Ontario also had the greatest number of acres licensed for cultivation (Table 2.3). The only province that came close to Ontario in that year, Manitoba, had licensed and planted only about half the total area licensed and planted in Ontario. However, a big difference occurred in 1999 when Manitoba planted close to 9 times the amount of hemp acres planted in Ontario. Interest for planting hemp in Ontario was declining due to lack of markets. By the year 2000, licensed hemp acres planted in Ontario had declined to 1/5 of their original 1998 size. Hectares licensed for hemp cultivation had declined to nearly 1/8 of their original size in 1998.

Table 2.1 1998 hemp production in Ontario (Pinfold and White, 1999)

Company name	*Number of contracted growers*	*Approximated land used (acres)*	*Products*
Kenex Ltd. (Now out of business)	54	2,000+	Fibre, grain, seed
Hempline Inc.	20	500	Fibre, grain
Natural Hemphasis	-	10	Fibre, grain,
Approximately 30 others	-	300-500	-

It is noteworthy that the number of hectares licensed for hemp cultivation in 1999 increased almost six-fold from 2400 in 1998 to 14200 for the total of all provinces (Table

2.3). The 1999 enthusiasm among farmers was not restricted to Ontario. One reason for the decline a year later, 2000, might be due to saturation of undeveloped markets and weaker hemp processing industry. Reports show that there were excess supplies of hemp grown in Manitoba and the rest of Canada (Manitoba Agriculture, Food and Rural Initiatives, 2000). Hempline stopped contracting more acres from 2000 until the time of interview (2005) since more focus was put on development of markets and processing infrastructure (Appendix 2, 37).

Table 2.2 Licensed hemp acres planted in Canada between 1998 and 2000 (Manitoba Agriculture, Food and Rural Initiatives, 2000)

Year	*BC*	*AB*	*SK*	*MB*	*ON*	*PQ*	*Maritimes*	*Total*
1998	178	94	650	1,497	2,873	59	576	5,926
1999	556	1,862	7,640	21,948	2,524	212	331	35,074
2000	719	756	3,522	7,178	534	590	252	13,550

BC: British Columbia; AB: Alberta; SK: Saskatchewan; MB: Manitoba; ON: Ontario; PQ: Quebec

Table 2.3 Hectares licensed for industrial hemp cultivation from June 1998 to June 2002 in Canada (Health Canada, 2005)

Middle of	*Total*	*BC*	*AB*	*SK*	*MB*	*ON*	*QB*	*NB*	*NS*
1998	2400	72	38	263	606	1163	24	214	19
1999	14200	-	-	-	-	-	-	-	-
2000	5487	291	306	1426	2906	217	239	0	102
2001	1316	96	113	392	472	209	30	0	0
2002	1530	200	123	449	596	142	19	0	0

There have been attempts to determine how much hemp fibre Ontario produced from 1998 to 2000. However, this had to be inferred from the number of acres grown by Hempline and Kenex, (the only hemp processing companies in Ontario and Canada at that time) due to lack of statistics. These inferences showed that about 2400 tonnes of hemp fibre had been produced from Ontario in those first three years (1998-2000) (Manitoba Agriculture, Food and Rural Initiatives, 2000). Part of the fibre was exported to the United States (US). National amounts and values of hemp fibre that was exported to the US from 1997 to 2000 as estimated by Statistics Canada are shown in Table 2.4. Again, the exports peaked in 1999 and went down in 2000. Bob von Sternberg, (1999) suggested that Canadian farmers came to realize that growing so much hemp without markets and processing industry was risky.

Table 2.4 Canada's hemp fibre, raw or retted, exported to the US (Manitoba Agriculture, Food and Rural initiatives, 2000)

Value (CND)				*Quantity (Kg)*			
1997	1998	1999	2000	1997	1998	1999	2000-Jul
0	9,925	153,413	107,362	0	4,152	182,694	102,505

Harvesting, storage and processing of hemp for fibres

Harvesting and retting (subjecting the hemp stalk to microbes either in a controlled environment or being left in touch with soil out in the field, *field retting*, to break down the lignin and pectin holding fibres together, making it easy for mechanical processes to separate fibres from the stalks) processes have a significant impact on the quality of hemp fibre (Manitoba Agriculture, Food and Rural Initiatives, 2000). In most cases industrial hemp is grown for both fibre and seed. This leads to a dual harvesting which can have consequences on the quality of fibre (Baxter and Scheifele, 2000).

Growing hemp for seed demands that harvesting be done later in the growing season. This is an optimum time when the seeds begin to shatter and have desirable moisture levels (Baxter and Scheifele, 2000). However, if hemp is to be used for fibre, an early flowering stage is ideal for harvesting. After this time, the fibre lignifies considerably, making a negative impact on the retting process. Where hemp is grown solely for fibre, Hempline begins its harvesting by early August (Kime, Apendix 2.2, 37). This is done by cutting down the stocks and allowing them to condition for a while in the field before being taken for storage.

The Ontario Ministry of agriculture and food encourages farmers to ensure that they use methods that keep hemp straw dry and clean in order to avoid rapid deterioration (weaker fibres result in weaker composites) (Baxter and Scheifele, 2000). For instance, soft-core balers lead to faster drying of bales. Twines used for baling should be made of natural fibres which do not contaminate the fibre and storage should be made indoors under dry conditions. After harvesting, Hempline puts hemp fibres under covered storage for protection before they can be shipped to the processing plant (Appendix 2, 37).

Retting is one of the most important aspects of processing hemp. It is the means through which bast fibre is obtained from the stalk (see chapter 6). If it is done properly, retting can give high quality fibre. It is reported that Ontario has the best climate in Canada for hemp retting (Manitoba Agriculture, Food and Rural Initiatives, 2000). The Ontario ministry of agriculture and food suggests that Ontario hemp farmers can do retting in the field to take advantage of the natural factors such as dew, rains and so on or make use of chemicals or enzymes under controlled conditions (Baxter and Scheifele, 2000).

Normally , dew retting is expected to take between 21 to 28 days to complete but can take as little as 14 days under favorable conditions or more than 28 days if weather conditions are not favorable (Baxter and Scheifele, 2000). Mechanical retting (decortication) is being developed in Canada and some parts of the world (Manitoba Agriculture, Food and Rural Initiatives, 2000). These methods would include steam explosion, use of ultrasound and so on. While these methods may be more efficient, they may also be costly.

Hempline has leading hemp processing facilities in Canada with the capacity to process hemp straw into fibre (Appendix 2, 30). It is able to extract and refine both primary and core fibre taken from the stock.

Uses and costs of Ontario hemp fibre

Markets for Ontario hemp fibre exist mainly outside of Canada, primarily in the US (Appendix 2, 37). The main markets for this fibre are in the composites industry, mainly automotive industry where hemp bast fibre is used to reinforce thermosets and polypropylene based materials. Other applications for Ontario hemp fibre include use in specialty papers and, potentially, building industry and many other applications which are being developed at a very rapid rate. Canadian hemp fibre can also be used in making rope or twine, and construction materials (Health Canada, 2002). Some of the many possible uses of hemp fibre are shown in Figure 2.1.

Prices for hemp fibres at any point in time are a function of several factors such as fibre format, market application, packaging format, volume, payment terms, currency exchange, commitment of the customer and amount of additional customer/technical support provided and market conditions (Appendix 2, 37). However, primary fibre prices range from $ 0.50 to $ 1.00 per lb while the core fibre ranges from $0.25 to $0.50 per lb.

However, much emphasis was placed on the fact that these prices fluctuate. There were no official market prices for hemp fibre (Appendix 2, 1). Appendix 3 has a list of Ontario hemp companies dealing with several kinds of hemp products.

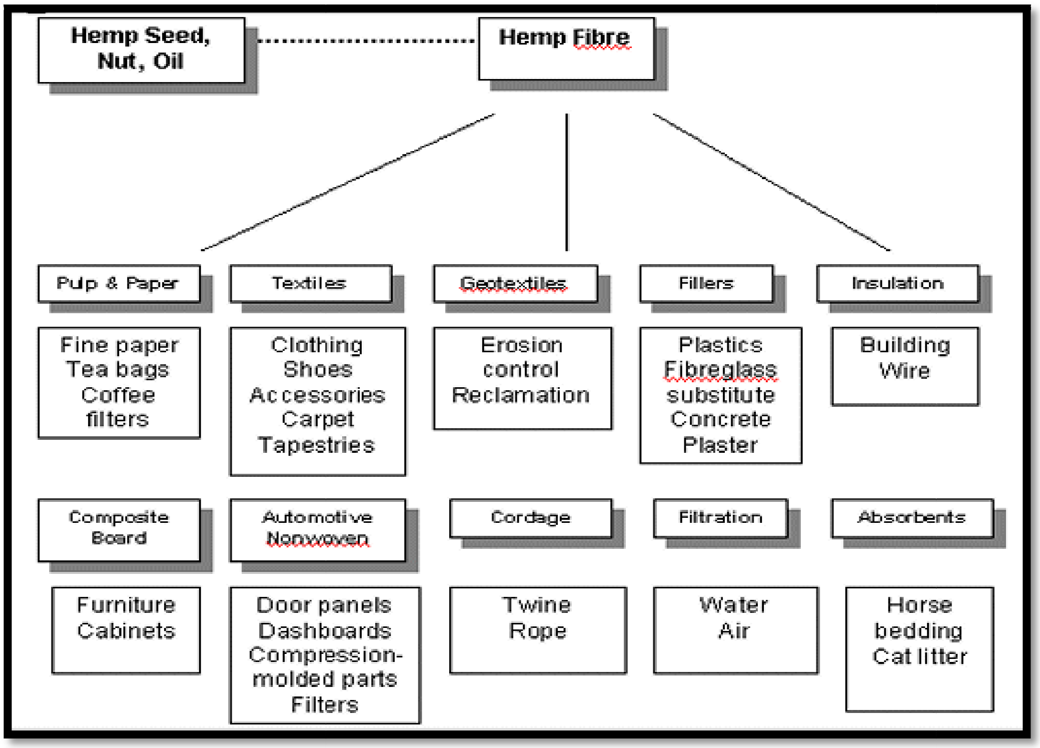

Figure 2.1 Uses of hemp fibre (Manitoba Agriculture, Food and Rural Initiatives, 2000)

Implications

Ontario and Canadian farmers had much enthusiasm to grow hemp after its legalization for commercial purposes in 1998. Therefore hemp produced by the year 1999 was far beyond the capacity of the processing infrastructure to process and to find markets for its products. There is little documentation showing how hemp industry in Ontario developed since 2001. This may also imply a decline in general interest in this product following the initial period of rapid rise and fall. The closure of Kenex Ltd., leaving Hempline as the only hemp fibre processor in Ontario may have worsened the situation of lack of processing infrastructure.

However, the immediate increase in hemp cultivation in Ontario when hemp was cultivated for the first time after its legalization in 1998 implies what can happen once the farmers are reassured of a solid basis to grow hemp. Therefore development of hemp fibre reinforced plastic composites may be established on the assumption that Ontario farmers have the capacity to grow hemp and they will grow it if the markets for it become developed.

2.3.2 Flax fibres

Most of the information concerning Ontario or Canadian flax is based mainly on the production of flaxseed as this is the main reason for growing flax in this country. Since growing flax for seed may show the potential of flax fibre in Ontario, the analysis will deal with both flax fibre and seed production (see chapter 6). Attention is also given to Western Canada where most of the Canadian flax is grown.

Production of flax in Western Canada

Canada is the largest producer and exporter of flaxseed in the world, (Agriculture and Agri-food Canada, 2002 and Ontario Agricultural Value-Added Innovation Network, 2003). However, flax fibre in Canada, as in the rest of North America, is far surpassed by

European flax fibre production. Long-line flax fibre processing plants are very few in North America due to undeveloped markets.

At present, most of Canada's flaxseed is produced in Western Canada for export as a source of industrial oil (Appendix 2, 38). Until 1987, Manitoba had been the leading producer of flaxseed whereas Saskatchewan had been leading since 1993 (Agriculture and Agri-Food, Canada 2002). Over the period (1987-1993), both provinces accounted for more than half of Canada's flaxseed production. The leading flaxseed producing provinces in Canada in the recent years are shown in Table 2.5. Saskatchewan is still the leader in flaxseed production and unlike the other two provinces its flaxseed output is increasing significantly.

Table 2.5 Canadian flaxseed production (Thousand tonnes) (Agriculture and Agri-Food Canada, 2002)

Province	*2002*	*2003*	*2004*
Saskatchewan	444.5	533.4	711.2
Manitoba	214.6	195.6	182.9
Alberta	20.3	25.4	26.7
All Canadian provinces	7193.2	9691.9	12094.4

The byproduct of these thousands of tonnes of flaxseed is the flax straw, the potential source of industrial flax fibre. In fact, Western Canada yields an annual amount of more than 1 million tonnes of flax straw which has become an environmental problem due to lack of alternative uses (Ulrich and Marleau, 2005 and Jonn et al., 2002)

Production of flax in Ontario

There are no official flax statistics for Ontario since flax is mainly a Western Canadian crop (Appendix 2, 38). This has not always been the case. Flax has been grown successfully in Ontario in the past, the time when according to Bennet (2002) linen mills were common in the province until they gradually vanished when the markets disappeared. This decline is shown in Table 2.6. They show how the Ontario flaxseed production had been declining until 1991 when the Ontario Ministry of Agriculture (OMAF), no longer showed collected data.

Table 2.6 Ontario flaxseed production from 1981 to 2003 *(Cumming, 2005)*

Year	*Flaxseed Harvested Area (acres)*	*Flaxseed Production ('000 bu)*	*Flaxseed Yield (bu/acre)*	*Flaxseed Price per unit ($/bu)*	*Flaxseed Total Value ($'000)*
1991	2,140	79	37	5.00	395
1990	3,000	79	26	5.10	403
1989	3,000	66	22	6.50	429
1988	3,000	40	13	7.45	298
1987	3,000	85	28	4.50	383
1986	8,437	194	23	4.90	951
1985	5,500	130	25	6.40	883
1984	7,800	130	25	7.45	1,450
1983	10,000	130	13	8.00	1,040
1982	20,000	440	22	6.85	3,010
1981	11,123	278	25	8.50	2,363

The little information that was found for the years following 1991 was that Ontario planted 640 ha and 800 ha of flax in 1996 and 2001 respectively (Ontario Agricultural Value-Added Innovation Network, 2003). The overall production of flax in Ontario went so low that from 1991, flax fibre could not meet the manufacturing demands in this province (Ontario Agricultural Value-Added Innovation Network, 2003) and it had to be imported from Manitoba

Recently, there have been attempts to revive the flax industry in Ontario. There was a two year flax project in the beginning of this decade which tried to determine the potential of flax fibre production in Ontario (Scheifele and Davies, 2001). If such a potential existed, Snobelen Farms Ltd. was prepared to invest in a future project that would establish 30,000 hectares of flax production and 15 supporting processing mills. The interim results of those pilot studies showed that certain flax varieties gave yields that were above 7000 kg/ha, which was the mean flax fibre yields in Europe (Ontario Agricultural Value-Added Innovation Network, 2003). The project went well only for 2 years and came to a halt when it was apparent the there was no appropriate processing equipment in Canada and that it was not feasible (Appendix 2, 47).

There was no information which showed how much Ontario flax fibre has been sold for the period 2000 to 2004. According to Agriculture and Agri-food Canada (2002), flax fibre exports in 2001 and 2002 made a total of 56, 331 tonnes and the US was the only market for this fibre.

Harvesting, processing of Canadian flax fibre

Much of the information concerning flax harvesting in Canada concentrates on the flaxseed rather that flax fibre. The Flax Council of Canada (2005) gives some guidelines for the harvesting of flax. These include using of combiner for cutting the stocks and avoiding delay by immediately harvesting when the flax it is fully mature.

Field retting of flax should not be done earlier than the end of July and should be done by turning of windrows to make even retting possible (Ontario Agricultural Value-Added Innovation Network, 2003). Retting in Ontario can take between 21 to 28 days but the real length of the retting period depends on how dry or wet the weather is. If the weather is too dry, retting takes more time.

For Western Canada, farmers are encouraged to undertake field retting since it is cheaper (Ulrich and Marleau, 2005). For better retting, the straw should be left in contact with the soil using a land roller.

Uses and costs of Canadian flax fibre

As mentioned, most flax in Canada is grown for seed. Therefore flax straw is a by-product. However, it is possible to find flax varieties that are suitable for producing long-line fibre but are poor for seed purposes (Ontario Agricultural Value-Added Innovation Network, 2003). Domestic uses for the flaxseed include crushing seed for oil, grinding it for inclusion in baked foods and using it as food for livestock (Agriculture and Agri-food Canada, 2002). Other than its uses as a fertilizer, the Canadian flax straw is regarded by most farmers as of little value (Ulrich and Marleau 2005). Therefore most of the straw in Canada is burned or tilled under (Appendix 2, 4). The straw that can be collected and baled can be used in applications like specialty paper or NFCs

On the other hand, flax fibre could be used in linen production and many other industrial purposes, (Ontario Agricultural Value-Added Innovation Network, 2003). Some of these industrial applications are uses in geotextiles (permeable fabrics which, when used in association with soil, have the ability to separate, filter, reinforce, protect, or drain), absorbent products and insulation (Obolenski and Beckman, 2004)

Though prices of flax fibre are highly influenced by the grower due to low supplies in Ontario, they are generally less than $1.80/kg (Ontario Agricultural Value-Added Innovation Network, 2003). If grown for export, flax fibre does become a source of reasonable income for Canadian flax farmers. Canadian flax fibre exports to the US in 2000 and 2001 earned Canada a total of $ 26.5 million (Agriculture and Agri-food Canada, 2002). Names and contacts of the businesses involved in flax products are found in Appendix 4.

Implications

Earlier in this decade, Ontario had to import fibre from other provinces as efforts to revive flax cultivation failed. But since flax has been grown successfully in the past as some reports have shown, it is possible that Ontario farmers only need markets for their produce to begin cultivating flax at large scale again.

2.3.3 Corn straw

Production of corn straw

Corn grain production is one of the most important agricultural activities in Canada (Table 2.7). Most of this production is based on Ontario which accounts for 64% of total

Canadian annual production, followed by Québec (33%) and Manitoba (3%) (Savoie and Descôteaux, 2004) (Table 2.8). The southern part of Ontario is the most corn producing area in the whole province (Levelton Engineering Ltd., 2000). The amount of corn straw produced in Ontario early this decade was estimated by Levelton Engineering Ltd. (2000) to be 3 million tonnes.

Table 2.7 Corn grain production and potential harvestable straw in Canada (Savoie and Descôteaux, 2004)

Year	*Area (10^6 ha)*	*Production (10^6 t)*	*Grain yield (t/ha)*	*Estimated straw yield (t/ha)*	*Harvestable straw yield (t/ha)*
1999	1.166	9.161	7.86	6.43	3.21
2000	1.206	6.954	5.77	4.72	2.36
2001	1.294	8.389	6.48	5.30	2.65
2002	1.299	8.999	6.93	5.67	2.83
2003	1.265	9.587	7.58	6.20	3.10
Average	1.246	8.618	6.92	5.66	2.83

Unlike Ontario flaxseed production which had been declining over the years, Ontario grain corn production and, therefore, corn straw production, had remained relatively high over the years.

Table 2.8 Corn grain production in Ontario (Cumming, 2005)

Year	*Grain corn harvested area (acres)*	*Corn yield (bu/acre)*	*Grain corn production ('000 bu))*
2003	1,725,000	127	219,000
2002	1,910,000	113	216,000
2001	1,960,000	103	202,000
2000	1,725,000	105	181,500
1999	1,800,000	128	231,000

Uses and cost of Ontario corn straw

Corn straw is normally incorporated into the soil to provide organic matter or it may be shredded and left on the surface to decompose in no-till operations (Levelton Engineering Ltd., 2000). It can also be harvested for cattle feed (Appendix 2, 19). When used for feed, (2000) it has higher feed value than straw from small grains (Manitoba Agriculture, Food and Rural Initiatives, 2000). Other potential uses of Ontario corn straw include provision of fibre for the pulp industry, short fibre for particle board and long fibre for oriented strand board industries. It can also be used for combustion purposes as fuel (Savoie and Descôteaux, 2004). Some studies have been done to determine the possibilities of using Ontario corn straw for production of ethanol. Levelton Engineering Ltd. (2000) estimated that Ontario could produce between 1.6 to 2.0 billion litres of ethanol per year from corn straw.

The number of corn producers in Ontario is also enormous. About 21 000 growers are registered with Ontario Corn Producers' (Appendix 2, 19).

Implications

Corn straw is a possible source of fibre for reinforcement of plastics. The abundance of harvestable corn straw and its relatively steady production in Ontario mean that corn straw composites are likely to have a large supply of straw. The abundance may also mean cheaper straw and cheaper corn straw composites. However, as new uses of this product are found, there could be high competition for the straw, increasing costs.

2.3.4 Wheat straw

Production of wheat straw

Wheat acreage in Ontario ranges from 600,000 to 1,000,000 every year with an average of 750 000 acres planted per year (Appendix 2, 32). Production is also highest in Southern Ontario. Winter wheat is the most prominent in this province (Table 2.9). It is estimated that production of Ontario winter wheat straw over the past several years totaled 1.3 million tonnes (Levelton Engineering Ltd., 2000).

Table 2.9 Ontario winter wheat production between the years 1999 and 2003 (Cumming, 2005)

Year	*Winter wheat production ('000 bu)*	*Harvestable straw('000 bu)*	*Winter wheat price per unit ($/bu)*	*Winter wheat Harvested area (acres)*	*Winter wheat yield (bu/acre)*
2003	75,500	52 850	4.04	990,000	76
2002	41,800	20 260	4.19	580,000	72
2001	38,800	27160	3.76	540,000	72
2000	50,500	35 350	2.70	680,000	74
1999	52,000	36400	3.36	710,000	73

Harvesting, storage and processing of Ontario wheat straw

Harvesting normally begins from July 20 to September 1. After harvesting, there is usually no further processing of straw (Appendix 2, 6). The next process is baling (Appendix 2, 23).

Uses and costs of Ontario wheat straw

There are several possible uses of wheat straw produced in Ontario (Appendix 2, 6). The main use is animal bedding for livestock. Farmers who do not have livestock sell straw to farmers who need the straw for their livestock. If not used for bedding or after bedding, wheat straw is taken back to the soil as fertilizer.

The export market for wheat straw is mainly for horse farmers in the US. Small amounts of Ontario wheat straw are used for industrial purposes like composites, textiles or paper (Appendix 2, 6). One Ontario wheat farmer interviewed said that most of their wheat straw was selling mainly in horse trade but some markets included mushroom growers, construction companies and building industry in winter where wheat straw was used to keep the frost out of the basement (Appendix 2, 16). Wheat straw can also be used for making ethanol fuel (Levelton Engineering Ltd., 2000). In 2004, it was announced that an Ontario based company called Iogen Corporation would be able to power nine hundred Canadian government vehicles using ethanol made from wheat straw cellulose (Farm Credit Services of Minnesota Valley, 2004).

Ontario wheat straw prices are highly dependent on local demand and trucking which adds more to the expenses. However the prices range from 2.6 to 6.0 cents/kg (Appendix 2, 23). One respondent said they put a value of 3 cents per pound on their wheat straw (Appendix 2, 16).

As many as 17 000 farmers grow wheat throughout Ontario (Appendix 2, 6). Either farmers themselves or hay and straw brokers help to distribute the wheat straw (Appendix 2, 16).

Implications

Just like corn straw, abundant production of wheat and wheat straw presents abundant materials for wheat straw composites in Ontario. If the composite industry becomes a further source of farmers' income, supply of wheat straw from Ontario is unlikely to be a problem unless competitive uses also gain prominence.

2.3.5 Agricultural waste plastic

Production of agricultural waste plastic

The use of plastics in agriculture is becoming an increasing phenomenon. For instance, Ontario has 904 acres devoted to greenhouse vegetables, the largest area in Canada, followed by British Columbia with 363 acres and then Quebec with 247 acres (Extension Vegetable Crops Specialists, 1999). In Ontario alone, as much as 2000 tonnes of agricultural plastics, bale wraps, silo bags and silo covers are used annually (Enviros RIS, 2001). Although the percentage of this value to the total waste plastic produced in the province is not known due to lack of data about other plastic waste, this value is significant enough to encourage efforts to recycle.

On the other hand an Eastern Ontario survey showed that 30% of municipal landfills would reject agricultural waste plastic in 1997 possible due to huge size of it (Clarke and Fletcher, 2002). In that study, other Ontario landfills would charge $80 dollars per tonne to take such kind of waste. Nevertheless, Clarke (1995) was hopeful that the problem of agricultural plastic waste in Ontario could be solved with up to 97% recovery rate, if necessary measures were taken.

Since 1992, there have been pilot studies to determine the potential of recycling agricultural waste plastic produced in Ontario. This project was supported by Ontario Soil and Crop Improvement Association, Ontario Agri-business and Ontario Ministry of Agriculture and Food (Clarke and Fletcher, 2002). The desire to implement this project at a large scale in Ontario was not realized because there was no funding (Appendix 2, 7).

Other efforts are being made. The Canadian Polystyrene Recycling Association (CPRA) works with users of greenhouse plastics and has become the largest horticultural polystyrene recycling facility in North America (Levitan and Barros, 2003). CPRA initially started working with farmers in South Western Ontario and Northern Ohio and expanded to growers in two Canadian provinces and to growers as far as Florida and Texas. Another body that had a significant impact is Crop Life Canada, a trade association representing the manufacturers, developers and distributors of plant science innovations. Ten years after being engaged in recycling since 1989, this institute had been able to get rid of 30 million containers of empty pesticides for recycling (Crop Protection Institute, 1999).

Under Crop Life Canada's national program, an Ontario company called Everwood was able to collect as much as 154 tonnes of high density polyethylene (HDPE) pesticide and herbicide containers from Ontario and a total of 960 tonnes from Manitoba, Quebec and the Maritimes (Enviros RIS, 2000).

Lately another Ontario based company called CS Plastics in Waterloo has proposed to help recycle agricultural waste plastic. In order to start, the company would need an annual supply of approximately 1.6 million pounds of stretch-wrap Linear Low Density Polyethylene (LLDPE) or approximately 34,000 pounds a week (Canadian Plastics Industry Association, 2005).

Sorting, storage and transportation of agricultural waste plastic

Farm plastics have different chemical make-up and degrees of dirtiness. Sorting is done to separate desirable waste plastics from those that do not fit recycling requirements. According to Clarke (2005), part of the criteria used to accept or reject the plastic waste is through inspection to determine the level of toxicity (possibly due to pesticides) and UV damage on them. The general rule is that the plastic waste that has more than 5% of its waste as contaminants is rejected.

A study made in the US showed that agricultural waste plastic could suffer high level of rejection for a number of reasons, especially contamination in some cases (Starr, 1997) (Table 2.10). Silage wrap rejection was as high as 90% of its waste brought to the companies (Starr, 1997).

Table 2.10 The level of rejection of plastic waste in one study in the US (Starr, 1997)

Type of waste plastic	*Accepted*	*Rejected*	*Percent rejected*	*Total*
ACSWMD drop-off				
Bunker silo covers	835	545	39	1,380
Silage wrap	25	235	90	260
Silage bags	410	180	31	590
ACSWMD on-site farm				
Bunker silo covers	1,050	2,850	73	3,900
LSWMD drop-off				
All materials (1)	2,340	2,260	49	4,600

ACSWMD = Addison county solid waste management district
LSWMD = Lamoille solid waste management district
(1) Rejection data by material were not collected. The majority of the material collected was silage wraps

Other waste companies are not so exacting. CPRA would accept nested and stacked material from which only excess soil and plant material had been removed and there was no need for washing (Levitan and Barros, 2003). The rest of the work was the responsibility of CPRA. In addition, it would be the responsibility of this organization to collect the material from farmers. Farmers package the material (CPRA instructs them on how to do this) and make a phone call to CPRA offices (Burnham, 2001). The truck is sent to collect the waste and transportation costs are accounted for by CPRA.

Applications and costs of agricultural waste plastic

Recycled agricultural plastics from Ontario have a potential of being used for plastic lumber, garbage bags, puck-board (plastic plywood) horse fencing, farm pens, and roadside posts (Clarke and Fletcher, 2002). These products can be made by making a one-to-one blend with plastics from other sources including virgin pellets, ground cover sheets, garbage bags and so on (Clarke, 2005). Some of these uses are already present in

Ontario. Everwood is able to turn agricultural waste into plastic lumber which can be sold back to farmers (Recycling today, 2002). The company can alternatively use this waste to make a blasting material. CPRA sells 50% of its recycled plastic back to the farmers, especially the horticultural industry where it is used to form trays, flats and packs. The other 50% had finds uses in office hardware, snow brushes and swimming pool panels (Burnham, 2001).

The Canadian Plastics Industry Association (2005) reported that CS Plastics, another Ontario based company was in collaboration with the Ontario Federation of Agriculture and Landscape Ontario to find the possibilities of recycling waste hay wrap and greenhouse film into lumber that would be sold back for use by farmers. The aim was to sell the products to cottage communities where it could have applications in building baleboards for dock applications.

If farmers take their waste to landfill, they are more likely to pay tipping fees. The opposite is true if they take their waste to some of these recycling companies. Farmers would receive anything between $ 200 and $1000 per truckload depending on how far they are from the CPRA plant in Mississauga (Burnham, 2001). Companies offering markets for agricultural waste plastic are found in Appendix 5).

Implications

Despite the fact that Ontario does produce significant amounts of agricultural plastic waste, the main issue may not only be how much of this waste exists to meet the demands for applications in NFCs but how well organized the farmers are to make sure that their waste meet the requirements of recycling industries. While 2000 tonnes of waste plastic annually may appear to be less significant in comparison to unknown but possibly huge amounts of total waste plastic produced in this province, it is still an environmental problem if it is not recycled since it ends being buried in farms if not taken to landfills.

2.4 Conclusions

It is not clear how much Ontario hemp fibre exists at present. But the evidence suggests that production of hemp is not as good as it used to be in the late 1990s following the legalization of hemp for commercial purpose in Canada. The decline of hemp production may be attributed to lack of processing technology and well developed markets for hemp fibre produced in this province. The Ontario flax production has declined in the 1980s following a decline in linen production. The production has remained low ever since that period. Past experiences show that Ontario farmers do have capacity to produce both hemp and flax. But they can only produce more of these fibre sources if enough processing technology and markets for their products are available to them.

Corn straw and wheat straw are readily available in Ontario. If they are utilized, they can form reliable and cheap sources of natural fibre for composite industry since their production is more consistent. Lastly, despite efforts to recycle agricultural waste plastic in Ontario, much of the waste is still a problem which the composite industry can be used to address.

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Chapter 3: Feasibility of establishing a natural fibre composite industry in Lesotho, Africa

Abstract

Abundance and low cost of natural fibres and waste plastics make them attractive for use in developing countries. This study determines the feasibility of establishing a community focused composite industry in Lesotho, Southern Africa. Drawing from previous records of unsuccessful community projects in this country, the study takes a different approach of, “needs analysis,” through a series of interviews and observations in order to take the views of those who would be affected by the project into account.

Locals suggested straw from local cereal crops and *Agave americana* fibres as potential raw materials for future NFCs projects and it is estimated that there would be enough raw materials to satisfy such projects. Responses from farmers, cooperative members, householders and others provide information into what the expectations of the local people would be concerning a possible NFC industry in Lesotho.

3.1 Introduction

The previous chapter focused primarily on availability of raw materials for composites and fibres in Ontario Canada. In a western country like Canada, where properties are normally viewed mainly in economic terms, the approach used may be sufficient. However, in a country like Lesotho (a small Southern African country completely surrounded by South Africa) where resources are viewed also through the prism of cultural frameworks, a purely materialistic approach may prove fruitless as we will show below.

This section starts by showing what possible environmental and socio-economic challenges and opportunities could be addressed or tapped by development of NFCs in Lesotho. The possible hurdles that could come from initiating such a project are inferred from the lessons learned from the economic and social contexts of the past decades and how they affected development projects similar to the ones we seek to initiate. These lessons form the bases of the “needs analysis” approach used in this study.

The first challenge the NFC industry could help address in Lesotho is the management of waste plastic. Lesotho’s urban centers face waste management problems and have no well-established waste programs (Chapeyama, 2004, Mvuma, 2003). Lack of effective waste management programs results in much of the waste being dumped and burned in open spaces, a practice which poses serious health problems, especially in Maseru, Lesotho’s main urban centre and a hub of industrial and commercial activities (Chapeyama, 2004). Mvuma (2002) showed that plastic waste comprised a large share of waste generated in Maseru. Lesotho, like other developing countries, generally resorts to collection and disposal of waste when faced with large quantities of these, rarely giving attention to possibilities of other more sustainable waste management options. NFCs projects based on recycling mainly waste plastic could help address this problem.

The second challenge is related to housing. It was shown in a demographic survey of 2001 that in Lesotho, nearly two thirds of the houses used corrugated iron as roofs (Lesotho Bureau of Statistics, 2001**).** This Figure rises to 90% in the urban areas and drops to 57% in the rural areas where grass or straw are the alternative traditional roofing material. These alternative materials are becoming scarce due to poor rangelands management (Marake et al., 1998). Lesotho's hot summer months and exceptionally cold winters make the use of insulating ceiling panels a requirement below poorly insulating iron roofs. However, only a few people can afford to purchase these insulating ceiling panels. Therefore cheap ceiling panels are among the most important products that could be made from NFCs in the country.

Other opportunities present in this country include the untapped potential of agricultural residues as a profitable industry for Lesotho and the possible job creation through waste collection. Agriculture is the key sector in Lesotho. Major crops include corn, wheat, sorghum, beans and peas**.** In most cases, these crops are mainly grown for the grain and the remaining residues are subjected to uncontrolled grazing. These residues are potential fillers for NFCs. Providing alternative uses for agricultural residues may not only increase the farmers' income; it may also boost agricultural production and multiply job opportunities in this sector. Furthermore, in 2002, informal waste recycling schemes already generated an estimated M 700 000 (about 150 000 CND) a year, resulting in 282 informal jobs **(**Mvuma, 2002**)**.

However, the idea of initiating this kind of development project in Lesotho is not new. Millions of dollars have been spent in this country for decades in the form of aid from tens of western governments and organizations. Despite good intentions, the results of such initiatives were generally unsuccessful. The classic documentation of such projects and the possible reasons behind their failure were provided by Ferguson (1990) in his book, "*The anti-politics machine: development, depoliticization and bureaucratic power in Lesotho."* This failure could be understood in light of the socio-economic reality in the country, which seemed to elude the initiators of the projects. To put the discussion into perspective, it is important to provide a brief background to the socio-economic settings in Lesotho.

As mentioned, Lesotho is a small country completely surrounded by South Africa. Several main factors affect the quality of life in this country, including poverty levels and women's position in society, AIDS and dependency on South Africa. As could be expected for any country bordering an economically advanced neighbor, relations with South Africa have driven much of the current situation in Lesotho. For the most of the past century, most of Basotho men worked in the gold mines of South Africa. An estimate of the numbers of migrant workers in 1978-1985 out of a total of 1.2 million is about 120,000 most of who were employed in the mines. This was about half of the adult male population (Ferguson 1990, p112) and had many profound effects.

The earnings of migrant labourers dominated the local economy. In 1977, 118 million USD came home in remittances compared with a GDP of 176 million USD (Ferguson, 1990, p112). Restrictions meant that migrant workers could not take their wives or children with them; they had to return home periodically and had to retire at a certain age. Also, labour contracts were not available to women. Lesotho has, as a result been described as 'an impoverished labour reserve' and 'a country with political autonomy combined with acute economic dependence' (Murray, 1980). It was described by Cobbe (1982) as 'a sort of rural dormitory suburb for South Africa, it consumes a great deal but produces very little' (Cobbe, 1982, p 4).

In an effort to help Lesotho achieve some economic independence from a then apartheid South Africa in the 1970s and 1980s, many countries and organizations showed an extraordinary interest in assisting this country. To give an idea, just in a period between 1975 and 1984, Lesotho was receiving development assistance from 27 different countries and 72 non- and quasi-governmental organizations, leading Ferguson (1990, pg 7) to ask, "What is this massive internationalist intervention, aimed at a country that surely does not appear to be of especially great economic or strategic importance?" Most of this "disproportionate volume of aid…given in astonishingly generous terms" (Ferguson, 1990, pg 7) hardly succeeded despite millions of dollars being spent. While this reality may lend itself to various interpretations, Ferguson identified one of the core reasons as the failure of Western donors to understand the way in which the local people viewed the projects or the commodities used in these developments. Projects were normally gladly accepted and then subtly and sometimes fiercely opposed. Some important projects provide good examples such as the livestock and agricultural land development projects of the 1970s and 1980s. Ferguson wrote about the failure of a rural livestock management programme in Lesotho, (Ferguson, 1990). 'Through all the (Thaba-Tseka) projects various phases the idea of commercializing and rationalizing livestock production remained at the heart of the planners' designs for development of the region (Ferguson, p35). However, many traditions and beliefs underlie the fact that villagers would rather keep their cattle than sell it 'I will never sell it if I already own it. I will never sell it,' (Ferguson, 1990, p146). What escaped the planners' attention was that an average owner of a cow in Lesotho viewed it not primarily as something to rear and sell. It provided milk for the family, it is used extensively in crop cultivation and harvesting, and many times, the use of its meat and skin in a family is seen as "binding" in some traditional ceremonies and rituals.

The other important example involves the issue of land-use and land ownership. The land is owned and managed by the communities in Lesotho. Ignoring this very important oversight, many land development projects would single out a few organized people out of the community and, in agreement with a chief, give part of the land to be used by the group to the exclusion of the rest of the members of the community. Almost always, these projects proved to be disastrous as the excluded community members found usually unlawful means to reclaim what they viewed as their legitimately owned land (Ferguson, 1990). People did not want to be told what to do and lost interest in government funded schemes. They were not even consulted. The "supposed beneficiaries and their sociopolitical organizations were excluded from the policy formulation process (Makoa, 1999, p47)... No serious studies were made regarding the role of the land tenure system in development and how people viewed it" (Makoa, 1999, p56). These developments are summarized by Baillie (2006) in her book, *Engineers within a Local and Global Society*.

Baillie concluded that the developments revealed that people of Lesotho were not consulted concerning what they wanted before the initiators of developments projects designed the schemes which cost many millions of dollars. This study is an attempt to work in another way, to conduct a needs analysis before any development is done and to work in a participatory way with local residents. It may not be extensive enough but it is meant to give some clue into the existing local environment and what they may expect out of NFCs project. Therefore this study investigates not only the present resources that could be used for making NFCs in Lesotho. It interviews and analyses the responses of likely players in such a project including farmers, householders and members of cooperatives to determine what would be suitable for them. At the end of the chapter, a brief description is made about the planned project coming out of this four year interaction with the local people. This project is likely to be funded by the Government of Canada for the development of NFCs in Lesotho. From the reviewed literature, the author is not aware of previous similar NFC related projects.

3.2 Methodology

Due to the partly social nature of the part of the study, it was approved by The Queen's University General Research Ethics Board to ensure it conforms to the accepted ethical standards.

The first action was to make a survey of the scale of agricultural fibre sources, waste plastics and identify relevant local organizations in Lesotho. A number of basic questions were formulated to achieve this objective (Table 3.1). Maseru district (one of the ten districts of Lesotho) was selected as the main focus for the project due to its potential for producing both the waste plastic and fibre needed for the composites. This is especially true in the capital city also called Maseru. Two visits were made to Lesotho. During the first visit, the data were collected over a period of nearly two weeks from the 09 August 2005 to the 19 August 2005. The first part of the data was obtained from published documents found in various institutions in Maseru city. The second part of the data was obtained from personal interviews with representatives of relevant institutions (Appendix 8). The sources of the documents obtained and the kind of information they contained are shown in Table 3.2.

Table 3.1 Areas of investigations for local raw materials

Area	*Questions*	*Objectives*
Present sources of natural fibres:	What are the present sources of natural fibres in Lesotho and how much of them are there?	To investigate if there are suitable sources of fibre existing in the right amounts for NFCs industry
Waste plastic production	What kind of plastic and how much of it is produced in Lesotho?	To investigate if the recyclable plastic waste exists in enough quantities to sustain NFCs industry
Waste plastic recycling institutions and technology	What kind of related technology and institutions already exist? What role can these institutions and technology assist in this industry?	To supply information relating to institutions that could work together to develop the industry taking advantage of existing local technology

The second action was to investigate the perceptions and views of relevant organizations and individuals concerning this project. Short questionnaires were prepared for farmers, householders and members of cooperatives (Appendix 9). The data for this part were collected in the second trip over a period of approximately 3 weeks from the 23 June to the 12 July 2006. Several interviews and workshops were held as shown in Table 3.3 and Table 3.4 respectively. The targeted groups were farmers, cooperatives and householders, who could work together from the supply to the end-use chain in the proposed industry. Telephone interviews of those already involved and interested partners were made as a follow-up to the interviews. This information became invaluable in the development of project proposal for the project described in section 3.3.7.

Table 3.2 Documents obtained from the local institutions

Type of information	*Name of the document*	*Source organization*
Present sources of natural fibres and their costs	Lesotho agricultural situation report (2000/01-2001/2002)	Lesotho Bureau of Statistics
	Lesotho agricultural production survey of crops (2003-2004)	
	Names and numbers of *Agave americana* cooperatives in Lesotho	Lesotho Producers Cooperatives (LEPCOP)
Information about waste plastic	The cleanest town competition report (May, 2004)	Lesotho National Environmental Secretariat
	Lesotho plastic companies	Lesotho Ministry of Trade and Industry
	National environment youth corps, annual report (1998)	UNDP Lesotho
Information about use of present roofing materials	Lesotho environmental statistics	Lesotho Bureau of Statistics

Table 3.3 Interviews made with different local groups in Maseru district

Area/group	*Location in Maseru district*	*Interviewees*	*Number of interviews*
Rural areas	3 villages at Roma area	Householders	60
		Farmers	60
Semi-urban and urban areas	3 semi-urban dwellings in Roma and 1 locality in Maseru city	Householders	54
		Farmers	10
Maseru Aloe groups	Maseru city	Representatives of groups	11
		Members of groups	25
Total number of interviews			220

Table 3.4 Workshops held with members of Maseru Aloe and other cooperatives

Place in Maseru and Roma	*Group name*	*No of attendees*
Semphetenyane	Boiketlong Multipurpose	11
Motimposo	Ithabeleng Multipurpose	20
Ha Tsosane	Boiketlong Multipurpose	9
Roma		10
Stadium area	Hlabollanang Multipurpose	9
Maseru down town	Lechabile Multipurpose	1
Total number of attendees		60

3.3 Results and discussion

3.3.1 Sources of natural fibres

Major crops in Lesotho include corn[3.1], sorghum, wheat, beans and peas (Lesotho Bureau of Statistics, 2002). There are no fibre crops[3.2] in this country. *Agave americana* plant is the only local source of strong fibres but it is not cultivated as a crop presently. This plant is evidently abundant throughout the country though its quantities are unknown. Corn is the most widely cultivated crop because its grain is a local staple food. The next most widely cultivated crop is sorghum[3.3]. On average, the area of land used to produce corn has been about three times as much as that used for producing sorghum per annum over the past two decades (Figure 3.1). Corn grain production is roughly four times more than that of sorghum per annum over the same period. It contributes 67% of all grain production per annum (Table 3.5, Figure 3.2). There is an upward trend of corn production even though the area devoted for it declines slightly over this period (Figure

[3.1] Also known as maize in Lesotho and other countries
[3.2] Crops rich in strong fibres such as hemp and flax
[3.3] Its grains are normally used in making traditional homemade beer and other drinks

3.3). High fluctuations in area planted and grain harvest can be expected in a country where crop production is heavily dependent on weather (Figures 2.1 and 2.2).

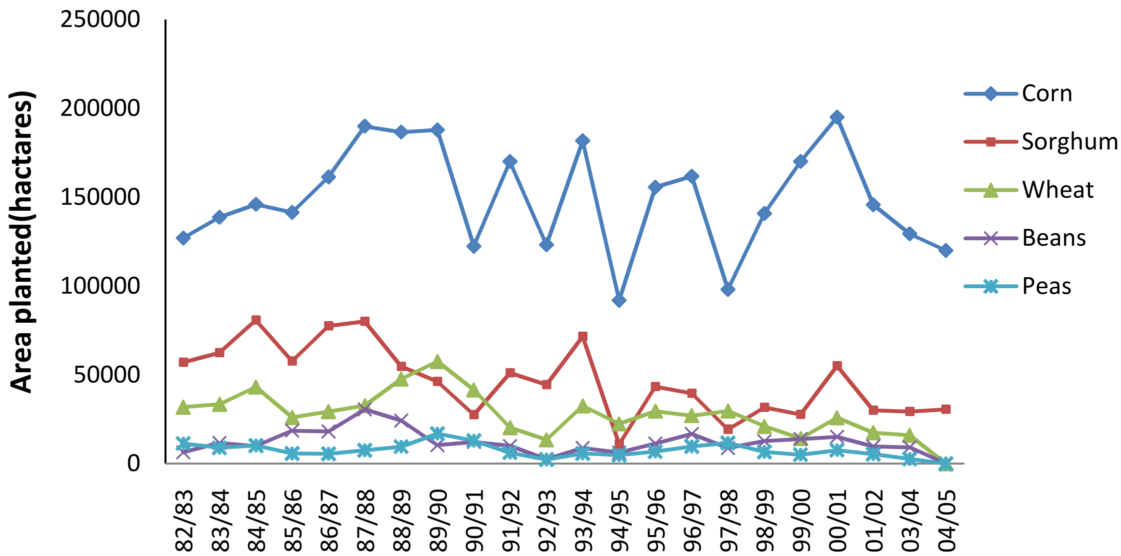

Figure 3.1 Area planted for major crops in Lesotho over time (Lesotho Bereau of statistics, 2002)

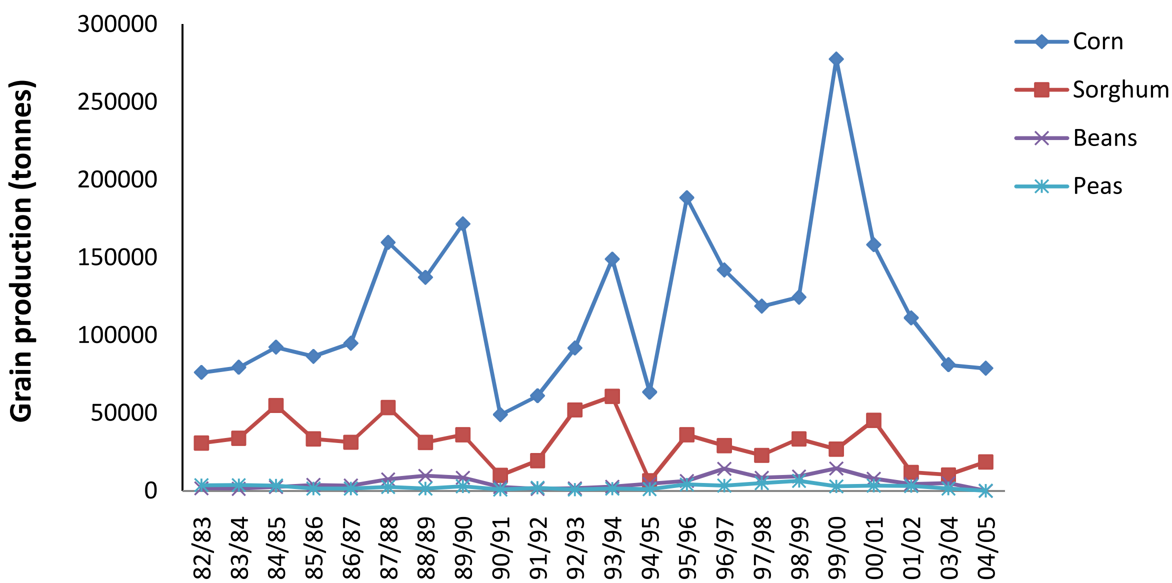

Figure 3.2 Grain production of the major crops in Lesotho over time (Lesotho Bereau of statistics, 2002)

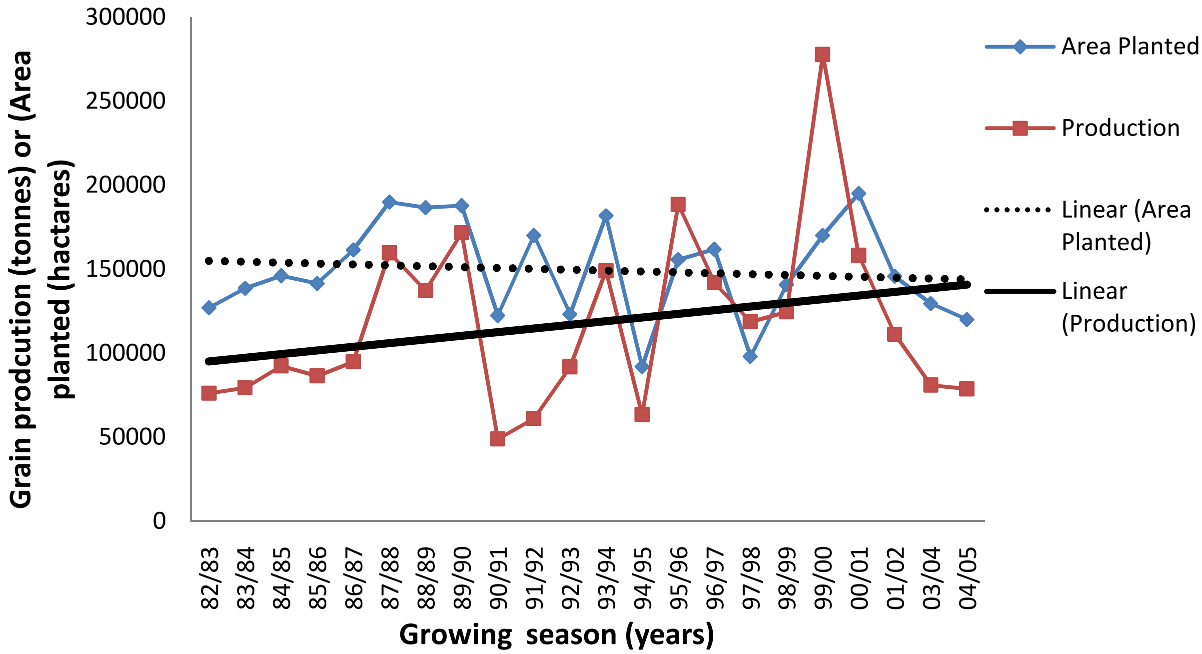

Figure 3.3 Trends in the area planted and production of corn grain in Lesotho (Lesotho Bereau of Statistics, 2002)

Table 3.5 Average production of grain and straw from major crops in Lesotho (Lesotho Bereau of statistics, 2002)

Parameter	*Corn*	*Sorghum*	*Wheat*	*Beans*	*Peas*	*Total*
Average grain production per annum (metric tonnes)	117848.3	31252.5	20236.1	5467.2	2531.4	177335.5
Average straw production in per annum (metric tonnes)	235696.6	62505.0	40472.2	10934.5	5062.8	354671.1
Percentage	66.5	17.6	11.4	3.1	1.4	100.0

The crops discussed above are not sources of strong fibres. The *Agave americana* plant was identified as the only source of strong fibres in the country. Although this plant grows in abundance all over the country, there are no records concerning how much of it exists. One of its advantages is that it grows in all four topographical regions of the country: Lowlands, Highlands, Foothills and Senqu valley. It does not need too much care; once it is planted it continually renews itself as seedlings keep growing. Its disadvantage is that it takes a long time to mature, hence its common name, century plant.

