Injection Moulded Radiata Pine Fibre Reinforced Polymer Composites: Properties and Applications

A thesis presented in partial fulfillment of the requirements for the degree of

Master of Technology

in

Product Development

at Massey University, Turitea Campus, Palmerston North,
New Zealand.

Vishwanath Sethuram

2004

ABSTRACT

New Product Development (NPD) is important for an organization's growth, profitability and competitiveness. The product being developed depends on an organization's unique context and could either be market-driven or technology-driven. Technology-driven product development begins with a new proprietary technology, and the firm then identifies products where the technology can be applied. Models like Technology Stage-Gate™ have been suggested for developing new technology-driven products. But this process has the drawback of isolating the technology development process from the product development process.

The present project began with the observation that New Zealand had an enormous amount of Pine wood fibre resource at her disposal, and there was growing research and use of wood fibre reinforced polymer composites worldwide for applications like automotive interior components, decking, furniture, and so on. Development of commercial products with this material was limited to thermoforming, extrusion, and compression moulding process. Although there was limited research initiated into injection moulding of pine wood fibre reinforced polymer composites, there was no documentation of the effect of varying the melt temperature on the mechanical properties of the material. There was also no documentation, either of commercial injection moulded products that have been manufactured with this material, or of the process that could be employed to develop commercial products with the new material.

This led to the broad research aim of identifying a commercial product idea that could be manufactured by injection moulding the composite material that was developed using wood fibre and medium density polyethylene powder (rotational moulding grade) and to document the process adopted to achieve this. Some of the objectives were to document the properties of the composite material that was developed without either pelletising, or modifying the properties of the wood fibre by chemical means. The effect of change in fibre content, melt temperature and fibre length were studied. The fibre content ranged from 10% to 40% (in steps of 10%), and the experiments were conducted at four melt temperatures (155° to 215°C, in steps of 20°C), and for two fibre lengths (up to 4mm, and between 4mm and 8mm). The results of the experiments were statistically analysed using the 'Analysis of Variance' method, for their significance.

Abstract

A new development model, "Technology Driven - Fuzzy Front End" (TD-FFE), was used to manage the "fuzzy" stage of developing the new material, identifying new product ideas, and analysing the product concepts. The model is discussed in detail. *Brainstorming* technique was adopted to identify new product ideas for the material.

The effect of the increase in fibre content on the tensile properties of the composite material was found to be more significant, compared to the effect of melt temperature. The interaction between fibre content and melt temperature on the tensile properties of the composite material was also found to be significant. The results of testing the composite material indicated that addition of wood fibre to the polymer increased the viscosity of the polymer melt. The density of the composite was found to increase with increase in fibre content (up to 40%). The tensile properties of the material increased steadily with increase in fibre content up to 30%, after which it decreased. The maximum ultimate tensile strength was found to be about 20MPa (when moulded at 175°C).

The brainstorming technique was *not* found to be very suitable for the current project as the number of *new* product ideas identified were very limited since there were constraints on the material and manufacturing method to be used. Nevertheless, the method identified a *building foundation insulation and boxing product.* The performance of the product was simulated using COSMOS software and from the results of the static stress analysis, it was concluded that the composite material had the required tensile strength to withstand the pressure exerted by wet concrete. A broad analysis to determine the financial viability of the product was also conducted. It was found that it was cheaper to manufacture the new product than assemble the formwork boxing in the traditional method. It offered additional benefits like improving the insulation of the house, and the feel (or appearance) of the foundation, and also could reduce the construction time of the foundation.

It is hence recommended that the product concept be investigated in greater detail by conducting consumer and market research to determine its commercial feasibility, and take it through to production and into the market.

ACKNOWLEDGMENTS

I would like to thank my supervisors, Mr. John Gawith and Mr. Ralph Ball for their advice, assistance, and guidance throughout the project, without which I could not have completed it successfully.

I am grateful to Dr. Jim Jones for permitting me to use the mixing equipment from his laboratory. The project could not have started without this equipment.

I would like to thank Dr. Robyn Phipps for her advice and assistance, which helped me understand the basics of residential building foundations.