Since it is not presently cultivated as a plant, *Agave americana* plants are not found concentrated in significant amounts in one place. Rather they form small clusters scattered all over the country, especially in the countryside where they were traditional used for fencing. It is presently used by a number of cooperatives in the production of Agave skin gels and which result in fibre as a waste product (section 3.3.6). Plans to make use of large amounts of this plant in the composite industry will surely need careful management. This could include efforts to cultivate it as a crop. Otherwise the existing plants could be overharvested. The scattered clusters of this plant could also create a challenge in collection. See chapters 4-6 for more information on the nature and reinforcement capabilities of *Agave americana* fibres in composites.

The results above help in finding which crops are more likely to be targeted for use in the composites, both for a short term and long term plans. Nevertheless they say little as to whether the crops are in *adequate quantities* for the proposed use in NFCs. Solving this problem is a challenge since there should be some reference against which to measure such adequacy. That would be the level of demand for the NFCs in the country which do not exist presently. The following section provides a scenario that could help in determining what the present quantities of crops are capable of achieving if they are used for making composites, based on the observed local needs.

3.3.2 A roof ceiling scenario

Table 3.6 Parameters for estimating the number and cost of roof ceiling and number of houses they can insulate in Lesotho

Property	*Symbol*	*Estimated value*
Grain production per year	M_g	177335.5 t
Straw production per year	M_s	354671.1 t
Mass of available waste plastic	M_m	unlimited
Harvest index	HI	0.5
Roof area needing insulation	A_h	15 m^2
Roof area each ceiling panel could cover	A_c	0.36 m^2
Volume of each ceiling panel	V_c	0.00216 m^3
Density of straw	ρ_f	1.2 g/ cm^3
Density of waste plastic	ρ_m	0.95 g/ cm^3
Straw mass fraction	m_f	0.3
Fraction of available straw	a_f	0.5
Cost of straw	C_f,	0.5 M/kg
Cost of fibre	C_m	0.6 M/kg
Cost of processing	C_p	0.7 M/kg

Cheap roof ceiling could help provide highly needed insulation in both summer and winter for householders in Lesotho (section 3.1). For simplicity, the houses can be taken as having similar shape and size and as following the model most common in Lesotho, *polata* (Figure 3.4). We pose the question, how many houses and at what cost could the houses be insulated given the present production of fibre? Suppose we decide to estimate the number of houses N_h which can be insulated with thin composite panels made from waste plastic and milled straw fibre from the existing local crops (Table 3.5). The panels are thin square prisms, with the base area A_c capable of insulating a roof area A_h which is equivalent to floor area in the house (Figure 3.4). To better focus on what the fibres can do, we assume unlimited supply of available kind of waste plastic *(M_m)* but limited supply of fibre. Therefore

$$N_h = \frac{n_c A_c}{A_c} \tag{3.1}$$

where n_c is the total number of panels that can be made from available straw and unlimited waste plastic in the country every year. The number n_c is a function of the total mass of all the composite material M_{ct} that can be made from available straw and unlimited waste plastic each year and the mass of each composite ceiling panel M_c of base area A_c (Figure 3.4). Thus

$$n_c = \frac{M_{ct}}{M_c} \tag{3.2}$$

Assume that the whole straw and not only fibre is used for reinforcing the plastic (chapters 6 and 7). Then the total mass of all the composite material that can be produced each year M_{ct} would equal the total mass of straw available for use in composites each year M_s divided by its mass fraction m_f in the composite. This amount of available straw can be obtained from total grain production per year M_g by dividing it with its Harvest Index (*HI*) or grain to straw mass ratio of the crops in use (see below for more information on HI). M_s would also depend on the *fraction of available straw to the total straw produced in the country* each year, a_f (for various reasons, not all straw produced will be available for use in NFCs).

$$M_{ct} = \frac{M_s}{m_f} = \frac{M_g a_f}{HI m_f} \tag{3.3}$$

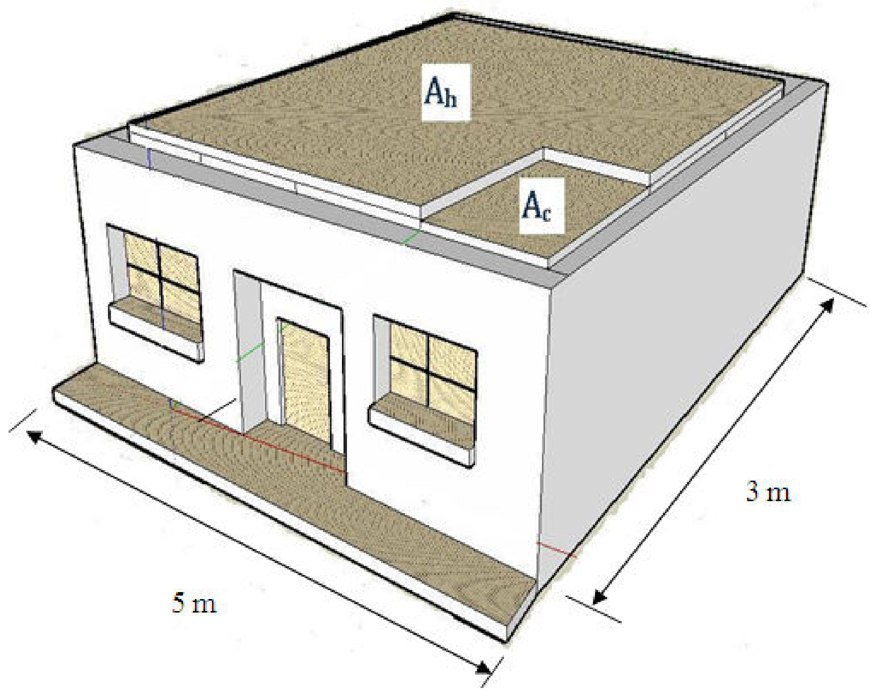

Figure 3.4 A typical corrugated iron roofed house popular in Lesotho usually referred to as "*Polata*" in local language. A_h is all the roof area between the walls of the house, it is equivalent to the floor area. This section of the roof is "cut" to show the area A_c covered by a square ceiling below it.

The mass of each composite panel M_c is:

$$M_c = \rho_c V_c \tag{3.4}$$

where ρ_c is the density of the composite panel and V_c is its volume. If v_f, ρ_f, and ρ_m are volume fraction of straw in a composite, density of straw and density of polymer matrix in a composite respectively, then, from rule of mixtures (Hull, 1990):

$$\rho_c = v_f \rho_f + (1 - v_f)\rho_m \tag{3.5}$$

Thus:

$$M_c = V_c\left[v_f\rho_{f+}\left(1 - v_f\right)\rho_m\right] \tag{3.6}$$

From (3.2), (3.3) and (3.6),

$$n_c = \frac{\frac{M_g a_f}{HIm_f}}{V_c\left(v_f\rho_f + \left(1 - v_f\right)\rho_m\right)} \tag{3.7}$$

However v_f can be expressed in terms of mass fraction[3.4] of straw in the composite m_f using the relationship (Hull, 1990).

$$v_f = \frac{\frac{m_f}{\rho_f}}{\frac{m_f}{\rho_f} + \frac{1 - m_f}{\rho m}} \tag{3.8}$$

From (3.7) and (3.8), the number of panels that can be made from known grain harvest

$$n_c = \frac{M_g a_f}{V_c HI}\left(\frac{m_f\rho_m + \rho_f - \rho_f m_f}{m_f\rho_f\rho_m}\right) \tag{3.9}$$

[3.4] In practice, it is easier to measure mass and use mass fractions of raw materials than calculate their volumes and volume fractions

If there is a need to assess the number of composite panels that can be made from a measured amount of available straw[3.5], Equation 3.9 can be simplified to

$$n_c = \frac{M_S}{V_c}\left(\frac{m_f\rho_m + \rho_f - \rho_f m_f}{m_f\rho_f\rho_m}\right) \tag{3.10}$$

From (3.1) and (3.9), the number of houses that can be insulated from known grain harvest per year

$$N_h = \frac{A_c M_g a_f}{V_c H I A_h}\left(\frac{m_f\rho_m + \rho_f - \rho_f m_f}{m_f\rho_f\rho_m}\right) \tag{3.11}$$

It may be necessary to estimate the cost of producing these panels and compare the price with that of conventional panels in the markets. The cost of producing each panel C_c

$$C_c = m_f M_c C_f + (1 - m_f) M_c C_m + C_p \tag{3.12}$$

where C_f, C_m and C_p are cost of straw per unit mass, cost of waste plastic per unit mass and cost of composite processing per panel respectively. From (3.1) and (3.12), the total cost of making composites that would insulate a known number of houses C_{ct} would be

$$C_{ct} = \frac{n_{\square}A_{\square}}{A_c}\left(m_f M_c C_f + (1 - m_f) M_c C_m + C_p\right) \tag{3.13}$$

[3.5] For instance, the amount of straw bought, measured and stored in a production site

The following crude estimates and assumptions can be made to estimate the number of houses that can be insulated from available straw in Lesotho and the cost of producing composites to insulate them. For simplicity, straws from different crops are assumed to have insignificant differences in reinforcing capabilities. Consider an annual average grain production of all major crops in Lesotho M_g (Table 3.5). This Figure can be used to calculate the amount of average annual straw produced in this country (crop production is normally given in grain rather than straw figures). To do this, the concept of HI or grain-to-straw mass ratio of the crops is used. As can be expected for natural materials, this property varies even within the same plant species. Prihar and Stewart (1991) had the following ranges of harvest indices: 0.48-0.53 for sorghum, 0.58-0.60 for corn and 0.38-0.47 for wheat. Hay (1995) suggested that HIs of the most intensely cultivated grain crops generally range from 0.4 to 0.6. The crops in Table 3.5 fit this description due to their common use as sources of food worldwide. Therefore it is assumed that the HIs for each of these crops range around the average of 0.5. With this HI, the annual average straw production M_s has been calculated (Table 3.5).

The question of how much straw can be available for use in composites depends on many factors such as willingness of farmers to sell it and ease of transporting this straw to the project site. Since estimating such factors would be a challenge, the middle number, 0.5 (50%) is arbitrarily taken as the fraction of available straw to the total straw produced in the country each year, a_f (which means half the straw produced in the country is assumed to be available for use in the composites). Of course this fraction can be varied to note the differences in whatever parameter is being estimated.

From observation, there is a tendency to build a number of small one or two roomed houses rather than one big house with many rooms in Lesotho. The most common house is a small corrugated iron roofed house made from concrete bricks whose average floor area dimensions A_h can be estimated as 5m× 3m (Figure 3.4). Suppose a manufacturing site produces 60 cm×60 cm×0.6 cm ceiling panels (this is the size of the panels planned to be used in the envisaged project in Lesotho (see section 3.3.7)). Each panel would insulate a roof area A_c of 0.36 m^2 inside the house and have a volume V_c of 0.00216 m^3. Densities of waste plastic and straw can be estimated as 0.95g/cm^3 (for instance, HDPE bags common in Lesotho) and 1.2g/cm^3 (common for natural fibres, although in straw, there is more than just natural fibres, see chapters 6 and 7) respectively. The mass fraction of straw in the composite will be taken as 0.3 due to ease of processing at this filler content (e.g. less viscosity during extrusion) and agglomeration of fillers and reduction in properties at higher weight fractions. The cost of waste plastic, straw and processing[3.6] are taken as 0.6 M[3.7]/kg, 0.5 M/kg[3.8] and 0.7M/panel[3.9] respectively. These crude estimates can be refined as more information becomes available. They are merely meant to give a reasonable idea of what the present size of raw materials in the country could achieve. The arbitrary numbers should not be viewed as facts. All the estimates are summarized in Table 3.6.

[3.6] Including all costs related to labour and power.

[3.7] Maloti (M) is the currency of Lesotho, 1 USD~8 Maloti. The currency is equivalent and tied to the South African rand. Price of waste plastic in 2005 was 0.5 M/kg. It can be assumed the price increased a little.

[3.8] Just put a little below the cost of waste plastic. Straw is more abundant and it is not presently sold in Lesotho. That could lower its prices.

[3.9] This is an arbitrary number, made to be a little higher than the cost of plastic. The true cost is unknown.

With these assumptions, the number of houses that can be roofed starting with the known annual production of grain of 177335.5 t each in Lesotho can be estimated at 6.5 million (Figure 3.5). When unlimited waste plastic is assumed, there is unlimited number of houses that could be insulated when the fibre mass fraction used in the composites approaches zero (Figure 3.6). However, given a limited supply of straw, increasing its mass fraction in the composites rapidly reduces the number of houses that could be insulated.

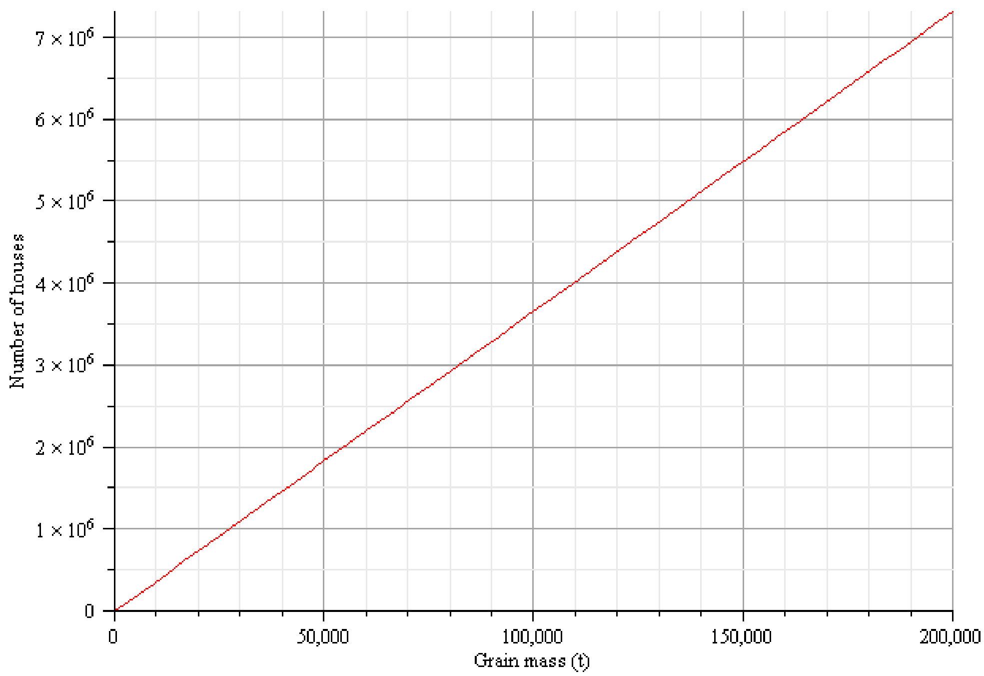

Figure 3.5 Number of houses that can be insulated from annual grain production in Lesotho (plotted from Equation 3.11 using estimates in Table 3.6 and assuming mass fraction of 0.3)

From Equation 3.14, it would take just M29 to make produce ceiling panels enough to insulate a single house in Figure 3.4 (see Figure 3.7).

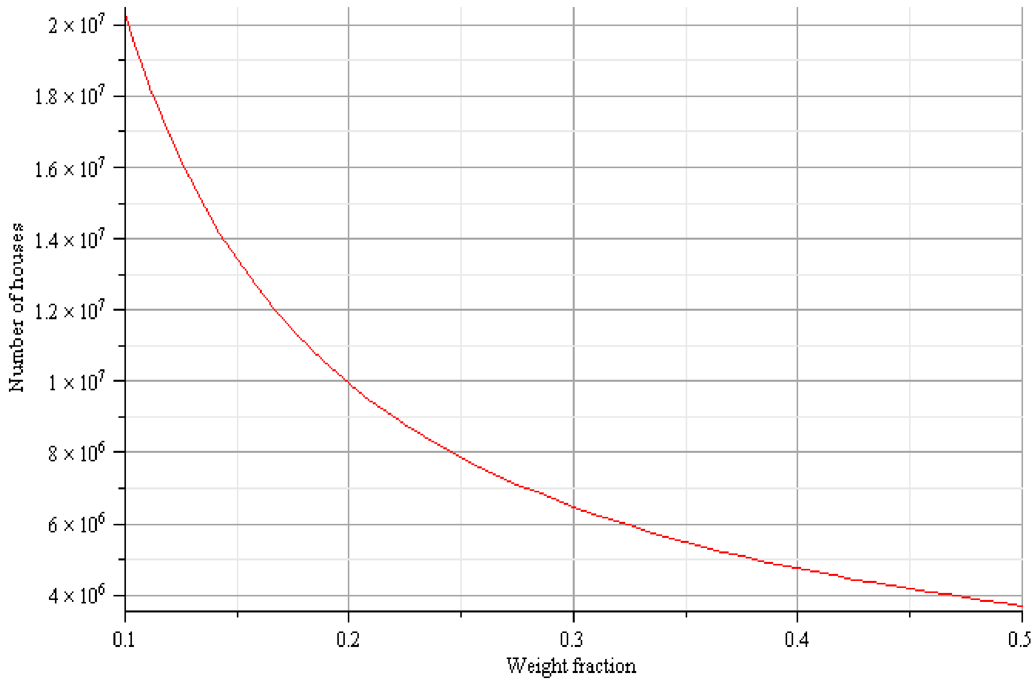

Figure 3.6 Effect of mass fraction of straw per panel on a number of houses that could be insulated given unlimited waste (plotted from Equation 3.11 using estimates in Table 3.6)

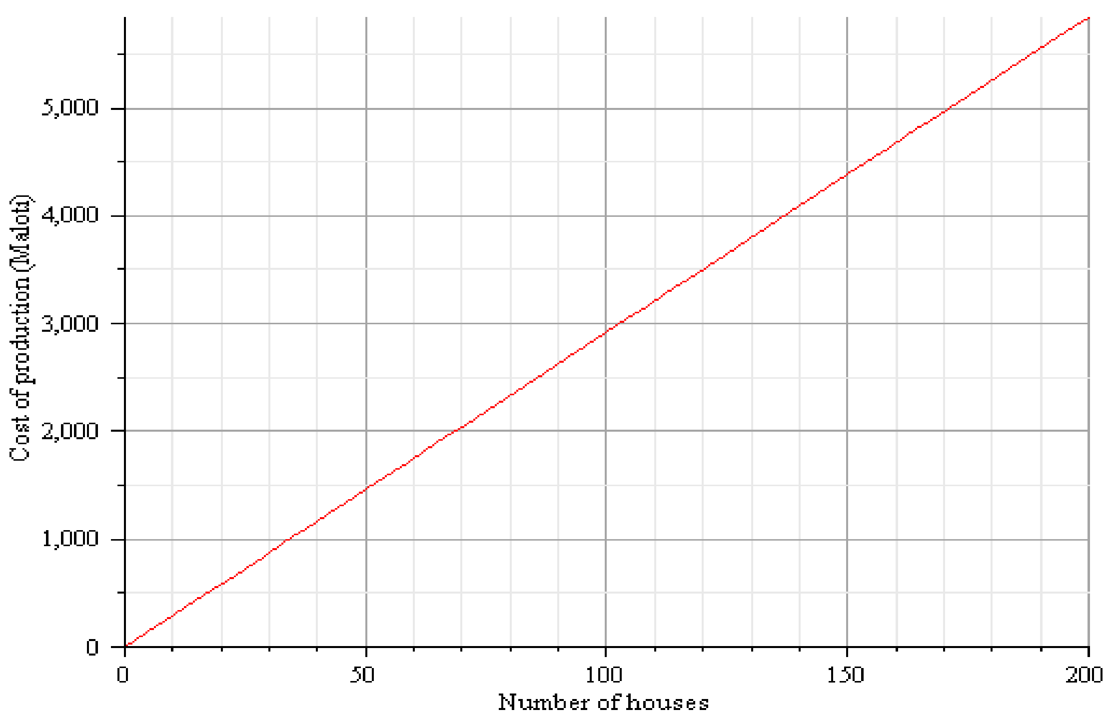

Figure 3.7 Cost of producing straw waste plastic composites as a function of a number of houses being insulated (plotted from Equation 3.13 using estimates in Table 3.6)

3.3.3 Production and recycling of waste plastic

The amount of waste plastic produced in Lesotho is not well known. Only one report, a PhD thesis by Mvuma (2002) gave an idea of how much plastic may exist there at least 6 years ago. The study focused on two areas, Maseru and Maputsoe[3.10] which are the two main industrial and commercial hubs in Lesotho. Table 3.7 shows the contributions of each sector in the total annual waste plastic produced. The commercial establishments (e.g. grocery shops) contributed the most waste plastic, even more than industries. Interestingly waste plastic shared a large percentage of solid waste produced, 36%, that is 48342.9 tonnes per annum. This is surpassed only by waste paper, 54%. This Figure does not likely reflect the amount of waste plastic produced all over the country in more than 10 other small towns.

Only one waste plastic recycling company of Chinese origin (MU plastics) was identified in Maseru[3.11]. It recycled mainly plastic bags from the neighbouring textile companies and commercial establishments. The plastic is sorted, cleaned and shredded before being passed through an extruder. The extruded material is pelletized and mixed with virgin plastic (bought from South Africa) to make mainly plastic bags though extrusion and blow molding processes. These plastics are later resold mainly to the grocery stores. The main challenge in this process was mentioned as the presence of small rocks and metals in the waste material which occasionally blocked the extruder.

[3.10] A town in Leribe district, besides Ficksburg town of South Africa

[3.11] According to records of the ministry of trade and industry, this was the only plastic recycling company in the entire country.

Table 3.7 Annual composition and quantity of waste generation per category and source in surveyed areas of Maseru and Maputsoe, Lesotho (Tonnes/Annum) (Mvuma, 2002)

Category	*Value (t/annum)*
Low income	72.38
Middle income	9.94
High income	83.12
Industries	29.54
Commercial establishments	48147.95
Total	48342.9
Percentage of plastic in total solid waste	36 %

Another waste company (Welcome Transport) which originated in 1980 and had 70 employees was identified. It did not directly recycle the waste plastic but collected it (and many other kinds of waste), sorted it and sold small amount to MU plastics. The rest of the plastic was sold to recycling companies in Johannesburg, South Africa. At the time of interview, the company had plans to ultimately recycle the plastic on the site. It was also installing a plastic shredding facility to make transport of bulky plastic easier in order to reduce transportation costs. It worked directly with an estimated 450 waste scavengers who supplied it with waste plastic for a price of M 0.5/kg (Figure 3.8). Welcome Transport claimed to send 8 tonnes of waste plastic to South Africa a month. It also burns a significant amount of unusable waste plastic each day. The biggest challenge to the company was a competition with what the company interviewee described as “shady” South African companies which came directly to the waste scavenges to buy plastic instead of through Welcome Transport.

Figure 3.8 The main dumping site at Ha T'sosane in Maseru Lesotho. People disposing and scavenging for waste can be seen as well as smoke from some of the waste

One informal waste scavenger supplying waste plastic to Welcome Transport was interviewed on the dumping site in Figure 3.8. She claimed to make an average of M20 a week from the process. Her challenges included the constant burning of the waste plastic by some members of the public, the practice of which reduced her source of income. It is important that any future waste plastic projects do not sideline the obviously poor scavengers who are making ends meet with this job. Rather it would be important to make them part of the project. These relationships could be summarized in Figure 3.9.

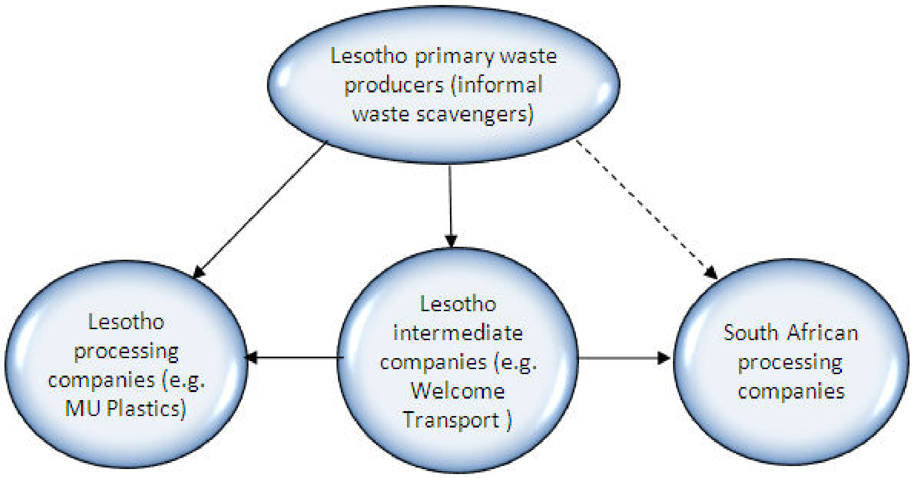

Figure 3.9 Relationships between waste plastic producers and users in Lesotho and South Africa

3.3.4 Householder surveys

According to Lesotho Bureau of Statistics, (2002), iron roofed houses makes 62% of the all the houses in Lesotho followed by thatch/straw, 35% and roof tiles, 2.1 %. The iron roofs are poor insulators. Yet many of the houses do not have insulating ceiling panels. Understanding how householders view their present roofing situations may shed light into how the ceiling panels could be used to answer their needs *and wants*. The results of a survey made on householders are summarized in Appendix 6. As expected, 67% of the houses belonging to the interviewed population of householders were roofed with corrugated iron, followed by thatch 22% and roof tiles 10%. The higher than National average percentage of roof tiles is likely due to the fact that a significant number of the interviewed population were from urban and semi-urban areas where roof tiles are more common. The use of thatch, a traditional roofing material which is perceived locally as a good insulator is declining due to poor management. It was traditionally harvested for free from community owned rangelands, but as found in this study 40% of the respondents now bought it.

Whereas the householders mainly lived in corrugated iron roofed houses, the majority of them (45%) would rather be living in tile roofed houses since tiles have a “good” appearance. Good appearance, associated mostly with tiles, was therefore the most cited reason (20%) for choice of roofing. The second and the third most cited reasons for choice of roofing were ability to insulate (18%) and durability (15%), attributes which were mostly associated with thatch and iron roofs respectively. In winter many iron roofed houses experience water condensation on the roofs due to steam from cooking, resulting in water dipping known locally as “*rothe*”[3.12]. This phenomenon does not occur in iron roofed houses with insulating ceilings which do not cool enough to permit condensation on their surfaces.

Showing the seriousness of lack of insulation in most houses, 85% of the interviewees were not satisfied with the temperatures in their houses. It was considered too hot in summer and too cold in winter. About 93% of these householders associated roofing with these extreme temperatures. The main culprits for this situation were the iron roofs. Nevertheless the majority of people eventually use iron because it is far cheaper than tiles and unlike both tiles and thatch; it needs little expertise in the roofing process. When they were given small flat samples (about 10 × 10 × 0.2 cm) of composites made from agave, corn straw and waste plastic and asked to suggest uses, householders gave a range of

[3.12] This is a highly unpopular phenomenon because the usually dirty droplets can land on anything in the house them. The most cited product was the floor tile. A range of products people thought about when they saw the composites may be the first step in getting to know what products are really in the local people's minds.

A few lessons can be learned from the responses. Introducing NFCs ceiling panels would help in that it would moderate room temperatures in iron roofed houses without a need to change the present roofs. However, for this to be successful, the ceilings have to be extraordinarily cheap. Otherwise most people will not afford them as they do not afford the existing ceiling panels in the markets now. They also have to be very durable and need little expertise to mount to the roof. Most importantly, they should require no change in the present roofing system to accommodate them. Since most people preferred products that "looked good," appearance of the final products may not be overlooked at the expense of providing them cheaply.

3.3.5 Farmer surveys

Success in making and using NFCs will depend on the cooperation with farmers who produce straw or *Agave americana*. The results of a survey made on farmers are summarized in Appendix 7. As expected the majority of farmers (39%) grow corn, followed by sorghum (28%) (compare with Table 3.5). These crops are grown mainly for subsistence (67%). Only 33% of the farmers sell their products and just 7% grow their crops exclusively for cash. If given the opportunity 76% of the farmers would sell their straw. This is a significant percentage and may have positive implications for the NFCs industry. The farmers who would not sell their straw cited the need to feed animals as the reason. Almost half of the respondents were not aware of alternative uses of straw except what they were already using it for. Whereas the majority of farmers who were aware of alternative uses of straw were mostly aware of its use as manure for a healthy soil (39%), only 5% of the farmers used straw as manure. Using straw as manure could mean decomposing it several months in soil well before the planting season. This is a helpful process which may prove costly for farmers since it means double –tilling each year. Rather 88% of the farmers gave their straw to animals. A huge majority of farmers (90%) would be willing to cultivate *Agave americana* for commercial purposes.

3.3.6 Cooperative surveys

While several local companies expressed interest in producing NFCs, it was deemed better to focus on cooperatives which would benefit a broader spectrum of people. More than a 100 different cooperatives were identified in all ten districts of Lesotho. One such cooperative was Maseru Aloe whose members were extensively interviewed. This is a mother body made of around 14 different cooperatives based in Maseru city. Under the direction and assistance of the Lesotho government department of cooperatives, this body takes juice from *Agave americana* leaves using it to make mainly skin gel and creams. The products are sold locally and to the neighbouring South Africa. Results of the interviews with mainly the individual members of this body[3.13] are shown in Table 3.8. These cooperatives consisted of mainly women (88%). The age average was 53 years. An

[3.13] A few members of other cooperatives from outside of Maseru district were included average member had at least completed the last year of elementary school [3.14] and had 4 children. Most of the respondents took farming as an alternative occupation (30%), 19% made and sold handicrafts and 22% had no alternative occupation. The age distribution shows most members falling between the age of 50 and 60 (Figure 3.10). Some members were as young as 27 and as old as 72.

Table 3.8 Responses of members of cooperatives and percentages according to their answers concerning their demographics and occupations

Question	*Answer*	*Response*	*Question*	*Answer*	*Response* (%)
Gender	Percentage of males	12 %	Other occupation	Farmer	30
	Percentage of females	88 %		Tailor	15
	Mean age	53		Nurse	7
Other demographics	Mean class	7		Make and sell handicrafts	19
	Mean number of children	4		Sell wood	7
				None	22

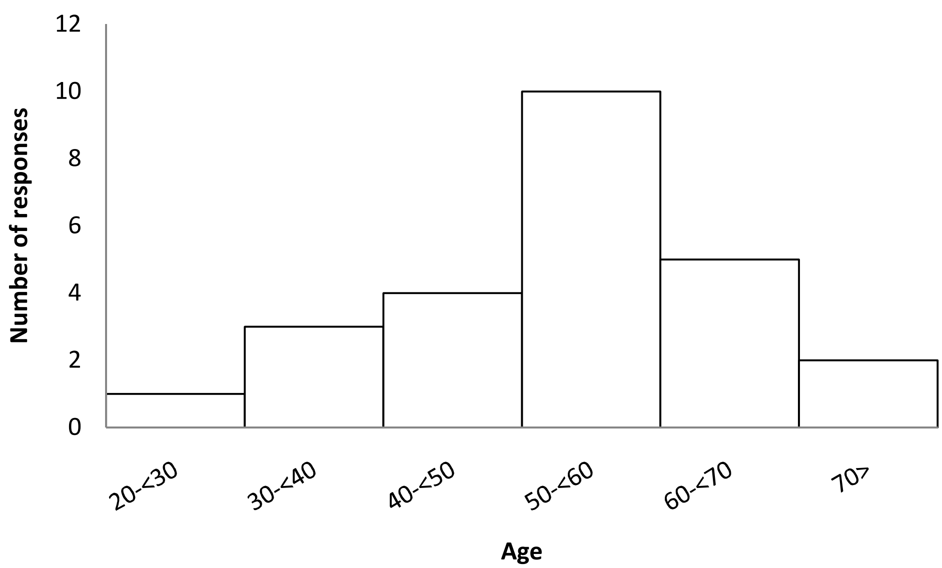

Figure 3.10 Members of cooperatives according to different age ranges

[3.14] Known as standard 7, a equivalent of grade 7 in some other countries

3.3.7 The proposed NFCs project resulting from this study

All representatives and workers of the cooperatives interviewed individually and, during the workshops (Tables 3.3 and 3.4), agreed that the plant fibre waste plastic composites would be an excellent additional product to create within their groups. They have access to waste plastic, straw and *Agave americana* fibre and they can learn the manufacturing techniques and house the necessary equipment at the cooperatives training centre where the *Agave americana* jellies and creams are presently made. This is where they have learnt the process and where they go once a week, bringing raw materials with them, to process their lot of gel or cream.

One of the major blocks to implementation of a composite manufacturing facility in Lesotho was deemed to be the high cost of equipment. Therefore low cost manufacturing would be a priority if composite projects were to succeed (Chapters 4, 6 and 7). Seeking low-cost alternatives, the Department of Mechanical Engineering at Queen's University worked collaboratively with the University of Napoli, Italy, Lerotholi Polytechnic, Department of Cooperatives and Maseru Aloe Cooperatives in Lesotho, to design a compression moulder or 'hot press' prototype shown in Figure 3.11. This basic machine can be used to make ceiling tiles and other flat panels using waste plastic. The hot press is designed to be manufactured from inexpensive materials that can be purchased locally or in neighbouring South Africa. Like any other hot press, the materials to be made are placed in a mould between two heated platens and compressed to desired shapes (see section 6.2.2).

Figure 3.11 A hot press designed at Queens University

As a result of this study, the proposal has been made and nominated, at the second stage of an application, by the Association of Universities and Colleges of Canada (AUCC) in their 2007 “Building on success competition” to the Canadian International Development Agency (CIDA) to be considered for funding. In the proposed project, Lesotho, Canadian and Italian institutions have agreed to work together at different capacities and levels in a project that is likely to take 3 years (Figure 3.12).

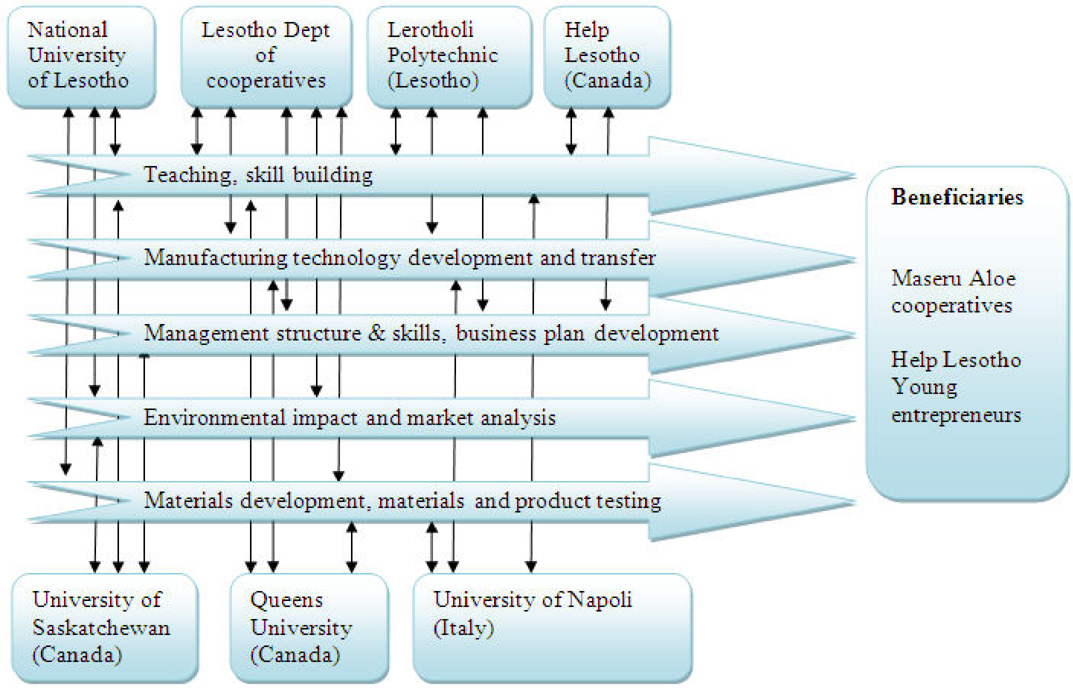

Figure 3.12 Partnership map: horizontal arrows represent 5 layers of project activities; vertical arrows indicate each institution's link with a particular project layer

3.4 Conclusions

This study balances the need to provide technical assistance in building up NFC industry in Lesotho with the need to provide solutions that are relevant and directly address the needs of the local people. It is argued that the massive failure of previous development projects in this country were partly due to lack of this or similar forms of consultation which we call needs analysis, understanding and providing what people need rather than what developers think they need.

The results show that any NFCs project that can be initiated in the near future in Lesotho would depend on available straw from the commonly cultivated crops. *Agave americana* fibre also has great potential to be used in composite in this country if accompanied by proper management which would include cultivating it in selected areas like other crops.

In a fictional project supplying roof ceiling for a common form of houses in Lesotho, it was estimated that up to 6.5 million of such houses could be insulated at the composite production cost of nearly M30 for each house. Results of the interviews revealed that the local people do need ceiling panels as these would moderate otherwise extreme winter and summer temperatures aggravated by iron roofs. Providing cheap panels, easy to mount to the existing houses could be a relief for the householders. With farmers willing to sell their straw for composites and cooperatives willing to take up the challenge of making composites, an NFC project in Lesotho is a possibility.

3.5 References

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Chapter 4: Tensile properties of *Agave americana* fibres and interfacial properties in *Agave americana* reinforced waste HDPE composites

Abstract

Surface treatment is often necessary for strong composites. But the challenge for developing countries is to find chemicals and treatment procedures that are cheap and simple but maintain good composite properties. Mercerization followed by silane treatment of natural fibres is among the simplest and cheapest methods used to improve composite interfaces. This study investigates the effectiveness of this method to improve the bond between *Agave americana* fibres and waste HDPE. The influence of the fibre extraction method, mercerization and mercerization followed by silane treatment on interfacial shear strength (ISS) and fibre tensile properties is determined.

The results indicate that ISS values are generally low but mercerization doubles the ISS values between *Agave americana* fibres extracted by traditional boiling of leaves and waste HDPE. Mercerization also improves fibre tensile and thermal properties. While triethoxyvinylsilane treatment of fibres after mercerization does not improve the ISS, it does not reduce it either, nor does it reduce tensile and thermal strengths of mercerized fibres. Fibres from non-boiled leaves resulted in poor fibre tensile strengths but improved ISS. There is a potential to use mercerization as cheap, simple technique to make *Agave americana* HDPE composites in Lesotho.

4.1 Introduction

The first two chapters provided information into which raw materials, processing methods and even socio-economic factors could be taken into account to better meet the requirements of specific geographical areas in making NFCs. *Agave americana* fibres identified in Lesotho are apparently the most important strong fibres the country has (chapter 3). This chapter investigates *Agave americana* fibers' ability to reinforce waste plastics by focusing on the fibre plastic interfacial bond.

Agave americana fibre is one of the most underused and least studied fibre in the world (Msahli et al., 2005). It is a monocotyledon plant that belongs to the *agava*ceae family. It normally grows in tropical, subtropical and temperate regions of the world. Traditionally, its fibres have been used in ropes and other textile applications. It can be extracted from the leaves in various ways including heating these leaves in hot water (Salerno1et al., 2005), retting them in seawater (Msahli et al., 2005) or using other chemical or mechanical means.

Chaabouni et al. (2006) showed that *Agave americana* fibres have some properties that are different from other fibres. Their ultimate fibres have very low diameters with an average of 3.1 µm. They contrast this with flax ultimate fibres which range from 10 to 30 µm and sisal ultimate fibres with diameters of around 24 µm. The study also reports that *Agave americana* fibre bundles have exceedingly high strain ranging from 39% to 49% owing to the helical nature of ultimate fibres and their ability to behave like a spring.

Waste HDPE could provide a suitable matrix for making composites with *Agave americana.* This is one of the most abundant plastics worldwide due to its low cost, ease of processing and other desirable properties (Gómez et al., 2005). Since it is used mainly in disposable packaging, it often finds itself in waste streams. This makes it a good candidate for recycling. It is particularly suitable for use in NFCs because of its low melting point, which reduces the chance of natural fibre degradation. Although studies have demonstrated that recycled HDPE plastics have some evidence of degradation such as scission, branching and cross-linking (Cruz and Zanin, 2003 and Boldizar et al., 2000), HDPE generally has high resistance to degradation. Also, this degradation can be reduced by restabilizing the plastic (e.g. adding antioxidants to the plastic before reprocessing).

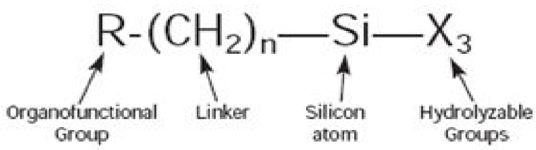
While surface treatments remain necessary to improve natural fibres/plastics bonding, the majority of these treatments use expensive equipment, complex treatment methods, and expensive chemicals (Zafeiropoulos, 2002). However some surface treatment methods such as mercerization (alkali treatment of natural fibres) and silane coupling involve no more than immersing fibres into solutions under ambient conditions. Some silane coupling agents are expensive in their concentrated form, but they are cost effective because they can be diluted with large volumes of water before treatments (Dijon, 2002 and Pickering et al., 2003)

If we identify mercerization and silane treatment as cheap and simple fibre surface treatments, these can be used to improve the interface between low cost *Agave americana* fibre and waste HDPE matrix. In ASTM D 1965, the standard for mercerization, it is described as “the process of subjecting a vegetable fibre to an interaction with a fairly concentrated aqueous solution of a strong base, to produce great swelling with resultant changes in the fibre structure, dimension, morphology and mechanical properties," (Bledzki and Gassan, 1999, pg 251) (Figure 4.1(a)). This process is believed to remove natural and artificial impurities away from fibres, create a rough fibre surface topography, and reduce fibre bundles into smaller fibres (Li et al., 2000 and Joseph et al., 1996). The result is increased adhesion due to increased fibre surface area and mechanical interlocking between fibre and matrix (Bisanda and Ansell, 1991). Mercerization also activates hydroxyl groups in natural fibre. The groups have a potential to bond with alkoxy silanes such as triethoxyvinylsilane used in this study (Wang et al., 2003 and, Pickering et al., 2003).

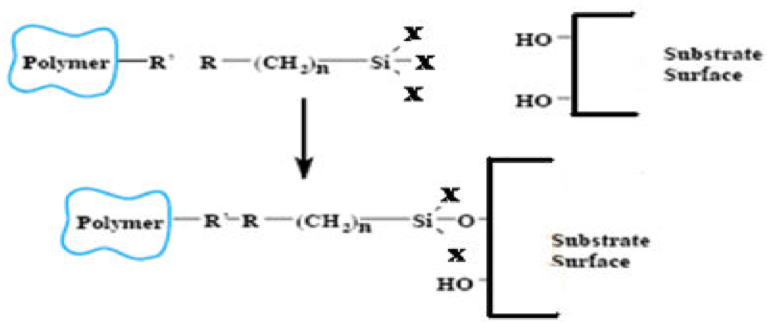
Further, mercerization improves fibre tensile strengths (the stress or force over cross-sectional area of a fibre at which it begins to break) of natural fibres. This treatment possibly orients fibrils along the direction of tensile forces by removing hemicelluloses from fibre, resulting in better load sharing between them (Bledzki et al., 1996). However, improving the fibre tensile strength is limited by a maximum duration of treatment. Studies by Prasad et al. (1983) showed that in 5% aqueous solution of sodium hydroxide (NaOH) at 28 $^{\circ}$C, fibre tensile strength increased but began to decrease gradually after 72 to 76 hour duration. The alkali modified surface, improved fibre tensile strength and fibre thermal stability help to improve properties of composites (Joseph et al. 1996, Arbelaiz et al., 2006).

Cell-OH + NaOH $\longrightarrow$ Cell-O-Na^{+} +H_2O +Surface impurities

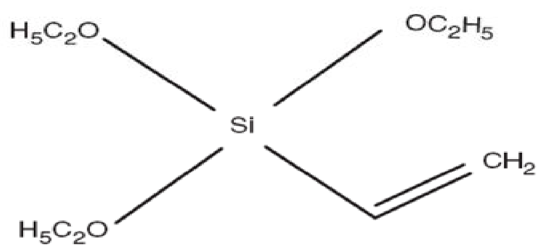
(a)



(b)



(c)



(d)

Figure 4.1 (a) Reaction of NaOH with plant cells during mercerization (b) The general structure of silane coupling agents (c) The "coupling" of polymer to the substrate (natural fibre in this case (d) The structure of triethoxyvynilsilane (Wang et al, 2003 and Ankles, 2006)

In the case of silane treatments the normal practice is to apply it on previously mercerized fibres. Unlike mercerization, the use of silane coupling agents to improve properties of NFCs has resulted in conflicting results. Silane coupling agents are chemicals that have groups attached to a silicon atom (Figure 4.1 (b)). Some of these groups can attach to hydrophilic fibre surface and others can attach to hydrophobic plastic surfaces, thus coupling the two surfaces (Pickering et al., 2003 and Plueddemann, 1991) (Figure 4.1 (c and d). There are cases where composite properties improved only when mercerization preceded silane treatment but failed to improve when each treatment was made independently (Herrera-Franco, and Valadez-González, 2004). Bisanda and Ansell (1991) reported that mercerized sisal fibre in an epoxy matrix lead to improved properties only in humid environments, due to saline's capacity to reduce fibre moisture absorption (Wang et al., 2003). Silane treatment did little to improve mechanical properties of dry composites in this case.

Other authors have shown that beyond particular silane concentration (for instance, 0.015% w/w), composite properties such as tensile strength decline (Herrera-Franco, and Valadez-González, 2004). Another study reports improvements by silane treatments only at 5w% fibre load and decrease in properties beyond that load (Pickering et al., 2003). The study alleges increased porosity and perhaps fibre agglomeration with fibre load to outweigh the effects of silane. Bledzki and Gassan (1999) cite a study where there was a decrease in mechanical properties of coir-unsaturated-polyester composites after treatment with dicloromethylvinyl silane and urge a need for more silane treatment studies.

There are two common approaches used to analyse the strength and the toughness of the interface in composite materials. The shear stress criterion is based on the assumption that de-bonding of fibre from the matrix takes place when the maximum stress reaches a certain critical value (Baillie, 1991). However, this approach assumes that shear distribution along the fibre is homogenous and friction between fibre and matrix is negligible. The second approach based on fracture mechanics assumes that crack propagation at de-bonding zone requires energy (Baillie, 1991). This energy characterises the nature of the fibre matrix bond. Other more advanced models have been developed but there is a general acceptance among researchers that no accurate model is available at the moment (Dijon, 2002, Piggott, 1997).

Testing the interfacial strength and toughness in composites is never a straightforward science and scholars have struggled for decades to determine the best way to do this (Baillie, 1991). It is not the aim of this paper to take an extensive analysis of the interfacial strength of the *Agave americana* HDPE composites. Rather, this paper picks one of test methods that could provide glue into the nature of this bond under different surface conditions of *Agave americana* fibre and provide a reasonable explanation of the observed behaviour. Again, it is important to note that none of the interfacial strength or toughness tests provides an actual measure of these values, rather they are used in a comparative way, guiding the researcher about changes they have made to the interface (Baillie, 1991).