The project required a supply of clean Radiata Pine fibre. I would like to acknowledge the assistance of Mr. Murray Birrell, Ms. Jane Walkinton, and other staff of Fletcher Wood Panel (Taupo) for generously supplying the wood fibre for the research. My appreciation is also due to KBL Rotational Moulders Ltd., Palmerston North, for supplying me with Medium Density Polyethylene powder.

My correspondence with Dr. Krishnan Jayaraman (Senior Lecturer, Dept. of Mechanical Engineering, University of Auckland, NZ), Dr. Kim Pickering (Senior Lecturer, Materials and Process Engineering Department, Waikato University, NZ), and Dr. Armando G. McDonald (Associate Professor, Wood Chemistry and Composites, University of Idaho, USA) proved invaluable, and provided me with some crucial leads during the execution of my project.

I would like to express my gratitude to: Mr. Leith Baker for his assistance, patience, and advice during the injection moulding of the composite samples; Mr. Leo Bolter for assisting me with the tensile test of the composite samples; Ms. Liz Nickless for her assistance with the confocal microscope to study the fractured region of the samples; and Mr. Mike Sahayam for his assistance with equipment to dry the wood fibre. I would like to thank all the staff members for their direct or indirect assistance, which helped me finish this project satisfactorily.

I would be failing in my duty, if I do not thank my parents and family for their support, understanding, and patience. I might not have been able to accomplish much in life, had it not been for their constant encouragement and the innumerable sacrifices that they have made for my sake. I am indebted to them. I am also grateful to some of my close friends, who have constantly encouraged and supported me during difficult times.

Acknowledgments

Ultimately, none of this could have been possible had it not been for the Almighty's blessings. He has been a perennial source of support to me throughout my life, for which I will be forever grateful.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF GRAPHS

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 New Product Development

New Product Development (NPD) is important for an organization's growth, profitability and competitiveness. Identifying and developing the right product that is either new to the market or far superior to a competitor's product is both challenging and formidable, and is the 'number one' factor of the product's success in the market (Cooper, 1994). It has been reported that as many as 3000 raw product ideas are required for one product to be commercially successful (Stevens and Burley, 1997). The product being developed depends on an organization's unique context, and could be a market - driven, technology - driven, platform, process-intensive, or a customised product. Firms adopting a technology-driven strategy begin with a proprietary knowledge (for instance, develop a new material, or an innovative processing method), and then look for appropriate products where the technology could be applied. Success rate of new products developed based on this strategy have been reported to be low, unless the technology offered a clear advantage in meeting customer's needs and suitable alternative technologies were unavailable, or very difficult for a competitor to utilize (Ulrich and Eppinger, 2000).

The early stages of developing a new product are often considered to be chaotic, unstructured and unpredictable, and this phase has aptly been termed the 'Front End of Innovation' (FEI) (or Fuzzy Front End (FFE)) of the NPD process (Koen *et al.*, 2002). This phase begins with experimental activity, with no formal development structure or funding in place, and normally has uncertain revenue expectations. Koen *et al.* (2002) defined an '*opportunity*' as, "*A business or technology gap that a company or individual realises that exists between the current situation and an envisioned future in order to capture competitive advantage, respond to a threat, solve a problem, or ameliorate a difficulty*". An '*idea*' was defined as, "*The most embryonic form of a new product or service*".

The present study was initiated considering the enormous wood fibre (radiata pine) resource that New Zealand had at its disposal. There was a need to identify an opportunity and a viable product idea that could take advantage of the abundance of this resource. To achieve this aim, the study considered the research conducted worldwide with similar materials that employed processing methods for high volume production.

Given the popularity of injection moulding as a manufacturing process and the abundance of wood fibre, the research developed a new wood fibre reinforced polymer composite material that was cheaper and eco-friendly. As a part of the investigation into the "Fuzzy Front End" of the product development process, the research studied some of the properties of the composite. Product ideas to apply the material were considered. In this context, the problems experienced by the NZ building industry in constructing foundations was researched, which led to the exploration of a product concept that was injection moulded and manufactured with the composite material.