There is a number of ways of testing the strength and toughness of composites and some of these are briefly described here (see Baillie and Bader (1994), Baillie (1991), Piggott (1997), and Dijon (2002) for more details). Fragmentation test involves embedding a single fibre in a polymer and straining the polymer to break the fibre into fragments and then calculating the interfacial strength required to cause these fragments. The benefit is that it uses a transparent matrix so that the deformation process can be observed through polarized microscope and analyzed. The need to use transparent matrix can be a limitation where non-transparent matrices cannot be avoided in composites. Also the strength of each of the fragments needs to be known to make calculations for the ISS. However, it is impractical to measure the strengths of fragments of up to 0.25 mm and Weibull extrapolations normally used are inaccurate.

In the micro-indentation test, a tensile force is applied to a composite coupon and the ISS needed to transfer the stress from the matrix to the fibre is estimated. It has the advantage of using the real composites, making it easy to account for influence of adjacent fibres. The challenge is that is relies on numerical methods that critically depend on the assumptions used to describe the stress field around the fibre.

Lastly, Pullout and Microtension tests involve measuring the de-bonding forces needed to pull a single fibre out of the matrix in which it is embedded. Its advantage is that the de-bonding strength can be plotted against the embedded length. Sudden drop of de-bonding force indicates interface failure. The pullout test is seen as the one that more closely simulate actual de-bonding process (Piggott, 1997) and it is the one chosen to be used in this study.

While many studies look at the impact of surface treatments on bulk composites, few studies consider the impact at micro level. Therefore the aim of this study is to determine the effectiveness of mercerization and silane treatment of fibres in an attempt to improve interfacial bond in *Agave americana*/waste HDPE composites using single fibre pullout tests. This is done by comparing the effect of mercerization alone with the effect of mercerization followed by silane coupling on the interfacial shear strength in these composites. It also determines the impact of these treatment methods on fibre surface morphology, tensile strength and thermal stability. Untreated fibres which have been extracted from the leaves in two different ways are used as controls.

4.2 Methodology

4.2.1 Materials

Extraction of fibres from *Agave americana* leaves followed a traditional method used in Lesotho. The hard leaves were cut from *Agave americana* central stocks using long knives. They were then boiled in water for 2 h, the point at which they became soft. Then fibres were removed by gently squashing the leaves with rocks and washing away the soft tissue with running water. They were then air and sun dried by hanging them along the fence in open spaces. This fibre extraction procedure is the cheapest method used in Lesotho to get *Agave americana* fibres. Untreated fibres (not mercerized or silane treated) extracted in this way forms the control group in this study. Some fibres were pulled by hand from the leaves before boiling them in order to determine the influence of not boiling the leaves during fibre extraction on fibre properties and interface. HDPE plastics were obtained directly from the waste stream.

4.2.2 Mercerization and silane treatment

Agave americana fibres from boiled leaves were dipped into a 1N NaOH solution for 24 h at room temperature to dissolve the lignin and hemicelluloses and to expose more of the fibre OH groups for reaction with the coupling agent. They were then washed in distilled water to remove NaOH and oven dried for 24 h at 70 ^{o}C. Some of the mercerized fibres were dipped into a solution of 0.05% (w/w) triethoxyvinylsilane (Aldrich Chemical) and agitated for 5 min to ensure a more uniform coverage of fibre surface by silane. The solution was kept at 5.5 pH by acetic acid. Acetic acid at this pH is used to promote hydrolysis of the alkoxy groups of silane to make them react with the OH groups on the fibre. Fibres were then washed and dried at 70 ^{o}C for 24 h.

4.2.3 Scanning Electron Microscopy (SEM)

Chemically treated and untreated samples of fibre were gold plated and examined under SEM at varying resolutions.

4.2.4 Fibre tensile and pullout tests

Chemically treated and untreated fibres were tested for tensile strength using a micro tensile tester at the speed of 0.2 cm/min and gauge length of 7 mm. For each variable, 20 fibres were tested. Image analysis software, Clemex Vision PE 3.5, was used to study fibre diameters with an average of 4 equally spaced readings per fibre. Most natural fibre cross-sectional areas are not perfectly round. But due to difficulties in determining the exact cross-sectional area with the present measuring equipment, the cross-sectional area is normally assumed to be perfectly circular (Dijon, 2002 and Zafeiropoulos, 2001).

For pullout tests, fibres were first placed on a rigid cardboard and stretched by gluing them on both ends. A rectangular piece was removed from the middle of the cardboard to make fibres accessible to plastic on both sides. 8 films of HDPE were placed on both sides of the cardboard to cover the fibres. Then the samples were hot pressed for 1 minute using a Caver laboratory press in a pressure of 3 MPa and temperature of 150 $^{\circ}$C.

Each sample of fibre embedded in plastic were cut and arranged as shown in Figure 4.2. The Embedded length was kept at 5 mm. This length was delimited by using a razor blade to cut the fibre within the matrix. Pullout tests were conducted using the micro tensile tester at a speed of 0.05 cm/min. For each variable, 20 fibres were tested. The free end of the fibre was gripped and the load was applied to pull the fibre out of matrix. Then load and displacement were measured.

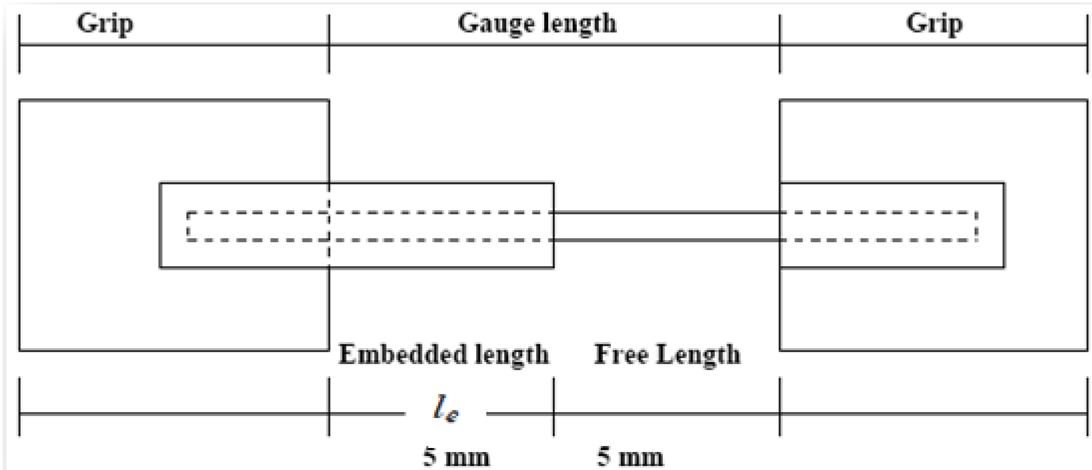


Figure 4.2 An illustration of arrangement used for fibre micro-tensile and interfacial testing

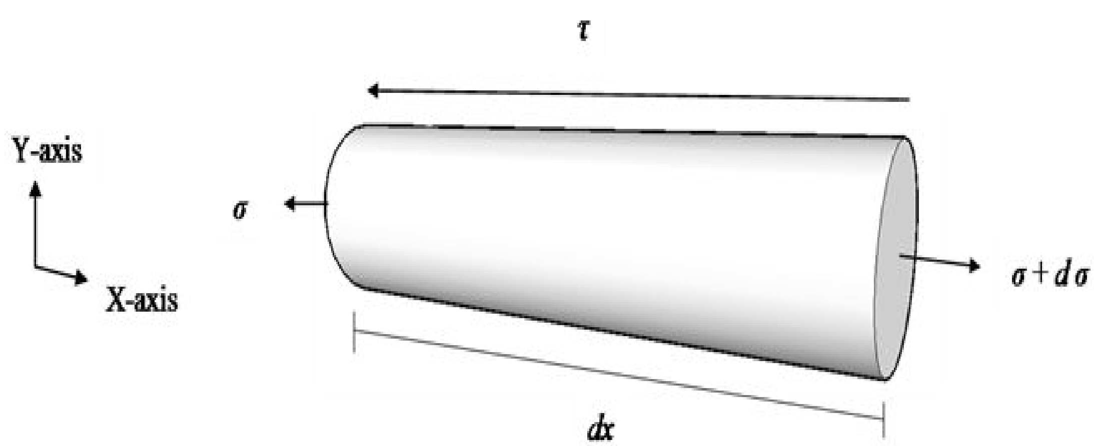


Figure 4.3 A single fibre under tension in a matrix

Interfacial shear strength was calculated from the Kelly Tyson (1965) model. Consider a fibre of diameter *D* and length *dx* embedded in a matrix being pulled by the stress $\sigma + d\sigma$ which acts in opposite to the stress $\sigma + \tau$ where τ *is* the interfacial shear strength (Figure 4.3). The relationships becomes

$$\sigma \frac{\pi D^2}{4} + \tau \pi D dx = (\sigma + d\sigma)\frac{\pi D^2}{4} \tag{4.1}$$

Using the definition of derivative, this relationship can be simplified to

$$\frac{4\tau}{D} = \frac{\sigma + d\sigma - \sigma}{dx} = \frac{d\sigma}{dx} \quad (4.2)$$

Then

$$\int_0^{\sigma_m} d\sigma = \frac{4\tau}{D} \int_0^{l_e} dx \quad (4.3)$$

where l_e is the embedded length of fibre in the matrix (Figure 4.2) and σ_m is the stress at fibre detachment from the matrix. Then interfacial shear strength becomes

$$\tau = \frac{P}{\pi D l_e} \quad (4.4)$$

where *D* is fibre diameter, *P* is maximum force at detachment.

The differences between the means of ISS at different variables were investigated using a paired t-test at 5% confidence interval.

Thermogravimetric analysis

Small fibre samples were put in a TGA machine (TA Instruments Inc.) in a nitrogen atmosphere. The heating rate was 20 °C/min from 25 °C to 500 °C. The results were analyzed by TA Instruments Universal Analyzer 2000 software.

4.3 Results and discussion

4.3.1 Surface morphology of *Agave americana* fibre

In Figure 4.4, the surface morphology of *Agave americana* fibre at different stages of treatment is presented. Plant fibres are made of major components like cellulose, hemicelluloses and lignin and minor components like pectin, waxes and other substances.

Leaves of *Agave americana* contain a thick cuticle which is made of fatty acids (Deshmukh et al., 2005). When the fibres are pulled out of the leaves by hand, they retain part of this material on their surface (Figure 4.4, (a)). In this figure, fibre bundles are embedded in the cuticle which makes a very rough surface morphology. Heating leaves in boiling water for 2 h help reduce the size of the cuticle during fibre extraction (Figure 4.4: (b)). Treatment in hot water apparently softens this layer which later is washed away in the extraction process.

The fibre extracted by boiling in water and later treated with NaOH can be viewed in Figure 4.4 (c). It appears smoother than the untreated fibre in (b). This treatment exposes small ultimate fibres (Figure 4.4 (d) and (e)). Msahli et al. (2005) has shown that these ultimate fibres have an average diameter of 3 μm which is very small compared to other natural fibres. In Figure 4.4 (f) a typical ultimate fibre is shown to have a zig-zag structure (see chapter 5 for the implications of this structure on the tensile behaviour of the fibres). These six figures can help explain the tensile and interfacial behaviour of *Agave americana* fibre bundles.

4.3.2 Fibre tensile properties

Average tensile properties of differently treated fibres are shown in Table 4.1. There is little difference between tensile strength values of mercerized and silane treated fibres. Large standard deviations are a characteristic of natural fibres.

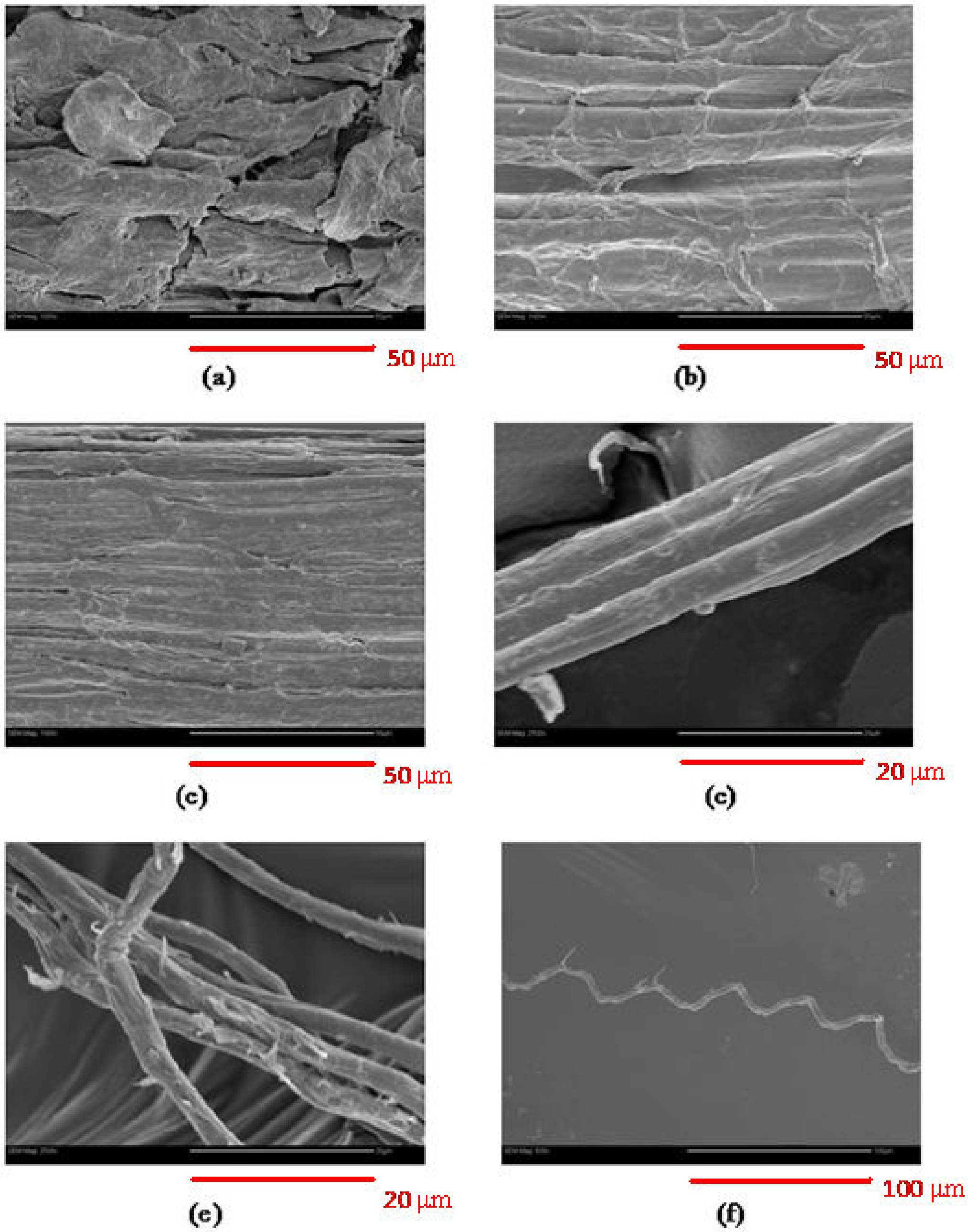


Figure 4.4 SEM examination of *Agave americana* fibres: (a) A fibre removed from leaves by hand [1000 ×] (b), A fibre removed after heating leaves in boiling water [1000 ×], (c) A hot water extracted and mercerized fibre [1000 ×], (d) Three bonded ultimate fibres after mercerization [2500 ×], (e) Separated individual fibres after mercerization [2500 ×], (f) A single ultimate fibre with a helical structure [500 ×].

Table 4.1 Tensile properties of *Agave americana* fibres at different extraction methods and surface treatments, N=20

Fibre Treatment	*Average Strength (MPa)*	*Standard Deviation (± MPa)*
Non-Boiled	126	32
Boiled-Untreated	160	74
Boiled-Mercerized	263	82
Boiled-Mercerized-Silane Treated	249	69

Natural fibres have large variations in strengths that can be described by Weibull distributions (Weibull, 1951 and Hull, 1990). A Weibull distribution is the most likely distribution for fibre strengths. This model assumes that failure in the most serious flaw on the fibre leads to a catastrophic failure of the whole fibre, weakest link theory. These statistical analyses have been significantly applied to natural fibres (Pickering et al., 2003, Bledzki and Gassan, 1999, Zafeiropoulos, 2001, Hull, 1990).The Weibull distribution is

$$P_f(\sigma) = 1 - \exp\left(-\frac{L}{L_o}\left(\frac{\sigma - \sigma_u}{\sigma_0}\right)^m \right) \tag{4.5}$$

where $P_f(\sigma)$ is the probability of failure of a fibre of length L at an applied stress σ, L_0 is the length of elementary units of the fibre, σ_u is the lowest value of strength normally set to zero and σ_0 is the characteristic strength (the most probable strength expected from a fibre of length L_0) and m is the shape parameter called Weibull modulus. If values of m are high, that indicates less variability in strengths. Examples of m values in some brittle materials are 5 for chalk, 10 for engineering ceramics and 100 for steel (Dijon, 2002).

Assuming L_0 is set to unity and $\sigma_u = 0$, the equation can be simplified to a two parameter Weibull Equation where L becomes dimensionless:

$$P_f(\sigma) = 1 - \exp\left[-L\left(\frac{\sigma}{\sigma_0}\right)^m\right] \qquad (4.6)$$

One of several ways of estimating Weibull characters is by using linear regression. Taking the logarithm of Equation 4.6 two times yields

$$\ln\left[\ln\left(\frac{1}{1-p_f(\sigma)}\right)\right] = m\ln(\sigma) + \ln(L) - m\ln(\sigma_0) \qquad (4.7)$$

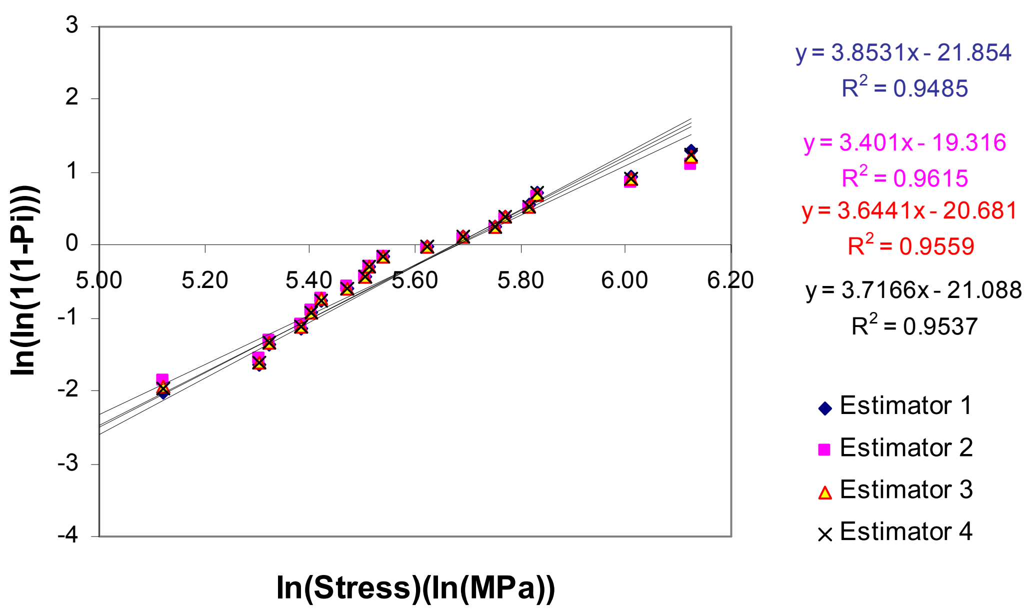


Figure 4.5 Weibull analysis of NaOH treated fibres using different estimator (N=20)

Setting $\ln[\ln(\frac{1}{1-p_f(\sigma)})]$ against ln (σ) gives a straight line with a slope m as shown in Figure 4.5. σ_0 is deduced from the y-intercept; ln (L) - $m$ln (σ_0). σ_n values are the experimental values which are ordered as $\sigma_1 < \sigma_2 < \ldots < \sigma_i < \ldots < \sigma_{n,}$, where n is the size of the sample and i the rank of each data point. σ_i is assigned probability of P_{fi} such that $P_{f1} < P_{f2} \ldots < P_{fi} < \ldots P_{fn}$ where $0 < P_{fi} < 1$. Since true value of P_{fi} is not known, estimators are selected and used so that on average, the errors arising from estimation compensate each other. In this study, four estimators mainly used in literature were chosen to find P_{fi} (Kimball, 1960, Zafeiropoulos and Baillie, 2007). Since P_{fi} unknown,

(a) Estimator 1; $P_{fi} = \frac{i-0.5}{n}$ (b) Estimator 2; $P_{fi} = \frac{i}{n+1}$

(c) Estimator 3; $P_{fi} = \frac{i-0.3}{n+0.4}$ (d) Estimator 4; $P_{fi} = \frac{i-\frac{3}{8}}{n+0.25}$ (4.8)

where n is the number of tested samples

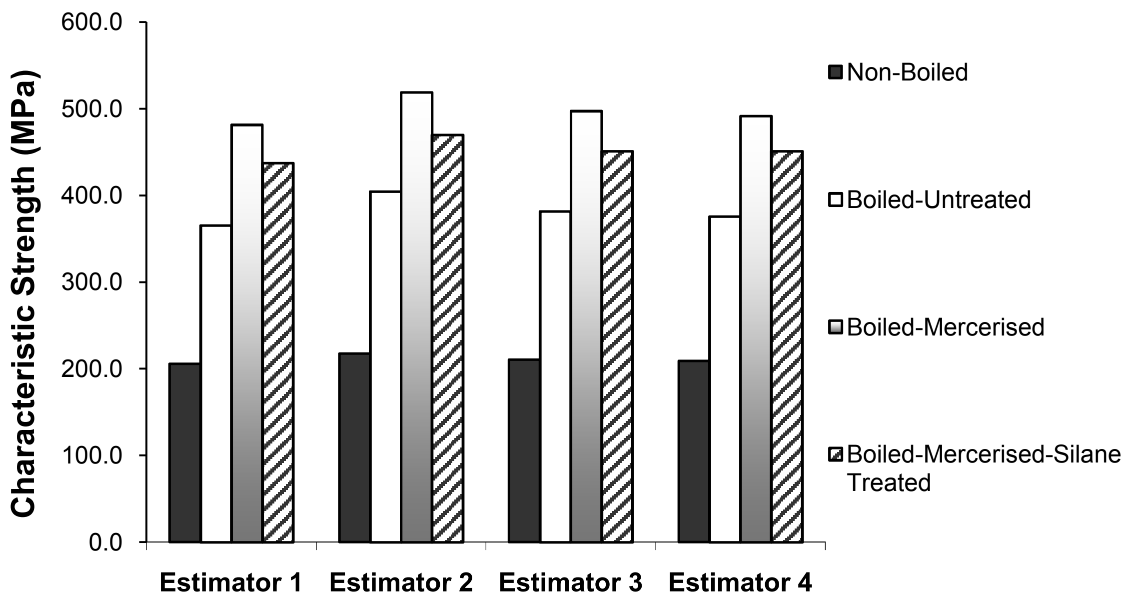


Figure 4.6 Weibull analysis of tensile strength of differently treated *Agave americana* fibres using for different estimators (Equation 4.8) (N=20)

From Table 4.1 (compare with values in Table 4.2) and Figure 4.6 fibres pulled out of non-boiled leaves had the lowest tensile and characteristic strengths respectively. The first reason for this is that since fibres from non-boiled leaves are thicker than other fibres, they have higher probability of flaws which increase the probability of fibre failure (Dijon, 2002). Secondly, Chaabouni et al. (2006) showed that in hot water treatment of *Agave americana* leaves for durations of 60, 90, 120, 150 and 180 min at 120 $^{\circ}$C, the fibre tensile strength peaked at 90 min duration. Of these durations, fibres that were heated for 60 min had the lowest tensile strengths. Even though the strengths peaked at 90 min and decreased from then, they never went below the strengths found at 60 min duration. The reasoning was that at 60 min duration, the fibres were not well separated and that required more mechanical force to separate (but also to damage) fibres during calendaring.

Table 4.2 Comparison of *Agave americana* tensile properties to properties of other fibres reported in literature, see Bledzki and Gassan (1999)

Fibre	*Tensile strength (MPa)*	*Fibre*	*Tensile strength (MPa)*
Agave americana	126-263	Sisal	511-635
Coir	175	Jute	393-773
Flax	345-1035	Cotton	287-597
Hemp	690	Soft wood kraft	1000

Similar reasoning was provided by Dijon (2002) in his studies of retted and unretted flax fibres. He argued that unretted (green) flax fibres had lower tensile strengths compared to dew retted flax because the latter required little mechanical force (less damage) to remove from the stem.

Thus it could be expected that in our case, 0 duration treatment required even more energy to separate fibre bundles, and that inflicted more damage to these fibres. Taking estimator 2 (Figure 4.6 and Table 4.3) results as an example, there is an 86% increase in characteristic strength of fibres when the leaves are heated in water to soften the matrix. In this way, fibre bundles are easy to separate without much force and damage. When the fibres from boiled leaves are treated with NaOH, the characteristic strength further improves by almost 30%. This is due to removal of hemicelluloses, lignin and pectin which free the fibrils in the fibre bundle.

Table 4.3 Weibull moduli (WM) and Characteristic strength (CS) of *Agave americana* fibres from different estimators at different extraction methods and surface treatments, N=20

Fibre Treatment	*Estimator 1*		*Estimator 2*		*Estimator 3*		*Estimator 4*	
	WM	*CS (MPa)*	*WM*	*CS (MPa)*	*WM*	*CS (MPa)*	*WM*	*CS (MPa)*
Non-Boiled	5.0	205.7	4.4	217.4	4.7	210.6	4.8	208.8
Boiled-Untreated	2.7	365.7	2.4	404.5	2.6	381.9	2.6	376.0
Boiled-Mercerized	3.9	481.5	3.4	518.9	3.6	497.3	3.7	491.6
Boiled-Mercerized-Silane Treated	4.0	437.3	3.6	470.1	3.8	451.2	3.8	451.2

Under stress, relatively freed fibrils get better oriented towards the direction of the tensile forces which lead to better load sharing (Bledzki et al., 1996). In a t-test analysis (p = 0.05) there is no significant difference between the mercerized fibres and the mercerized and silane treated fibres in terms of tensile strengths. In Table 4.2, average tensile properties of *Agave americana* fibres in comparison with those of other fibres as found in literature are shown. Of course, there are different testing conditions of these properties and high variability in natural fibre tensile properties. Therefore this Table provides a general idea of how *Agave americana* fibres differ from other fibres.

Weibull moduli of *Agave americana* fibres are presented in Table 4.3. Similar values for natural fibres have been reported, (Dijon, 2002, Pickering et al., 2003, Bledzki and Gassan, 1999, Zafeiropoulos, 2001, Panthapulakkal et al., 2006).

Fibres from non-boiled leaves have the highest weibull moduli, signifying less variability in strengths of these fibres. Those from boiled-untreated leaves had the lowest Weibull moduli.

4.3.3 Interfacial shear strength

The ISS values are generally low (Figure 4.7 but comparable to some values in literature (Khalil et al., 2001). This reflects little compatibility between the *Agave americana* fibre and HPDE matrix. The main factors that influence the strength of interface in fibre plastic composites are fibre surface topography and surface area and chemical compatibility between fibre and matrix (Li et al., 2000, Joseph et al., 1996 and Prasad et al., 1983). Therefore the ISS between fibres and matrix is a function of both the type of fibre and matrix. For instance, Khalil et al. (2001) showed that coir (a natural fibre) fibres acetylated or not, had higher ISS values than oil palm empty fruit bunch (EFB) fibres because of their higher lignin content. For coir and EFB fibres in polystyrene, improvements in ISS ranged from about 1.4 to 2.3 MPa and 1.2 to 2 MPa with acetylation of fibres. For untreated fibres in that study, thermoplastics had lower ISS values than thermosets due to the ability of the latter to wet fibres better.

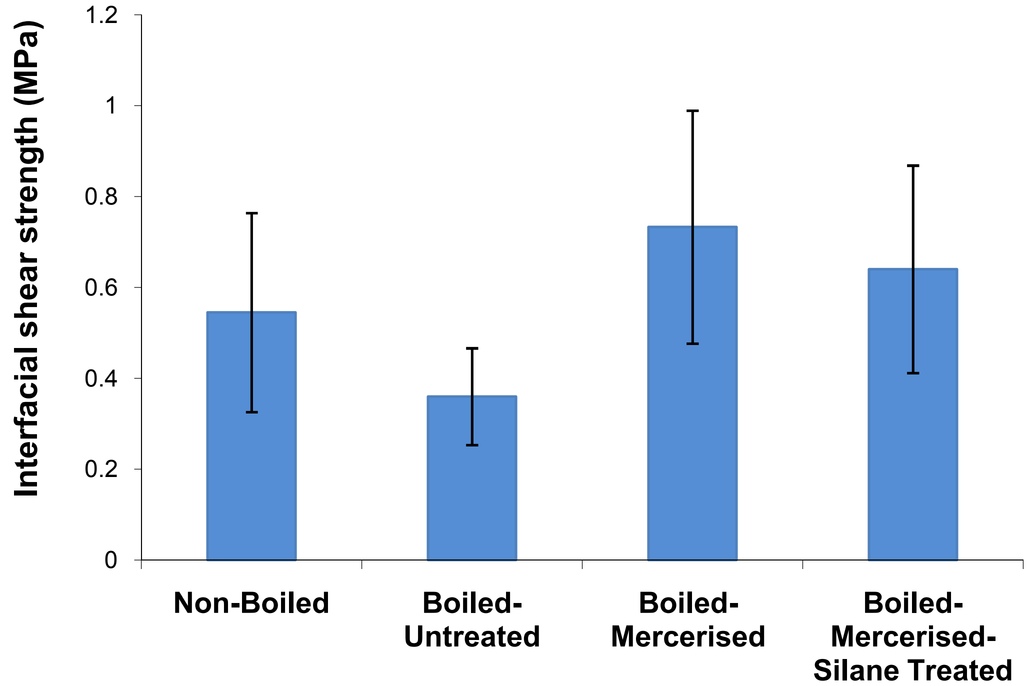


Figure 4.7 The ISS values for different fibre extractions and surface treatment N=20 (Error bars represent standard deviations)

From these results in Figure 4.7, removing *Agave americana* fibres without boiling the leaves can preserve ISS by 51%. Assuming that the cuticle covering the fibre in Figure 4.4 (a) is a waxy layer consisting mainly of fatty acids, these acids are not compatible with the plastic matrix (Prasad et al., 1983). However, heating the leaves in hot water may further stabilize low molecular weight substances on the surface of the fibres, thereby reducing the ISS. Relatively rough surface of the fibres from non-boiled leaves can contribute to higher ISS values in non-boiled fibres.

Treating fibres from boiled leaves with NaOH solution does several things. It cleans up the matrix incompatible waxes and impurities on the surface of the fibre, exposes lignin on fibre surface and exposes smaller fibres (Joseph et al., 1996 and Prasad et al., 1983).

Whereas NaOH treated fibres appear smoother than the untreated fibres, some chemical and physical factors likely dominate and improve the interface as shown in Figure 4.7. Lignin is an amorphous hydrophobic glue-like substance that cements fibres together. The presence of hydrophobic lignin on the fibre surface can improve interface due to its better affinity with hydrophobic thermoplastics (Bhattacharyya et al., 2003 and Thielemans and Wool, 2004). Lignin does get partially removed during mercerization and this assists fibre bundles to break into smaller fibres depending on the intensity of the process (Joseph et al., 1996). Exposure of individual fibres increases the surface area of contact between fibre and also the ISS. Exposing extremely small ultimate fibres (3μ in diameter) may be an added advantage in increasing surface area of contact between plastic and *Agave americana* fibre. In addition, as mercerization cleans impurities off the fibres, ISS is improved. In this case, treating fibre from boiled leaves with NaOH solution increases the interface by 104 %.

As mentioned in section 4.1, silane treatment can make little improvement in mechanical properties of composites. In this study, silane treatment had no effect on the interface between *Agave americana* fibre and HDPE. The reaction of silane with thermosets is more easier in that the silanes can react better with monomeric precursors. This is not the case with thermoplastics (Ankles, 2006). Silanes must react directly with the polymer in a copolymerization process and this reaction is a challenge. While silanes may not improve the interface in dry composites, they work better in wet composites since they reduce moisture absorption as they react with hydroxyl groups on the surface of fibres (Li et al, 2000).

However, the standard deviations in Figure 4.7 are so wide that it was necessary to test whether the differences noticed are significant. As shown in Appendix 10, the only statistically significant difference when any of the variables is compared with the other is between the non-boiled and the boiled - untreated fibres. Therefore statistically speaking, there could is no improvement in ISS due to mercerization and silane treatment of the fibres.

Thermal behavior of *Agave americana* fibres

Unlike human-made fibres, natural fibres are more prone to degrade when processing at higher temperatures. It is important to know how the treatments influence the fibers' thermal behavior. The degradation is indicated by the loss in weight of the fibres as a percentage of their initial weight. Thermal properties of *Agave americana* fibres are given in Table 4.4 and Figure 4.8. The initial weight loss in natural fibres can be associated with loss of water (Arbelaiz et al., 2006, Hull, 1990, Hornsby et al., 1997, and d'Almeida et al., 2006). Moisture content of these fibres would depend on the humidity of the surrounding environment. High values of moisture in fibres signify need for pre-drying them before making composites. Untreated fibres from boiled leaves had the lowest onset of degradation temperature (272 $^{\circ}$C) while fibres from non-boiled leaves had higher onset temperature (288 $^{\circ}$C). Fibres treated with NaOH and NaOH-silane began to degrade at even higher temperatures, 314 $^{\circ}$C to 315 $^{\circ}$C respectively. High values of onset of degradation may be due to high scan rates but we are mainly interested in relative values (Arbelaiz et al., 2006).

Table 4.4 Thermal characteristics of *Agave americana* fibres under different treatments

Fibre treatment	*Initial moisture content (%)*	*Onset of degradation (°C)*	*Peak degradation temperature (°C)*
Non-Boiled	7.5	288	335
Boiled-Untreated	11.8	272	369
Boiled-Mercerized	9.6	314	354
Boiled-Mercerized-Silane Treated	4.0	315	363

Before mercerization, untreated fibres had some initial peaks (*shoulders*) before the final peaks (Figure 4.8). These shoulders indicate the onset of degradation of hemicelluloses and pectin (Arbelaiz et al., 2006).Mercerization removed these substances so that the mercerized fibres had no shoulders. The final peak for all fibres indicates degradation of cellulose. In this case, fibres from boiled leaves had the highest point of cellulose degradation. The possible reason is that without chemical treatment, there is little interference with crystallinity in cellulose (Hull, 1990). High peak values can be associated with high crystallinity of cellulose (Uesu et al., 2006).

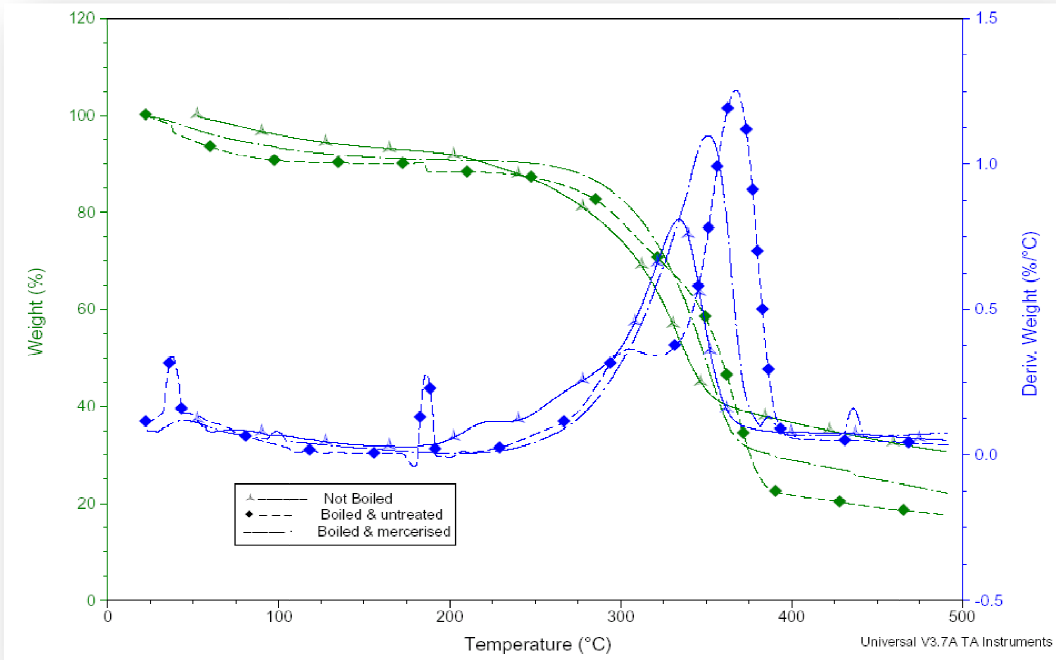


Figure 4.8 Thermal behaviour of *Agave americana* fibres showing loss of weight with increase in temperatures. The beginning of rapid loss of weight at some level normally signify degradation of the material being tested.

4.4 Conclusions

We have shown that mercerization of *Agave americana* fibres can improve the fibre properties of *Agave americana* fibres and its interface with waste HDPE. However, there were generally low values of ISS in this study. This reflects a normal lack of compatibility between natural fibres and (especially) thermoplastic polymers. But mercerization of *Agave americana* fibres doubled the interfacial bond within the composites. This is because mercerization removes impurities, exposes hydrophobic lignin, and increases the fibre surface area by exposing some ultimate fibres. The extremely small size of these ultimate fibres compared to other natural fibres may be an added advantage in increasing the surface area of contact between plastic and fibre. Silane treatment does not have an influence on the interfacial shear strength between *Agave americana* fibres and HDPE.

Untreated fibres extracted from non-boiled leaves had greater ISS than those from boiled leaves. This could be due to stabilization of low molecular weight substances on the surface of the fibre during boiling, resulting in poor interface and due to a relatively rough high surface roughness of the fibres from non-boiled leaves. Fibres from boiled leaves had much higher tensile strengths than those from non-boiled leaves. Possibly, removing fibres from non-boiled leaves takes much force and creates more flaws on fibre. Silane treatment after mercerization makes no difference on tensile strength. Lastly, mercerization increased thermal stability of fibres by shifting onset of degradation to higher levels.

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Chapter 5: Microstructural and tensile nature of *Agave americana* fibres

Abstract

This chapter looks at the influence of mercerisation and fibre microstructure on the tensile properties of *Agave americana* fibre bundles. Fibres were immersed in 1 N solution of NaOH for intervals of 50 h from 0 to 200 h at 25 °C. They were also immersed in the same solution for periods of 0, 0.5, 1, 25 and 300 h at 130 °C.

Mercerization improves the tensile strengths of the *Agave americana* fibre bundles between 0-50 h of exposure. The strength is less affected by the duration of mercerization during the period from 50-200 h. The fibre bundles of *Agave americana* also found to demonstrate high tensile strains. These high strains were explained by modelling the geometry of their single fibres which show a zigzag structure at rest, making it easier for them to straighten before deformation

5.1 Introduction

In the last chapter, we reported that mercerization (soaking natural fibres in a solution of NaOH) improved the tensile strengths of the fibres. However, the treatment was only done for 24 h and only at 25 °C. As the NaOH attacks the lignin binding the fibres, both the duration and temperature of the treatment can influence the final fibre properties. In this study we look at how the duration and temperature of mercerization may affect the tensile strength of *Agave americana* fibre bundles.

Further, Chaabouni (2006) observed that *Agave americana* fibre bundles have high breaking strains which could be related to the nature of their single fibres. This study also focuses on explaining the microstructural impact of the fibres on their breaking strains. This is done by modelling the behavior of single fibres during deformation under tension and relating this to apparent deformation of the fibre bundle. To our knowledge, these unique properties of *Agave americana* fibres have not been explained with such models.

5.2 Methodology

5.2.1 Materials

The method for obtaining *Agave americana* fibres is described in section 4.2. Mercerisation was done in two ways. First the fibres were soaked in 1N NaOH solution for varying periods of 0, 50, 100, 150 and 200 h to determine the influence of duration at 25 °C on the properties. To determine the influence of temperature, the fibres were soaked in 1N NaOH at 130 °C in an autoclave (Autoclave engineers Inc.) for periods of 0, 0.5, 1, 25 and 300 h.

5.2.2 Mechanical testing and SEM

The process used to extract single fibres of *Agave americana* for SEM analysis is found in Chaabouni et al., 2006. It involved heating the *Agave americana* fibres in 1N solution of NaOH at 130 °C for 300 min in an autoclave as described above. The process breaks down the lignin binding the single fibres without destroying the single fibres. All SEM analyses were made following the method detailed in sections 4.2.3.

Mechanical testing of 20 samples per variable was done following the method detailed in section 4.2.4. In chapter 4, the tensile strengths of *Agave americana* fibres were analysed using the two parameter Weibull model detailed in section 4.3.2. In this chapter, *Agave americana* fibres were also analysed using this model.

To determine *P* in this case, estimator 1, (see Equation 4.8) as one of the most widely used estimators was the only one chosen in this chapter (Zafeiropoulos and Baillie, 2007). The two parameter Weibull equation is developed in chapter 4. The Weibull average strengths $\bar{\sigma}$ and standard deviation in Weibull average strengths σ were determined using Equation 5.1 and 5.2 respectively (Baillie and Bader, 1994, Dijon 2002), where Γ is gamma function

$$\bar{\sigma} = \sigma_0 \times L^{\left(\frac{-1}{m}\right)} \Gamma\left[1 + \frac{1}{m}\right] \tag{5.1}$$

$$\sigma = \sigma_0 L^{\left(\frac{-1}{m}\right)} \left[\Gamma\left(1 + \frac{2}{m}\right) - \Gamma^2\left(1 + \frac{1}{m}\right)\right]^{\left(\frac{1}{2}\right)} \tag{5.2}$$

5.3 Results and discussion

5.3.1 Mercerization and the tensile properties of *Agave americana*

The alkali treatment is thought to improve the overall strengths of the natural fibres by removing weaker binding materials such as lignin and hemicelluloses while leaving a load bearing cellulose (chapter 4). These weaker materials can be viewed as impurities which could initiate stress concentrations under applied tension. However it can be assumed that after much longer exposure, the alkali would begin to degrade the load bearing cellulose structure, thus reducing fibre properties (Prasad et al., 1983)

The inherent variability of natural fibres makes it difficult to make conclusive observations. Many kinds of defects and irregularities during natural growth are characteristic in natural fibres and result in high coefficients of variability of typically 15-30% (Dill-Langer, 2003). However, the results in Table 5.1 indicate that the fibre strength is improving during the mercerisation period of 0-200 h. The average strength values suggest improvement from 160 MPa to 228 MPa at 0-50 h of treatment. There is almost constant strength between 50-200 h of soaking. The Weibull average strengths show the fibres, which have reached a plateau between 50 h and 150 h, reaching the highest strength of 332 MPa at 200 h. The average strains are generally large and range from 0.38 to 0.45.

Table 5.1 Influence of mercerization duration on the tensile properties of *Agave americana* fibre bundle at 25 °C

Duration (H)	*Average strength (MPa)*	*Characteristic strength (MPa)*	*Weibull modulus*	*Weibull Average Strength (MPa)*	*Average Breaking Strain (mm/mm)*
0	160 ±73	367	2.8	162 ± 63	0.38 ± 0.16
50	228 ± 57	380	4.6	228± 56	0.45 ± 0.15
100	204 ± 68	395	3.5	237± 65	0.39 ± 0.13
150	221 ± 80	478	3.0	222 ± 81	0.45 ± 0.11
200	227± 58	538	4.9	332 ± 77	0.45 ± 0.07

± Limits represent standard deviations

From the surveyed literature, the highest temperature to which *Agave americana* fibres have been subjected to an alkali solution is 130 °C at 3.8% NaOH (Chaabouni, 2006). The above authors assumed that the structure of cellulose was not destroyed at these conditions. In this study, the fibres were subjected to these conditions to determine the behaviour of the breaking strains, the implications of which are analysed in section 5.3.6. In Table 5.2, it can be seen that in the first hour, there was almost no differences in tensile strengths of the fibre. However, the strength values had declined significantly after 25 h and, as expected, have dropped considerably after 300 h of treatment. The Weibull parameters at 300 h are not included as it was evident the fibre no longer followed Weibull distributions at this point (i.e. its Weibull plots did not fit straight line (Figure 5.1)). The next section investigates the microstructure implications of these observations and the reasons behind the large breaking strains of *Agave americana* fibre bundles in general.