Various types of composite materials have been used for automotive, aerospace, and defence applications. Carbon fibre, glass fibre, aramid fibre, and Kevlar® have been used for reinforcing polymers. Although these materials are popular because of their low weight, high strength and stiffness, they are very expensive, and lately have been found to harm the environment, as they are not easily recyclable (Peterson *et al.*, 2002). This has made it necessary to look for alternate eco-friendly and renewable resources for reinforcing polymers, wherever feasible. Natural fibres from crops like hemp, sisal, and flax have been found to have mechanical strength comparable to that of glass fibre (Hepworth *et al.*, 2000; Zafeiropolous *et al.*, 2002a). Moreover, they are cheap, renewable, biodegradable, and have a very low density. The use of natural fibres for manufacturing composite materials has been on the rise over the last decade and it is expected that this trend will increase in the years to come (Principia Partners, 2003).

1.2 Birth and growth of Wood Fibre Reinforced Polymer (WFRP) composites

Over the last few years, there has been a growing need to reduce the environmental impact of materials, which has led to the development of new materials. In light of growing petroleum shortages, rising prices of commodity polymers, and pressure to decrease the dependence on petroleum products, there is an increasing interest to maximise the use of renewable resources contributing to the development of new agro-based composites (Rowell *et al.*, 1997). A perusal of the literature shows increasing research being conducted world-wide, in the area of wood fibre reinforced composites (WFRP) (Karmaker and Youngquist, 1996; Balasingam, 1997; Coutinho *et al.*, 1997; Lee and MacDonald, 2000; Balasuriya *et al.*, 2001; Marek and Widdecke, 2001; Abdalla *et al.*, 2002; Peterson *et al.*, 2002; Jayaraman, 2003). The resulting material has superior properties when compared to the properties of the individual materials, and finds structural and non-structural applications (Peterson *et al.*, 2002)

According to a market study undertaken by Principia Partners, a leading consulting firm serving the wood fibre-polymer composite industry, demand in North America and Western Europe for products made from this material was 1.3billion pounds (approx. 590million kilograms) in 2002, a growth of 20% from 2001 levels. Principal markets in North America where this composite material was applied were building and construction (decking & railing systems, window & door profiles, and shingles), infrastructure (structures like boardwalks and docks), and transportation (automotive interior panels, spare tyre covers). In Western Europe, although the market for WFRP products is still in its infancy, automotive applications dominate its use, accounting for over 50% of the overall consumption. The study projects the market to grow at an annual rate of 14% in North America, and at 18% in Western Europe till 2010. Specifically, it has been projected that the market demand for injection moulded WFRP products will increase to US$300 million by 2007, from the present US$15 million (Principia Partners, 2003).

Wood fibre reinforced polymer composites have been used in a variety of structural and non-structural applications, like automotive interior components, building products, furniture, toys and playground equipment, and interior & exterior parts for houses (Bledzki and Sperber, 1999).

As was mentioned earlier, European and American automotive interior component manufacturers have been the major consumers of WFRP composite materials. Peijs (2002) reported the research conducted by various automotive manufacturers in the area of WFRP composites, in the development of specific automotive components. Daimler-Chrysler has produced several automotive exterior parts like underbody panels, flax-reinforced polyester engine (for their A-Class cars), and transmission covers for its travel coach. Audi has developed automotive interior door trim panels from polyurethane reinforced with flax / sisal non-woven mats. Ford has made considerable in-roads in the development of an injection-mouldable flax-polypropylene (PP) grade of polymer, for the development of radiator grills and engine shields. Kafus Environmental Industries (a company that grows kenaf in Texas, USA) and Visteon (Ford's component subsidiary) have collaborated to develop and produce compression-moulded parts, based on non-woven mats of kenaf, hemp and PP. While the application of wood fibre reinforced polymer composite materials has been limited to substituting existing materials, it is the endeavour of the present research to identify

an application for this material that would lead to the development of "new-to-the-world" products.

The popularity of WFRP composites is driven by its attractive properties like recyclability (Kenny, 2001) when compared to glass reinforced polymers, apart from other properties like abundance of the resource, low cost, low density, and non-abrasive nature. For instance, Europe, after implementing the End of Life Vehicles Directive, has set its automotive parts recycling target at 85% (by weight) by 2006, and 95% by 2015, (Kenny, 2001).

Most of the research into wood fibre based polymer composites has been conducted in Europe and North America, and has been limited to sisal, hemp, flax, jute and kenaf fibres. Only recently, softwood fibres like radiata pine have been used to reinforce polymers and process the material by injection moulding (Karmaker and Youngquist, 1996; Coutinho *et al.*, 1997; Lee and MacDonald, 2000; Marek and Widdecke, 2001). A bulk of this research has been conducted in Australia and New Zealand, because of the abundance of softwood fibres in these countries.

New Zealand is known for its abundant forest resources, 89% of which is covered by radiata pine (*Pinus Radiata D. Don*) species (Kininmonth and Whitehouse, 1991; New Zealand Forestry statistics, 2002). Primarily applied in the building & furniture industry, and for paper manufacture, these fibres are known for their versatility, and are used to manufacture plywood, particleboard, and medium density fibreboard. It is suitable for both interior and exterior use, in structural and non-structural applications (Kininmonth and Whitehouse, 1991).

Although WFRP composites have been injection moulded, the bulk of research into the use of wood fibre reinforced polymer composites has centred on extruding, compression moulding, thermoforming, and hot pressing. It has been acknowledged that the use of injection moulding has not been properly understood and needs to be explored seriously (Marek and Widdecke, 2001). Injection moulding offers advantages that other processing methods do not, like, product design flexibility, high volume production enabling part cost reduction, highly accurate parts with close dimensional tolerances, and improved mechanical properties.

The use of WFRP composites is not without problems. Wood fibre is hydrophilic by nature, while the polymer matrix is hydrophobic. This makes the two materials incompatible, and affects the composite's fibre - polymer interfacial bonding. Various chemical treatments have been investigated to modify the structure of the wood

fibre to make it hydrophobic, so that the fibre – polymer interfacial bonding is improved (Lee and MacDonald, 2001; Eichhorn *et al.,* 2001; Pickering *et al.*, 2003). Wood fibre degrades at high temperatures. This restricts the temperature range at which the material can be processed, which in turn limits the types of polymers that can be used as a matrix material to develop the composite.

1.3 Injection Moulded Radiata Pine Fibre Reinforced Polymer Composites: Properties and Applications

The primary aim of the project was to identify a new product idea for the vast pine fibre resource available in New Zealand. In this context, the use of rotational moulding grade Medium Density Polyethylene (MDPE) as a polymer matrix for injection moulding the composite material was investigated. Rotational moulding grade of MDPE was used because it was readily available in powder form, and had a high melt flow index (low viscosity). Further, there was no documentation of the use of this grade for injection moulding WFRP composites. The properties that were measured were the tensile strength of the material, its thermal resistivity, and the percentage of moisture absorption.

Researchers and material manufacturers are interested in determining the effect of injection moulding processing conditions, fibre content, and fibre orientation on the mechanical properties of composites, because such studies can help optimise the processing conditions for desired properties. The parameters that govern the injection moulding process are melt temperature, mould temperature, filling time, and packing pressure (Fung *et al.*, 2003). There is no documentation in the literature on the effect of different melt temperatures on the properties of WFRP composite materials. Since temperature is crucial while working with wood fibre, the effect of different melt temperatures on the composite material was studied. Other variables studied were the effect of fibre length, and fibre content on the tensile strength of the composite material, which would help determine the optimum fibre content and melt temperature at which the sample could be moulded, so that the product had optimum strength. The results were statistically analysed to determine the significance of their effect on the tensile strength of the composite.

1.4 Research aim:

To identify a viable 'new' product that could make use of the Radiata Pine fibre resource available in New Zealand, and be manufactured by injection moulding.

1.5 Research objectives:

1a. To study the suitability of rotational moulding grade MDPE as a matrix material for injection moulded, radiata pine fibre reinforced polymer composites by determining its mechanical (tensile) properties.

1b. To study the effects of different melt temperatures, fibre content, and fibre length on the composite's properties.

2. Use a systematic process to identify an application for the material.

3. To develop an idea that stems from the opportunity and research a practical product that would utilise the composite material.