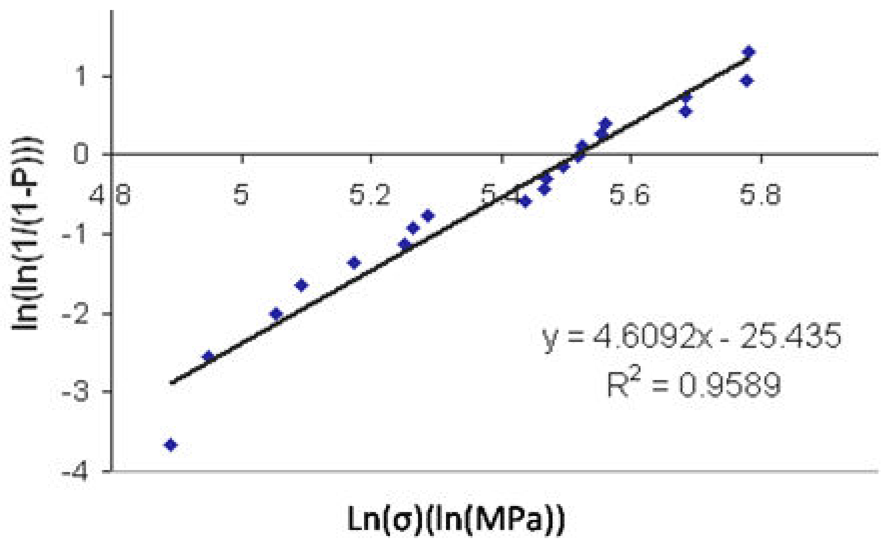


Figure 5.1 Weibull analysis plot of *Agave americana* fibres treated at 25 °C for 50 h

Table 5.2 Influence of mercerization duration on the tensile properties of *Agave americana* fibre bundle at 130 °C

Duration (h)	*Average strength (MPa)*	*Characteristic strength (MPa)*	*Weibull modulus*	*Weibull Average Strength (MPa)*	*Average Breaking Strain (mm/mm)*
0	160 ±73	367	2.8	162 ± 63	0.38 ± 0.16
0.5	159 ± 52	292	3.8	159 ± 46	0.30 ± 0.07
1	160 ± 68	346	2.9	160 ± 59	0.33 ± 0.28
25	136 ± 61	334	2.5	136 ± 58	0.38 ± 0.15
300	28 ± 15	N/A	N/A	N/A	0.11 ± 0.11

N/A: None Applicable
± Limits represent standard deviations

5.3.2 The nature of *Agave americana* single fibres

The single fibres of *Agave americana* have a very small diameter of around 3 µm (chapter 4). If we assume a circular cross-section[5.1] of both the fibre bundle of a cross-sectional area A_d and the single fibres in of a cross-sectional area A_s and assume the single fibres are so close to each other so as to ignore spaces left between them (Figure 5.2 (a)), the number of single fibres n_s which each fibre bundle would hold is

[5.1] The fibres are considered circular for simplicity. SEM pictures reveal a more complex shape

$$n_s = \frac{A_d}{A_s} \tag{5.3}$$

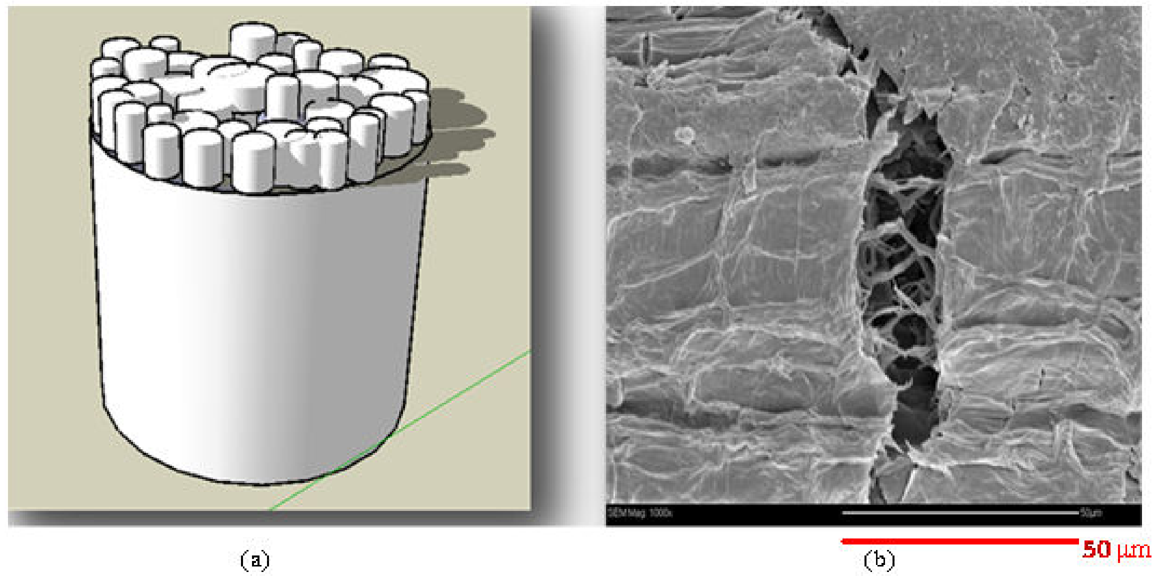
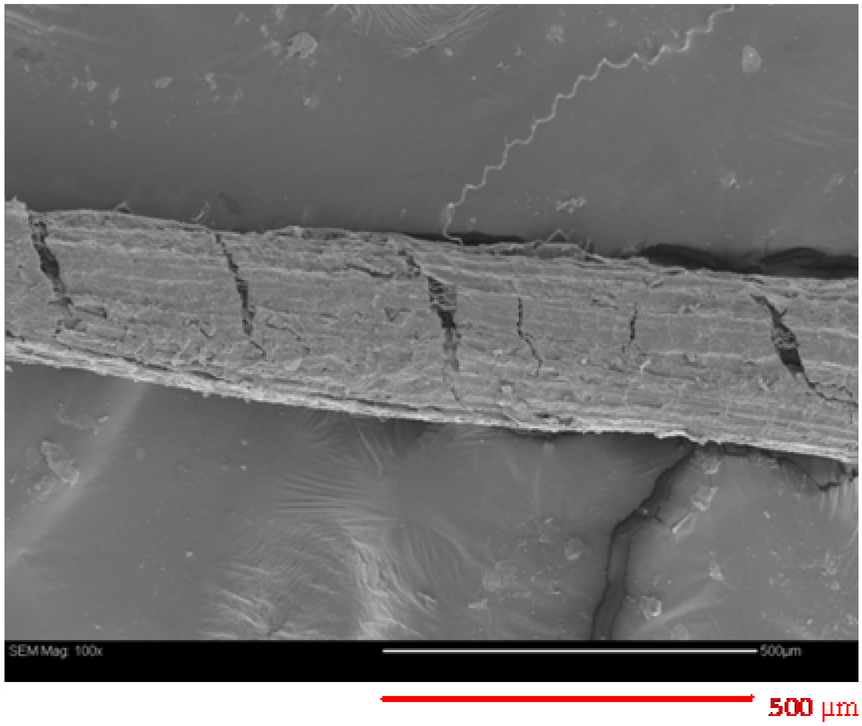
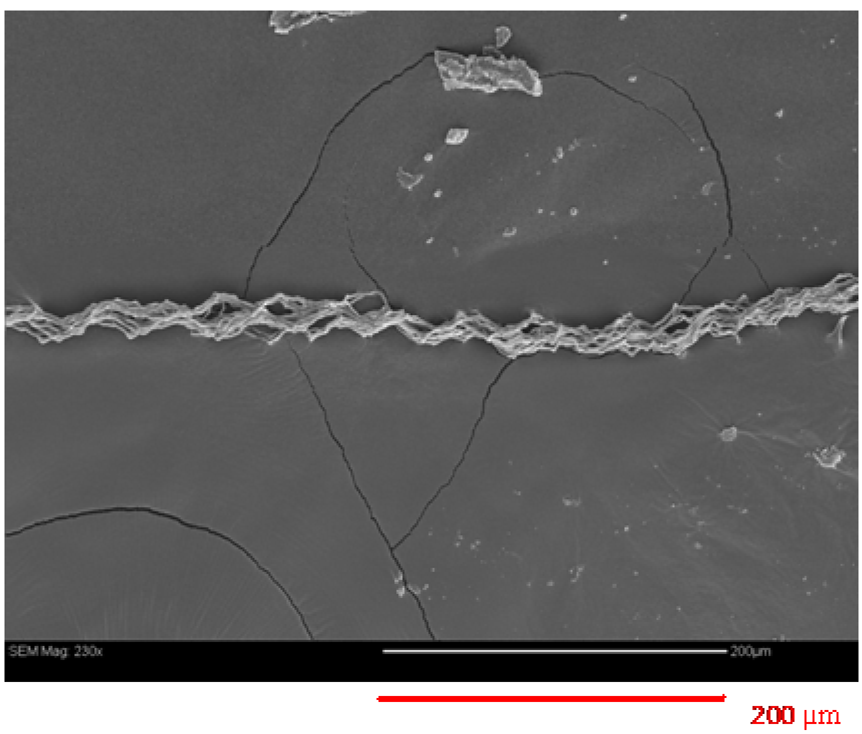


Figure 5.2 (a) *Agave americana* single fibres assumed to be fitting side by side in a bundle. (b) An SEM picture of *Agave americana* single fibres in fibre bundle (1000×)

From Equation 5.3, an *Agave americana* fibre bundle with a diameter of 200 μm would hold around 4500 single fibres. In reality, a smaller Figure can be expected if significant spaces between single fibres are taken into account (Figure 5.2 (b)). Each fibre bundle holds many of these single fibres. From the SEM pictures (Figure 5.3), if we observe these single fibres at rest, they are not long straight cylinders. Rather, they show a form of a zigzag structure. Figure 5.3 (a) shows one of the single fibres sticking out of a fibre bundle and Figure 5.3 (b) has a portion of a group of these single fibres in their intertwined state. The observable zigzag structure of *Agave americana* single fibres has implications for the tensile properties of the fibre bundles.



(a)



(b)

Figure 5.3 (a) An SEM picture of a zigzagged *Agave americana* single fibre sticking out of a fibre bundle (100×) (b) An SEM picture of a group of *Agave americana* single fibres (200×)

Fibre bundles of *Agave americana* have relatively high strains of up to over 60% (Figure 5.4 and Table 5.2). Looking at Figure 5.3 (b), it can be suggested that an applied force on these fibres will first straighten ("unravel") them before pulling them apart to a breaking point. This factor is assumed to contribute to the high strains of the fibre bundles and forms the basis of our modelling.

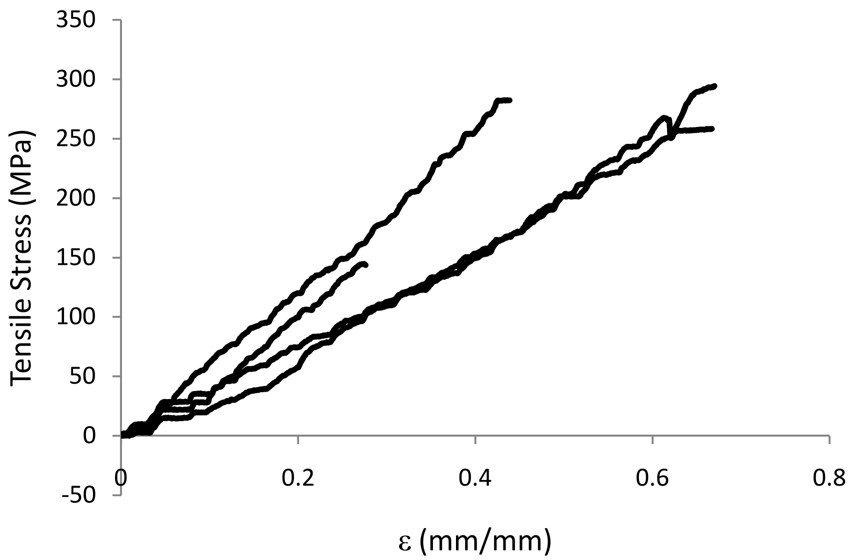


Figure 5.4 Typical stress strain graphs of *Agave americana* fibre bundle (the strain is used an engineering strain)

5.3.3 Modelling the influence of the single fibre angles

It is difficult to model the behaviour of natural materials such as natural fibres without the risk of being overly simplistic. The structure of natural fibres is complex, highly variable and poorly understood. However, we attempt to model the structure in the following section in order to understand as much of the behaviour as possible.

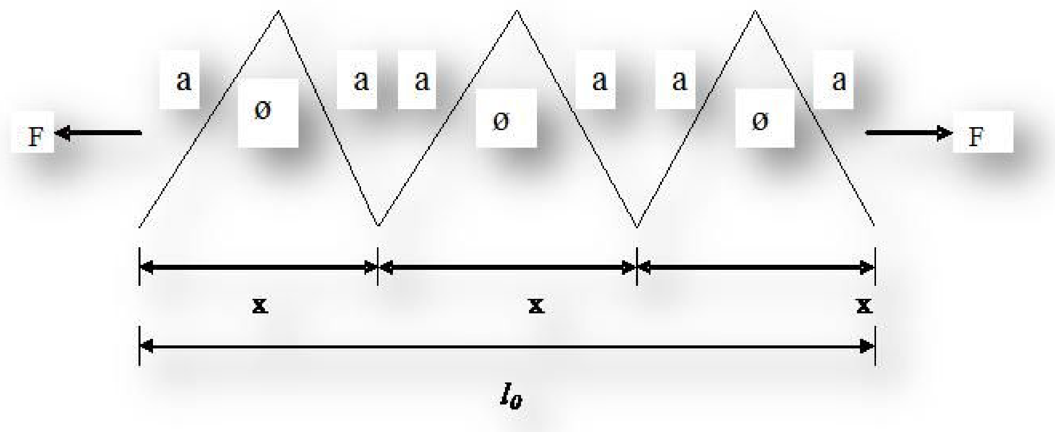


Figure 5.5 The simplified geometry of *Agave americana* single fibres

Agave americana single fibre can be considered as having a zigzag structure at rest, before a tensile force F is applied to it (Figure 5.3). Straight lines may be drawn as shown in Figure 5.5 to simulate a zigzag structure. This structure can then be reduced to a series of isosceles triangles, each triangle having two equal sides of length a and the base of length x representing the apparent length of one structure element. The angle ø, opposite to x relates true length $2a$ to the apparent length x:

$$x = 2a\sin(\tfrac{1}{2}\phi) \tag{5.4}$$

The length l_0 can be any length that covers a number n of sides x such that

$$l_0 = nx \tag{5.5}$$

If the force F is applied on the single fibre, the single fibre will increase from l_0 until the fibre is fully extended at length Z such that all the angles *ø* are equal to 180°. Therefore from Figure 5.5:

$$Z = 2an \tag{5.6}$$

From (5.4), (5.5) and (5.6), it can be shown that

$$Z = \frac{l_0}{\sin(\frac{1}{2}\phi)} \tag{5.7}$$

Equation 5.7 implies that starting with the fibre of length l_0 where the fibre is at rest, the length to which the single fibre will extend to the full, *Z*, is a function of the fibre angle *ø*. The smaller the fibre angle *ø,* the larger the length *Z* will be and vice-versa (Figure 5.6, plotted from Equation 5.7). Since the length l_0 is the length of the fibre before any application of force, it can also be viewed as a gauge length. In Figure 5.6, a gauge length of 7mm was assumed.

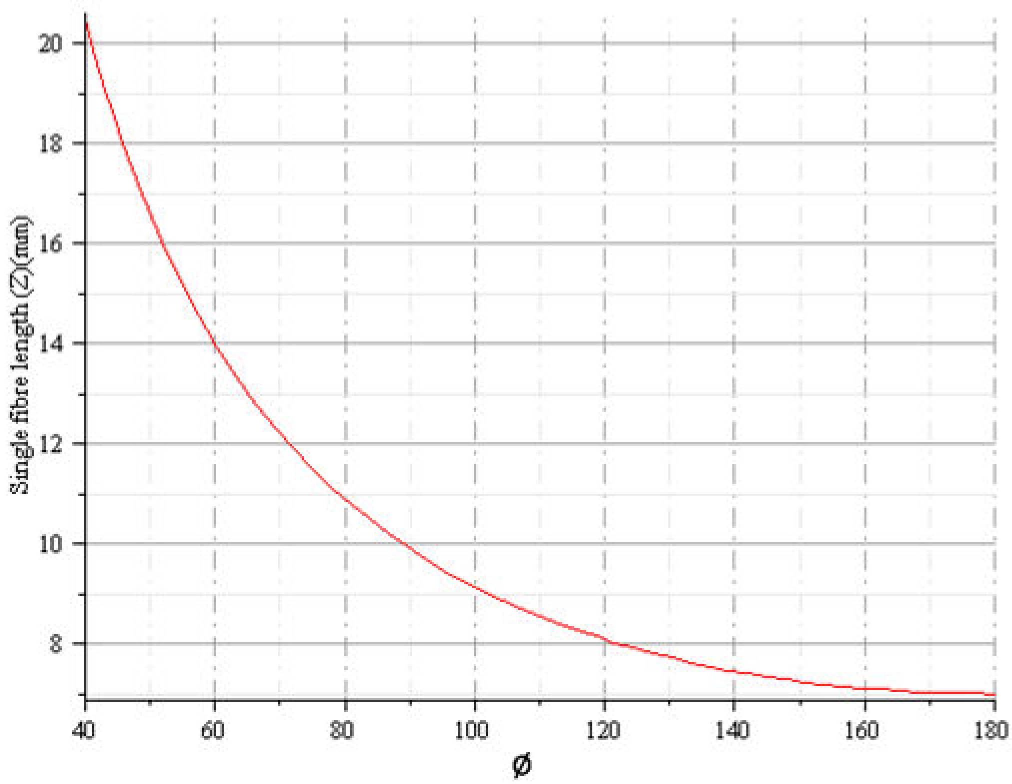


Figure 5.6 The theoretical influence of *Agave americana* single ø (°) fibre angle on single fibre length extension *Z* assuming a gauge length of 7mm

As a first approximation, it can be assumed that a fibre bundle is made up of any number of single fibres which have similar properties[5.2] and do not interact with one another during deformation[5.3]. Then the length Z will be the same for both the bundle and any one of the single fibres if the same stress σ is applied to them until they are fully extended. Therefore, what appears as an extension of a fibre bundle to a length Z is, in fact, the unravelling of the single fibres within the bundle until they are fully stretched.

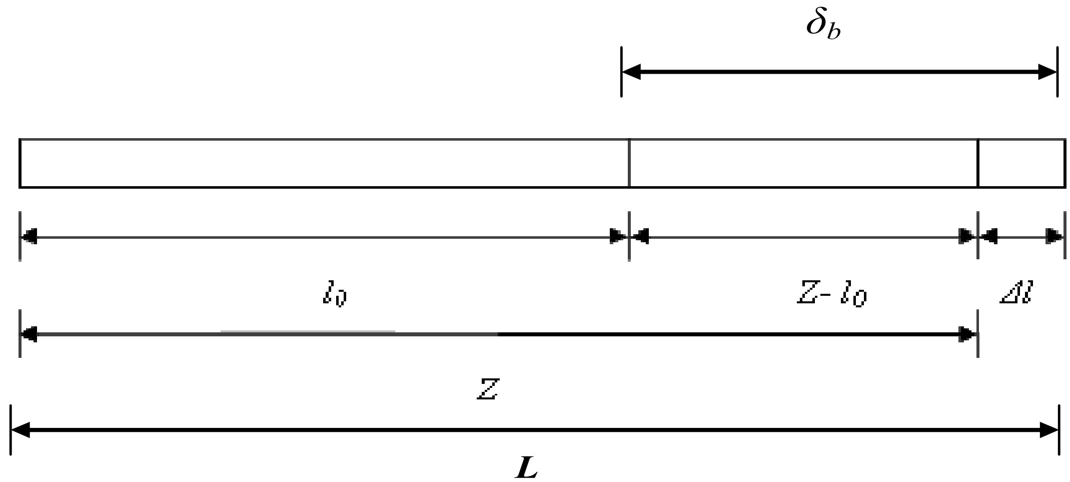


Figure 5.7 A model of *Agave americana* single fibre extension at different stages of deformation

From above discussions, when a single fibre of length l_0 is extended by force F until it breaks at length L, the apparent strain ε_b measured on this fibre is a function of two extensions (Figure 5.7). The *unravelling extension* is the extension $Z- l_0$ which is a result of unravelling of the single fibres of angle $\o$ in its structure. When the angle $\o$ reaches 180º, Z stops increasing, and the secondary extension begins. This secondary extension Δl is the *structural extension* of the single fibres (i.e. the extension of its molecular chains). Given the gauge length l_0, the total fibre extension δ_b will be the sum of unravelling and structural extensions:

[5.2] Same shape, length, and zigzag angles
[5.3] Section 5.3.6 discusses why this assumption presents a problem

$$\delta_b = (Z - l_0) + \Delta l \tag{5.8}$$

The *total single fibre strain* ε_b resulting from both the unravelling and structural extensions follows

$$\varepsilon_b = \frac{\delta_b}{l_0} = \frac{(Z + \Delta l - l_0)}{l_0} \tag{5.9}$$

From strain definition, Figure 5.7 and Equation 5.7, the structural extension Δl can be expressed as

$$\Delta l = Z\varepsilon_f = L - Z = l_0 + \delta_b - Z = L - \left[\frac{l_o}{\sin(\frac{1}{2}\phi)}\right] \tag{5.10}$$

Where the strain ε_f is the *structural strain* or *single fibre structural strain* (due to structural extension Δl). From (5.7), (5.9) and (5.10), the total single fibre strain ε_b can be expressed as a function of the structural strain, ε_f and the angle ϕ:

$$\varepsilon_b = \frac{1 + \varepsilon_f}{\sin(\frac{1}{2}\phi)} - 1 \tag{5.11}$$

Rearranging (13), the structural strain, ε_f, can be written as

$$\varepsilon_f = \sin(\tfrac{1}{2}\phi)(\varepsilon_b + 1) - 1 \tag{5.12}$$

Since both the *total single fibre strain* and *fibre bundle strain* are equal (under the assumptions mentioned previously), the Equation 5.12 implies that if we know the angle *ø* and the fibre bundle strain ε_b, both of which can be measured, we can find the structural strain of the single fibre ε_f without measuring it directly. Note that ε_f is independent of the values of *a, x* and l_0 in Figure 5.5. Figure 5.8 shows the fibre bundle strain ε_b as a function of single fibre structural strain ε_f and single fibre angles *ø* plotted from Equation 5.12. Low values of *ø* and high values of ε_f lead to high fibre bundle strains ε_b and vice versa.

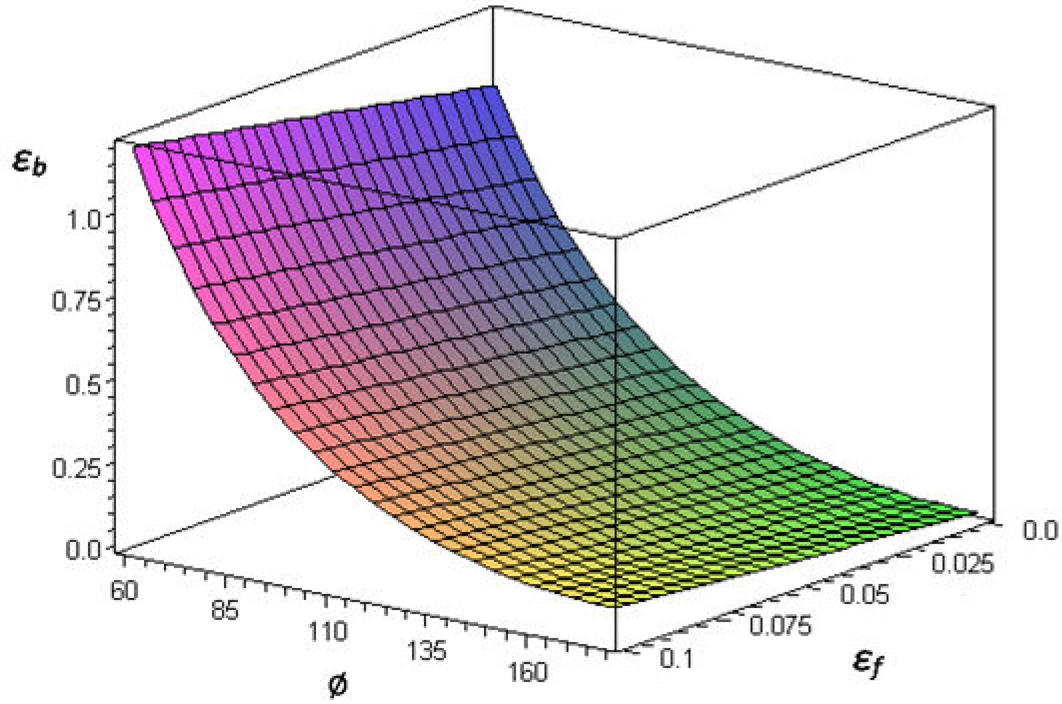


Figure 5.8 A theoretical relationship between *Agave americana* fibre total fibre bundle strain ε_b and its single fibre structural strain ε_f at different single fibre angles ø (°)

It can be expected that for any single fibre angle, there are ε_b values below which ε_f is negative (does not exist). These points are at the extension point *Z* at which the single fibre becomes fully extended and extension *Δl* begins to occur. As can be seen in Figure 5.9 (plotted from Equation 5.12), these critical points are 0.74, 0.41, 0.15, and 0 when single fibre angles are 70°, 90°, 120° and 180° respectively.

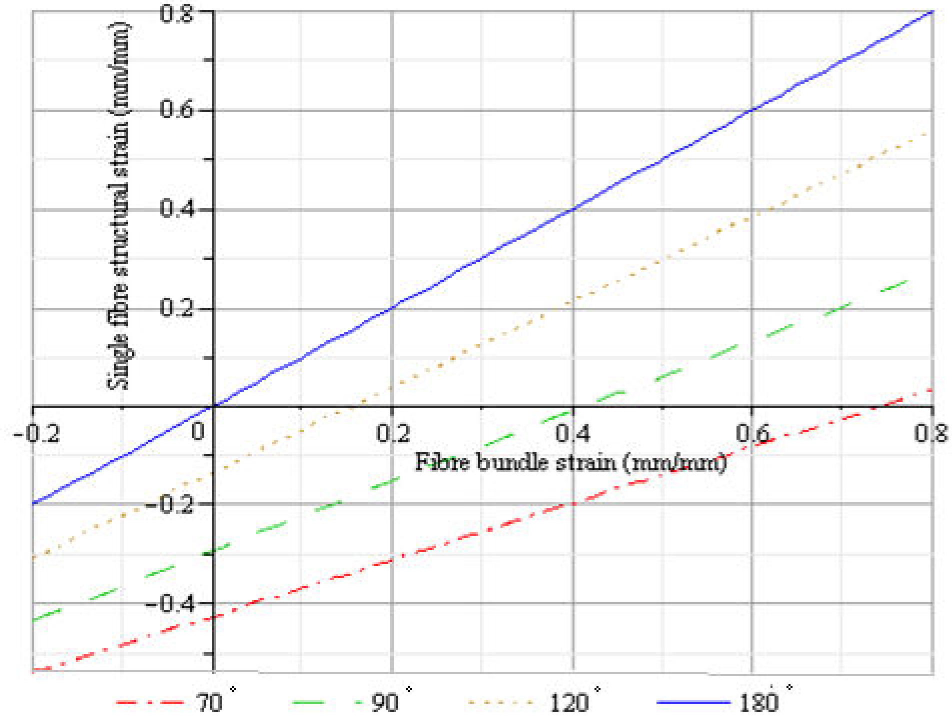


Figure 5.9 The theoretical relationships between *Agave americana* fibre bundle strain ε_b and single fibre structural strain ε_f at different single fibre angles

As can be seen in Figure 5.9, when the single fibre angle is 180° from the start, ε_b equals ε_f at any point of fibre bundle deformation. This would happen when the zigzag structure of the single fibres have been destroyed so that the unravelling extension Z- l_0 equals zero. The single fibres are already straight before deformation.

5.3.4 Influence of single fibre angle on the toughness of the fibre bundle

Assuming that *Agave americana* fibre bundles follow Hooke's law from the beginning of deformation to the point of fracture (Figure 5.4), the fibre bundle stress σ_b versus the fibre bundle strain ε_b curve for the fibre bundle would follow

$$\sigma_b = E_b \varepsilon_b \tag{5.13}$$

where E_b is the modulus of the fibre bundle. Taking the integral to find the toughness of the fibre bundle U_b leads to

$$U_b = \tfrac{1}{2} E_b \varepsilon_b{}^2 \quad (5.14)$$

From (5.11) and (5.14)

$$U_b = \tfrac{1}{2} E_b \left(\frac{1+\varepsilon_f}{\sin(\tfrac{1}{2}\phi)} - 1 \right)^2 \quad (5.15)$$

According to Figure 5.10 (plotted using Equation 5.15) , a combination of low single fibre angles $\o$ and high single fibre structural strains ε_f leads to very high fibre bundle toughness U_b (J/m^3) assuming a constant modulus of 400 MPa (An average modulus of 10 randomly selected untreated *Agave americana* fibres). If *Agave americana* fibre has any of these combinations, it would resist fracture better.

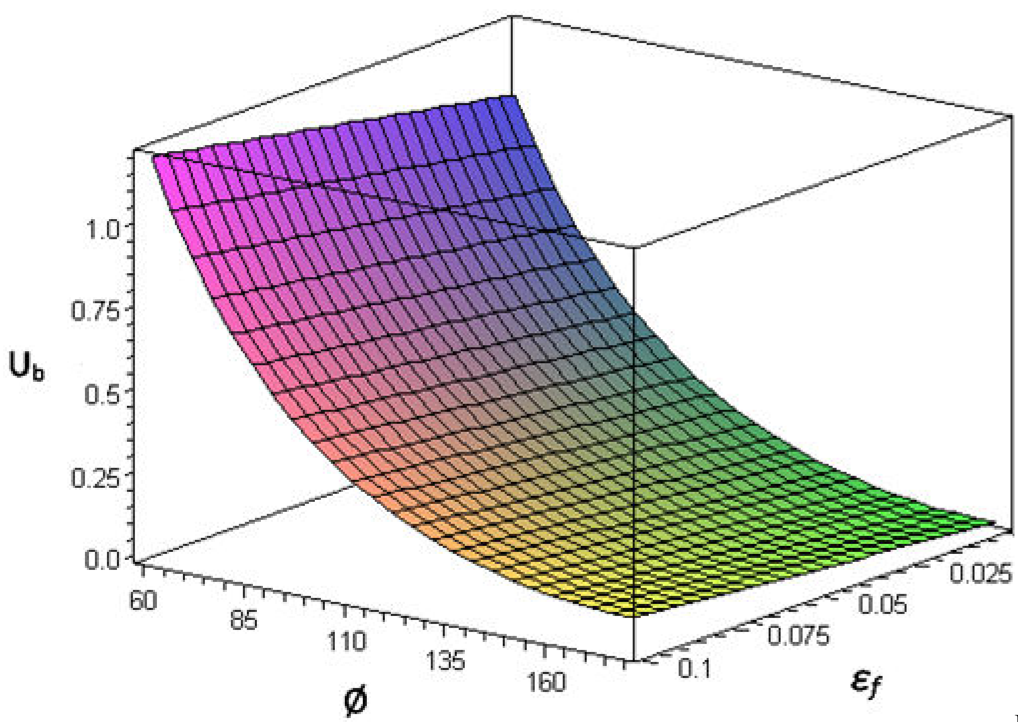


Figure 5.10 The theoretical *Agave americana* fibre bundle toughness U_b (J/m^3) against single fibre structural strains ε_f at a modulus of 400 MPa and different single fibre angles $\O$ (º)

Therefore it can be predicted that the ability of these fibres to extend so much before deformation helps them to absorb energy under extension. This may help them survive breakage during extrusion or high speed shear mixing with plastics to make composites.

5.3.5 Model verification

Theories that relate synthetic fibre bundles to their single fibre properties are normally not too difficult to verify. This is because both the properties of single fibres and fibre bundles can be tested independently. This situation does not apply in the case of *Agave americana* fibres. The modeled single fibres are so small that handling them with the present equipment is impractical. If ε_f could be independently measured, one way to verify this model would be to estimate it using Equation 5.12 where ε_b and average $\emptyset$ are known. Then the directly measured ε_f could be compared to the ε_f calculated from this equation.

From the above discussions, it is possible that the higher angles of single fibres in Figure 5.11 (b) compared to 5.11 (a) may have added to its comparatively short strains after 300 hour mercerization at 130 °C, perhaps by weakening the joints at which the fibres form angles.

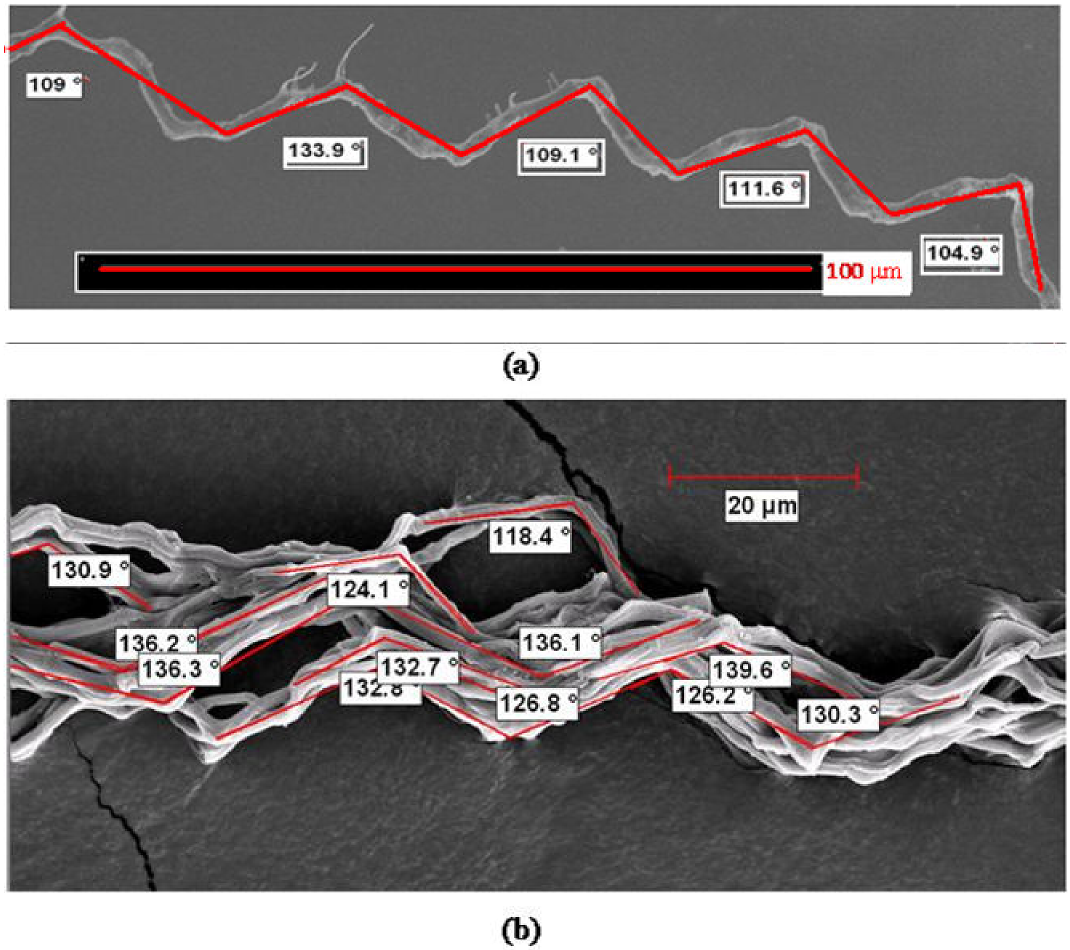


Figure 5.11 (a) The *Agave americana* single fibre angles of a fibre bundle mercerized for 24 hrs at 25 $^{\circ}$C (500×) (b) The single fibre angles of a fibre bundle mercerized for a duration of 300 hrs under at 130 $^{\circ}$C (1000×)

5.3.6 Limitations of the model

The model assumes the single fibres are lying side by side without any meaningful interaction in a bundle and it ignores the influence of lignin matrix. In reality, single fibres of *Agave americana* fibre bundles have a complex interwoven structure as shown in Figures 5.3 (b) and 5.11(b). If viewed as if the fibres do not interact and are not embedded in a matrix, the fibre bundles would register a minimal force between l_0 and Z (Figure 5.7). The resistance would only be due to the single fibres resisting transition from their preferred conformations. The significant force would register only from Z to *L* as the individual fibres would now be structurally deforming (not just unraveling).

The fact that the bundles seem to register a significant force in this region, l_0 to Z, shows that they encounter some significant resistance during deformation making it difficult to identify where extension *Z* is. There are several possibilities during deformation. One possibility is that some sides of the arms named *a* (Figure 5.5) of the single fibres are likely pushing against the walls of the matrix as they straighten (Figure 5.12). On the other hand, the opposite sides of the fibre could be pulling away from the matrix as shown in Figure 5.12. Keeping in mind that the fibres are intermingled, there will be frictional forces among themselves and between them and the matrices as they unravel and extend. Hence each single fibre may experience tensile, compressive and shear forces to contend with during extension. All these possibilities give rise to the resistance force *F* in the region of l_0 to Z. It is possible that some of the single fibres (or even all of them) do not survive to see the extension Z.

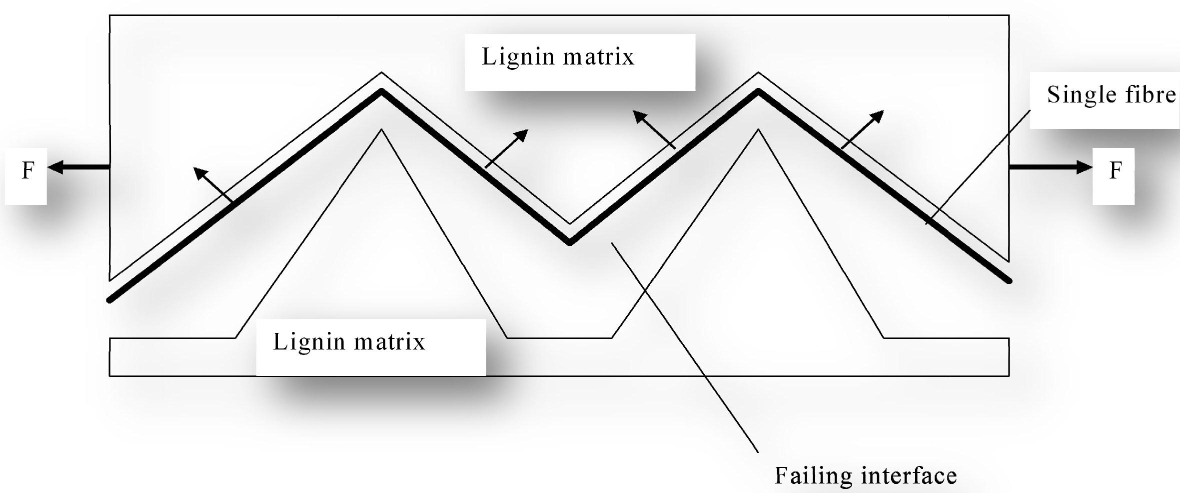


Figure 5.12 The likely picture of deformation during *Agave americana* single fibre extension

Lastly, the model ignores the size dependence of fibre tensile strength. It is well known that fibre tensile strength improves as the fibre gets smaller. This is due to the fact that large fibres have more flaws than small fibres, hence more probability of failure. Consequently a fibre bundle with more flaws may break “before its time”, that is before the fibre could be fully extended.

5.4 Conclusions

The study found that at 25 °C mercerization improves the tensile strengths of the *Agave americana* fibre bundles between 0-50 h of exposure. The strengths are less affected by the duration of mercerization during the period from 50 to 200 h. At high temperatures of 130 °C, fibres loose strength and strains rapidly with time. It is possible that mercerizing the fibres at 130 °C weakens the joints that form the angles of single fibres, increasing the sizes of these angles and reducing the breaking strains of the fibre bundles.

The high breaking strains of *Agave americana* fibres can be understood by modelling the geometry of their single fibres which show a zigzag structure at rest, making it easier for them to straighten before deformation. Therefore it can be predicted from these observations that the ability of these fibres to extend so much before deformation helps them to absorb energy. This may help them survive fibre breakage during extrusion or high speed shear mixing with plastics in composites processing.

5.5 References

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Chapter 6: Processing parameters and mechanical properties in agro fibre/ straw waste plastic composites

Abstract

This study seeks to optimize flexural properties of composites made from waste materials, corn stalk, seed flax and *Agave americana* fibres along with waste LLDPE and HDPE matrices. The surface morphology of fibres and composites were characterized with Light and Scanning Electron Microscopes. Thermal behaviour of the corn stalk outer rings and pith were shown using thermogravimetric analysis.

There was found to be no significant difference between the LLDPE composites made with corn stalk outer rings versus whole stalks, possibly due to an insignificant role played by parenchymatous part of the pith. Water retted seed flax fibres in LLDPE matrix optimized the composite flexural strengths at 6-8 days of retting, above which the properties declined. Field retted seed flax varieties in LLDPE matrix showed no significant differences in their flexural strengths. With additional fibre loading, flexural Strength of *Agave americana* HDPE composites first dropped before improving after extrusion, and only improved when using the layer method

6.1 Introduction

The last two chapters (chapters 4 and 5) focused on the micro-tensile and interfacial properties of the little studied *Agave americana* fibres. This and the next chapter present studies of composites made from corn, wheat straws, *Agave americana* and flax fibres. Since raw materials for NFCs are readily available worldwide, one way to fully benefit from them is to select those materials that are underutilized and on the basis of a specific availability in each region to reduce costs.

Studies of corn stalks and fibres in composites are beginning to surface. Ganjyal et al. (2004) obtained corn stalk fibres by immersing the stalks in NaOH. The fibres were then used to reinforce starch acetate matrices and used as packaging material. The shear strength of the composites improved with increasing fibre content, which could be attributed to good compatibility between starch acetate and corn stalk fibres. Panthapulakkal and Sain (2007) used milled corn stalks to reinforce HDPE. HDPE reinforced with corn stalks did not improve much in mechanical properties and this was attributed to a weak interface between the filler and matrix. However, mechanical properties of the corn stalk HDPE composites were comparable to those of HDPE reinforced with commonly used wood particles.

Corn stalk has a heterogeneous structure (Peterson and Hixon**,** 1929). The outer ring is a concentration of stronger fibres bound by pectin and lignin. Despite a few fibres forming part of the vascular bundles, the pith has mainly a cellular parenchymatous tissue which would presumably act chiefly as a filler rather than reinforcement in composites. It would be assumed that separating the outer ring from the pith and reinforcing with this ring alone could make stronger and stiffer composites than if the whole stalk was used. However, if there is no significant difference in properties between using the entire stalk compared with just the outer ring, then the composite production process becomes more efficient and cost-effective as the separation step could be eliminated. The author is not aware of any study that has examined the influence of using the whole stalk versus the outer ring on the mechanical properties of corn stalk thermoplastic composites; this became the subject of one of our studies.

Compared to corn fibres, flax fibres have recently received a fair amount of attention from researchers; however, the major focus has been on fibre flax (flax grown solely for the fibre) rather than seed flax (flax grown for the seed). The successful use of seed flax could provide further environmental and cost benefits as they are already extremely abundant at the end of seed harvest and have no current applications. A necessary process in flax fibre production is retting, which makes use of microorganisms to free fibres from stems. In water retting, a bacterium, which is naturally available in surrounding air, water and soil, degrades the pectin that binds fibres to the woody stem (Morrison et al., 2000). Fungus is mainly responsible for field retting where straw is left on the ground for some extended periods. Composites from retted fibres are predicted to have superior properties as retting removes gummy pectinic substances (impurities) that cause stress concentrations in composites (Van De Weyenberg et al., 2006). Furthermore, the freed microfibres are able to orient themselves in the direction of the applied force, which allows them to bear greater loads.

Retting can be performed for various periods of time where the degree of retting has an influence on the properties of natural fibres (Sain and Panthapulakkal, 2003). Over-retted fibres begin to lose strength due to excessive degradation of load bearing cellulose, whereas under-retted fibres are not able to achieve the described purpose of retting. Currently, the direct effect of degree of retting in terms of time duration on the mechanical properties of the composites is not well known. Such knowledge would give a clearer picture of what constitutes optimum retting times and could help decrease mechanical variability between composites. Another aspect of flax is that seed flax fibres come in many different varieties and it is necessary to know which varieties give the strongest composite properties. These aspects have been focused on in our study.

Although an advantage of NFCs is the local availability of natural fibres in most regions of the world, many fibres that have a strong potential for reinforcement have not been sufficiently studied. *Agave americana* fibres are a good example. To our knowledge there are no studies that show the direct influence of these fibres on mechanical properties of thermoplastic composites. Some of the unique properties of these fibres may help dictate the choice of composite processing materials and methods for many parts of the world (see chapter 5).

Finally, it has been shown that NFCs are environmentally superior to glass fibre composites particularly in automotive applications mostly due to weight reduction. However, they may not necessarily be superior in other applications like housing

(Thamae and Baillie, 2008 and Baillie, 2003), (see chapter 8). The use of waste polymers instead of virgin ones can enhance the environmental benefits of NFCs in housing and other applications. Polymers that are widely used such as polyethylene are more attractive.

In this study we demonstrate how flexural properties of composites from waste sources can be optimized with respect to cost, environment and regional availability. For different fibres, there are different variables and processing parameters which affect composite properties. These are demonstrated in this study. The products are targeted at both a developed (Canada) and a developing (Lesotho) country. The objective is to develop materials products that could be used in building and furniture applications and would be able to withstand a substantial load.

6.2 Methodology

6.2.1 Materials

Corn stalks, seed flax straw and *Agave americana* leaves are the sources of fibres used in this study. Chemical contents of fibres from these sources are shown in Table 6.1. Corn stalks were obtained from local farmers in Kingston, Ontario, Canada. In order to examine the influence of the use of the outer ring versus the whole stalk on the composite flexural properties, the outer ring was easily peeled from the pith using knives. Both the outer rings and the whole stalks were cut to pieces small enough to feed into the milling machine. These samples were then milled separately with a Thomas Wiley laboratory mill using a sieve pore size of 2mm.

Table 6.1 The chemical content of corn stalk, seed flax and *Agave americana* fibres (Reddy and Yang, 2005, Han, 1998)

Fibre	*Cellulose (%)*	*Lignin (%)*	*Hemicellulose (%)*	*Ash (%)*
Corn stalk	38–40	7–21	28	3.6–7.0
Seed flax	43-47	21-23	24-26	5
Agave americana	66-72	10-14	12	-

Seed flax fibres came from Biolin Research Inc, Saskatoon, Saskatchewan, Canada. Six different types of seed flax straw were used. Vimy seed flax with samples water retted in non-distilled tap water for a period of 0, 2, 4, 6, 8, 10 and 12 days at room temperature. Flanders, Omega, Nuggets, Evelyn and Hermes seed flax samples were field retted for 121 days (this took much time because weather conditions were less conducive). The straws were then passed through a decorticator to extract the fibre, which was cleaned by scutching.

Agave americana fibres were sourced from Lesotho. The method used for obtaining these fibres is detailed in section 4.2.1. Certain characteristics of the fibres used in this study and their respective extraction processes are summarized in Table 6.2. Before use, all the fibres and particles were dried in an oven at 60 $^{\circ}$C for 24 h to reduce moisture.

The HDPE plastic bags produced by Hymopack Ltd. (similar to those used as commercial packing bags in Lesotho) were sourced from the waste stream. The LLDPE films which were produced by AEP Industries Inc. and used as waste bale wrap were obtained from local farmers in Kingston, Ontario, Canada. All the plastic films were washed using a commercial dish washing liquid to remove the dirt. They were then dried in an oven for 24 h at 60 $^{\circ}$C. The rationale behind material selection is summarized in Table 6.3.

Table 6.2 The characteristics of the fibres used in this study (Zah et al., 2007 and chapter 4)

Fibre	*Diameter*[a]	*Length/sieve pore size (cm)*		*Tensile strength (MPa)*	*Fibre extraction /straw processing*
		Layer	Extrusion		
Corn	N/A	N/A	0.2[b]	N/A	Milling
Flax	30-105	N/A	1-3	345-1500	Retting, decortication scutching
Agave americana	80-210	4-15	1-3	120-260	Hot water treatment

[a]Measurements of 40 samples per fibre types were made using Clemex Vision image analysis software, assuming cylindrical shape of fibres. [b]Sieve pore size for corn stalk particles

6.2.2 Methods

Corn Stalk/ seed flax LLDPE composites

Corn stalk particles and LLDPE films were weighed to achieve the desired weight fractions (Table 6.3). Then the particles were evenly laid between several films of LLDPE (up to three films on both sides of the particles) and hot pressed for a few seconds between two films of Teflon sheets (by CS Hyde Company) at 150 °C and a pressure just enough to pre-impregnate the fibres into the matrix (Figure 6.1). Nearly the same ratios of plastic and fibres/particles were used per composite film made to maintain their uniform distribution. This resulted in thin composite films which were chopped using scissors into nearly square pieces of about 1 cm × 1 cm to make their feeding into the extruder easier. The pieces were then taken into the Wayne single screw laboratory extruder for further compounding. There were five heating zones on the extruder which were set at 140°C, 150°C, 160°C, 170°C and 180°C, with the highest temperature (180°C) at the last heating zone towards the end of the barrel. The screw speed was set at 15 rpm. The compounded composites came through a circular die that resulted into long cylindrical composites with a diameter of around 6mm. These composites were then cut into pellets of around 1-2 cm in length. The pellets were put into a 127 × 12.7 ×3.2 mm stainless steel mould and again hot pressed between Teflon sheets at 3 MPa and 150 °C for 3 min into approximately 3.2-mm-thick sheets ready for cutting and testing (Figure 6.2).

To make the seed flax LLDPE composites, the long seed flax fibres were first chopped into 1-3 cm long fibres using scissors. Then the composite production followed the same process described for the corn stalk LLDPE composites above.

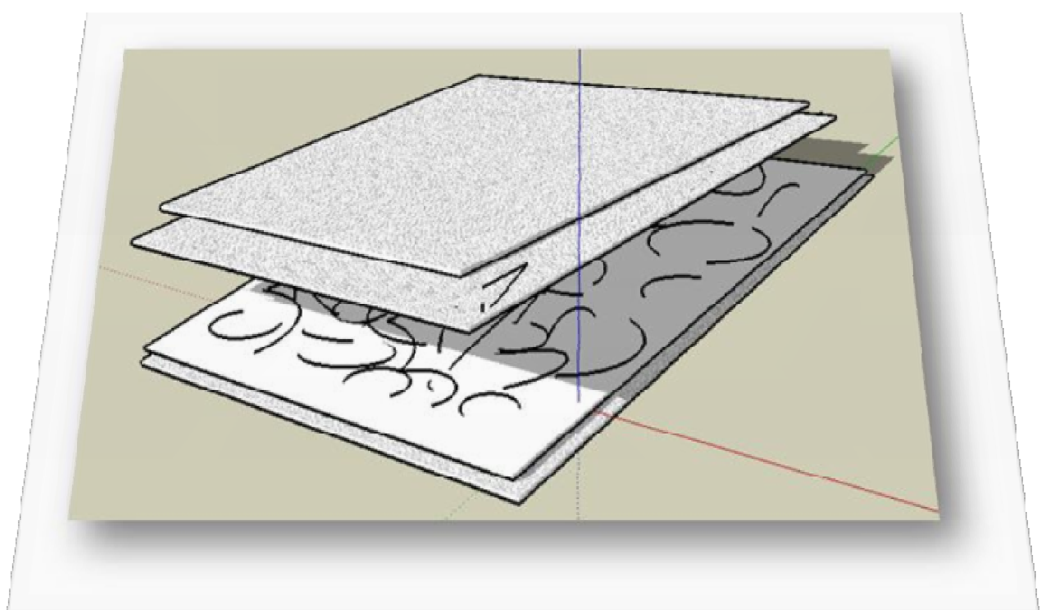

Figure 6.1 The layering of fibre and plastic films to make thin composite sheets for further compounding or hot pressing

***Agave americana* HDPE composites**

The production of *Agave americana* HDPE composites followed two methods. Firstly, the composites were made using the process detailed above. The second method (layer method) involved using the *Agave americana* fibres of the length 4-15 cm (Table 6.2). These longer fibres were laid between thin films as illustrated in Figure 6.1 and then hot pressed as in the previous section to make thin composite films (Figure 6.2). Nearly the same ratios of plastic and fibre were used per composite film made to maintain uniform distribution of fibres. After hot pressing, the roughly 127 × 127 mm composite films made were again layered together in a 127 × 127 ×3.2 mm stainless steel mould and hot pressed under the conditions mentioned above (Figure 6.2). The products were approximately 3.2-mm-thick sheets ready for cutting and testing. The weight percent of these composites is shown in Table 6.3.

Flexural tests

The flexural tests were performed through the three-point bend tests using an Instron 3369 machine following ASTM D790-97. The three-point bend test method was specifically developed for testing flexural properties of unreinforced and reinforced plastics and it has been commonly used for testing composites similar to the ones in this study (Panthapulakkal, Sain, 2007, White and Ansell, 1983). Whereas the three-point bend tests may underestimate flexural modulus, it is often the preferred method over the four-point bend test since it requires less material for each test and does not need determination of centre point deflections (White and Ansell, 1983). The method was considered to be acceptable for this study as it is mainly comparative. The specimens for testing were cut by machining, making 5 specimens per variable. The dimensions of each test specimen were kept at approximately 127 × 127 × 3.2 mm. The support span was 51.2 mm, using the span to thickness ratio of 16:1.