The project began with the study of the literature on Radiata Pine fibre to understand its properties and the methods used to add value to it. Experiments with the wood fibre-polyethylene mixture then commenced to develop a composite material. The properties of the resulting composite material were tested. A systematic process was adopted to identify new products that could utilise the material. Once the possible product was identified, it was realised that the material had to be tested to understand some of its other properties. Its performance was simulated using computer-aided analysis software. The project concluded with defining a specification of the proposed product and suitability of the composite material for manufacturing the product with it.

1.6 Research outcomes:

1. List of properties of the material.

2. Product specification of the proposed product, including material test results, basic design, and analysis of the concepts designed in CAD, with a broad financial model.

3. Documentation of the model adopted to develop the '*technology-driven*' product.

4. Recommendations for further development of the proposed product, and future research in the area of injection moulded wood fibre reinforced polymers.

1.7 Organization of the thesis

The flowchart in Figure 1.1 shows the complete process adopted for developing the wood fibre composite material and identifying the product idea, which will make use of the new material.

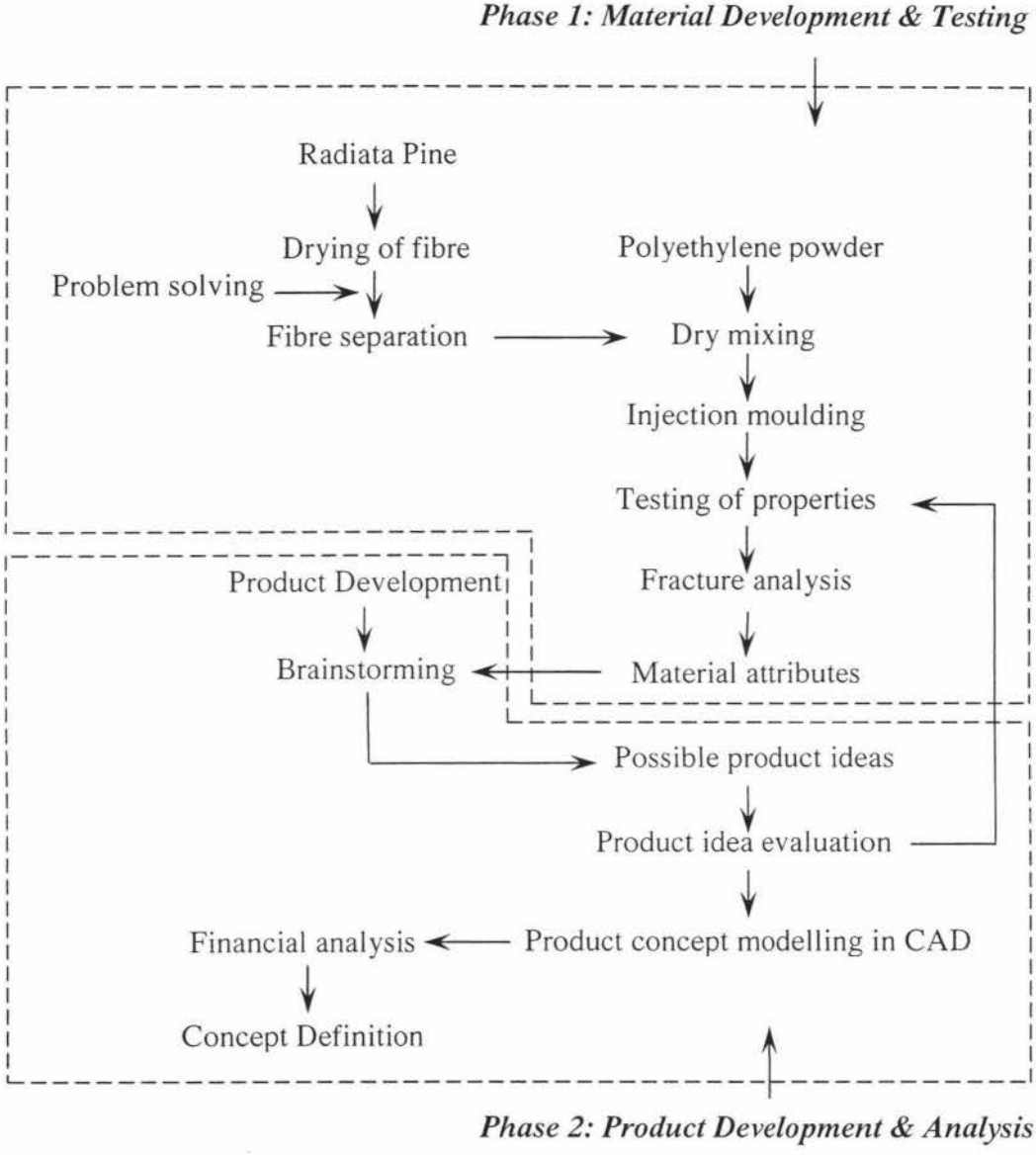


Figure 1.1 Flowchart of the WFRP composite development process employed

The entire project can be divided into two phases. The development of the material and testing of its properties was conducted during *Phase 1* of the project and the identification of product ideas, evaluation of the product idea (for instance, testing of some other properties of the material that might be required for the product idea at hand) and concluded with a financial analysis and concept definition.

The next chapter reviews the developments, emerging technologies, and research that have been conducted in the area of wood fibre reinforced polymer

composites. This includes properties of the fibre, influence of polymer matrix on the properties of the composite material, processing methods adopted, with the mechanical properties of similar composites. Chapter 3 details the methods adopted for testing the composite material and the results of the tests. In Chapter 4, structured models used for idea generation, product development and analysis of the product concepts are discussed. A new model to manage technology driven product development is proposed and discussed in Chapter 5. The approach of the project is also critically analysed, and recommendations made for future research. The thesis concludes with Chapter 6, in which inferences are drawn.

CHAPTER 2

LITERATURE REVIEW