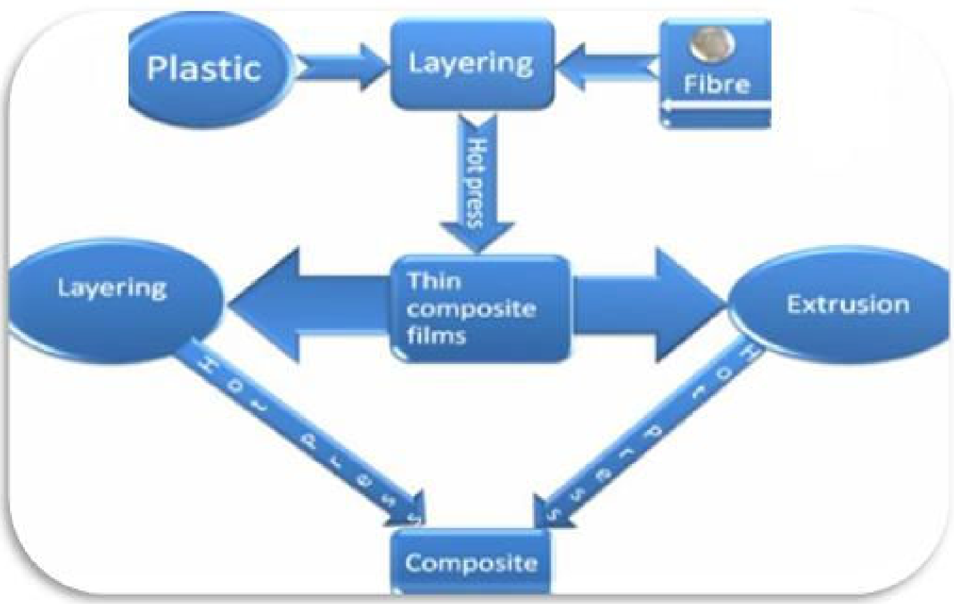

Figure 6.2 The stages and processes of making the composites

The rate of crosshead motion R, was 1.37 mm/min, calculated using Equation 6.1,

$$R = \frac{ZL^2}{6d} \tag{6.1}$$

where L is support span (mm), d is thickness of the beam (mm), Z (Z= 0.01) is the rate of straining of the outer fibre (mm/mm/min) (Figure 6.3). The stress in the outer fibres at mid span, σ (MPa) or flexural strength was taken when the strain reached 0.05. It was calculated using the Equation 6.2:

$$\sigma = \frac{3PL}{2bd^2} \quad (6.2)$$

where P is Load (N), L is support span (mm), b is width of the beam (mm) and d is the thickness of the beam (mm). The flexural modulus E (MPa) was calculated using Equation 6.3:

$$E = \frac{L^3 m}{4bd^3} \quad (6.3)$$

where L is the support span (mm), b is the width of the beam (mm), d is the thickness of the beam (mm) and m is the slope of the tangent to the initial straight line portion of the load-deflection curve (N/mm).

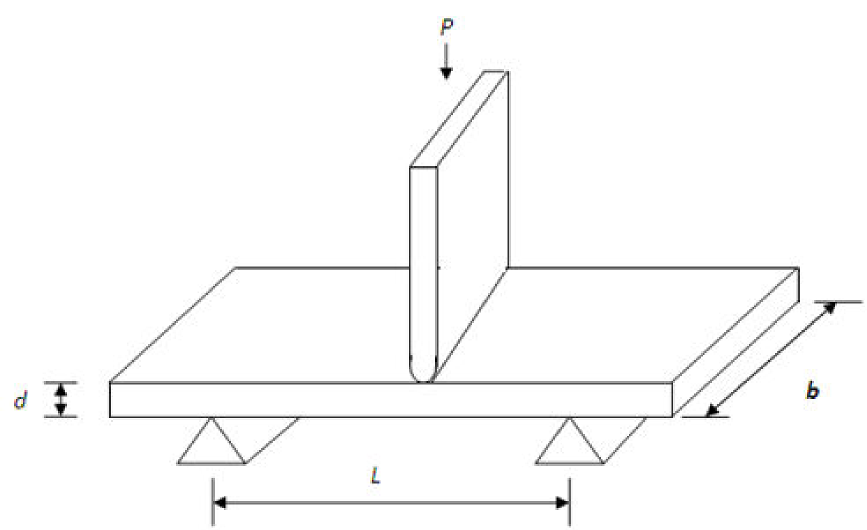

Figure 6.3 A representation of three point bend test

Microscopy

In order to determine the influence of processing on the morphology of the fibres and the composites, two kinds of microscopes were used to characterize these materials. An Olympus stereo light microscope connected to a camera was used to capture the surface morphology of the composites and corn stalks. For finer morphological details, samples were first gold plated and then examined under the SEM. The method for obtaining single fibres of *Agave americana* for SEM analysis is detailed in section 5.22.

Thermogravimetric analysis

Small samples of the parenchyma (with the vascular bundle fibres removed) and the outer ring were put in platinum pans and analyzed with a thermogravimetric analysis machine (TA Instruments Inc.) in a nitrogen atmosphere. The heating rate was 10 $^{\circ}$C/min from 25 $^{\circ}$C to 700 $^{\circ}$C. The results were analyzed using TA Instruments Universal Analyzer 2000 software.

Table 6.3 The materials, processing, experimental parameters and the rationale behind their choice

Target country/ Rationale	*Fibre/Plastic*	*Method*	*Parameters*	*Weight fraction (%)*
Canada	Corn stalk/LLDPE	Extrusion	Influence of corn stalk outer ring vs. whole stalk	0,10,20,30,40,50
Rationale	Corn stalk: abundant agricultural waste in Canada (i.e. in Ontario and Québec, Hoover et al., 2003 and Mcgee, 2006) LLDPE: abundant recyclable polymer used in Canada as bale wrap	Affordable in a developed country	Using whole stalk could save processing costs	Little knowledge on the influence of weight fraction for corn stalk fractions
Canada	Seed flax/LLDPE	Extrusion	Influence of retting duration/fibre variety	20
Rationale	Seed flax: abundant agricultural waste in Canada (i.e Saskatchewan and Manitoba, Kissinger et al., 2007)	Affordable in a developed country	Optimizing properties while avoiding costs of over-retting. Variety may have effect on properties	Influence of flax fibre loading in thermoplastic is well studied; Keeping it constant helps in measuring other vital variables
Lesotho	*Agave americana*/HDPE	Extrusion/layer	Influence of processing method	0, 5,10,20,30
Rationale	*Agave americana*: abundant but less used source of strong plant fibres in Lesotho (Baillie, 2006, and chapter 4). HDPE common waste in Lesotho	The layer method could be cheaper for developing countries	A cheaper processing method that could also optimize properties would be ideal	Little knowledge on fibre loading influence, could not go beyond 30% due to too high viscosities in extrusion

6.3 Results and discussion

6.3.1 Corn stalk LLDPE composites

Few studies show the potential of using corn stalks in reinforcing thermoplastics. Therefore it was necessary to vary fibre loading and to investigate both the strength and moduli of the composites in addition to variables of concern (Table 6.3). Corn stalk is made of a woody fibrous outer ring consisting of epidermis and mainly peripheral vascular bundles (Peterson, 1929 and Hooper, 1931). It has an inner tissue consisting of vascular bundles and parenchyma. The tensile strengths of corn stalk fibres are not well documented in literature. However, the more fibrous outer ring should add more stiffness and strength to the matrix than the more cellular inner tissue. Therefore separating this ring from the center of the stalk should result in better composite flexural properties than if whole stalks were used. The results of this comparison are shown in Figures 6.4 and 6.4.

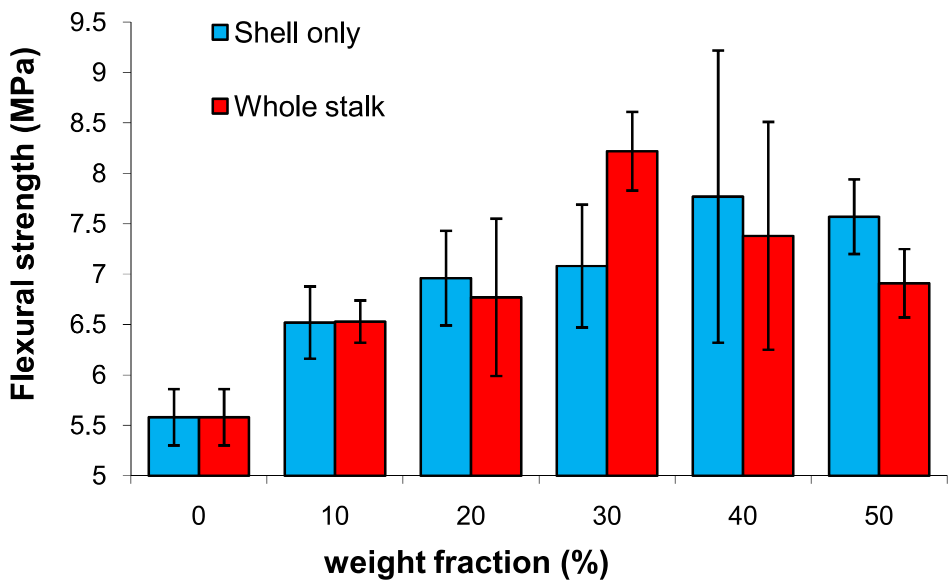

Figure 6.4 The flexural strengths of LLDPE reinforced with the corn stalk outer rings and the whole stalks (N=5) (Error bars represent standard deviations)

High standard deviations are a characteristic property of both natural fibres and materials based on them. The whole corn stalk composites reached the maximum flexural strength at 30% fibre loading (47% improvement compared to pure LLDPE) and then declined from 40% fibre loading. The outer ring corn stalk composites reached maximum flexural strength at 40% fibre loading (39% improvement compared to pure LLDPE). However, the two reinforcements did not differ significantly at each fibre loading. Corn particles could be expected to improve the properties moderately. In addition to their weaker strengths, milled corn particles come in many shapes. This results in a reduced area to volume ratio and therefore less contact area between the filler and the matrix. This is in contrast with flax or *Agave americana* fibres which, in addition to their greater strengths, have a higher aspect ratio (length to diameter ratio) and therefore larger contact area between fibre and matrix per volume of fibre added.

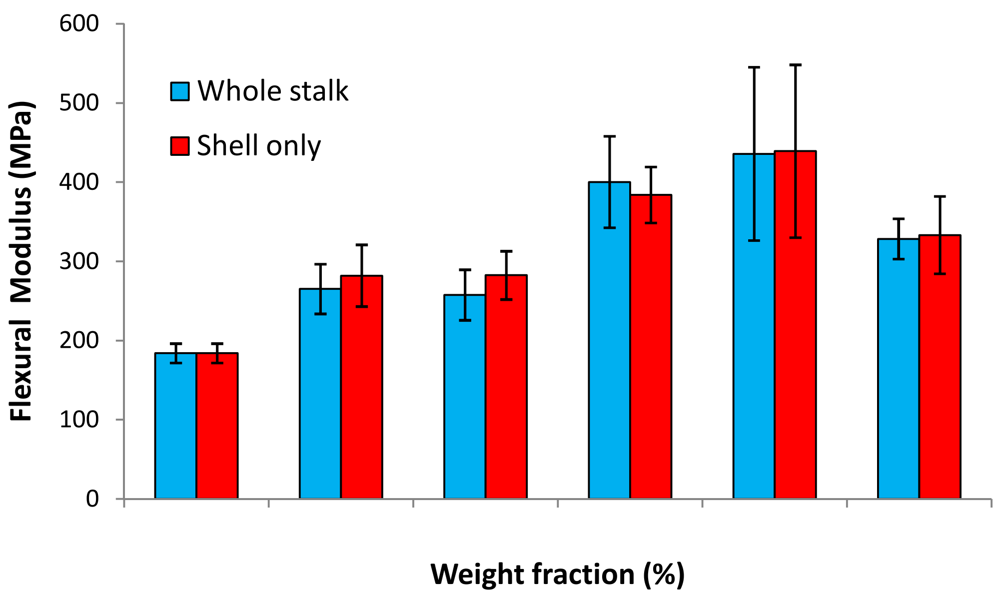

Figure 6.5 The flexural moduli of LLDPE reinforced with the corn stalk outer rings and the whole stalks (N=5) (Error bars represent standard deviations)

There are possible reasons for the small differences between the two composites in Figure 6.4 and Figure 6. 5. The most apparent would be the weight distribution in the corn stalk. The outer ring consists of densely glued fibres which make up the majority of the weight of the stalk (Figure 6.6). For instance, a piece 11 cm long with a diameter of roughly 3.4 cm cut from the stalk had only 30% of its weight as the pith. That weight included both the parenchyma and vascular bundle fibres. Consequently, the percentage weight of the parenchyma compared to the whole stalk is relatively small, or according to Hooper (1931), negligible. Therefore, the minor influences of the parenchyma on composite properties, along with the presence of stronger fibres in the pith, result in little change when using the entire stock compared to just the outer ring. In both composites, the modulus was almost doubled at 40% fibre loading although the two composites remained almost the same at all fibre loadings (Figure 6.5). The decline in flexural properties at higher fibre loading could be due to poor dispersion as the amount of corn stalk in the plastic increased. Hydrophilic corn stalk particles likely interact more with themselves as their content increases, resulting in poor interface (Arib et al., 2006 and Kazayawoko, 1999).

6.3.2 Thermal degradation effects on corn composites

Thermal degradation analysis showed that strength and moduli of the whole stalk composite could be maintained beyond processing temperatures. The thermal analyses showed that the parenchyma began to degrade at 250 $^{\circ}$C, well above the highest composite processing temperature of 180 $^{\circ}$C (Figure 6.7 (a and b)). In contrast, the outer ring had some components that began to degrade at around the processing temperatures (186 $^{\circ}$C).

Whereas the parenchyma had only one significant peak at 335 $^{\circ}$C signaling the degradation of cellulose, the outer ring had several peaks at 208 $^{\circ}$C, 275 $^{\circ}$C and 328 $^{\circ}$C, likely signaling the degradation of pectin, hemicelluloses and lignin and cellulose respectively. The curve in Figure 6.7 (a) may imply that the parenchyma is mainly cellulose due to little evidence of other peaks. The first peak below 100 $^{\circ}$C for both corn stalk components is due to dehydration. At 500 $^{\circ}$C, the outer ring and the pith had 27%

and 10% of the weight remaining respectively. Higher residues in the outer ring might be due to higher lignin and mineral content in this component (Panthapulakkal, Sain, 2007).

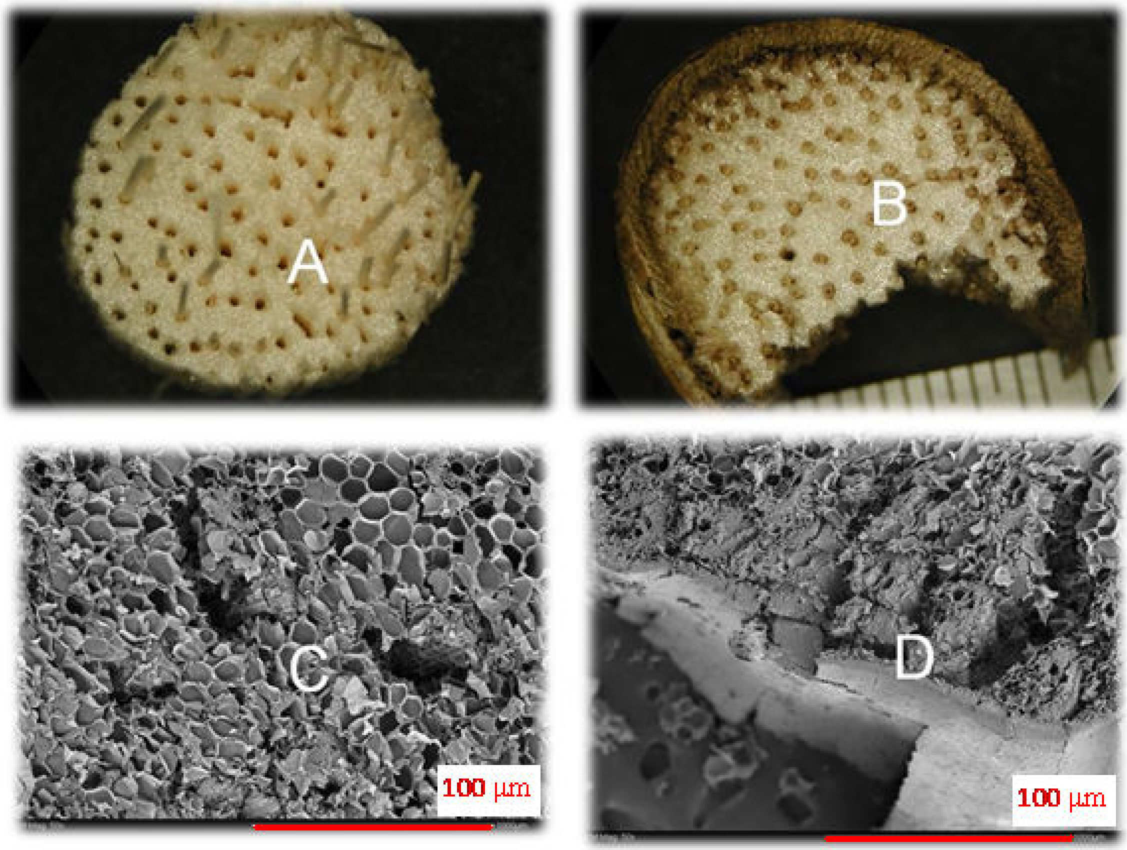

Figure 6.6 (a) The light microscope pictures of corn stalk pith showing spongy parenchymatous tissue with some vascular bundles in the form of fibres distributed within the tissue. (b) The picture of corn stalk pith surrounded by woody outer ring which consists of peripheral vascular bundles and epidermis. A bar on the scale represents 1 mm (c): The SEM picture (50×) of a cross-section through corn stalk pith showing walls of dead parenchymatous cells. (d): The SEM picture (50×) of a cross-section through corn stalk showing the woody outer ring and a region of peripheral vascular bundles.

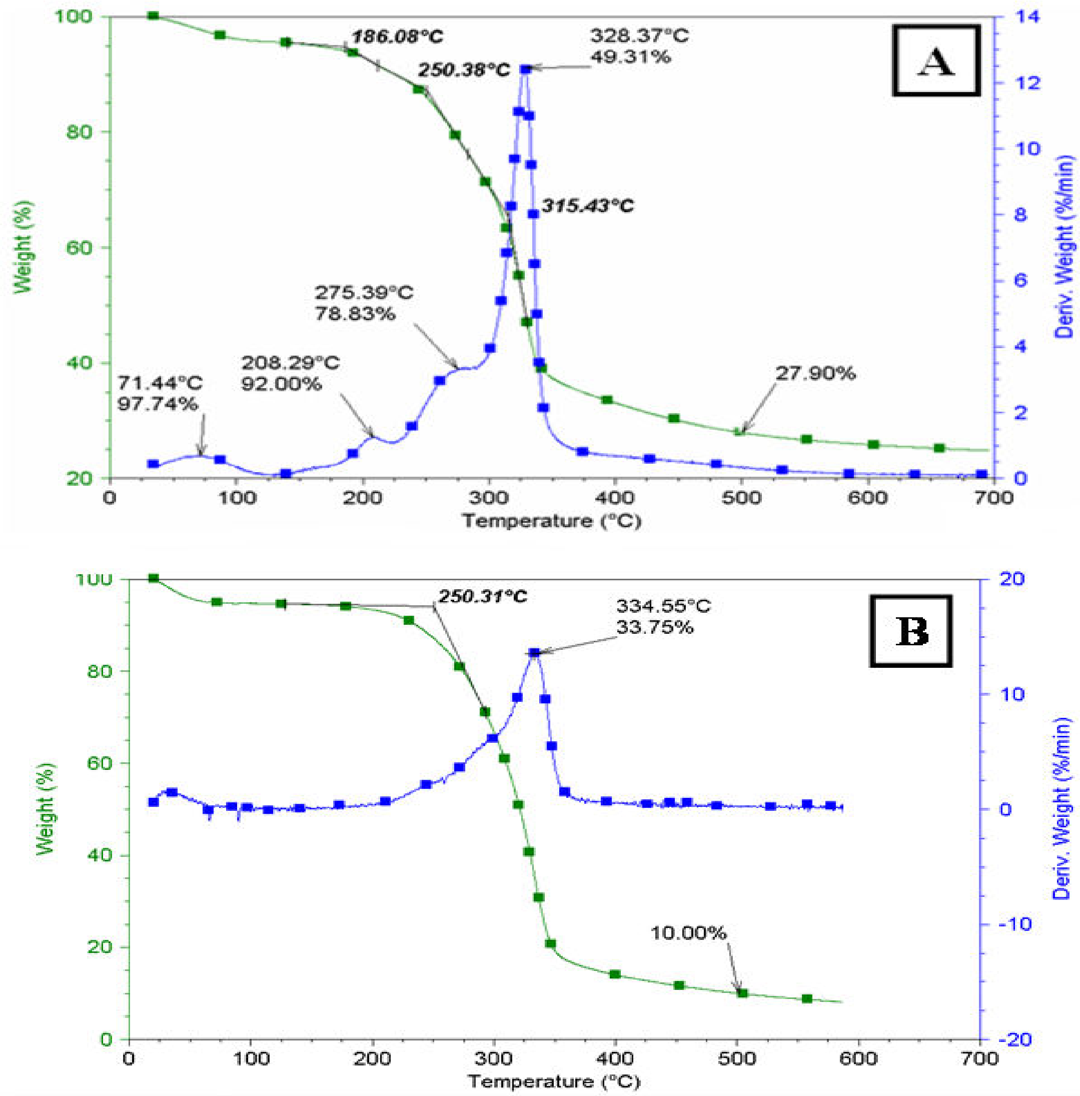

Figure 6.7 The thermal behaviour of (a): The outer ring and (b): The parenchyma

6.3.3 Influence of flax fibre type and retting duration

The primary purpose of retting is to make fibre separation (decortication) easier by reducing energy consumption and other costs during the process. Besides this primary function, retting adds an additional benefit to composites by cleaning the fibre. The pictures (a) and (b) in Figure 6.8 show the SEM images of unretted and 12 day water retted Vimy seed flax fibres bundles respectively. The unretted flax fibre has some pectinic materials on its surface (Figure 6.8(a)). The retted flax shows a relatively smooth surface (Figure 6.8 (b)).

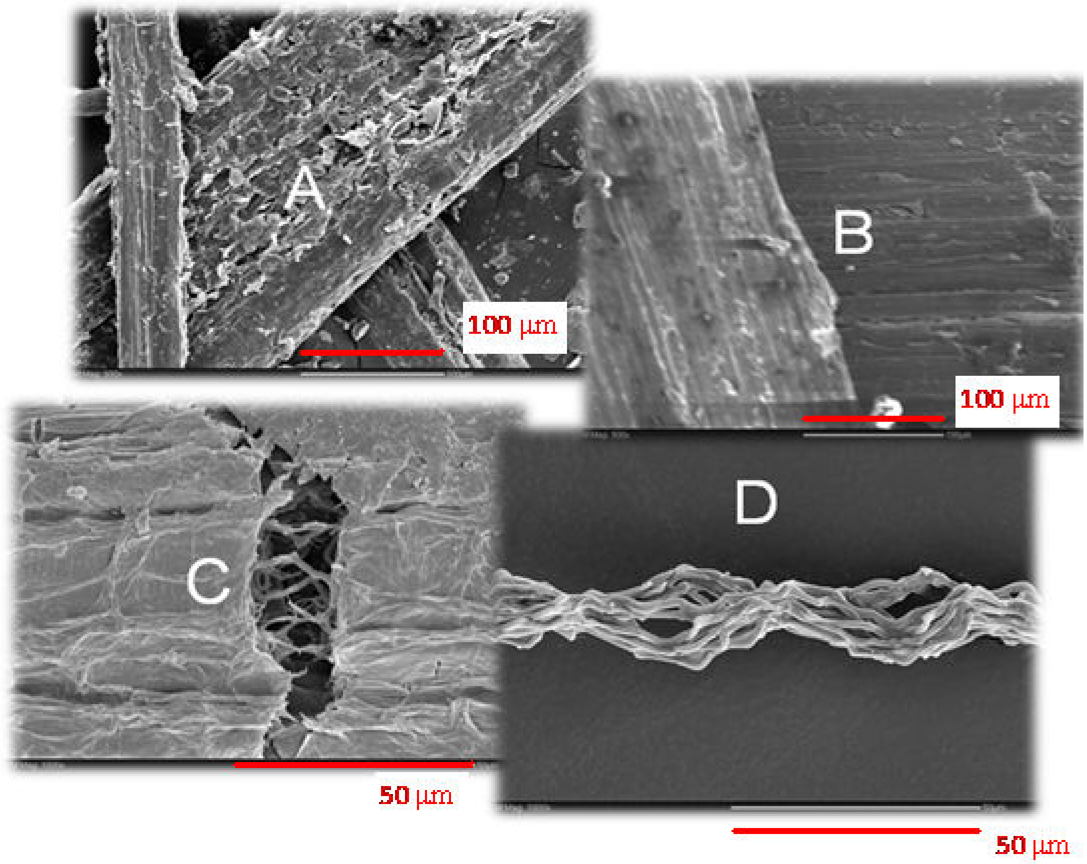

Figure 6.8 (a) The SEM picture (300 ×) of unretted seed flax technical fibre showing gummy pectinic substances on the surface and (b) The SEM picture (300 ×) of a relatively smooth 12 day water retted seed flax technical fibre. (c)The SEM picture (1000 ×) of the surface of a technical fibre of *Agave americana* which has been extracted by immersing *Agave americana* leaves in boiling water. Cracks on the surface reveal presence of minute ultimate fibres of the diameter ranging from 1.5 microns to 3 microns. (d) The SEM picture (1000 ×) of a group of single fibres of *Agave americana* showing a zigzag shape of these fibres

The seed flax LLDPE composites were manufactured using extrusion (Figure 6.2). The pure LLDPE matrix had a flexural strength of 5.6 MPa. Unretted flax fibre at 20% fibre loading improved the flexural strength of the matrix by 98% to 11.1 MPa (Figure 6.9). The degree of retting had some influence on the flexural properties of the composites. The flexural strength increased from 11.1 MPa for unretted to 13.4 MPa after 8 days

(21% improvement). But the flexural strengths declined after 8 days of retting until they reached a low of 9.9 MPa after 12 days of retting. This was a 26% percent decline from the peak at 8 days of retting. At this time (12 day duration), the strengths were also 11% below those of the unretted seed flax composites.

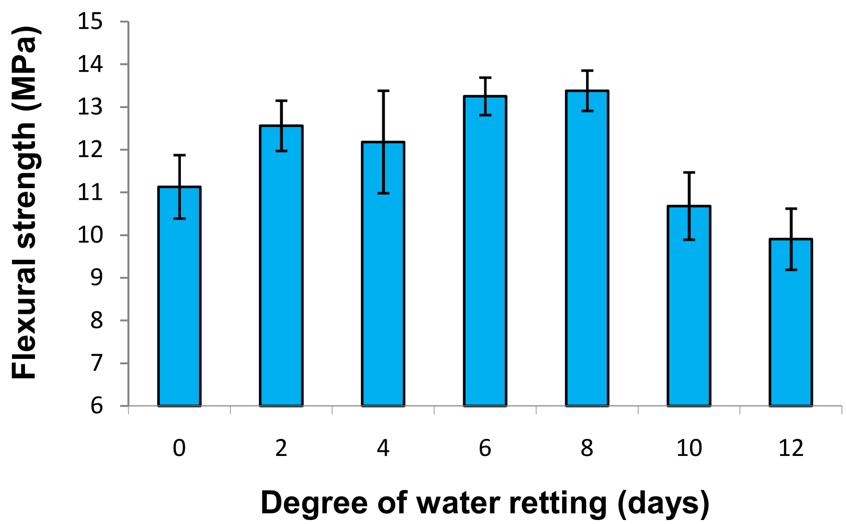

Figure 6.9 The flexural strengths of extruded Vimy watter retted seed flax fibre/LLDPE composite at 20% fibre weight according to the number of days of retting (N=5) (Error bars represent standard deviations)

Retting has the capacity to remove impurities that cause stress concentrations which propagate cracks during application of force on the composites (Van De Weyenberg et al., 2003). Also, as the pectin, lignin and hemicelluloses are degraded by the bacteria, the freed, mainly cellulose fibres can bear load better in the direction of applied load. They are better oriented towards the direction of load. In addition, unretted flax fibres were subjected to more mechanical force, therefore more damage, during decortications (Van de Weyenberg et al, 2003).

Natural fibres can be under-retted or over-retted (Sain and Panthapulakkal, 2003). It is important to closely define these terms especially on the direct influence of these possibilities on the composites. This knowledge can inform fibre processors concerning how far the retting process could go. Based on the conditions of this study (section 6.2), the optimum number of days for water retting Vimy seed flax fibre was between 6 and 8 days. The smaller standard deviations in this period also show that the fibre properties may be more homogenous at this duration as weaker more variable materials are removed. However, the results may vary with seed flax variety and different fibre processing conditions.

In Figure 6.10, flexural strengths of the composites reinforced with different field retted seed flax varieties are compared. Higher standard deviations are noticeable on this graph compared to results from water retted seed flax composites (Figure 6.9). Field retting exposes flax straw to a variety of inconsistent localized biological and weather conditions, which results in inconsistent fibre properties (Morrison et al., 2000). These inconsistencies can be reflected on the composite properties. There are some variations between the flexural properties of the composites from these fibres. The noticeable difference of 1.9 MPa is between Hermes and nugget seed flax fibres. Omega, Flanders and Evelyn fibres are not much different. The generally small differences leave farmers with a large choice of fibres to grow.

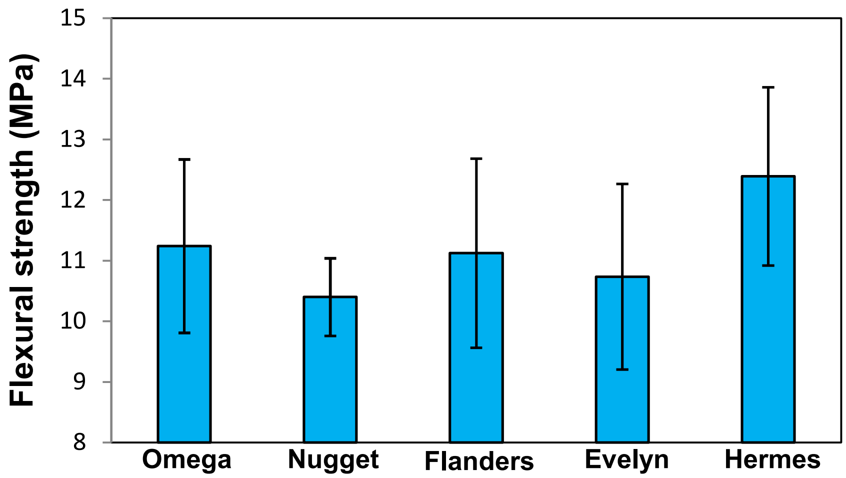

Figure 6.10 The flexural strengths of extruded seed flax/LLDPE composites using different varieties of field retted seed flax fibres at 20 % fibre weight (N=5) (Error bars represent standard deviations)

6.3.4 *Agave americana* HDPE composites

The SEM images of *Agave americana* shows that its typical technical fibre is made up of hundreds of zigzag-shaped micro fibres (see Figures 5.3 and 5.11). The surveyed literature does not show any studies of composites reinforced with *Agave americana*. Therefore it was necessary to vary fibre loading and investigate both the strength and moduli of the composites in addition to the targeted variables (Table 6.3). The two methods of production, layering and extrusion, lead to different results for *Agave americana* HDPE composites (Figures 6.11 and 6.12). Pure HDPE had flexural strength of 15.8 MPa using the extrusion. Upon reinforcement the flexural strength dropped down to 11.7 MPa (26% drop) at 10% fibre loading, but began to improve at 20% fibre loading and even more so at 30% fibre loading. Assuming a reasonable interface, the properties should increase with increasing fibre content.

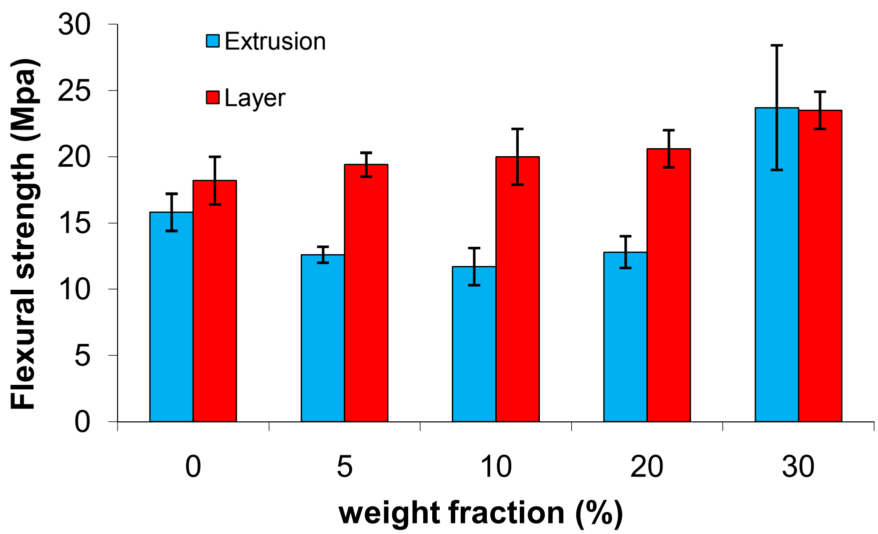

Figure 6.11 The flexural strengths of *Agave americana HDPE* composites of different processing methods (N=5) (Error bars represent standard deviations)

The initial loss in strength in Figure 6.11 is likely due to the use of pellets. The pictures (a) and (b) in Figure 6.13 show what might be the cause of poor strengths in the extruded *Agave americana* HDPE composites. The distinct unmerging pellets can be seen on the pictures. These distinct pellets in a composite are in contrast to the homogenous surfaces of the seed flax LLDPE and the corn stalk LLDPE composites (Figure 6.14 (a) and (b)). HDPE has a higher viscosity and therefore lower melt flow index of around 0.3 g /10 min compared to LLDPE with the melt flow index of 0.7-1.3 g/10 min (Benham and Mcdaniel, 2005). Also the influence on viscosity of adding fibre to thermoplastics can be likened to the influence of reducing temperature (Czarnecki and White, 1980). For instance, due to high viscosity of these composites, the extruder could not handle fibre loadings above 30% as a result of the high pressures needed to convey them. High viscosity due to both the polymer and addition of fibre likely reduced integration of flows where the pellets met during hot pressing. The unmerging pellets could result in lines of weaknesses between them which reduced composite strength. The outcome is similar to a phenomenon of weld lines formation that can occur from injection molding where polymer flows from opposing directions meet. Further investigations could explain better, why the properties improved at higher fibre loadings.

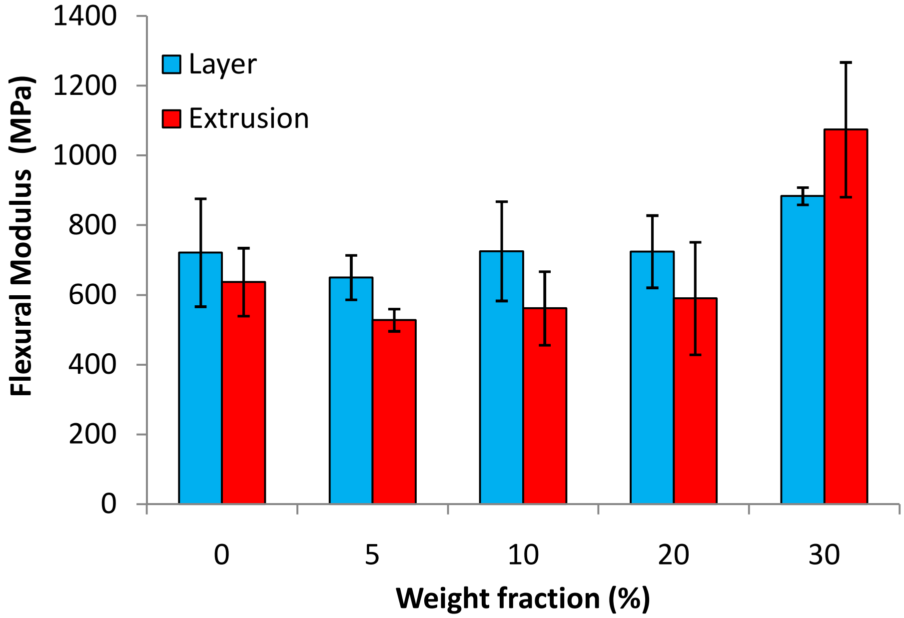

Figure 6.12 The flexural moduli of *Agave americana* HDPE composites of different processing methods (N=5) (Error bars represent standard deviations)

If the use of pellets is a problem as Figure 6.13 (a) and (b) indicate, the process could be improved. By changing the extruder die, the extruded materials could come out not as long cylindrical pellets but as flat thin rectangular sheets that could be placed against each other as in layer method and hot pressed.

The use of the layer method did not show the same problem for *Agave americana* HDPE composites (Figure 6.11 and Figures 6.13(c) and (d)). With this method, the flexural strengths improved with increasing fibre content, reaching 29 % improvement at 30 % fibre loading compared to pure HDPE. This shows that there could have been weak lines present in the extruded samples that are clearly not there with the layer method. The modulus did not vary much with fibre loading except for the highest loading (Figure 6.12). Also, Figure 6.12 shows that except at 30%, the layer method has a little higher modulus values than the extrusion.

Although the layer method does not result in good mixing (Figure 6.14 (d) and 6.15 (a) and 6.15 (b), the fibres in this method are randomly oriented mainly along the horizontal plane as opposed to all possible directions (Figure 6.13 (c) and 6.13 (d) and compare 6.15 (c) and 6.15(d)). Being better oriented could help them bear load better in plane of applied load.

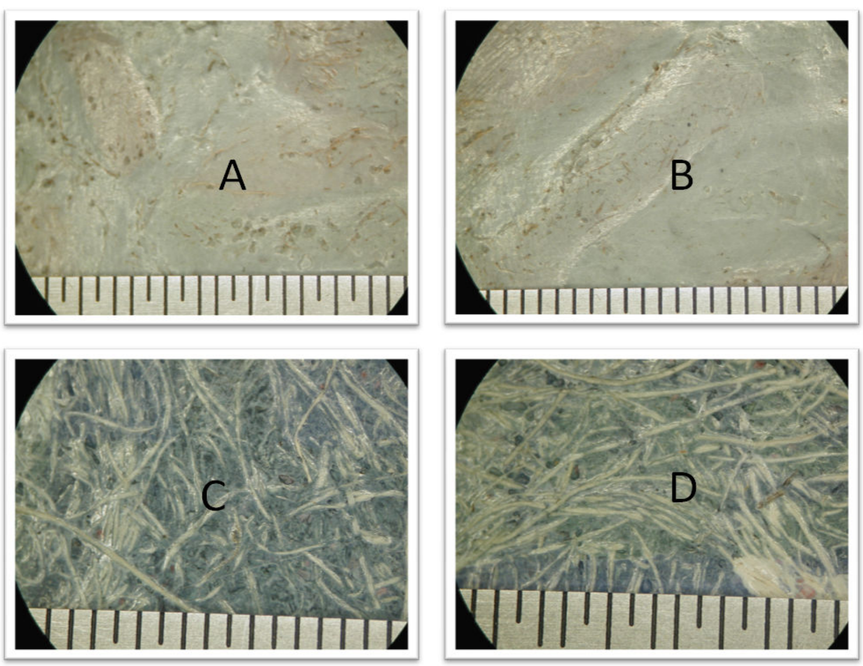

Figure 6.13 (a) and (b): The Light microscope pictures of the surface of *Agave americana* HDPE composites hot pressed from extruded pellets. Some several mm thick pellets are evident with no signs of fully merging. (c) and (d): The surfaces of the *Agave americana* HDPE composites made using the layer method. They show randomly distributed fibres on the horizontal plane of the composite. Each bar in the scale represents 1 mm.

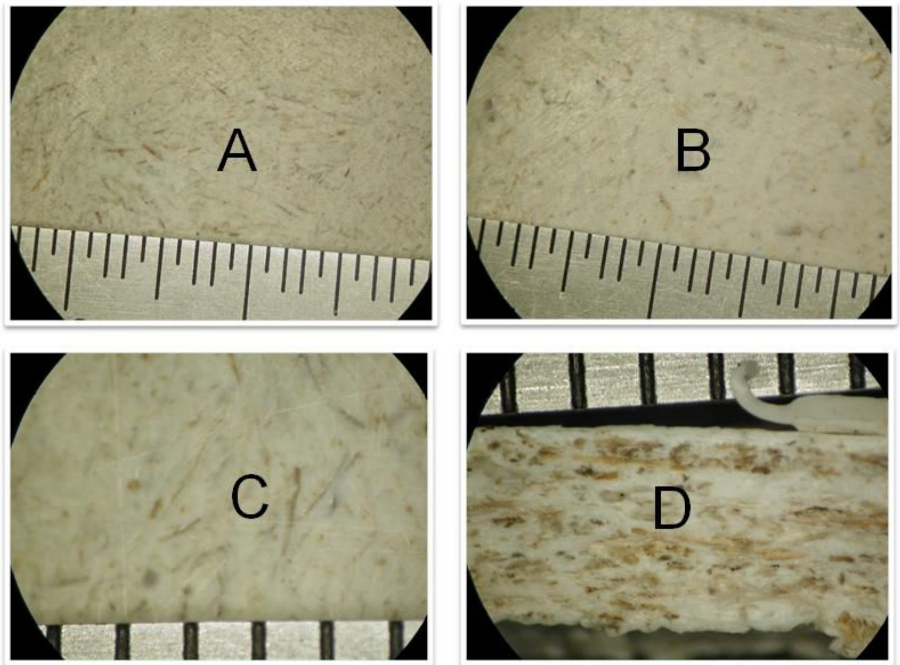

Figure 6.14 (a) and (b): The Light microscope surfaces of seed flax LLDPE composites and corn stalk respectively, made using the extrusion (20% w/w for both). (c): Cross section through the beam showing better fibre distribution in extruded seed flax LLDPE composites. The fibres are more randomly oriented in all possible directions and more encapsulated in a matrix. (d): Layered seed flax LLDPE composites. Fibres are not fully encapsulated; the fibres are oriented mainly on the horizontal plane of the composite. A bar on the scale represents 1 mm

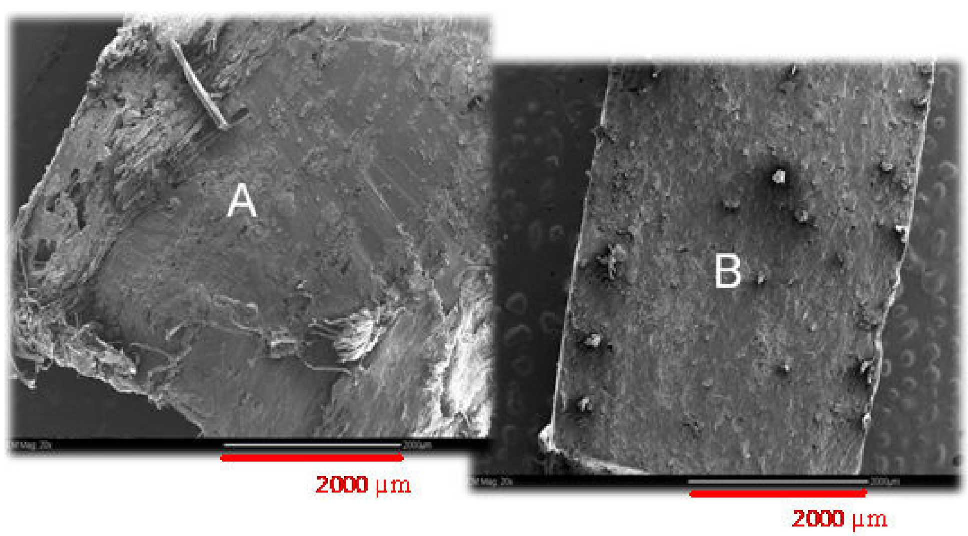

Figure 6.15 (a): The SEM picture of the cross section in a seed flax fibre LLDPE composites using the layer method 20 × (b): The SEM picture of the cross section in a seed flax fibre LLDPE composites using the extrusion 20 × (20% w/w for both)

6.4 Conclusions

In this study we demonstrate how flexural properties of composites from waste materials can be optimized with regards to cost, the environment and the regional availability of materials. This is done through a careful selection of relevant fibres, matrices, and processing parameters.

The presence of pith in corn stalk LLDPE composites does not make a significant difference in the flexural properties compared to when only the outer ring is used. Even though the pith takes a large volume of corn stalk, it consists of very light parenchymatous tissue and strong vascular bundle fibres which together make its influence on the composite properties relatively insignificant. Therefore, bypassing the process of separating the pith from the outer ring will decrease costs and energy use without compromising the composite properties.

Under the experimental conditions of this study, 6-8 days of water retting for Vimy seed flax fibre produced maximum composite properties. The fibre is possibly over-retted beyond this period as shown by the decline in properties. This result can inform processors concerning how far the retting process could go, thereby saving the costs arising from over-retting while optimizing the composite properties. Further, the relative similarity between flexural strengths of composites produced from different seed flax varieties shows that seed flax could be an abundant source of natural fibre for the NFCs industry.

Lastly, the *Agave americana* HDPE composites lost and recovered their flexural strengths in response to increased fibre loading when they were extruded, pelletized and hot pressed. High viscosity of the composites could result in poor merging of pellets during hot pressing. In contrast, the same composites showed improvements at increasing volume fractions when the layer method was used.

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Chapter 7: Mechanical properties of wheat straw waste plastic composites

Abstract

This chapter investigates the mechanical properties of wheat straw LLDPE composites. Composites were fabricated and tested with the aim of finding the influence of straw particle size, arrangement and orientation on the flexural and tensile properties of the composites.

It is found that the particle size has little influence on the properties of the composites. While tensile strength is not improved by the addition of wheat straw possibly due to a poor interface, improved flexural strength can be associated with the less interface dependent compressive component. This compressive component may have been improved by the random-in-plane arrangement of the straw particles. Also the flexural and tensile strength which depend more on the favorable arrangement of the particles made very significant improvements.

7.1 Introduction

Wheat is one of the most cultivated cereal crops in the world. It is estimated that the world produces an average of 2900 million tonnes of wheat cereal straw annually (Schirp, 2006). Other than tilling the straw back to the soil, which is good for soil fertility, wheat straw has limited industrial applications so far. Nevertheless, research shows that wheat straw has a potential to be used as reinforcement in NFCs. Wheat straw composites have demonstrated properties that may equal or rival those of conventional wood composites. Panthapulakkal and Sain (2006) found that the wheat straw reinforced polypropylene (PP) composites had similar or better strength and moduli than those made from wood particles. The same authors later showed that wheat straw composites had generally better mechanical properties than wood particles, corncorb and cornstalks in HDPE matrix (Panthapulakkal and Sain, 2007). Wheat is an annual crop in contrast to wood which may take as many as 30 years for renewal**.** Therefore wheat straw would be a more viable substitute for wood fibre in composites if properties of these composites are comparable.

The nature of wheat straw has been a subject of much study. A closer analysis shows that the straw has an outer layer called epidermis with a soft inner tissue beneath it (HaiLan et al., 2005). This epidermis comprises of a thin layer of silica together with wax and proteins making up a cuticle (Liu, 2005, White and Ansell, 1983, and Schmidt et al., 2002). The cuticle serves to shield the stem from external environment and to prevent moisture loss. The presence of hydrocarbon rich wax could make the outer layer more hydrophobic and more compatible with hydrophobic plastics (Brahmakumar et al., 2005).

The epidermis also contains cellulosic fibres in a matrix of lignin and hemicelluloses, both of which act as binding materials. Lignin can also serve to stiffen the fibres (Le Digabel et al., 2004). There is a loose cellular region of mainly cellulose, containing parenchyma and vascular bundles beneath the epidermis (White and Ansell, 1983 and Hornsby et al., 1997). Being mainly cellulose this region should be more hydrophilic (i.e. have more hydroxyl groups) and less compatible with hydrophobic thermoplastics. This property, together with its loose crisscrossed structure can encourage more water absorption in composites (Patil et al., 2000).

The strengths of fibre composites depend on the strengths of the fibres. Wheat straw fibres have relatively low strength values (45-146 MPa) compared to bast fibres such as flax and hemp fibres for several reasons (Panthapulakkal et al., 2006 and Hornsby et al., 1997). Natural fibres owe some of their strength and stiffness to cellulose (Aziz and Ansell, 2003). The long unbranched polymer chains of cellulose make packing alongside each other easier. This results in a crystalline structure of oriented chains that can take load better (Marklund, 2005). Like other straw fibres, wheat straw fibres have less cellulose content compared to bast fibres (White and Ansell, 1983, Panthapulakkal and Sain 2006). The other reason could be the shorter fibre cell lengths of wheat straw compared to some bast fibres. According to Hornsby et al. (1997), wheat straw has the fibre cell length of only 1.4 mm compared to flax with a fibre cell length of 8-30 mm. The smaller fibre cell lengths lead to a higher concentration of internodes or points of weaknesses on the fibre, resulting in poor strength. Also, wheat straw has a smaller concentration of fibrils than bast fibres. More fibrils in a fibre can share load better (Hornsby et al. 1997).

Therefore, it could be expected that the composites reinforced with wheat fibres are not as strong compared to those of bast fibres. Nevertheless, results of research show that wheat straw is worth consideration. White and Ansell (1983), noticed that at lower wheat straw concentrations (10% by weight), the polyester had its flexural strengths reduced by the addition of the straw before improving them at higher fibre loading (A maximum of 41% improvement at 50 by weight) .They concluded that at very low concentrations, the fibre acted as impurities as opposed to reinforcement for flexural properties. In that study, tensile strengths reached a maximum of 148% improvement at 40 % weight fraction. Panthapulakkal et al. (2006) improved the tensile and flexural strengths of polypropylene (PP) by 29% and 49% respectively with 30 % by weight of mechanically pulped wheat straw fibres. Wheat straw fibres bring more significant improvements in tensile and flexural moduli. Johnson et al. (1997), doubled the tensile modulus of virgin PP by adding 30 % by weight of wheat straw fibres, and increased its flexural modulus 2.5 times. Panthapulakkal and Sain (2006) also doubled the tensile and flexural moduli of PP composites by adding 30% by of milled wheat straw. They argued that modulus is less dependent on the interface and stiffer wheat particles would logically increase the modulus of the less stiff polymer.

However, most of the above studies on wheat composites focus on the impact of pulped wheat fibres rather than milled wheat straw. Since milling would likely be cheaper than pulping, it is attractive to investigate the potential of milled wheat straw in composites. Composites from milled wheat straw would fit in the category of particulate composites. In the past, much work has been done to bring about the theoretical and experimental models on the influence of particle size, shape and arrangement on the properties of these composites (Ahmed and Jones, 1990 (1), Bose and Mahanwar, 2005, Liang, 2007, Okuno and Woodhams, 1974, Leidner and Woodhams, 1974, Ahmed and Jones 1990 (2), Alter, 1965). However, little work has been done to understand how these parameters influence properties of wheat straw composites. Given a physically and chemically heterogeneous structure of wheat stalk, particle size, shape and arrangement could influence composite properties in a manner different from conventional fillers. Therefore this study investigates the influence of these parameters on the nature and properties of milled wheat straw/ LLDPE composites. The matrix chosen is waste bale wrap, keeping in view low cost and environmental benefits of using waste materials for composites (see chapter 7)

7.2 Methods

7.2.1 Hypothesis

In designing this study, we have proposed that the particle size, shape, arrangement, orientation of the wheat straw particles would have an influence on the mechanical properties of the wheat LLDPE composites. Reducing particle size would improve particle surface area which would in turn improve the interface between the plastic and particles, resulting in stronger composites. The particle shape, which would be controlled by the nature of the wheat stems, would influence the arrangement and orientation of the particles in the composite. These parameters would also have influence on the mechanical properties of the composites.

7.2.2 Materials

Wheat straw and waste white colored LLDPE bale wrap of unknown age were obtained from local farmers. Virgin transparent low density polyethylene (LDPE) was supplied by Sigma-Aldrich Inc, USA. It was used for the purpose of observing size and picturing the shape and arrangement of particles in the composite samples more clearly since it was transparent.

7.2.3 Processing, tensile and flexural tests

To compare the influence of particle size on the properties of composites, a mill (Thomas Wiley laboratory mill, model 4) was used to grind the wheat straw into small particles. The particles were forced out of the mill through small circular holes of a sieve with a fixed diameter referred to as pore size. The 2000 µm sieve was used to obtain what will be referred as < 2000 µm particles in this study. The < 250 µm particles were obtained by first milling the wheat using a 500 µm sieve and then hand sifting the wheat particles with a 250 µm sieve sifter (W.S. Tyler Company of Canada). The composites of the two different particle sizes in LLDPE were made (using the extrusion method) and prepared for flexural testing according to the process detailed in section 6.2.2.

The Tensile samples were cut out with a die from 3.2 mm thick molded composites and tested according to an ASTM 638-97 method. The dimensions of the test specimens were cut according to Type I specimen dimensions designed for reinforced plastics. The test speed and gauge length were 5mm/min and 50 mm respectively. The former is used when the rapture of the composites is achieved between 0.5 to 5 min of testing and the latter is based on Type 1 specimens for reinforced plastics in ASTM. Five samples were tested for each variable. Both the tensile and flexural tests were carried-out using a Universal Instron Testing Machine, Model 3369 (Instron Ltd., U.S.A) with a load cell of 5 kN.

The tensile strength σ was calculated according to

$$\sigma = \frac{F_{max}}{A} \tag{7.1}$$

where F_{max} is the maximum load from the load-extension curve and A is the original cross-sectional area of a specimen. The tensile modulus E was calculated as

$$E = \frac{\Delta\sigma}{\Delta\varepsilon} \tag{7.2}$$

where $\Delta\sigma$ is the difference in stress taken on any two points along the initial linear portion of stress strain curve and $\Delta\varepsilon$ is the corresponding difference in strain for each sample tested.

7.2.4 Microscopy and image analysis

The wheat straw LDPE composites were observed using an Olympus Stereo light microscope connected to a camera in order to observe and/or measure size, shape and arrangement of the milled wheat particles as seen from the surface. The images were saved and analysed using Clemex Vision image analysis software. The measurements of length and widths of particles were made by taking 70 different samples from a randomly selected portion of the composite for each particle size. The Clemex Vision software measures the orientation of particles such that if a dotted line was to be drawn on any portion of the composite as shown in Figure 7.1, the orientation of the particles on either side of the line will only range between 0º and 180º.

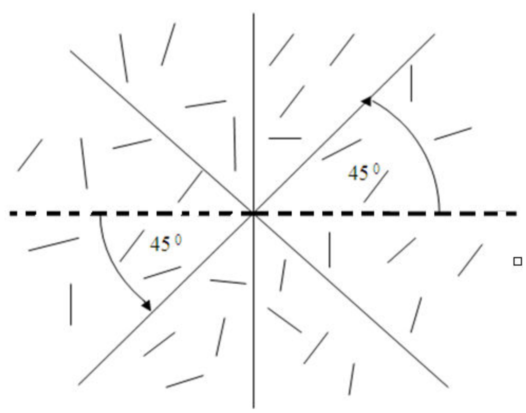


Figure 7.1 Method used to measure orientation of particles using Clemex Vision image analysis software

To calculate the aspect ratio consistently, this parameter was first defined as the ratio of length to width of each of the nearly cuboidal shaped particles as observed on the surface of the composites. This was done by imagining a rectangle around a wheat particle (Figure 7.2) and then measuring its length and width.

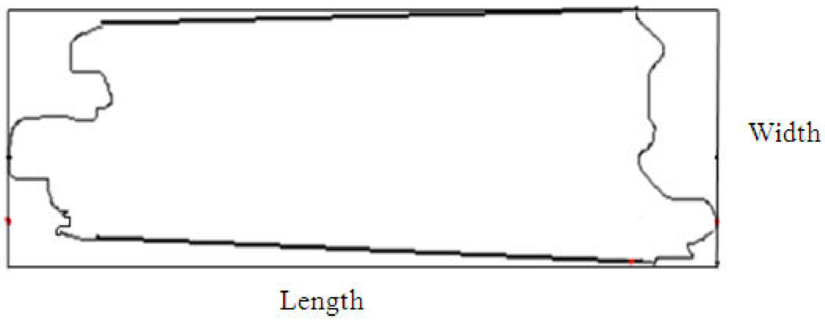


Figure 7.2 Measuring width and length of a wheat particle on the surface of composites

7.3 Results and discussion

This section begins by observing the nature of wheat particles as affected by the process of milling and how the particles are arranged in the composites. These observations are then used to explain the tensile and flexural properties of the composites.

7.3.1 The shape of milled wheat straw particles

The process of milling straw into finer particles, a normal practice in making wood polymer composites, can be cheap and simple. However, it is important to understand the impact of milling on the shape of the particles since this parameter affects composite properties.

In the processes of milling, wheat stalks are hit by the machine's sharp blades rotating at very high speeds, breaking them into smaller pieces enough to pass through whatever sieve pore size is at the outlet. Logically, the smaller the sieve pore size, the longer the process of milling for any given load of wheat straw and vice versa. Therefore making smaller particles is likely to be more costly since it uses more milling energy. If the stalk was a physically and chemically homogenous material with isotropic properties, it would break into flat particles of irregular shapes as shown in Figure 7.3 (a). However, the particles that result from the milling process have a shape approaching a rectangular prism or a cuboid (taking thickness of the particles into account); Figure 7.3 (b).This kind of shape is influenced by the nature of the initial straw itself. The straw has well defined lines of weaknesses running lengthwise along the wheat stalk, Figure 7.4 (a) and (b). These lines are a series of weak points between long fibre bundles.

During the milling, the stalks continue to break along these straight lines. As illustrated in both Figure 7.3 (b) and shown in Figure 7.4 (c) and (d), the results are nearly cuboidal shaped particles which, if milled further, just change in size but maintain a similar way of breaking and hence similar shapes. The shape is maintained in composites (Figure 7.5). An interesting feature of these particles is that each of them can be viewed as a composite of unidirectionally arranged cellulose fibres in a matrix of lignin and hemicelluloses. This attribute has implications for the properties of composites reinforced with these fibres (section 7.4). There is no evidence that these fibres are released from the stalks during the milling process. It takes either chemical or mechanical pulping to get the fibres (Panthapulakkal et al., 2006).

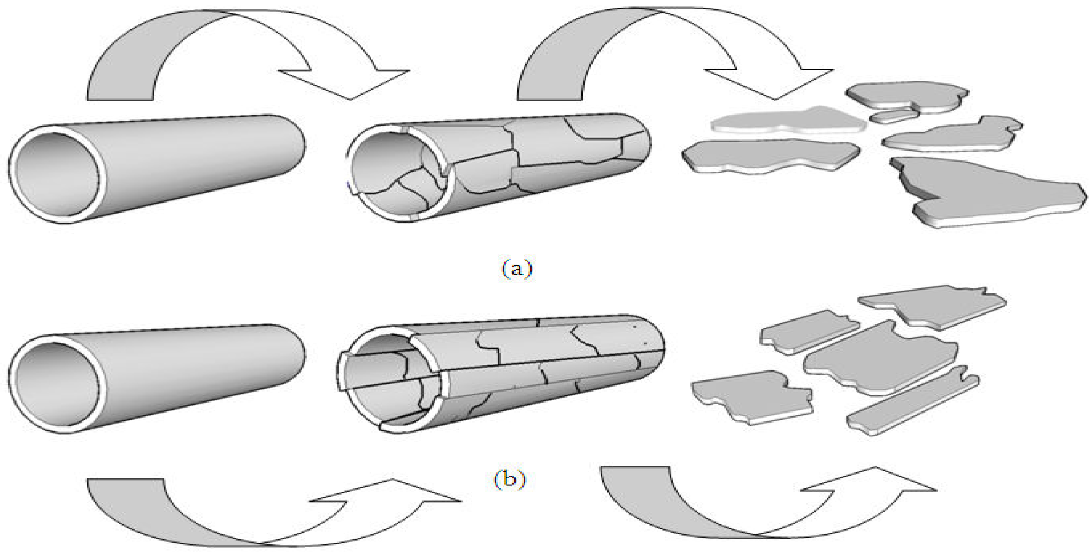


Figure 7.3 (a) The likely transformation followed by an imaginary physically and chemically homogenous wheat stalk during the milling process. The lines of breakage on the stalk are random and cannot be predicted, resulting in particles of irregular shapes. (b) The apparent transformation followed by a real wheat stalk during the milling process. The lines of breakages follow straight predictable lines, resulting in particles that approach a cuboidal shape.

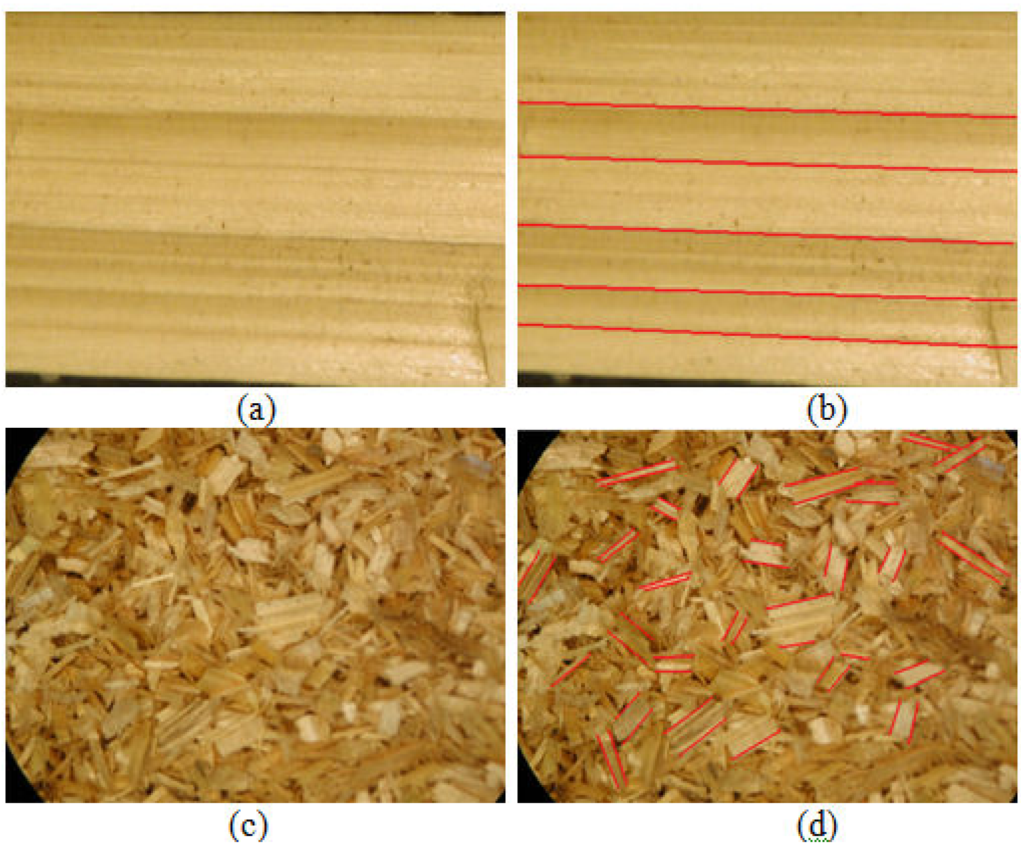
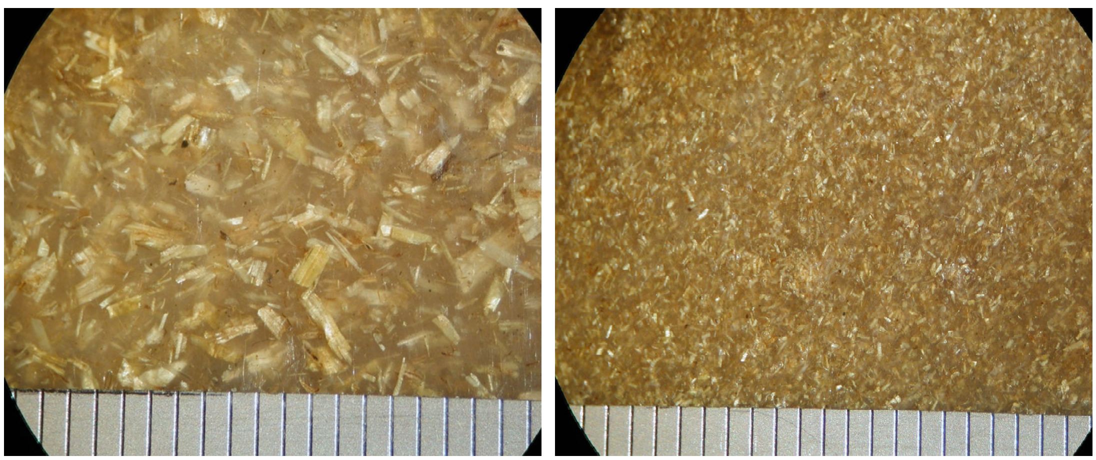


Figure 7.4 (a) and (b), light microscope picture of a typical wheat stalk with lines of weakness running lengthwise, (c) and (d), Light microscope picture of < 2000 µm particles of wheat stalk after milling approaching a cuboidal shape. These particles are not yet in a composite.

7.3.2 Particle size, surface area, arrangement and orientation

Particle size and surface area

Both the < 2000 μm and < 250 μm particles can be classified according to their length, width and aspect ratio. Since they nearly approach a rectangular shape, they were viewed as in Figure 7.2.



(a) (b)

Figure 7.5 (a) Light microscope picture of < 2000 μm particles in an LDPE matrix, (b) Light microscope picture of < 250 μm particles in an LDPE matrix. A bar represents 1 mm.

In Figures 7.6 and 7.7, the length distributions of the particles of the two pore sizes are shown. Generally, more particles have length closer to the average in both cases, showing a distribution closer to a normal distribution. The average particle length of the smaller particles is about 40% shorter than the average particle length of the bigger particles. The average length changed from 1141 μm for bigger particles to 453 μm for smaller particles

(Table 7.1). Interestingly, the width was reduced by almost the same percentage, 41% from 377.6 µm for larger particles to 153.8 µm for smaller particles.

These results imply that the average aspect ratio did not change. It has remained essentially the same at 3 despite change in both average lengths and widths (Table 7.1). If the aspect ratio improved, the shapes would have changed from a more cuboidal shape to a more fibrous one. However, the particles just became smaller while maintaining the same shape. The relationship between average particle length and width and the sieve pore size for wheat straw could be a subject of future studies.

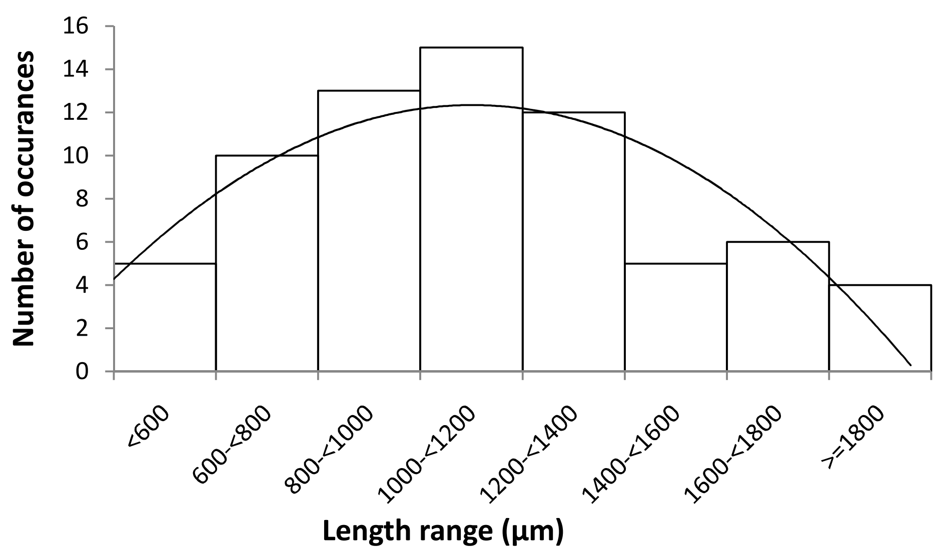


Figure 7.6 Length distribution of < 2000 µm particles.

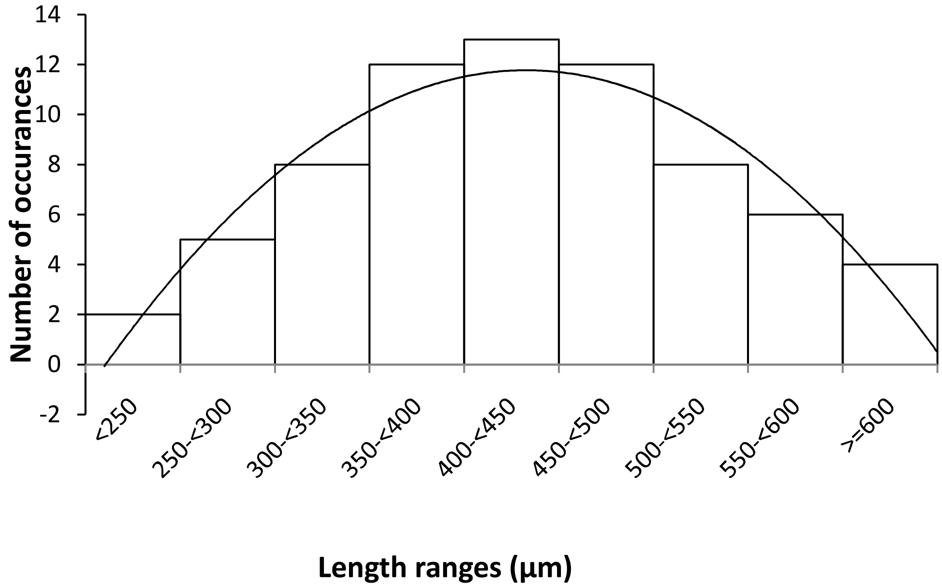


Figure 7.7 Length distribution of < 250 µm particles of wheat straw

It is logical that as particles of a fixed mass decrease in size, their surface area increases, hence their area of contact with a matrix in a composite. A challenging task is to find how much surface area has increased from 2000 µm to < 250 µm particles which do not have completely regular shapes.

Table 7.1 Lengths, widths, aspect ratios and orientation of wheat particles as observed on the surface of milled wheat straw LDPE composites

Sieve pore size (µm)	*Description*	*Length(µm)*	*Width(µm)*	*Orientation (degrees)*
2000	Minimum	1283.9	194.2	3.5
	Maximum	1126.9	233.8	178.0
	Average	1140.6 =*L*	377.6 = *W*	87.0
	Standard deviation	374.8	185.8	45.2
	Aspect ratio	3.0		
250	Minimum	204.9	122.2	8.4
	Maximum	1200.5	255.8	170.5
	Average	452.6 =*l*	153.8 = *w*	92.4
	Standard deviation	155.6	39.3	31.8
	Aspect ratio	2.9		
	Average thickness*	150 µm = *t*		

*Average thickness of the wheat straw stalks *t* measured and averaged from 10 samples with a calliper

This can only be approximated by viewing an average wheat particles of a given pore size as a perfect cuboid of a length L, width W and thickness t (Figure 7.8 and Table 7.1). Breaking down this particle would yield smaller cuboidal particles of any number more than 1. An average particle coming out of this milling has a length l, width w and thickness t (Figure 7.8 and Table 7.1). Thickness of a particle is assumed to be unaffected by the milling and extrusion processes.

Wheat stem has a thin outer layer of epidermis which is estimated to be one fifth of the thickness of the whole stalk (HaiLan et al., 2005). The rest of the inner layer is parenchyma (If we ignore vascular bundles for simplicity). Since these two layers are chemically and morphologically different, their interfacial interaction with the plastic would differ (chapter 3). Therefore the shaded region in Figure 7.8 represents the epidermis, and the rest is parenchyma.

The average epidermal surface area before the milling (A_{EP}) is

$$A_{EP} = LW + \tfrac{2}{5}tL + \tfrac{2}{5}tW \qquad (7.3)$$

After the milling, the average epidermal surface area has increased to (A_{ep})

$$A_{ep} = \tfrac{LW}{lw}\left(lw + \tfrac{2}{5}tl + \tfrac{2}{5}tw\right) \qquad (7.4)$$

Where $\frac{LW}{lw}$ is equal to the number of particles that result from milling of the first particle. Therefore the ratio of epidermal surface area after milling to that of the epidermal surface area before milling is

$$\frac{A_{ep}}{A_{EP}} = \frac{LW(5lw+2tl+2tw)}{lw(5LW+2tL+2tW)} \tag{7.5}$$

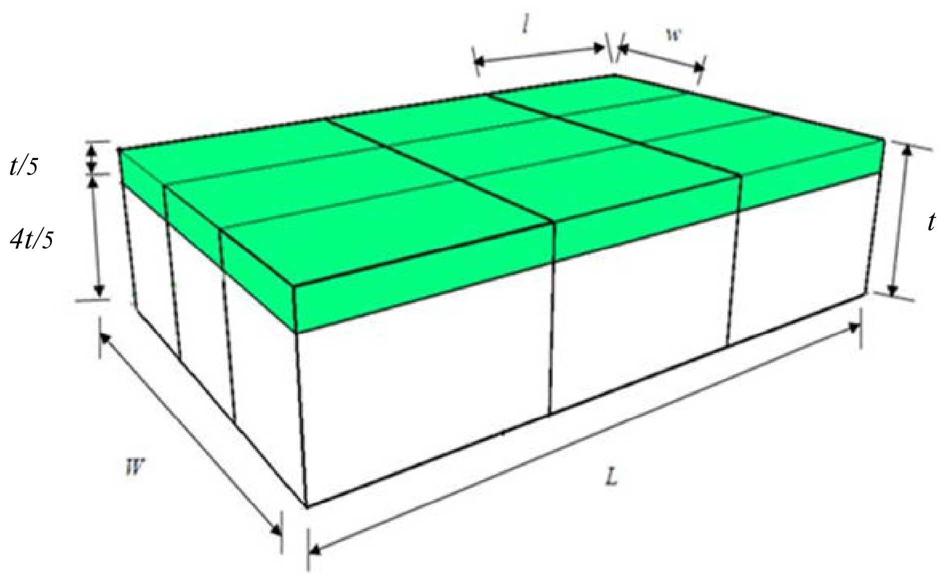


Figure 7.8 A simplified shape of a wheat particle obtained after milling

Similar arguments can be made for the ratio of average parenchymal surface area (non-shaded area in Figure 7.8) after milling A_{pa} to that of average parenchymal surface area A_{PA} before milling such that

$$\frac{A_{pa}}{A_{PA}} = \frac{LW(5lw+8tl+8tw)}{lw(5LW+8tL+8tW)} \tag{7.6}$$

And the ratio of the total surface area after milling A_{tot} to that of the total surface area before milling A_{TOT} is

$$\frac{A_{tot}}{A_{TOT}} = \frac{LW(lw+tl+tw)}{lw(LW+tL+tW)} \quad (7.7)$$

These equations can be used to estimate the average surface area difference in the < 2000 µm particles as compared to the < 250 µm particles in the composites. Using the average values of *L, W, l, w, t* in Table 7.1, it can be shown that the composite reinforced with < 250 µm particles has an estimated 26% more epidermal surface area, 68% more parenchymal surface area and 51% more total surface area exposed to the interface with the plastic (Table 7.2).

Table 7.2 Likely gain in average surface areas as particles of reinforcement changed from < 2000 µm particles to < 250 µm particles

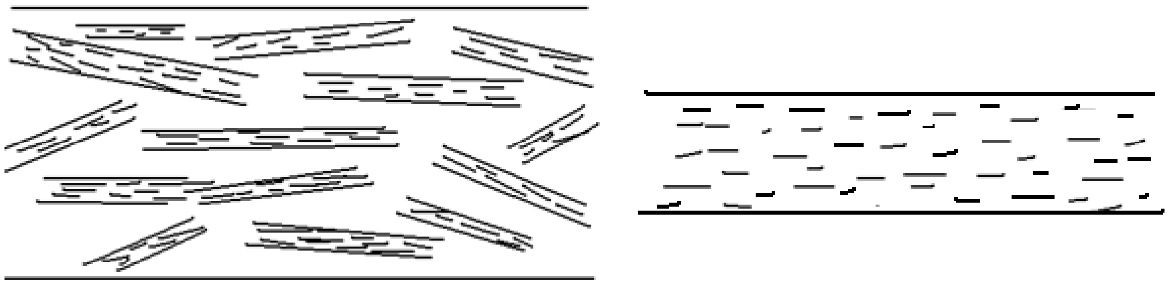
Surface area type	*Notation*	*Surface area (mm^2)*	*Ratio*	*Surface area Increase (%)*
Epidermal	A_{ep}	0.657	1:1.3	26
	A_{EP}	0.522		
Parenchymal	A_{pa}	1.336	1:1.7	68
	A_{PA}	0.795		
Total surface area	A_{tot}	1.993	1:1.5	51
	A_{TOT}	1.317		

Particle arrangement and orientation in the composites

Looking at the pictures in Figure 7.5 (And from direct observation with a naked eye), both particle sizes appear to be arranged *predominantly* in a random-in-plane fashion as opposed to random in 3 dimensions (McCrum et al., 1988). This behaviour is likely affected first by the extrusion process. The exact process of particle orientation during flow is complex and depends on the properties of the plastic and the fibre, the processing temperature and pressure and many other factors (Hull, 1981 and McCrum et al., 1988). However, a simplified explanation can be offered in this case. Consider a melted viscoelastic plastic containing small particles of cuboidal shapes oriented in all directions. This material is being forced through a cylindrical die of 6 mm in diameter during extrusion.

Therefore the material will experience high pressures due to narrow die diameters and expansion under high temperatures. The compressive forces acting on the material will potentially reorient the particles in the melted plastic from random orientations due to mixing to the orientation parallel to the direction of flow. This is the observed particle orientation when pellets come out of the die.

The random-in-plane arrangement of the particles in the final composites is further reinforced by the process of pressing the pellets into thin flat 3.2 mm composite sheets. The pellets as demonstrated in Figure 7.9 (a) are placed nearly horizontal in a mould facing randomly in any direction. Applying force on the mould leaves more particles facing randomly in plane as shown in Figure 7.9 (b) as if thin films of a composite of random-in-plane particles were later stacked together to make a laminated composite (see Figure 6.1). It is noteworthy that these wheat straw particles are also not laid on their edges but are laid flat as they appear on the surface of the composites (it is worth emphasizing that this is the predominant arrangement)(Figure 7.10).



(c) (d)

Figure 7.9 (a) The pellets come out of the extruder with oriented particles. They are laid in mould nearly lengthwise but facing randomly in all directions, (b) applying heat and pressure at the top and bottom of the mould (hot pressing) resulting in a composite with particles oriented randomly in plane.

When the particles are viewed from the surface of the composites, they can be approximated as rectangles as shown in Figure 7.10. If axial lines are drawn along these rectangles, we need to ascertain if they assume any particular orientation. However, the average orientation of the axial lines may be localised at any sampling spot (since they depend on the orientation of the pellets in the neighbourhood), requiring many sampling spots on the surface of the composites, a time consuming process. It is also a challenge to characterise the orientation of the particles buried beneath the surface (hidden by other particles) although they are no less influential on the composite properties.

The nature of the observed particle orientation can be understood by assuming a scenario where orientation of the particles within any randomly selected area on the surface of a composite is perfectly distributed. This ideal orientation will be such that the angle between one orientation of particle A ($ø_A$) and that of the closest particle in orientation, particle B or C, ($ø_B$ or $ø_C$) is $180^0/n$ where n is the number of measured orientations (Figure 7.11). It is worth emphasizing that the closeness of particles referred to here is in orientation, not proximity. Particles can be positioned anywhere on the plane (see Figure 7.1).

Figure 7.10 The milled wheat particles on the surface of the composite approximated as rectangles with axial lines

This perfect and evenly distributed particle orientation always has the average of 90^0. Any deflection from this ideal situation means that particles prefer a particular direction on average, in the sampled portion. The strength of this preference can be measured by standard deviation. For instance the average orientation of 70 particles of < 2000 µm in the sampled part of the composite as shown in Table 7.1 is 87^0 and the standard deviation is 45.2^0. This can be compared to the average orientation of 92.4^0 and standard deviation of 31.8^0 for 250 µm particles. The lower standard deviation of the latter scenario shows that more particles are oriented closer to the average direction than in the former case. These orientation distributions can be better visualised in Figures 7.12 and 7.13. It is worth emphasizing that these orientations are localised and depend on the orientation the local pellets assumed prior to being merged into a single entity. Many sampling spots will be needed to better characterize the whole composites.

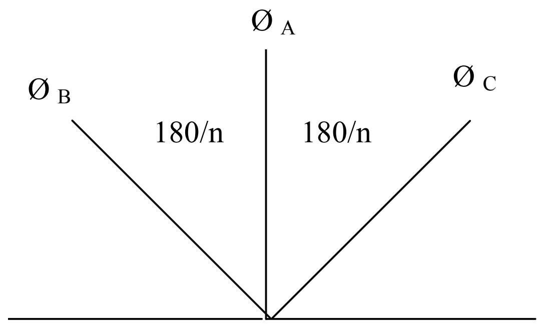


Figure 7.11 An ideal particle orientation

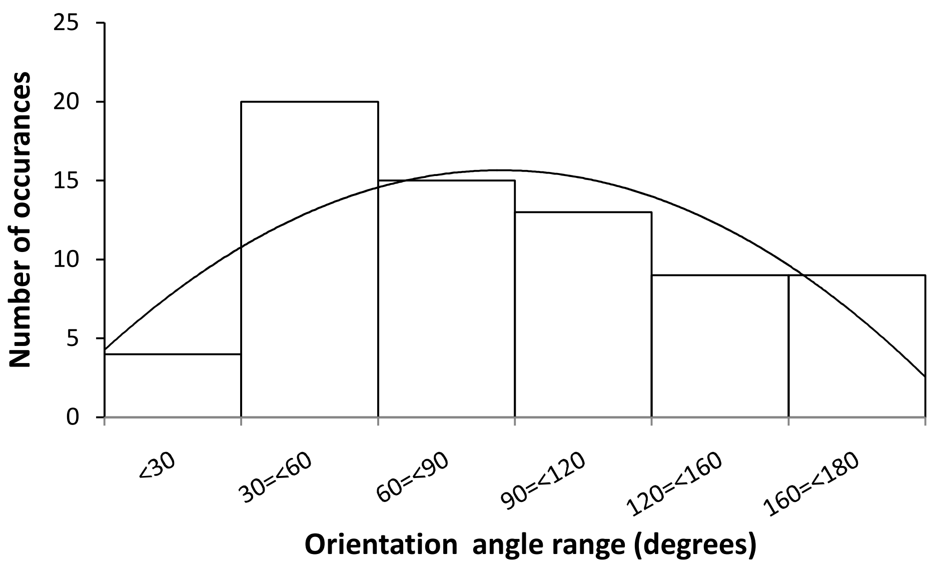


Figure 7.12 Orientation distribution of < 2000 μm particles in the randomly selected portion of the composite

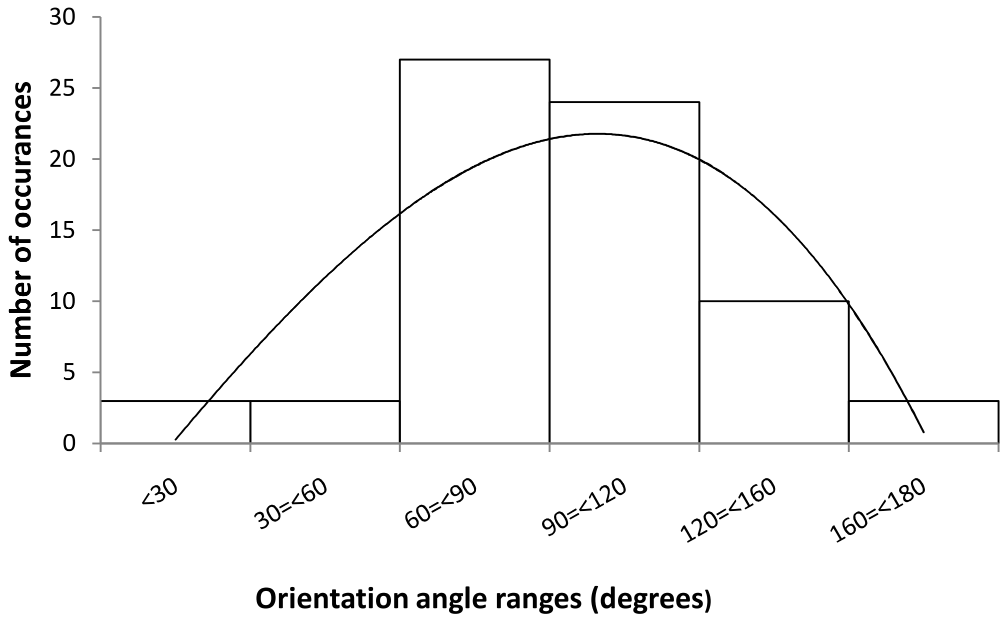


Figure 7.13 Orientation distribution of < 250 μm particles in the randomly selected portion of the composite

7.3.3 Tensile and flexural properties of the composites

Tensile and flexural strengths

Tensile strength is not a function of filler and matrix properties only. It also depends on the strength of the interfacial bond between them. The stronger the bond, the more efficiently the stress is transferred from matrix to filler. This bond is a function of chemical and physical interactions between the two phases of the composite (chapter 3). Tensile strength can also be a function of surface area of contact between the particles and the matrix which offers space for bonding. The widespread use of fillers in the form of fibres takes advantage of this factor since long cylindrical fibres have a high surface area to volume ratio compared to fillers of other shapes. Hypothetically, the following differences between < 2000 µm particles and < 250 µm particles could have influenced the tensile strengths of the composites.

As mentioned, smaller particles offer more surface area of contact with the matrix than bigger ones. It is estimated in Table 7.2 that < 250 µm particles may have about 50% more surface area compared to < 2000 µm particles. This could serve to improve the surface area of contact between the matrix and the particles hence the strengths of the composite. Also, bigger particles can create bigger flaws in the composites contrary to smaller flaws created by smaller particles, thus reducing composite strength (Landon, 1977, Leidner and woodhams, 1974). On the other hand, it is again estimated in Table 7.2 that under the given assumptions, smaller particles have 68% more parenchymal surface area than bigger particles. This is in contrast to 26% more epidermal surface area gained by smaller particles over bigger ones. Parenchyma is mainly hydrophilic cellulose which does not bond well with hydrophobic polymers. On the contrary, epidermis is more hydrophobic since it is richer in hydrophobic waxes and lignin (Brahmakumar et al., 2004). Thus exposing more parenchymal surface area could reverse the benefits of increased surface area. In addition, since each particle can be viewed as a composite, consisting of fibres and matrix, the shear forces during the milling likely weaken these two components, hence the strength of the particles. Smaller particles are likely to be weakened more because they take more time to break and force through small sieve pores.

With these opposing possibilities in mind it is not surprising that the tensile and flexural strengths of composites reinforced with particles of the two different sizes are generally similar (Figures 7.14 and 7.15). The addition of wheat particles of both sizes actually leads to a slight decline in tensile strengths of the composites as particle weight fraction increases. When the interface is poor, whatever bonds exist before applying forces to the composite diminishes rapidly and vanish at high forces.

Flexural strength combines tensile and compressive components acting on a composite. Due to the compressive component, which is less dependent on in the interface compared with the tensile component (Pak and Caze, 1997); there is an improvement in flexural strength of the composite as particle weight fraction increases. The platy nature (Figure 7.10) and the random-in-plane arrangement of the particles likely lead to rigidity and better absorption of compressive forces, leading to increases in overall flexural strengths as particle weight increased. Thus the flexural strength of the composites improved by 123% at 40% by weight of < 2000 μm particles (Figure 7.15).

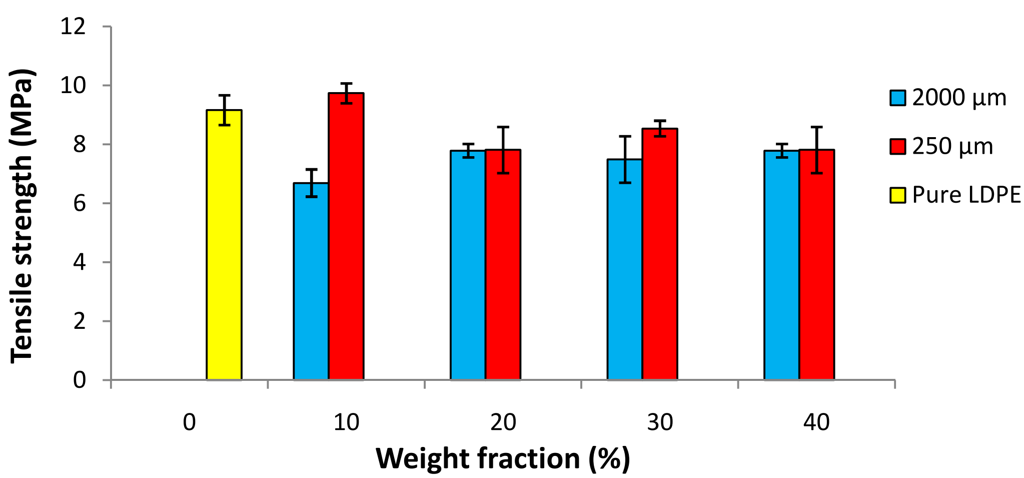


Figure 7.14 Tensile strengths of wheat straw LLDPE composites of different particle sizes (N=5) (Error bars represent standard deviations)

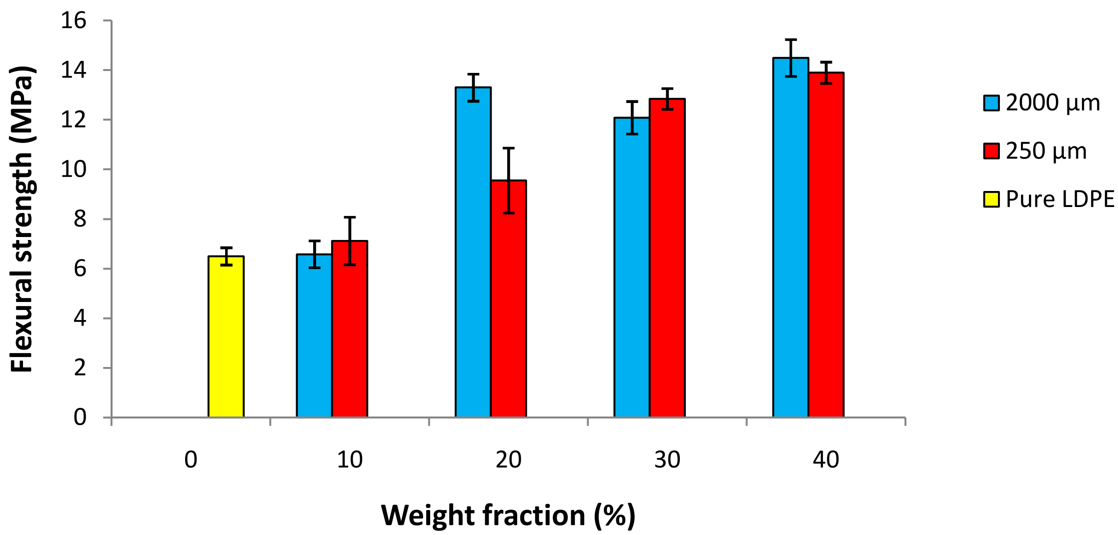


Figure 7.15 Flexural strengths of wheat straw LLDPE composites of different particle sizes (N=5) (Error bars represent standard deviations)

Tensile and flexural moduli

The tensile and flexural moduli of composite materials are a function of filler modulus shape, orientation and weight fraction. They are less dependent on the strength of the interface. Thus particles size, which affects interface, does not necessarily affect the moduli. With the exception of 20% weight fraction for both flexural and tensile moduli, there are no significant difference in the properties of particles of both sizes (Figure 7.16 and 7.17).

The wheat particle depicted in Figure 7.8 can be viewed as a composite of unidirectionally arranged cellulose fibres in a matrix of lignin and hemicelluloses (assuming all fibres in a straw run along the length of the stalk and they are parallel to each other). Consider the following scenario. If the tensile modulus E_c of this *composite wheat particle* were to be tested parallel to the direction of the fibres, it would give the highest strength since stronger fibres (values of fibre moduli can be far higher than matrix moduli) bear nearly all the load in this direction (see McCrum et al., 1988). Hence,

$$E_c = v_f E_f + (1 - v_f)E_m \qquad (7.8)$$

Where v_f is the volume fraction of the fibre, E_f is the modulus of the fibre, and E_m is the modulus of the matrix. Assuming that $E_f \gg E_m$, then the Equation 7.8 could be simplified to

$$E_c \cong v_f E_f \qquad (7.9)$$

If this composite were to be tested transverse to the direction of the fibres, the load would be carried mainly by the weaker matrix, giving the smallest value of modulus E_c

$$E_c = \frac{E_f E_m}{(1-v_f)E_f + v_f E_m} \qquad (7.10)$$

Assuming that is $E_m \ll E_f$ then the Equation 7.10 could be simplified to an approximate expression

$$E_c \cong \frac{E_m}{1-v_f} \qquad (7.11)$$

The *composite wheat particles* described above can also be viewed as fillers themselves in LLDPE matrix as it is the case in this study. Since these *composite wheat particles* have unidirectionally arranged fibres, the orientation of these particles in the LLDPE can be viewed as the orientation of their fibres. The arrangement of wheat particles (and therefore the fibres in them) in the composites follows the arrangement in number 3 in Table 7.3 which is the second most efficient arrangement for tensile modulus. Thus the tensile modulus of the composites improved by 125% at 40% weight fraction of < 250 μm particles (Figure 7.16).

Table 7.3: Reinforcement efficiency as a function of fibre orientations and direction of stress application (Callister, 1997)

Fibre orientation	*Stress direction*	*Reinforcement efficiency*
1. All fibres parallel	Parallel to fibres	1
2. All fibres parallel	Perpendicular to fibres	0
3. Fibres randomly and uniformly distributed within a specific plane	Any direction in the plane	0.375
4. Fibres randomly and uniformly distributed within three dimensions in space	Any direction	0.2

If the flexural modulus is also viewed as having both tensile and compressive components, similar arguments made for tensile modulus above could be applied to the tensile component of the flexural modulus. Adding to that, the influence of the compressive component is likely improved by both the flat-wise and random-in-plane arrangement of the particles which makes it possible for particles to provide enough composite rigidity. The combination of the two factors resulted in the huge improvement in modulus. The flexural modulus of composites improved by 210% at 40% by weight of < 2000 μm particles (Figure 7.17).

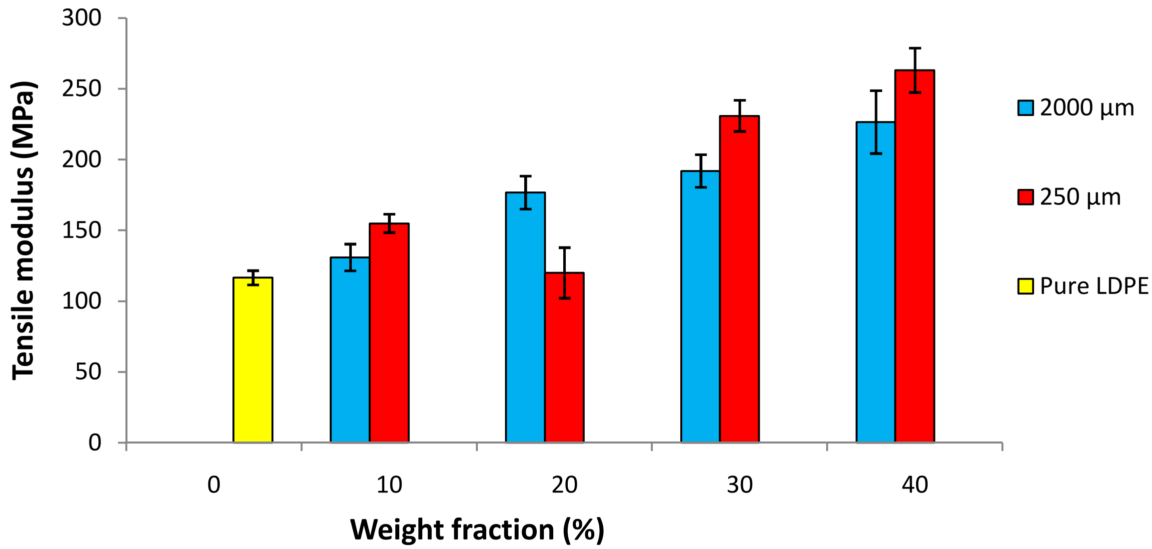


Figure 7.16 Flexural strengths of wheat straw LLDPE composites of different particle sizes (N=5) (Error bars represent standard deviations)

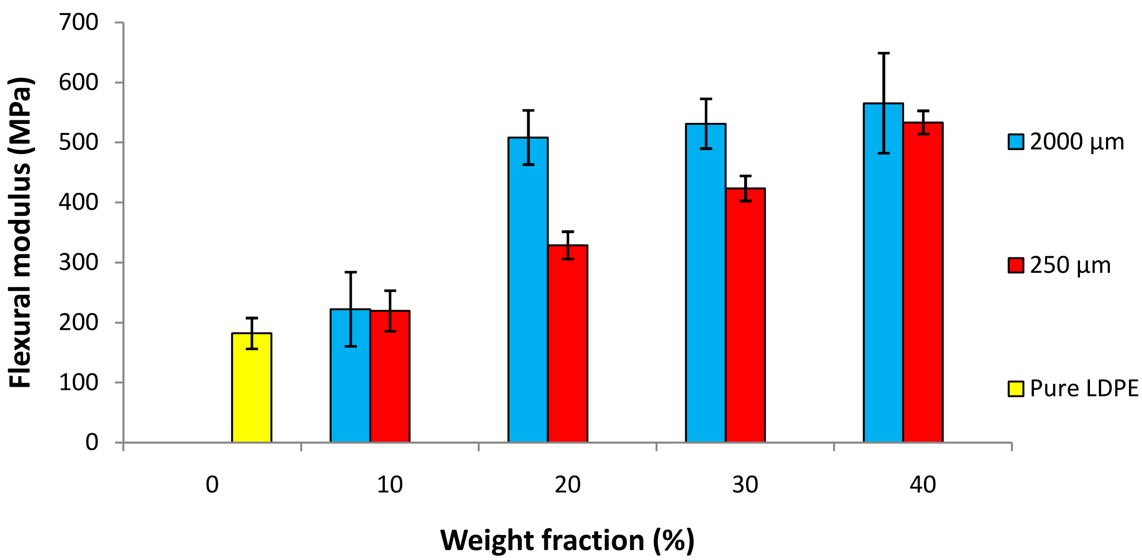


Figure 7.17 Flexural strengths of wheat straw LLDPE composites of different particle sizes (N=5) (Error bars represent standard deviations)

7.4 Conclusions

In this study, we have found that the milling of wheat straw broke the stems along nearly straight lines which gave the resulting particles a nearly cuboidal shape. The < 250 µm particles had 40% less length and width than the 2000 μm sieve pore particles, maintaining the same aspect ratio of 3. The smaller particles had an estimated 51% more surface area compared to the bigger ones. They also had 68% more parenchymal surface area and 26% more epidermal surface area. The route followed in the processing of the milled wheat straw/LLDPE matrix composites lead to the flat-wise random- in-the-plane arrangement of the particles in the composite. The orientation of the particles in the composites were localized and governed by the prior orientation of the pellets at any given area.

The composites of different particle sizes did not show any significant differences in properties. Also, particles of different sizes did not improve tensile strengths with increasing particle weight fraction probably due to poor particle matrix interface. However, the flexural strengths of the composites improved significantly with particle weight fraction. This could be attributed to the improvement in the compressive component of the flexural strength which is not interface dependent. The tensile modulus of composites of smaller particles reached up to 125% improvement at 40% particle weight fraction. The flexural modulus of composites of bigger particles reached up to 210% improvement at 40% particle weight fraction. These improvements are believed to be due to the suitable particle arrangement and orientation governed by the selected processing method.

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Chapter 8: Life cycle assessment of natural fibre composites: a case study

Abstract

Life Cycle Assessment (LCA) is a tool used to evaluate environmental impact associated with a particular product throughout its entire life cycle. Using Simapro software, an LCA was carried out to compare environmental impact of a polypropylene (PP) car door panel reinforced with glass fibre against PP car door panel reinforced with wood fibre. The study shows that replacement of glass fibre by wood fibre in PP composites used as car door panels reduces environmental impact of these panels.

Life cycles of the two panels mainly have impact on fossil fuels, ecotoxicity, climate change and respiratory inorganics categories according to EI99E/E method. They have most impact on fossil fuels. This is because, the use stage, which dominates the impact of life cycles by 86% and 85% for WFP and GFP respectively depends heavily on fossil fuels (petrol). Production of both glass fibre and mechanical pulp; and PP are also highly energy intensive and use much fuels. PP production dominates the impact in the assembly stage for both panels.

8.1 Introduction

The preceding chapters focused on the developments of NFCs. These developments are partly based on the premises that NFCs are more environmentally friendly than conventional composites. However, do these claims and similar assertions about NFCs find support in facts? The answer is not as straightforward as it may seem as the analysis of and with life cycle assessment (LCA) will show below.

Life cycle assessment is a tool used to evaluate environmental impact associated with a particular product throughout its entire life cycle (from extraction of raw materials to the end-of-life; from cradle to grave) (Murphy, 2003 and SETAC 1993). LCA can be used to compare two or more products to find which of them is more preferable from an environmental point of view. For a fair comparison, products should meet the same service requirements. Also, since different products have different impact at different stages in their life times, comparing them at only one stage can give misleading results. Their whole life cycles should be considered.

The automotive industry makes a significant contribution to environmental pollution, especially in emitting greenhouse gases. However, researchers in the field of NFCs suggest that these products can help to reduce the environmental impact of this industry. In North America, the transportation sector shares 10% of the use of wood fibre composites and 16% of the use of other NFCs (Suddell and Evans, 2005) and in Europe, the automotive industry had a share of 55% of the 65 000 tonnes of wood fibres in the markets in 2003 (Markarian, 2005).

One of the main reasons for the current increase in the research and application of NFCs is that they are viewed as eco-friendly (Li and Wolcott, 2004). Nevertheless, environmental impact of a product can be case specific. For instance, one study which analyzed impact of a hemp fibre plastic door panel compared with a glass fibre plastic door panel for housing using LCA showed that both panels had almost similar impact on the environment (Murphy, 2003). According to Baillie (2004), LCA reports from EU CRAFT projects showed that NFCs had more negative impact on the environment than glass fibre plastic composites except for automotive applications where NFCs performed better due to fuel savings due to their light weight.

There are other reports showing LCA studies in automotive applications (Corbiere-Nicollier et al., 2003; Schmidt and Beyer, 1998; Wotzel et al., 1999 and Diener and Siehler, 1999). A review of these studies by Joshi et al. (2004) concluded that NFCs were more eco-friendly than glass fibre composites in automotive applications because (1) natural fibre production has lower negative impact than glass fibre production; natural fibres depend mainly on solar energy to grow and as they absorb CO_2 during growth (2) they take more volume per unit weight of a composite, therefore NFCs require less polymer matrix (which has more negative impact on the environment) than glass fibre in composites at similar volume fractions, (3) due to their light weight, NFCs improve automotive fuel economy, thereby reducing emissions during use; (Sivertsen et al., 2003), and (4) It is possible to recover and use energy by incinerating natural fibre but not glass fibre.

If the above observations hold true, these findings have important implications for the automotive industry. They may encourage policies and voluntary adjustments that act in favor of NFCs as opposed to other conventional composites in this industry. However, LCAs make a large number of assumptions. This factor causes high uncertainties in data and can make LCA studies unreliable (Ayres, 1995; Joshi et al., 2004). Therefore there is a need to confirm or contradict previous studies by carrying out further LCAs under different assumptions.

This study compares the life cycle impact of wood fibre reinforced polypropylene (PP) and glass fibre reinforced PP car door panels. Environmental areas in which both panels have major impact are identified. The two panels are compared on the basis of their impact on these environmental areas. Further, it carries out sensitivity analysis to determine how environmental impact of the panels change with changes in the initial assumptions which is called a reference scenario. The study concludes by looking at the recent European Union (EU) environmental legislation on the end-of-life vehicles (ELVs) and its possible impact on the automotive life cycles. It would be preferable to use some of the composites mentioned in the preceding chapters instead of wood fibre and PP but that proved difficult due to the lack of data associated with their raw materials. The only comprehensive LCA databases and impact assessment methods available were based on Europe which is why the study used the data based on European scenarios. Wood fibres were chosen because the database used had no LCA data related to other natural fibres (including those used in this study) except of wood fibres. Nevertheless, these results can be generalized since NFCs share much in common.

8.2 LCA process

8.2.1 Data collection

One of the strengths of LCA is its attempts to include impact of 'all' inputs and outputs during the entire life cycle of a product. But this can also be a weakness. LCAs require much time and resources in order to collect data. As a result, some authors argue this might have contributed to a decline in LCA studies with time (Sivertsen et al., 2003). The problem has been addressed by creation of commercial public databases. Nevertheless, these databases cannot be specific enough to address every situation. The normal problem of lack of data for some unit process of a system is resolved by carefully selecting and using similar processes or by leaving some out if they are deemed less significant (Corbiere-Nicollier et al., 2003). For instance in this study, lack of data related to mechanical pulp for composites lead to the use of data related to the production of newsprint which is also made of mechanical pulp (see below).

However, public databases can have several deficiencies. They may have data that is aggregated into categories that are too broad. For instance, Ayres, (1995) cites a database that has a category 'hydrocarbons'. The author argues that hydrocarbons may be as different as their environmental impact. Failure to distinguish between compounds can lead to questionable results. For example, it is argued that Cr^{3+} has equivalent impact on human toxicity of 6.7 while that of Cr^{6+} is 47 000 (Krozer and Vis, 1998). Yet some databases do not distinguish between compounds of these ions. Granted, the attempt to satisfy this means more details, more analyses, more time, and perhaps, less cost effective databases.

8.2.2 Modelling LCA

LCAs normally begin with a goal and scope definition. This is the stage that defines the goals of an LCA and delineates boundaries of the study. It determines the outcome of the LCA. Without such boundaries, there is no end to the amount of data any single study can include.

An LCA goal must be stated precisely to leave no room for ambiguity (UNEP, 1996). For most studies, goals may fall within the following areas: comparisons between two products, product and process development, decisions on buying, structuring and building up information, eco-labeling, environmental product declarations and decisions on regulations (UNEP, 1996). One may ask specific questions to formulate goals. Will the study be for internal or external applications? Who will form the audience for the results of this study? To what level of complexity shall the LCA be confined (Murphy, 2003)?

The goal and scope definition part of LCA includes defining functional unit, functions of the system, system boundaries, allocation procedures, types of impact and methodology for impact assessment and interpretation that follows, data requirements, assumptions, limitations and so on (UNEP, 1996).This is the most subjective part of LCA. Consider a functional unit. It is defined as a measure of performance of a product (SETAC 1993). It is a standard into which all inputs, outputs and processes of a system are related. In practice, it measures the amounts of a product or service needed to perform a particular function. However, one product can have different functions. For instance, a technical function may differ from a social one but both are functions (Krozer and Vis, 1998).

Then system boundaries determine the extent of assessment. LCA practitioners decide which inputs, outputs and processes to include or exclude (Murphy, 2003). Where will boundaries be drawn and how? Goedkoop and Oele (2004, pg 5) illustrate, 'In an LCA of milk cartoons, trucks are used…to produce trucks, steel is needed, to produce steel coal is needed, to produce coal trucks are needed…one cannot trace all inputs and outputs…' Undoubtedly, the question of where to draw a line in this endless chain is a problematic one.

The list of emissions and use of resources per functional unit is called an inventory. The inventory is normally followed by impact assessment. This part determines impact of products or services on predetermined impact categories affecting areas of ecosystem quality, human health and resource depletion (Daniel and Rosen, 2002). Different substances have different impact on the environment. So it is important to know their relative contributions to a specific environmental problem. For instance, global warming potential of nitrous oxide (N_2O) is 310 times that of carbon dioxide (CO_2). So the impact assessment goes beyond quantities of these substances to their significance.

There is the challenge. Whenever practitioners try to connect the inventory results to the impact they have on the environment, these results begin to lose spatial, temporal, dose-response relationships (change in effect on an organism resulting from differences in levels of exposure) and threshold dimensions (Daniel and Rosen, 2002). Most impact assessment methods do not reflect these complex realities and they may not do so in the near future (UNEP, 1996). Also, the majority of impact assessment methods use the criteria that more mass of a substance means more impact (Daniel and Rosen, 2002). However, beyond certain thresholds in the environment, whether an impact is '1 or 10 units' does not change the damage made.

Despite the limitations, LCAs provide insights into life cycle impact of products that no other tool can provide. The interpretation stage facilitates estimation of uncertainties.

8.3 Goal and scope definition

The main goal of this LCA is to compare the environmental impact of replacing a glass fibre reinforced PP car door panel with wood fibre reinforced PP car door panel. Wood fibre as opposed to the fibres examined in this study is chosen because it is the only one have that has its environmental data documented in the available databases used. The secondary goals are to identify the impact of glass fibre replacement on major greenhouse gases and major sources of air pollution, to identify major environmental impact categories to which these two panels have significant impact, to identify processes and substances that contribute more to the main impact categories for both panels and to determine changes in LCA results due to changes in basic assumptions or reference scenario.

8.3.1 Functional unit and system boundaries

The functional unit will be a car door panel of volume 992 cm^3 for a service life of 200,000 km. This life time duration is recommended by European Council of Automotive Research (EUCAR) for petrol and diesel cars of weight greater than 1500 kg assumed in this study (Ridge, 1998).

One of the door panels under comparison is made up of glass fibres and PP (GFP). The other one is made up of wood fibres (mechanical pulp) and PP (WFP). In both panels, fibre component contributes 40% and PP component contributes 60% by weight.

WFP and GFP must perform the same function to be compared. This means they should have the same volume and mechanical properties. In practice, glass fibre composites will have higher mechanical properties than wood fibre composites. But the panels do not experience high stresses in use (stresses during use are normally lower than the strengths of wood fibre panels (Suddell and Evans, 2005)). Therefore differences in their strength properties have little impact on their functions.

The impact will be considered in the following 3 stages: assembly (raw material extraction, raw material processing and panel fabrication), use and end-of-life (Figure 8.1)

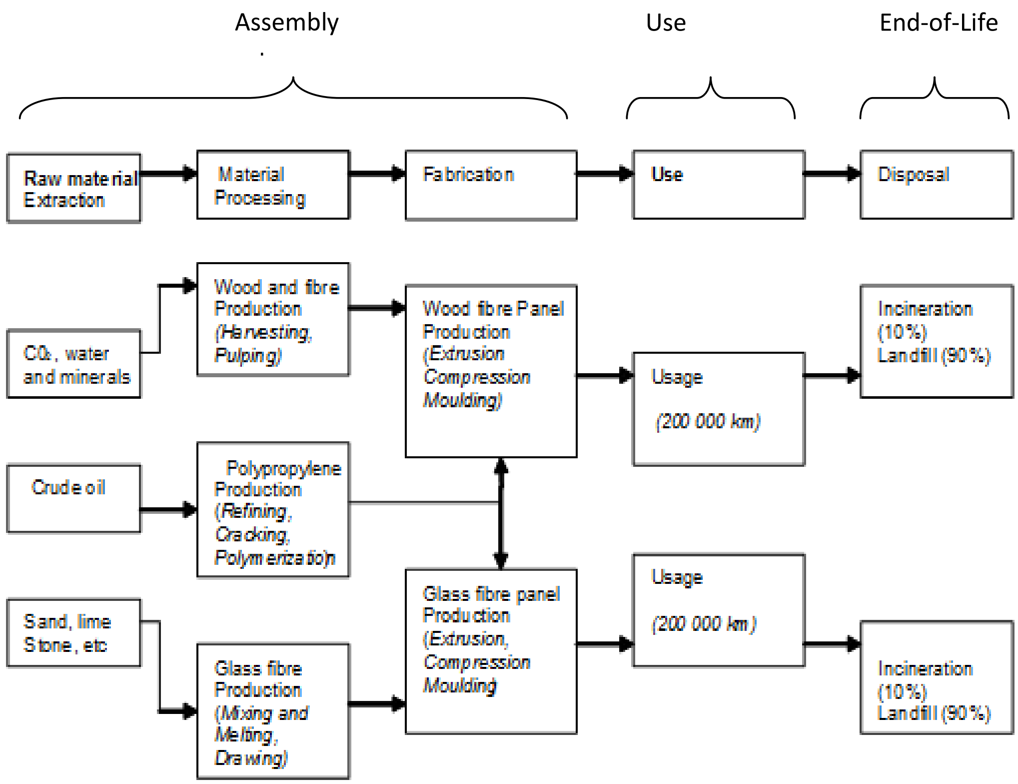

Figure 8.1 The system boundaries: the stages in the Life Cycles of WFP and GFP

8.3.2 Sources of data

Background data were used to estimate quantities of inputs and outputs for different unit processes within a system. The BUWAL 250 (Renilde, 2004) database is selected because it covers more data related to the products under study. This database is based on European scenarios. The choice of data is limited to BUWAL 250 to avoid uncertainty caused by using data from different sources which are based on different assumptions.

8.3.3 Assembly

Polypropylene

PP is produced by cracking of natural gas or light oils. The cracking results in the monomer, propylene, which is then polymerized into PP. There are several impact associated with production of PP. There is much energy used in the extraction process (drilling for oil, or mining of coal). The process of refining is also energy intensive. Hydrocarbons are combined with steam and heated under temperatures of beyond 900 $^{\circ}C$.

Some of the main impact also include release of nitrogen oxides (impact on eutrophication) and hydrocarbons (impact on photochemical oxidation) (Honngu and Phillips, 1997). Other emissions include CO_2 and sulphur oxides which have impact on global warming and acidification respectively. In the BUWAL 250 database, it shows that producing 1 tonne of PP releases 1800 kg of CO_2, 11 kg of SOx and 10 kg of NOx.

Glass fibre

Glass fibre is made up of sand, chalk, soda, and other components. It is mainly based on silica (SiO_2) but includes impurities. Sodium carbonate (Na_2CO_3) is included to lower melting temperatures to about 1000-1500 $^{\circ}C$. Calcium carbonate ($CaCO_3$) or calcium oxide CaO is added to provide chemical durability of the mixture. These raw materials are normally melted in a bushing (e.g. platinum-rhoduim alloy bushing in some cases) and passed through orifices with a network of small round holes to make fibre rovings

(Chakravorty, 1981). The production process is energy consuming. In this study, data used for production of glass sheets rather than fibres is used as a similar process due to lack of data in available databases. Corbiere-Nicollier et al. (2003) used the impact of glass wool production to represent glass fibre production to address the same problem of lack of data in their studies.

Wood fibre (mechanical pulp)

Mechanical pulp can be used in the production of wood plastic composites. The process of obtaining pulp begins with tree felling (using tree harvesters), piling and hauling the trees to the roadside for further processing (Smook, 2002). Debarking and delimbing can be done before transportation to the mill to reduce weight and costs. The wood can then be transported to a sawmill where the logs are turned into small chips. The chips are used in mechanical pulping to produce fibre. All these processes require machinery: sawing machines, mechanical debarkers, sorting machines, chipping machines and transportation. Therefore they are heavily dependent on energy.

Other environmental impact include the emission of lignin, which adds to biological oxygen demand, volatile organic compounds which pollute air, water and soil bodies and reduction in forest resources (Das and Patnaik, 2000).

Transport of raw materials

The transport distances are already included in the BUWAL data. The rest of the distances such as moving raw materials to make panels are not included in this study. However, transport of raw materials can contribute very little impact in life cycles of many products (Corbiere-Nicollier et al., 2003; Schmidt and Beyer, 1998). Therefore they can be safely ignored.

Panel production

It is assumed that the panels are injection molded. The fabrication of the panel is assumed to use 2.88 MJ/kg during injection molding (Corbiere-Nicollier et al., 2003). Other processes are ignored.

8.3.4 Use phase

To model this phase a specific car was selected and some of its features are shown below. Equation 8.1 below by Keoleian et al. (1998) was used to determine the contribution of door panel weight to the fuel consumption of a car. In this Equation, it is assumed that fuel consumption has a linear relationship with weight. No other weight savings are modeled.

$$F = M_t \times L \times \left(\frac{FE}{M_v} \right) \times \left(\frac{\Delta f}{\Delta M} \right) \tag{8.1}$$

where F is the fuel consumed over the life of a panel during as a car travels (litres), M_t is the mass of the door panel (kg), L is life of a door panel which is assumed to be the same as life of the car (200 000 km), FE is fuel economy (l/km; 11.9 l/100 km for city and 7.8 l/100 km for high way), M_v *is* mass of the vehicle (1504 kg). $\Delta f / \Delta M$ is a fuel consumption correlation with mass. It is assumed that fuel reduction of 4.38 %(Δf) follows every 10% reduction in weight (ΔM) (Keoleian et al. 1998). Combined fuel economy, FE_{comb}, which is 9.62 l/100 km, is calculated using the Equation 8.2 by Sullivan and Hu (1995).

$$FE_{comb} = \frac{1}{\left(\frac{0.55}{FE_{city}}\right) + \left(\frac{0.45}{FE_{hwy}}\right)} \tag{8.2}$$

where FE_{city} is city fuel economy and FE_{hwy} is highway fuel economy.

8.3.5 End-of-life

The data for recycling, landfill and incineration of wood fibre is taken from recycling, landfill and incineration of newsprint. Newsprint is made of mainly mechanical fibre similar to that used in composites (Lundquist et al., 2003). In the past 10 years, it was reported that very little plastic waste was either recycled or incinerated (Bruce et al., 1999). The figure may have changed little due to increasing use of plastics. Most of the waste goes to landfills and a small fraction may be incinerated. It is assumed that there is 10% incineration and 90% landfill for both panels for this reference scenario.

8.3.6 Allocation

For incineration, it is assumed that some energy is recovered during the burning of wood fibre and PP. No energy is recovered during glass incineration. The energy generated from incineration replaces the energy that does not have to be produced within the system (expansion of system boundaries).

8.3.7 Impact assessment methods

This study uses Simapro software to make the analyses. Simapro is a commercial software package that comes with a number of free and commercial environmental databases of unit processes (list of materials and energy inputs and outputs in a system) in the manufacturing of specific products such as PP. The software has capacity to transform this data into the impact the processes have on the environment depending on the scenarios put in by LCA specialists. The study also uses the impact assessment method selection criteria below (Table 8.1) as provided by the Simapro method selector (http://www.pre.nl) to choose the best among available impact assessment methods.

Table 8.1 The criteria used for choosing impact assessment method (http://www.pre.nl)

Choice area	*Expected method characteristics*
Single scores	Able to switch between single scores and separate impact category indicator
Weighting set	Uses panel (group of experts) to determine weighting factors
Time perspective	A very long time perspective should be applied in the modelling (future generations are very important)
Geographic coverage and acceptance	Valid in Europe (almost all foreground data is European based)
Simplicity versus scientific quality	Uses advanced scientific models to calculate characterization values
Completeness	As complete as possible, including land use, small particulates, radioactive substances, solid waste etc.

It is shown in Table 8.2 that Ecoindicator 99 egalitarian version (EI99E/E) is the most suitable method that meets the criteria above. It scores the highest number of points (18 points). The description of this method and other possible methods can be found in the relevant impact assessment methods manual (Goedkoop and Oele, 2004).

Table 8.2 Results of Simapro method selector (http://www.pre.nl)

Method	*Points*	*Single scores*	*Weighting set*	*Time perspective*	*Geographic coverage and acceptance*	*Simplicity versus scientific quality*	*Completeness*
EI99E/E	18	3	3	3	3	3	3
EI99 H/A	17	3	3	2	3	3	3
EI99 I/I	16	3	3	1	3	3	3
EPS	14	3	0	3	2	3	3
EDIP	14	3	3	3	1	3	1
Impact 2002+	13	2	0	2	3	3	3
CML2000	10	0	0	3	3	3	1
EI95	9	3	2	1	2	1	0
GWP	6	1	0	1	3	1	0
CML92	5	0	0	2	2	1	0
UBP	5	2	0	0	1	1	1

In short, EI99E/E method calculates impact in terms of damage to the environment; a damage oriented approach. It assesses damage to human health, ecosystem quality and resources. Other methods, EPS (Environmental priority strategy in design), CML method and Ecoindicator 95 (EI95) method are used in this study to check the results. These methods are considered to be reasonably documented and most commonly used (Ridge, 1998).

8.4 Inventory

This section focuses on identifying major contributing substances to the use of energy and emissions to air in the life cycle of the two panels. The stage gives attention to the quantities of substances rather than their environmental impact.

8.4.1 Use of energy

Figure 8.2 sums use of energy for different stages in the life cycles of the two panels. To produce 1 kg of wood fibre requires more energy (15.55 MJ) than to produce one kg of glass fibre (12.08 MJ). The energy used in logging, processing of wood chips and the process of mechanical pulping can be very high (Das and Patnaik, 2000). However, there is a little more energy used in assembly of 1 kg of GFP than the same amount of WFP. GFP has a higher volume of PP which needs more energy to produce. It also has a higher weight which uses more energy during fabrication. The same thing applies to energy for the entire life cycle (assembly, use and end-of-life). Due to higher weight, GFP uses more energy especially during use.

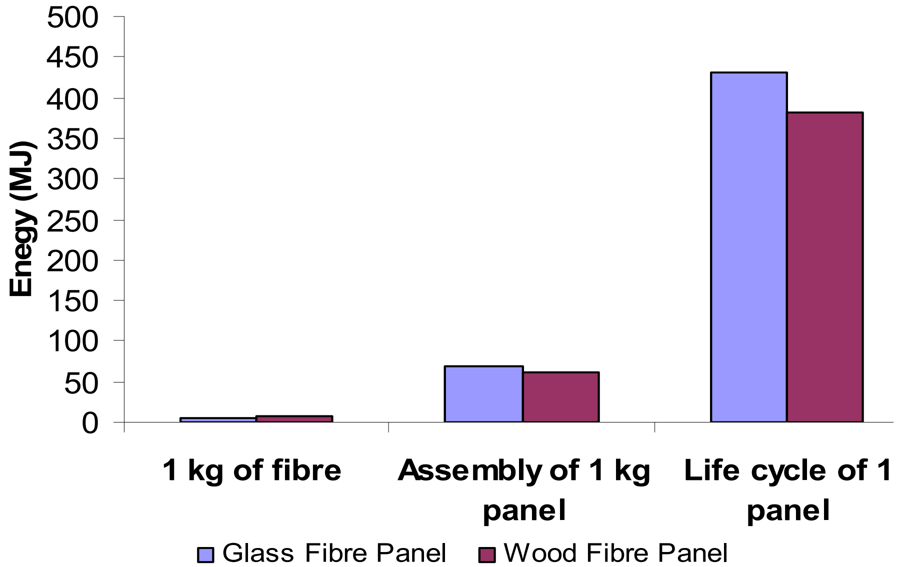

Figure 8.2 Cumulative energy use per panel at different life stages

8.4.2 Major greenhouse gases

Although CO_2 has the least global warming potential, it clearly surpasses others as the major greenhouse gas produced during the life cycles of the two panels (Table 8.3). As shown in Figure 8.3, replacing GFP with WFP leads to highest benefits in reducing N_2O (which has global warming potential of 296) emissions by 57%. There is a reduction in all greenhouse gases due to this replacement.

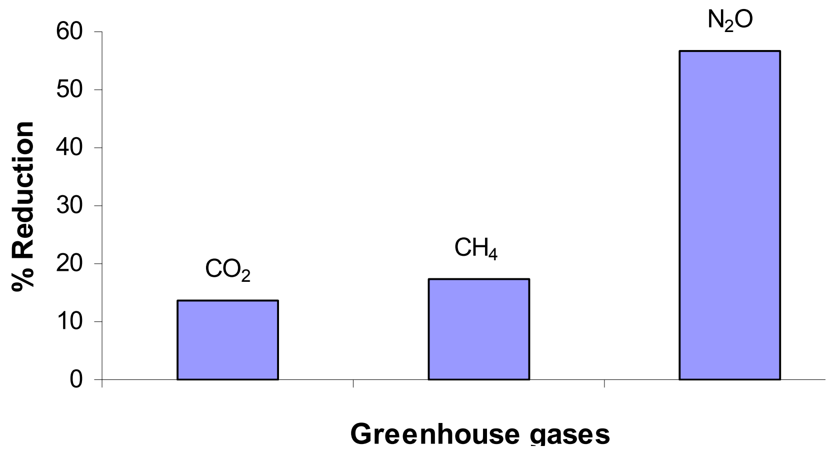

Figure 8.3 Reduction in greenhouse gases due to replacement of glass fibre by wood fibre

Table 8.3 Amounts of life cycle emissions of three major greenhouse gases per panel (Ramaswamy et al., 2001 and Harrison, 2001)

Substance	*Global warming potential*				*Atmospheric life time (years)*	*Life cycle of WFP*	*Life cycle of GFP*
	Time horizon (years)	*20*	*100*	*500*			
CO_2		1	1	1	50-200	24.9 kg	28.3 kg
CH_4		62	23	7	12-17	9.62 g	11.3 g
N_2O		275	296	156	120	1.82g	2.85g

8.4.3 Major air pollutants

Substances shown in Table 8.4 can be identified as major air pollutants (Harrison, 2001). These pollutants reduce as a result of replacement of GFP by WFP. This reduction ranges from 8.5 % for Cadmium, 100.4% for lead and 595.5% for ammonia (NH_3). The data analysis shows that it is the production of glass fibre that results in large amounts of NH_3.

Table 8.4 Amounts of life cycle emissions of major air pollutants per panel

Substance		*Amounts per Life Cycle*			*Description*	*Areas of negative environmental impact*
		WFP	*GFP*	*% saving due to replacement*		
Ammonia (NH_3)		3.11mg	21.6mg	594.53		Vegetation, acidification, eutrophication
Non Methane Volatile Organic Compounds (NMVOCs)		176g	200g	13.64	Compounds with high vapour pressure that makes them escape easily to the atmosphere	Human health, form photochemical oxidants, plants and human health
Nitrogen oxides (NO_x)		9.62g	11.5g	19.54		Human health, acidification, eutrophication
Sulphur oxides (SO_x)		47g	52.8g	12.34		Human health, corrosion, crops and forests
Carbon monoxide (CO)		509g	574g	12.77		Human health, modify climates,
Particulates		5.37g	6.55g	21.97	Liquid or solids particles suspended in air with diameter from 10nm to 100 µm	Affect health, crop quality, visibility
Heavy metals	Cadmium (Cd)	725µg	787µg	8.55	Atomic weights between 63.546 and 200.590 and specific gravities greater than 4.0.	Human health, vegetation, food chain
	Mercury (Hg)	102 µg	114 µg	11.76		
	Lead (Pb)	24.4 mg	48.9 mg	100.41		
	Zinc (Zn)	6.99 mg	7.91 mg	13.16		

8.5 Impact assessment

This section uses the EI99E/E impact assessment method to identify main impact categories and impact of different substances or processes in these categories. Characterization is a step that quantifies impact of substances on the environment in each impact category. Since characterization values are given in different units, this part presents normalized values to compare relative impact of different impact categories.

Normalization is done by calculating the contribution of each impact category to the overall environmental problem. Different impact assessment methods use different normalization criteria. Results using EI99E/E showed that categories described in Table 8.5 receive comparatively more significant impact as will be shown below.

Table 8.5 Main impact categories for the life cycles of the two panels (Goedkoop and Oele, 2004)

Category	*Definitions*	*Unit*
Fossil fuels	Surplus energy per extracted MJ fossil fuel as a result of lower quality resources,	MJ Surplus
Respiratory inorganics	Respiratory effects resulting from winter smog caused by emissions of dust, sulphur and nitrogen oxides and other gases to air	DALY /kg (where DALY is Disability Adjusted Life Years)
Climate change	Damage resulting from an increase in disease and death caused by climate change;	DALY/kg
Ecotoxicity	Damage to ecosystem quality, as a result of emission of ecotoxic substances to air, water and soil	PAF×m^2×yr/kg (where PAF is Potentially Affected Fraction)

DALY: disability adjusted life years.
PAF: potentially affected fraction.

8.5.1 Production of fibre

Production of wood fibre has less environmental impact in most of the impact categories except carcinogens (Figure 8.4). Wood fibre has more effects in the carcinogens category because wood fibre production emits more than 4 times nickel to air, and 3 times arsenic (carcinogens) to water than glass fibre production. Glass fibre production has twice the impact of wood fibre production in the fossil fuels category.

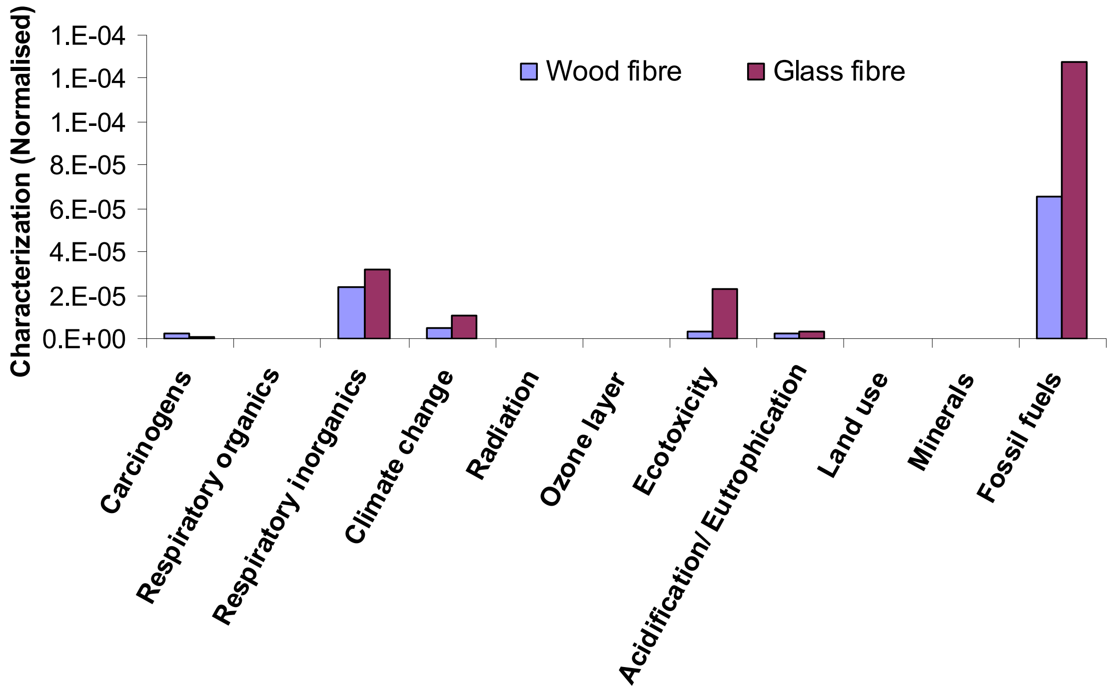

Figure 8.4 Comparison between production impact of 1kg of glass fibre and 1kg of wood fibre

It was shown in section 8.4.1 that the production of wood fibres consumes more energy than the production of glass fibre. Therefore production of wood fibres could be expected to have more impact on the fossil the fuel category than the production of glass fibres. However, from the BUWAL library, the use of energy includes energy from non-fossil sources such as hydro and nuclear power which are not part of the fossil fuel category (see Table 8.5).

Assembly of the panels

Assembly of the two panels involves fibre production, PP production and panel fabrication. In this stage, the two panels have little differences in their environmental impact although GFP still has more impact than WFP in most categories (Figure 8.5).

The highest impact lie in the fossil fuel category. While production of wood fibre had almost half of the impact of glass fibre production on this category (Figure 8.4), assembly of WFP has only 15% less impact compared to GFP production.

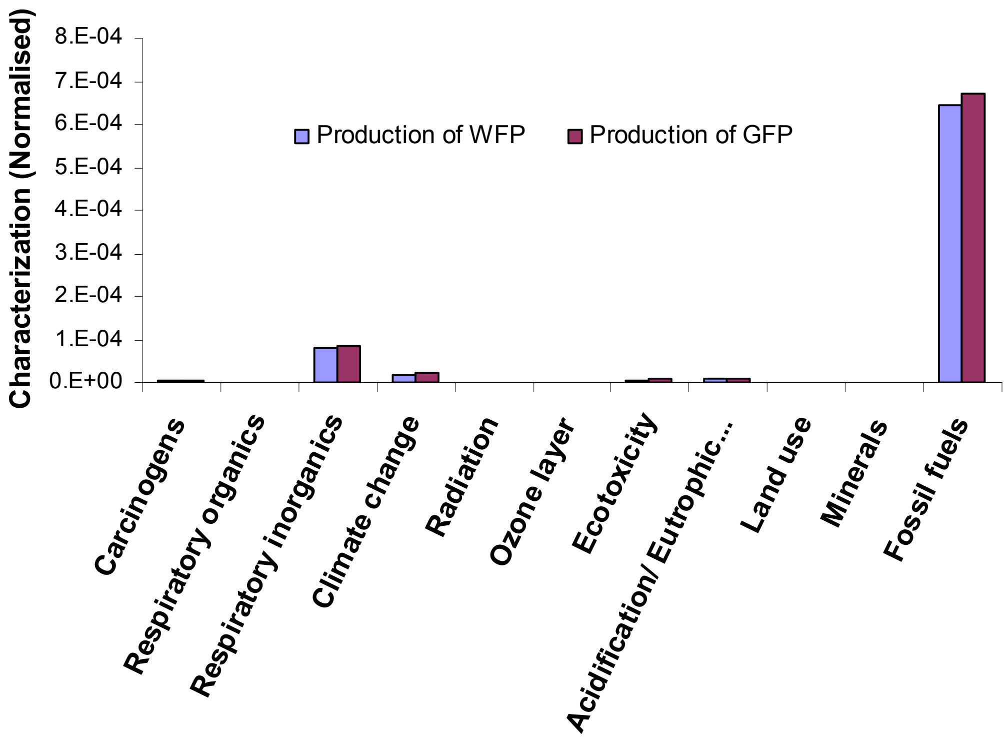

Figure 8.5 Comparison between assembly impact of WFP and GFP

8.5.2 End-of-life

At the end-of-life, the climate change category has the highest impact for both panels (Figure 8.6). This is due to emission of CO_2 and NH_4 in both incineration and landfill in both panels. In contrast, fossil fuel category gets the highest environmental benefits (Note: Just as positive characterization values indicate a degree of negative impact of a particular process on the environment, negative values indicate a degree of positive impact of a process on the environment, see section 8.6.1). This is partly due to incineration of both panels which releases heat that can be used to replace heat produced by burning fossil fuels within the system. There are more benefits in incineration of WFP than in incineration of GFP in this category. This is because in burning GFP, only PP releases energy whereas in burning WFP, both PP and wood fibre release energy.

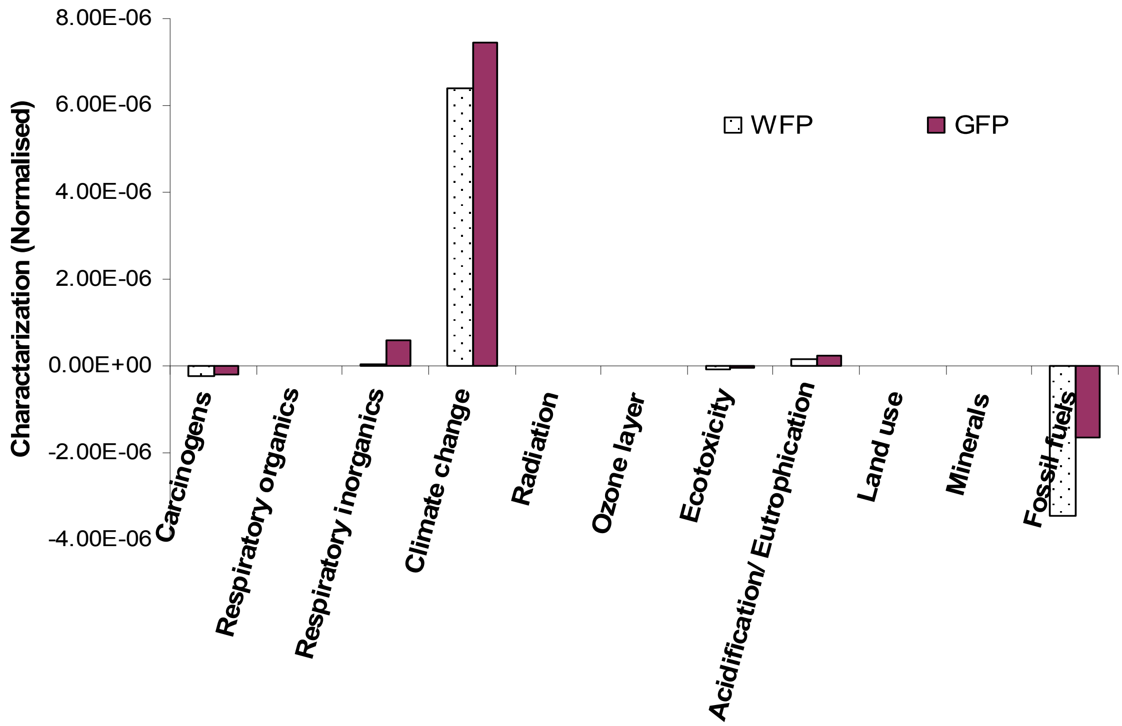

Figure 8.6 End-of-life impact of the two panels

8.5.3 Life cycle comparisons of the panels

This is the stage where we compare the impact of the whole life cycles of the two panels (assembly, use and end-of-life together). Fossils fuel category has the highest impact (Figure 8.7).In this category, WFP has 12% less impact than GFP. Except for fossil fuel category, there are little differences for in both panels for other categories.

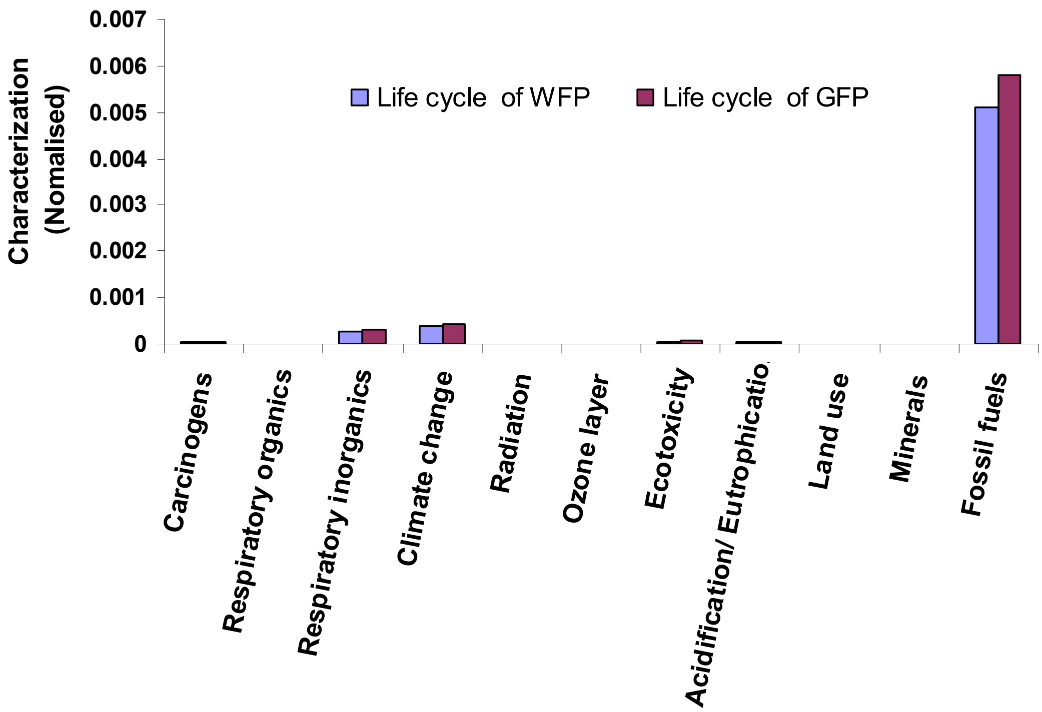

Figure 8.7 Comparisons of Life cycle (assembly, use and disposal) impact between the two panels

Figure 8.8 illustrates degree of impact of different life stages on the life cycle of WFP. The use stage which contributes 86% of the life cycle impact for WFP and 85 % for GFP uses petrol, a fossil fuel, as the car moves around. The assembly stage contributes 13.9% for WFP and 14.6% for GFP on the life cycle impact. Production of PP contributes 90% of assembly impact of WFP and 86% of assembly impact of GFP. At the end-of-life, end-of-life contributes 0.09% for WFP and 0.15% for GFP on their life cycle impact. Thus the end-of-life impact are insignificant compared to the other two life stages for both panels. The impact of natural fibres in reducing the use of PP per unit volume of composite (due to their low density) and fuel consumption of car during use is what makes them more attractive than glass fibres in this application.

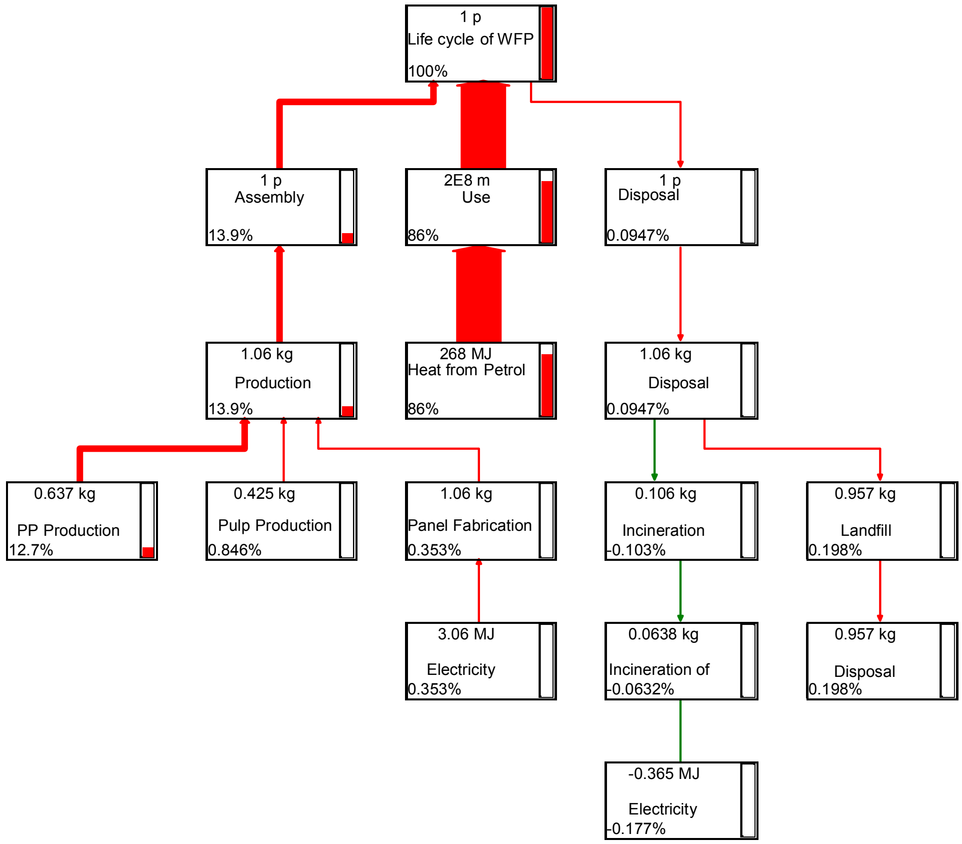

Figure 8.8 Percentage share of impact of different life stages in the life cycle of WFP according to Ecoindicator 99 method (p represents panel)

8.5.4 Contribution of major substances to impact categories

Fossil fuels

Crude oil has the highest contribution in this category, followed by natural gas (Figure 8.9). Coal has the lowest impact. This is true for both panels and all three fuel sources contribute more impact in GFP life cycle than in WFP life cycle.

Climate change

In this category, CO_2 has the most impact (Figure 8.10). This is despite the fact that it has the least global warming potential. CO_2 is emitted in greater amounts than any of the major greenhouse gases (Table 8.3). Methane is the next most contributing factor and N_2O is the least.

Ecotoxicity

For metal emissions to air, the most dominant element is the emission of nickel while cadmium has the least impact for both panels (Figure 8.11). Impact of GFP still dominates in all elements, especially lead.

Respiratory in-organics

Sulphur oxides emissions dominate this category followed by nitrogen oxides, particulates and carbon monoxide respectively (Figure 8.12). GFP slightly dominate impact for all emissions.

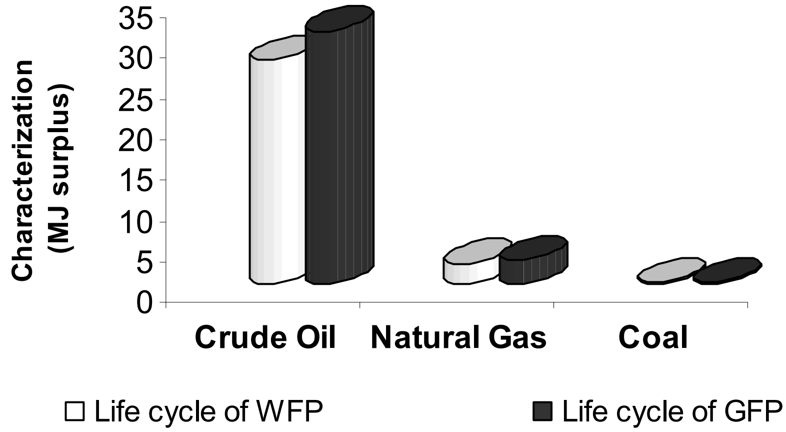

Figure 8.9 Contribution of fossil fuels to fossil fuel category

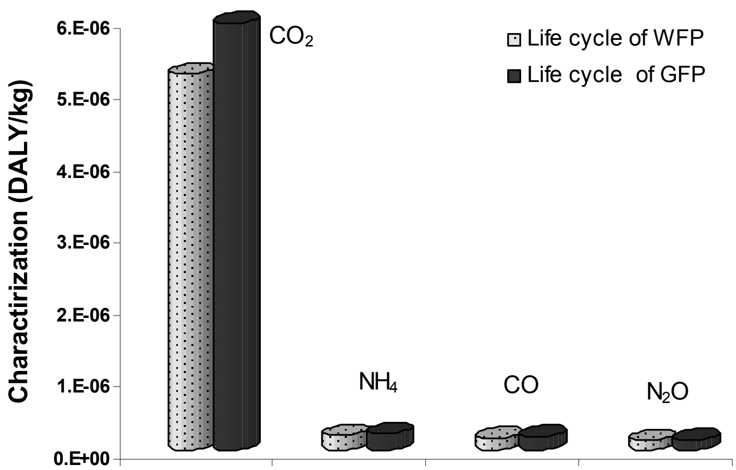

Figure 8.10 Impact of airborne emissions on climate change category

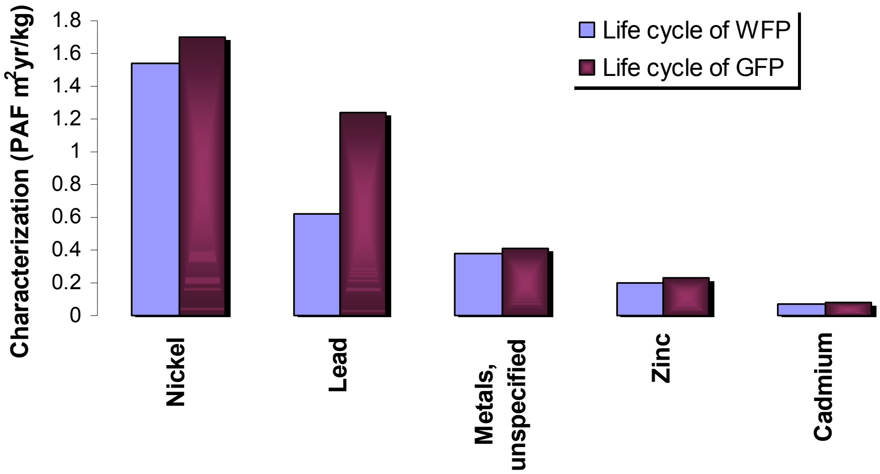

Figure 8.11 Impact of airborne metal emissions on ecotoxicity category

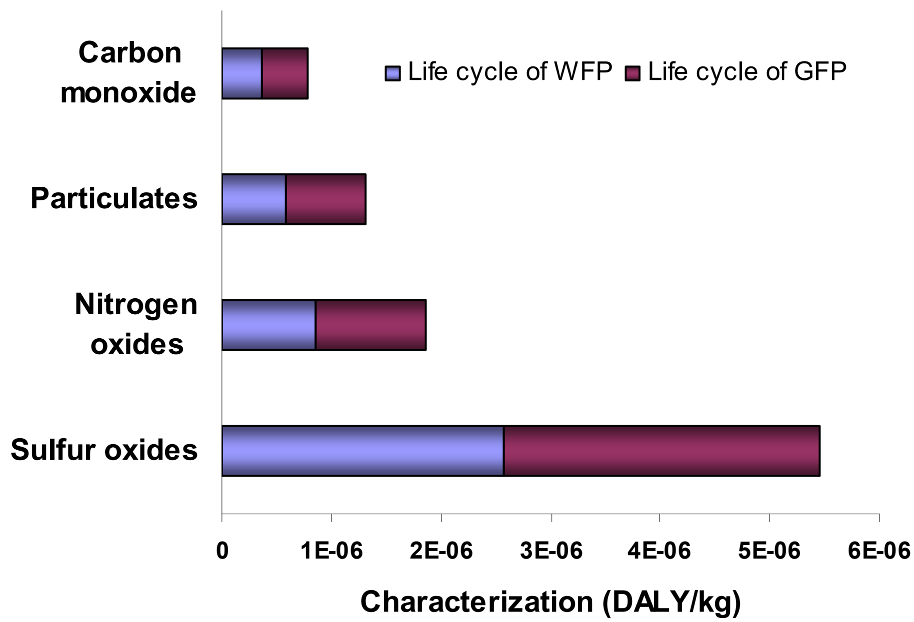

Figure 8.12 Impact of airborne emissions on respiratory inorganics category

8.6 Interpretation

8.6.1 Sensitivity analysis

Basic assumptions were made in section 8.3. These assumptions were referred to as the reference scenario. The purpose of sensitivity analysis is to check how LCA results change in response to changes in some of these assumptions. Figures 8.13 and 8.14 summarize environmental benefits or burdens that result from changes in the reference scenario. Negative percent values show the degree of environmental benefits obtained by deviating from this reference scenario. Likewise, positive percent values indicate degree of environmental burdens incurred due to these changes. Extreme cases (ultimate possible deviation from reference scenario) are considered in some cases.

Incineration and use of recycled materials

Wood fibre/plastic composites can range from the use of 100% virgin plastic and fibre to the use of 100% recycled plastic and fibre (Godavarti, 2005).Three categories: respiratory inorganics, fossil fuels and climate change benefit as a result of using 100% recycled PP for both panels (Figures 8.13 and 8.14). Most benefits are realized in the category of respiratory inorganics. However, use of recycled PP increases impact on ecotoxicity a little.

‘All recycled’ materials involves using 100% recycled PP and 100% recycled wood fibre or glass fibre as reinforcement. This scenario results in slight improvement compared to when only 100% recycled PP is used in all categories for WFP. There is a significant improvement in the category of ecotoxicity for GFP. In this panel, the improvement compared to when only recycled PP is used is 21% (Figure 8.14). Recycling reduces impact because some unit processes like raw material extraction and processing (e.g. polymerization) are cut.

For 100% incineration (incineration of the whole panel), there are little benefits for both panels in 3 categories. The fourth category, climate change, experiences more burdens due to this incineration. This is because of greenhouse gas emissions, especially CO_2 which results from burning of these products.

Replacing the matrix (PP)

Polyvinyl chloride (PVC) and polyethylene (PE) are other alternative plastics normally used in wood fibre composites (Godavarti, 2005).In using PVC, the only slight benefit is in the category of fossil fuels for both panels. Burdens increase by about 14% for both panels as a result of this replacement in the category of respiratory inorganics. The other categories experience little or no change at all. So in cases where fossil fuels are a category of more importance, replacement by PVC will be slightly beneficial. Any decisions on replacement in this case would depend on which category gets higher priority between the respiratory inorganics and fossil fuels categories. For both panels, substitution by PE makes very little difference in all categories.

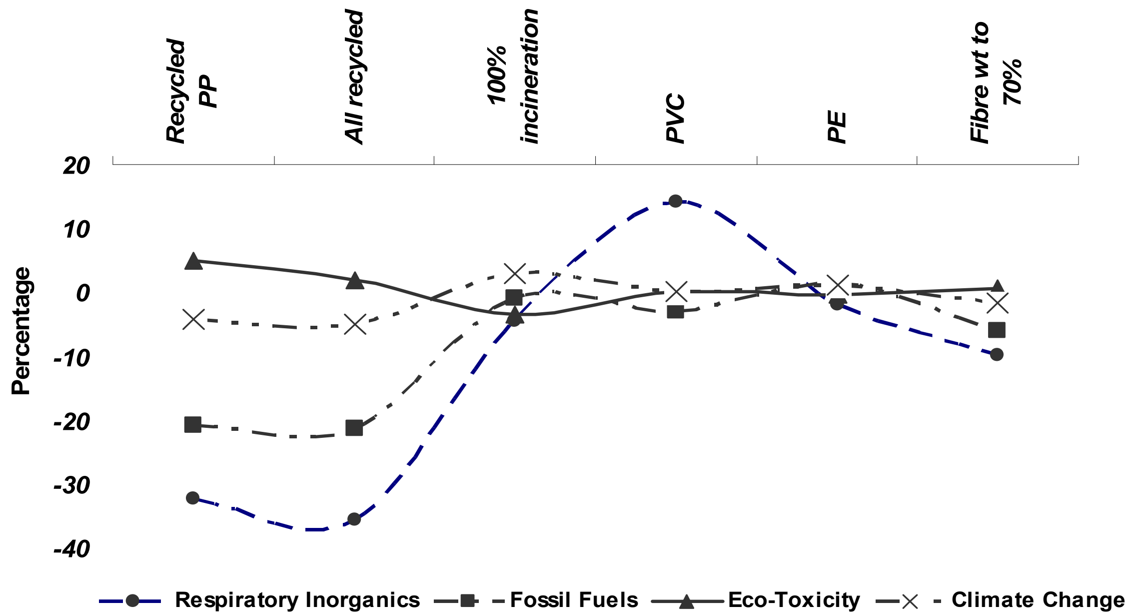

Figure 8.13 Percentage share of environmental benefits or burdens due to deviations from reference scenario in life cycle of WFP according to Ecoindicator 99 method

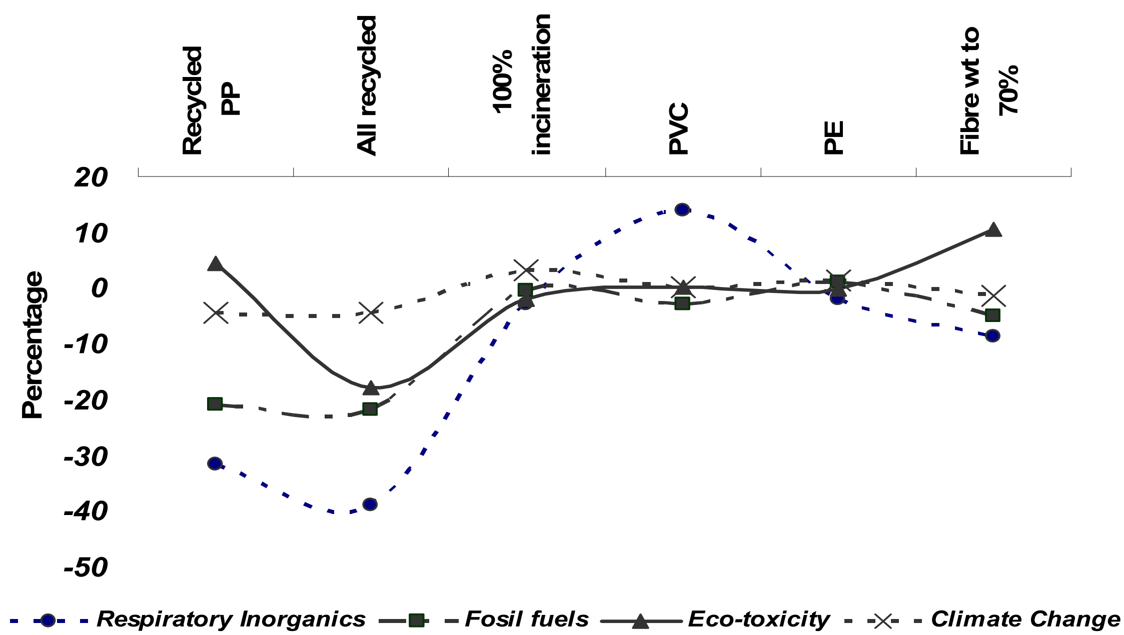

Figure 8.14 Percentage share of environmental benefits or burdens due to deviations from reference scenario in life cycle of GFP according to Ecoindicator 99 metho

Fibre weight fraction impact on distributions of main life stages

Most wood plastic composites in car applications can use up to 70% by weight of fibre (Suddell and Evans, 2005). Increasing fibre weight fraction to 70% benefits all the categories except ecotoxicity. This shows slight increase in burdens (0.7%) for WFP and higher increase in burdens (11%) for GFP. The most benefited category is respiratory inorganics which has impact decreased by 9.8% for WFP and 8.75% for GFP.

Typical changes in life cycle impact distribution of three main life stages (assembly, use and end-of-life) due to changes in glass fibre weight fraction are shown in Figure 8.15. Similar changes occur in WFP due to changes in wood fibre weight fraction. These changes in impact distribution are a result of reduced impact that happens when PP is substituted by fibre. PP production was identified as the main polluter in assembly stage (Figure 8.8). Therefore, reduction in PP weight in the composite leads to less and less impact contribution of assembly stage.

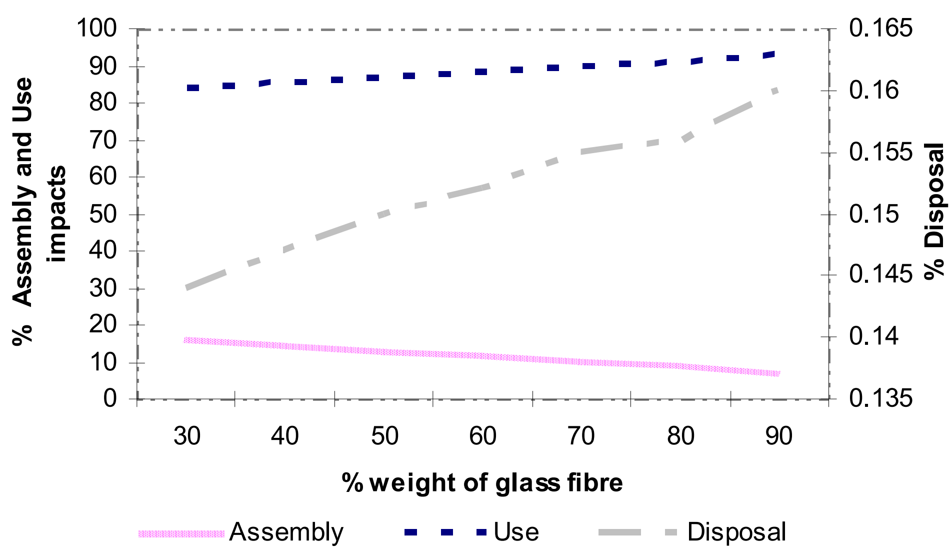

Figure 8.15 Impact of weight variation on the contribution of 3 life stages to life cycle impact of GFP

Influence of different impact assessment methods

The three methods below show that for all categories, life cycle impact of GFP is greater than life cycle impact of WFP (Figures 8.16, 8.17 and 8.18).

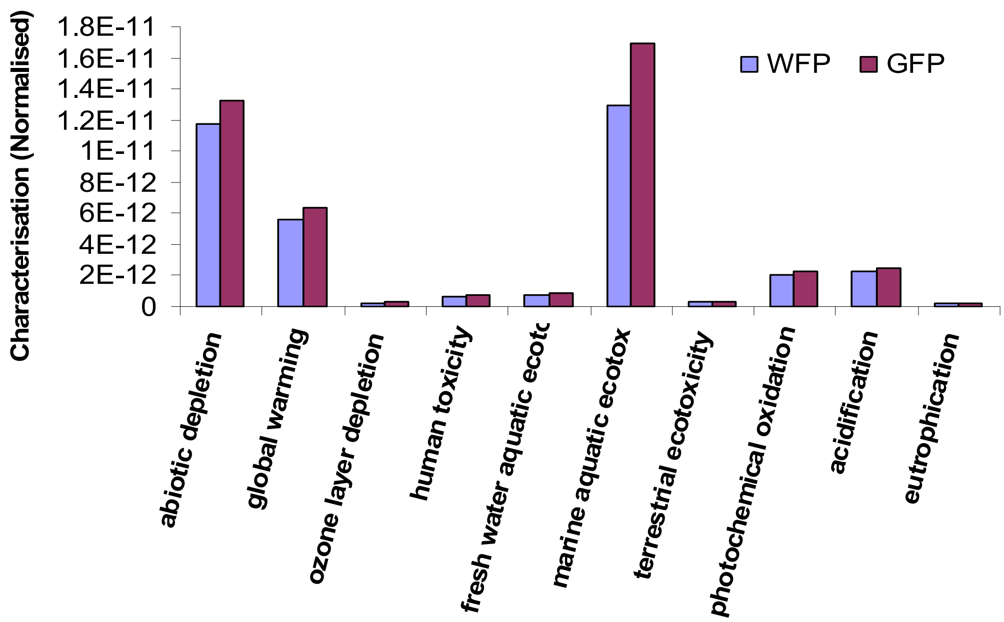

Figure 8.16 CML baseline 2000 method

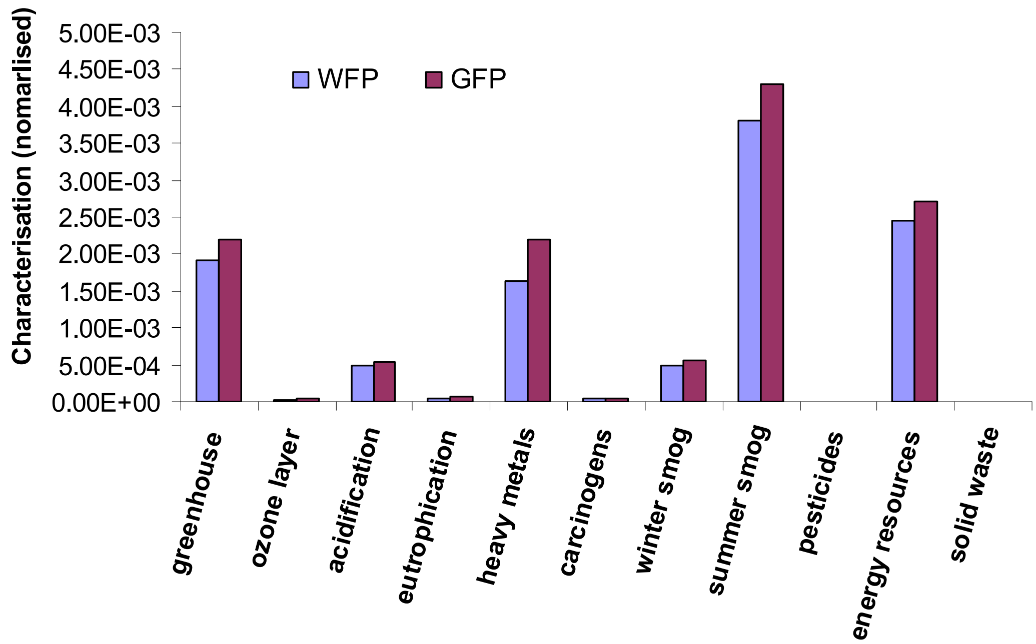

Figure 8.17 Ecoindicator 95 method

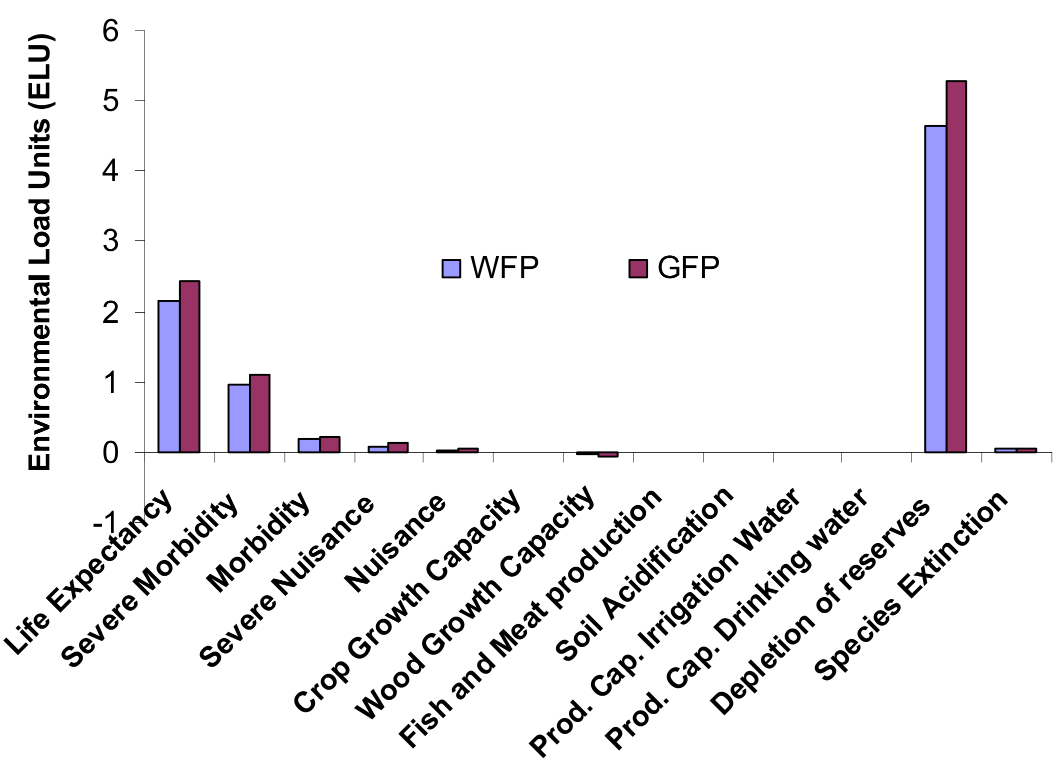

Figure 8.18 EPS 2000 method

8.7 Discussion

Although the scenarios above are based on wood fibre, the results can be extended to other natural fibres. This is because natural fibres have some specific environmentally friendly attributes detailed in section 8.1 the most important of which is their lightweight especially in automotive industry. However as discussed in the same section, the results of LCAs are never certain due to the inevitable complexity of the “environment.” So the conclusion as to whether natural fibres are better environmentally than glass fibres for use in composites may not be viewed in light of a single study but a series of studies like this one which use different sources of data.

8.8 European Union Directive and the end-of-life vehicles

While is progress is being made to find more environmentally friendly alternatives such as NFCs over glass fibre composites as this LCA shows, there are concerns that some well intentioned legislations may actually hinder these developments. As an example, since this LCA is based on Europe, it is important to analyze the recent European Union (EU) environmental legislation on end-of-life-vehicles (ELVs) and its possible impact on automotive life cycles.

By the year 2000, the fifth EU Environmental Programme issued an environmental directive for the ELVs. The purpose of this mandatory directive was to better manage ELVs waste and improve their environmental impact (Marsh, 2005). To meet the directive targets, 95% and 85% by weight of vehicles should be recoverable/reusable and recyclable respectively by the year 2015 (Smink, 2007 and Markarian, 2007). Interestingly, the current ELV recycling rate is already high. It is estimated that 70-80% of the ELVs are recycled in the EU jurisdiction (Gerrard and Kandlikar, 2007). While most of the recycled material is ferrous metal, the remaining 20-25% consists of mainly plastics and their composites which are hard to recycle. So the EU directive is more likely to have a direct impact on the use of these materials.

Plastics and their composites have continued to replace metals in automotive applications due to their desirable properties such as light weight and flexibility in processing (Deanin and Srinivasan, 1998). However, despite breakthroughs in recycling technologies for plastics and plastic composites, these materials are yet to be fully recycled. There are several obstacles to overcome. For ELV plastics and composites, the difficult task is getting all stakeholders involved to work together to ensure a smooth and stable flow of materials (Marsh, 2005 and Ferrão and Amaral, 2006). Also, recycling may be difficult because of plastic physical problems like aging and contamination and complications due to presence of undocumented fibres and plastics (Deanin and Srinivasan, 1998)

Nevertheless, the industry is already making a progress to meet the targets set by the directive. Gerrard and Kandlikar (2007) observed that the players in the automotive industries have begun taking concrete steps to recycle and disassemble the vehicles. They noticed increased innovations in methods of recycling and separation of residues. Automotive companies like Ford in the UK already have large recycling facilities for ELVs and there is a progress towards recycling of fibre reinforced plastics (Marsh, 2005). However, Gerrard and Kandlikar (2007) also noticed a slow progress towards designing for reuse and remanufacturing in this industry. This is possibly due to high cost of labour and a need for significant organizational changes necessary to achieve these.

On the other hand, some authors argue that the directive puts so much emphasis on meeting recycling targets that automotive manufacturers may miss other greener alternatives. This is especially important in cases where using these alternatives would be cheaper and perhaps environmentally better (Handley et al., 2002). For instance, it is reported that DaimlerChysler is already making 140 auto parts containing natural fibres (Gerrard and Kandlikar, 2007). Given the pressure to recycle, companies could opt for use of more metals which are easy to recycle but lead to high fuel consumption. Therefore the benefits of using NFCs and bioplastics in automotives could be forfeited since these materials are presently hard to recycle (Markarian, 2007 and Gerrard and Kandlikar, 2007). This could reverse the progress made in their use.

8.9 Conclusions

We have shown that by using a life cycle assessment that replacement of glass fibre by wood fibre in PP composites used as car door panels reduces the environmental impact of these panels. Air pollution, especially emission of greenhouse gases is an important environmental topic due the suspected impact of these gases on global warming. Replacing GFP with WFP can reduce major greenhouse gases significantly.

Life cycles of the two panels mainly have impact on fossil fuels, ecotoxicity, climate change and respiratory inorganics categories according to EI99E/E method. They have most impact on fossil fuels. This is because, the use stage, which dominates the impact of life cycles by 86% and 85% for WFP and GFP respectively depends heavily on fossil fuels (petrol). Production of both glass fibre and mechanical pulp; and PP are also highly energy intensive and use much fuels. PP production dominates the impact in the assembly stage for both panels.

Replacing PP with PVC slightly benefits the category of fossil fuels which is the major impact category although it increases impact on respiratory inorganics significantly. Any replacement in this case would depend on which category gets higher priority between the two. Replacement by PE results in almost no changes in environmental impact. However, use of recycled PP and recycled fibre results in generally high improvements in the main categories. Some benefits are realized by increasing fibre weight fraction from 40% to 70% for both panels in the main categories. But, this increase brings more burdens in GFP in the category of ecotoxicity.

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Chapter 9: General discussion

This study takes a more comprehensive approach to the investigation and development of NFCs. The approach includes several factors; materials availability, environmental and social implications of developing NFCs and optimization of mechanical properties of NFCs for applications in Canada and Lesotho based mainly on waste materials. Abundant sources of waste natural fibres and recyclable waste plastic exist both in Canada and Lesotho that could be used in NFCs. Some of these sources such as flax straw and hemp in Ontario, Canada and *Agave americana* in Lesotho, have been used successfully in the past for various traditional applications and will surely be cultivated more should new uses like natural fibre composites be developed. Other sources such as wheat and corn straw whose grains have been used for food from time immemorial are already abundant in these regions at present. They just need to have their potential demonstrated through studies like this one for the better use of their straw.

By exploring the most simple production and treatment methods it was discovered that mercerization of fibres not only improves interfacial properties of *Agave americana* HDPE composites, it also improves tensile properties of these fibres. Further, it is critical to understand the fibre structure/property relations in order to develop a full picture of the way in which the natural fibres reinforce the composite material. In a close study of *Agave americana*, it was found that the relatively large breaking tensile strains can be modeled by associating them with the zigzag structure of their single fibres and the single fibre angles. These findings imply that unlike other natural fibres, *Agave americana* fibres may not break as much during composite mixing with extruders and high shear mixers. This property could conserve fibre and hence composite properties.

New low cost processing methods and materials that may be applied in building and furniture industries have been developed. Development of composites from the selected underutilized fibres, corn, seed flax and wheat, can be optimized by making material selection, processing and testing choices based on the availability, costs and possible environmental impact of the composites.

From the study of the composites of these fibres, we learned that: there is not difference in flexural properties of corn stalk composites if the whole stalk versus the outer shell only were used as reinforcement, seed flax fibres give better flexural strengths if water retted for a period of 6-8 days, and the nature and processing of wheat straw result in plate-shaped straw particles that are predominantly arranged in all directions in plane in a composite and this has positive influence especially on tensile and flexural moduli of the composites.

Lastly, life cycle assessment is a process which is necessary if claims of 'environmentally friendly NFCs' are to be justified. In this work LCA of the NFCs were compared with glass fibre composites to show why and in which areas natural fibres perform better than synthetic fibres in composites. NFCs based on wood fibre performed better environmentally.

Summary, conclusions and future work

The objectives and specific questions asked in this research were detailed in Table 1.1. In this section, we conclude by summarizing the answers and conclusions made as in the table below.

Summary of the investigations

Objectives and rationale		*Conclusions*
Objective 1	To determine the availability of raw materials and other resources and feasibility of composite industry in Ontario, Canada and Lesotho.	1. In Ontario, Canada, hemp and flax straws have great potential as fibre but are not yet widely grown. Corn and wheat are widely grown although their straws have no industrial value at present. In Lesotho, important fibre sources are *Agave americana* and corn straw. 2. The situation in Lesotho took more than just a materialistic approach and incorporated views from the society that were deemed necessary for any future NFCs project. (see chapters 2 and 3)
Rationale	To guide the choice of materials and methods to be used for making composites in this study based on the situation in each country.	
Objective 2	To investigate the interfacial, tensile and microstructural, properties of the fibres and how these may affect the composites properties.	1. Mercerization doubles the interfacial strength values between *Agave americana* fibres extracted by traditional boiling of leaves and waste HDPE. Mercerization also improves fibre tensile and thermal properties.
Rationale	Interfacial and microstructural properties of *Agave americana* fibres, as a new fibre in NFCs, are still largely unknown. Knowledge of these properties is critical for understanding how the fibres will behave in composites.	2. The high breaking strains of *Agave americana* fibres can be understood by modelling the geometry of their single fibres which show a zigzag structure at rest, making it easier for them to straighten before deformation. This could improve the fibre's resistance to break. (see chapters 4 and 5)
Objective 3	To optimize and characterize the mechanical properties of the NFCs by a careful selection of raw materials and manipulation of processing methods and fibre treatments.	1. The procedure followed for fibre retting for flax, milling for corn and processing method for *agave americana* plastic composites have significant influence on the final composite flexural properties.
Rationale	The kind of processing and fibre treatment affects the final composite properties. The aim is to find processing and treatment methods that optimize properties without	2. The wheat LLDPE composite properties were influenced mainly by

	sacrificing environmental and low cost benefits of these composites. Fibre treatment methods such as retting and milling the fibre are selected since they are cheap.	shape, orientation and arrangement of particles. (see chapters 6 and 7)
Objective 4	To investigate the environmental properties of the NFCs, especially as compared to conventional composites.	1. Wood fibre reinforced PP car door panels have generally better environmental properties than similar glass fibre panels. 2. Both panels have most of their impact during the use stage of the car This is the main reason why light-weight natural fibres perform better environmentally; they reduce car fuel consumption throughout the cars' life times. (see chapter 8)
Rationale	It is important to test the claims that NFCs are environmentally superior to conventional composites at a variety of circumstances.	

Future work

1. Chapter 3: There is need for a proper estimation of the amount of waste plastic existing in Lesotho, not only in Maseru and Maputsoe but also in more than ten other towns and thousands of villages all over the country. This will provide a clearer picture of how much of this resource can be harnessed to make particular products that benefit the local people.
2. Chapter 3: A more detailed analysis of costs of producing the composites, their possible markets and use of resources such as electricity needed for the production is needed to give an idea of the potential of NFCs in Lesotho.
3. Chapter 4: Tensile properties of *Agave americana* fibres and their interface with HDPE need to be analysed with more samples per variable in order to increase the reliability of the results.
4. Chapter 5: The tendency of the *Agave americana* fibres to exhibit high breaking strains has important implications concerning the toughness of these fibres and their composites. The ability of these fibres to resist break during processing

(extrusion) and to absorb energy in composites needs to be evaluated in comparison with other stiffer fibres.

5. Chapter 6: It is important to analyse the influence of the degree of retting of other forms of flax fibres or other types of fibres on the flexural properties of the composites to confirm the influence of the number of days necessary for retting. This has important implications for the farmers, since it can save them retting time and costs, and the composite manufacturers, as the expected maximum strength of the fibres can be related to the duration of retting.
6. Chapter 7: The predominantly random in-plane arrangement of wheat particles is assumed to be responsible for the high improvements in tensile and flexural moduli of the composites upon the addition of wheat. Any process that can further maximise this arrangement is likely to improve the moduli even further.
7. Chapter 8: The Life Cycle Assessment was done using wood fibres rather than the fibres analysed in this study. Since it is preferable to use more renewable non-wood natural fibres such as flax, it is necessary to carry out a similar study using one of these more renewable fibres, perhaps in comparison to wood fibre itself.

List of Appendices

Appendix 1 Questionnaire of interviews made with representatives of relevant Canadian institutions

Production of fibres/waste plastics

1. How much fibres/agricultural waste plastics have been produced in Ontario for each of the years 2000 to 2004?
2. How much fibres/ agricultural waste plastics produced in Ontario has been sold for each of the years 2000 to 2004?

Names and locations of growers, processors and distributors of fibres/waste plastics

1. Who are the growers, processors and distributors of fibres/ agricultural waste plastics

Uses and costs of fibres/waste plastics

2. What percentage of Ontario's fibres/ agricultural waste plastics is used for composites, textile, and paper?
3. What is the cost of Ontario's fibres/ agricultural waste plastics per unit per application in the year 2005?

Handling methods of fibres/waste plastics:

1. What are usual methods used in the harvesting, storage and decortication of fibres in Ontario?
2. At what time of the year and how long does each of these harvesting, storage and decortication methods occur?

Handling of agricultural thermoplastic wastes

1. What are usual methods, used in the collection, cleaning, storage and transportation of agricultural waste plastic in Ontario?

Appendix 2 Individuals and organizations contacted

Date of contact	*Fibre/plastic*	*Position of the interviewee*	*Contact form*	*Response*
24/03/2005	All	Farmer	Meeting	Information given
28/03/2005	Hemp	Organization	Email	Email automatically rejected
	Flax	Flax researcher (KCAT)	Email	No response
		Coordinator (FCC)	Email	Information given
	Corn straw	Production Issues Manager (OCPA)	Email	Information given
	Wheat straw	Manager of research and innovation (OWPMB)	Email	Information given
	Agricultural waste plastic	Engineering specialist, (OMAF)	Email	Information given
		Strategic planning and	Email	No response

		business (OMAF)		
		Nutrition-horticulture program leader (OMAF)	Email	No response
		Contact member (OSCIA)	Email	No response
		senior materials specialist(MOE)	Email	Email automatically rejected
29/03/2005	Flax and Hemp	Contact person (S C)	Email	Directed to sources of Information
	Agricultural waste plastic	Contact person (IFAO)	Email	No response
		Contact person (OSCIA)	Email	No response
	Wheat straw	Contact person (IFAO)	Email	Directed to other resources
		Contact person (OWPMB)	Email	Information given
		Contact person (OWPMB)	Email	No response
		Contact person (OWPMB)	Email	No response
	Corn straw	Contact person (OCPA)	Email	Information given
		Contact person (OSCIA)	Email	No response
		Contact person (SCGO)	Email	No response
30/03/2005	Flax and Hemp	Statistician (OMAF)	Email	Directed to sources of information
31/03/2005	Wheat straw	Cereal specialist (OMAF)	Email	Information given
	Agricultural waste plastic	Organization	Email	No response
03/04/2005	Agricultural waste plastic	Organization	Email	No response
		Executive assistant (EPIC)	Email	No response
		Organization	Email	Directed to sources of information
		Organization	Email	Email automatically rejected
		Contact person (OWE)	Email	No response
13/04/2005	Hemp	President (OHA)	Email	Information given
	Flax	President (FCC)	Email	No response
	Wheat straw	Cereal crop specialist (OMAF)	Email	Information given
	Corn straw	Corn specialist (OMAF)	Email	No response
		Contact person (OCPA)	Email	No response
	Plastic	Research coordinator (OCA)	Email	No response
		Contact person (OSCIA)	Email	No response
14/04/2004	Hemp	President (Hempline)	Email	Information given

22/04/2004	Hemp& flax	Acting chief, crops cection (SC)	Email	Information given
		Head, user services (SC)	Email	Information given
		Contact person (SC)	Email	No response
		Contact person (SC)	Email	No response
25/04/2004	Hemp	Oilseed analyst (AAFC)	Email	Information given
		Markets information officer (AAFC)	Email	Directed to sources of information
		(AAFC)	Email	No response
		Contact person (NH)	Email	Directed to sources of information
		Senior market development advisor	Email	Directed to sources of information
27/04/2004	Flax	Contact person	Email	Information given

1. AAFC: Agriculture and Agri-food Canada
2. CARI :Canadian Association Of Recycling Industries
3. EPIC : Environment and Plastic information Council
4. FCC: Flax Council of Canada
5. IFAO: Innovative Farmers of Ontario
6. KCAT: Kemptville College of Agricultural Technology
7. MOE : Ontario Ministry of the environment UG: University of Guelph
8. NH: Natural Hemphasis
9. OCA: Ontario Cattlemen Association
10. OCPA: Ontario Corn Producers' Association
11. OHA : Ontario Hemp Alliance
12. OMAF: Ontario Ministry of Agriculture and Food
13. OSCIA: Ontario Soil and Crop Improvement Association
14. OWE: Ontario Waste Exchange
15. OWPMB: Ontario Wheat Producers' Marketing Board
16. RCO : Recycling Council Of Ontario
17. SC: Statistics Canada
18. SCGO: Seed Corn Growers of Ontario

Appendix 3 Ontario hemp companies

Name	*Telephone*	*Website/email*	*Comments*
Hempline Inc.	(519) 652-0440	http://www.Hempline.com/	Producer and processor of hemp fibre for textiles ,animal bedding, automotive industry etc
Hempola Valley Farms	705-730-0405	http://www.hempola.com/	A variety of hemp products such as soaps, salad dressings, paper and clothing
The Natural Order	(416) 588-4209	http://www.thenaturalorder.com/	Design and manufacture of knitted jersey fabrics from hemp
Ecohemp Inc.		tvatcher@ecohemp.net	
Hemp Agro, Inc.	+(604) 683-5888	http://www.hempagro.com	
Kawartha Hemp Co.		sunshne@auracom.com	
John Baker/ Stonehedge Phytochemical Cosulting Ltd.	613-966-0569	John.Baker6@sympatico.ca	Breeding/selection project
Purity Hemp	1(888) 547-8112	http://purityhemp.com/oil.htm	Develop and market hemp food products and oil
Indusrial hemp seed development corp			Out of business
Kenex Ltd.		http://www.kenex.com/english/Default.htm	Out of business

Appendix 4 Canadian growers, processors and distributors of flax fibre and flaxseed

Name	*Telephone*	*Website/email*	*province*	*Comments*
Fibrex Quebec	450-371-0333		Québec	Growers and Processors of textile flax and hemp fibre
Durafibe Inc.	1 204 947 6196	www.agfibre.com	Manitoba	Process of flax fibre
Argosy International Inc.	(1) 416 242-8855	argosy@idirect.com	Ontario	Flaxseed supplier
Bi-pro Marketing Ltd.	(1) 204 433-7056	www.bi-pro.com	Ontario	Flaxseed supplier
Port Royal Mills	(1) 905 713-1712	portroyal@primus.ca	Ontario	Flaxseed supplier

Appendix 5 Markets for Ontario agricultural plastic waste

Name	*Telephone*	*Website/email*	*comments*
Canadian Polystyrene Recycling Association	905/612-8290	http://www.cpra-canada.com	Agricultural polystyrenes are processed with non-agricultural polystyrenes (such as fast food containers and industrial scrap) at the CPRA recycling plant
Polychem Products, Ltd.	514/348-7392	http://www.polychemproducts.com/	Silage Bags, Mulch Films
Crop Protection Institute (now crop life Canada)	416/622-9771	http://www.cropro.org/english/index.cfm	Collects empty pesticide containers from the environment through an empty container recycling management program
Everwood Agricultural Products International Inc.	909.390.7799	http://www.poly-pacific.com	Everwood is able to take the waste from their customers and turn it into plastic lumber for the agricultural industry

Appendix 6 Responses of householders and percentages according to their answers concerning their present housing and roofing situation

Question	*Answer*	*%*	*Question*	*Answer*	*%*	*Question*	*Answer*	*%*
What are the reasons for preferring a particular kind of roofing?	Cheap	8	What are possible uses of the composites?	Roofs	13	Source of thatch?	Bought	40
	Wind resistant	14		Ceiling	16		Free	60
	No water dipping	7		Floor tiles	30	Preference of roofing type?	Thatch	32
	Needs no expertise	8		Wall tiles	8		Tiles	45
	Durable	15		Furniture	13		Iron	22
	Insulating	18		Face board	5	Are householders satisfied with temperatures levels in their houses?	Yes	15
	Good appearance	20		Other	14		No	85
	Good for cooking	4	What roofing is used in each of the buildings householders have?	Tiles	10	What are the reasons for not being satisfied with temperatures levels in the house?	Summer fine, winter too cold	39
	Noise resistant	5		Corrugated iron	67		Winter fine, Summer too hot	5
	Fire proof	2		Thatch	22		Summer too hot, winter too cold	57
Does roofing affect in-house temperature?	Yes	93	How do householders view the cost of iron roofs?	Cheap	16			
	NO	7		Moderate	29			
				Expensive	56			

Appendix 7 Responses of farmers and percentages according to their answers concerning their present farming situation and views on future opportunities

Question	*Answer*	*%*	*Question*	*Answer*	*%*	*Question*	*Answer*	*%*
What crops do farmers grow?	Maize	39	What is farming done for?	Subsistence	67	What is the straw presently used for?	Animals	88
	Sorghum	28		Cash	7		Back to soil	5
	Wheat	3		Both	26		Burn it	7
	Legumes	24						
	Vegetables	7						
Would famers sell their straw?	Yes	76	Why would some not sell their straw?	Animals	82	Are farmers Aware of alternative uses for straw?	Yes	51
	No	24		Other	18		No	49
What alternative uses of straw are farmers aware of?	Heating	31	Are they willing to grow agave for commercial purposes?	Yes	90			
	Animal food	25		NO	10			
	Manure	39						
	Handicrafts	6						

Appendix 8 Personal interviews made during the first data collection tip to Lesotho

Information needed	*Institution/business*	*Position of the interviewees*
Present sources of natural fibres	Ministry of Agric: Crops section	Contact person
	Ministry of Agric: crops section	Chief crop inspector
	Cooperatives college	Lecturer
	Mahloenyeng trading	Contact person
Information about local weaving	Meliehe weavers	Contact person
	Matela weavers	Contact person
	Seithati weavers	Contact person
	Thabong weavers	Contact person
	Itjareng vocational training centre	Contact person
Information about plastic and plastic waste	MU plastics	Managing director
	T'sosane plastic waste scavengers	Representative
	MOS plastic manufacturers	Contact person
	Pioneer plastics	Contact person
		Managing director
	Appropriate technology services	Chief engineer
	National environmental secretariat	Contact person
	Masianokeng environmental centre	Contact person

Appendix 9 Questionnaire of interviews made with famers, householders and cooperatives in Lesotho

TO FARMERS

Name and Location of the farm………………………………………………………

1. What crops do you normally grow?

I grow (i)………………….. (ii)……………………. (iii)…………………. (iv)………………… (v)………………..

2. On average, how much yield do you produce for each crop a year?

3. Do you do subsistence farming, cash farming or both?

Cash only	Subsistence only	Both

4. What do you do with your crop straw or straw?

Give it to animals	Burn it	Take it back to the soil	Other (Explain)……………… ……………………………..

5. Would you sell your straw/straw if opportunity arises?

Yes	No	Why …………………………………………….

6. If you were to sell your straw/straw, what factors would you consider before putting a price?

I would consider (i)……………………………. (ii)…………………………. (iii)…………………. …. (iv)……………………….. (v)………………..

7. Are you aware of any other alternative uses for this straw/straw? If yes, what are they?

No	
Yes they are	(i)………………………………. .(ii)……………………….. (iii)……………………………… (iv)………………………..

8. Do you think Agave americana is something you can cultivate for commercial purposes?

TO HOUSEHOLDERS

Name and location of the village…………………………………………………………...

1. How many houses do you have?

2. How many people live in your house?

3. What kind of roofing do your houses have: tiles, corrugated iron, thatch or other? Explain "other".

Tiles	Corrugated iron	Thatch	Other

			…………………..

4. If you used a Thatch for roofing, did you buy it or did you get it from public areas for free?

I bought it	I got it for free

5. If you had enough money, what roofing would you choose and why?

I would choose ………………………roofing	Why ……………………………………………….

6. When you look at this sample, what products do you think it can be used for?

I can be used for (i)………………….. (ii)………………….. (iii)…………………. (iv)………………… (v)………………..

7. Giving priority, which of those products do you think most people in your neighborhood really need?

Product	priority
	1
	2
	3
	4
	5

8. Are you satisfied with the temperature levels in your house in both summer and winter? Why?

YES/NO	Why………………………………………………………………..

9. Do you think roofing has anything to do with your house temperatures? Why?

YES/NO	Why………………………………………………………………..

10. Do you consider the corrugated iron roofing as "cheap, moderate or expensive"?

Cheap	Moderate	Expensive

TO SPOKE-PERSONS OF AGAVE AMERICANA COOPEATIVES

Name and location of the group……………………………………………………………

Source of *Agave americana*

1. Do you grow your own *Agave americana* or do you harvest the existing one from public areas. If you harvest the existing one, do you do anything to ensure its sustainability? Explain

I grow my own	I get it from public areas. To ensure sustainability, I ………………………………………………………………… ………………………………………………………………..

2. From your sources *of Agave americana*, do you think there is enough Agave americana for products you want to make?

Yes	No

3. Do you have to get legal permission to grow or extract *Agave americana* leaves? If so how do you get permission?

No	
Yes	I get the permission by …………………………………………………………..

Processing

4. How do you cut the leaves from the whole plant?

…………………………………………………………………………………………

5. How do you open the leaves to get the product you want out of them?

………………………………………………………………………………………… ………………………………………………………………………………………… …………………………………………………………………………………………

6. What do you do with the *Agave americana* fibre after getting the product you were looking for?

…………………………………………………………………………………………

Products

7. What products are you making out of *Agave americana* leaves?

We make (i)………………….. (ii)……………………………. (iii)…………………. (iv)………………… (v)………………..

8. What products do you still hope to make out of *Agave americana* leaves?

We want to make (i)………………….. (ii)………………….. (iii)…………………. (iv)………………… (v)………………..

Challenges

9. What are some of the problems you get in working with *Agave americana* plants?

………………………………………………………………………………………… ………………………………………………………………………………………… ………………………………………………………………………………………… …………………………………………………………………………………………

TO MEMBERS OF AGAVE AMERICANA COOPERATIVES

Name and location of the group…………………………………………………………….

Demographics

1. Male or female?

Male	Female

2. How old are you?

	Years

you have any schooling, if you did, what class did you do?

No	
Yes	I did class ………………...

4. Do you have children, if so, how many?

No	
Yes	I have ………children

Income and its sources

5. How much income per month do you make out of the Agave americana products sales?

[ ] Maloti per month

6. other occupations? What are they?

No	
Yes	I also work as (i)………………………. (ii)…………………… (iii)…………………….. (iv)…………………………

Possible Applications

7. When you look at this sample, what products do you think it can be used for?

I can be used for (i)………………….. (ii)………………….. (iii)…………………. (iv)………………… (v)………………..

Production Process

8. What do you think is the easiest method to remove fibre from the leaves

……………………………………………………………………………… ……………………………………………………………………………. …………………………………………………………………………….

Appendix 10: t-test analysis results for interfacial strengths in *Agave americana* fibres HDPE composites

Non-bolied vs. Boiled untreated

	Variable 1	*Variable 2*
Mean	0.545054	0.359883
Variance	0.047965	0.011328
Observations	20	20
Pearson Correlation	-0.15758	
Hypothesized Mean Difference	0	
df	19	
t Stat	3.207902	
P(T<=t) one-tail	0.002316	
t Critical one-tail	1.729133	
P(T<=t) two-tail	0.004631	
t Critical two-tail	2.093024	

Not-boiled vs. NaOH Treated

	Variable 1	*Variable 2*
Mean	0.545054	0.732832
Variance	0.047965	0.065644
Observations	20	20
Pearson Correlation	-0.04313	
Hypothesized Mean Difference	0	
df	19	
t Stat	-2.44002	
P(T<=t) one-tail	0.012329	
t Critical one-tail	1.729133	
P(T<=t) two-tail	0.024658	
t Critical two-tail	2.093024	

Not-boiled vs. silane treated

	Variable 1	*Variable 2*
Mean	0.545054	0.640088
Variance	0.047965	0.052133
Observations	20	20
Pearson Correlation	0.253097	
Hypothesized Mean Difference	0	
df	19	
t Stat	-1.55412	
P(T<=t) one-tail	0.068327	
t Critical one-tail	1.729133	
P(T<=t) two-tail	0.136655	
t Critical two-tail	2.093024	

Boiled vs. NaOH treated

	Variable 1	*Variable 2*
Mean	0.359883	0.732832
Variance	0.011328	0.065644
Observations	20	20
Pearson Correlation	-0.29401	
Hypothesized Mean Difference	0	
df	19	
t Stat	-5.46897	
P(T<=t) one-tail	1.41E-05	
t Critical one-tail	1.729133	
P(T<=t) two-tail	2.82E-05	
t Critical two-tail	2.093024	

Not boiled vs. silane treated

	Variable 1	*Variable 2*
Mean	0.359883	0.640088
Variance	0.011328	0.052133
Observations	20	20
Pearson Correlation	-0.5282	
Hypothesized Mean Difference	0	
df	19	
t Stat	-4.19731	
P(T<=t) one-tail	0.000244	
t Critical one-tail	1.729133	
P(T<=t) two-tail	0.000488	
t Critical two-tail	2.093024	

NaOH treated vs. silane treated

	Variable 1	*Variable 2*
Mean	0.732832	0.640088
Variance	0.065644	0.052133
Observations	20	20
Pearson Correlation	0.425795	
Hypothesized Mean Difference	0	
df	19	
t Stat	1.591024	
P(T<=t) one-tail	0.064053	
t Critical one-tail	1.729133	
P(T<=t) two-tail	0.128105	
t Critical two-tail	2.093024	