The project began with the author reviewing the literature on wood fibre reinforced polymer composites to understand the advances made in the area and also to identify gaps in the literature, which could provide a ground for new research. The first step of the project was to understand the structure and composition of the wood fibre, and how it affects the mechanical properties of the composite material. This chapter concisely reports the latest advancements made, and the areas that have not been dealt with in the literature, which would be studied in this project.

2.1 Introduction to wood fibre reinforced polymer (WFRP) composites

The growth of environmental awareness has led to the use of natural fibre reinforced polymer (NFRP) composite materials in automotive interior panels and as building materials, since the early 1980s (Olesen & Plackett, 1999; Jayaraman, 2003). In the early 1990s, composites made of wood fibre – polypropylene were successfully used in the manufacture of deck boards, landscape timbers, and industrial flooring. In the year 1996, some of the US companies specializing in wood and natural fibres began producing compounded pellets for processors who did not do their own compounding. In 2000, wood and natural fibres accounted for 7% of the 250 million kilogram market for fillers and reinforcements in the United States, which depicted a 135% increase in the demand for these reinforcement materials, since 1990, with the bulk of growth taking place after 1995 (Clemons, 2000).

In addition to being recyclable, WFRP composites are in general lighter than man-made composites, and have mechanical properties comparable to those of glass fibre composites (Hepworth *et al.,* 2000). Some of the properties of natural fibres, which make their application attractive, are (Stamboulis et al., 2001):

1. Renewable and abundantly available
2. Low cost
3. Low density
4. Good thermal and acoustic insulation
5. Tensile and impact strength are comparable to that of glass fibres
6. Non abrasive to tooling
7. Biodegradable

Some of the disadvantages of natural fibres are:

1. Moisture absorption
2. Dimensional instability
3. Anisotropy of the fibre and low transverse strength
4. Incompatibility between the polar fibre and non-polar polymer matrix, results in poor interfacial bonding
5. Low thermal resistance
6. Discontinuity of the fibre
7. Seasonal variations in quality
8. Demand and supply cycles

For the development of any commercial product, there must be a guaranteed long-term supply of agro-based resources (Rowell *et al.*, 1997). The resource must preferably be locally available and abundant in supply. Although the properties of the product being manufactured drives the final choice of material, factors like seasonal growth of the crop from which the fibre is extracted, requirements for harvesting, separating, cleaning, storage, drying, handling, and transportation of the wood fibre also need to be considered.

New Zealand has a plantation forest area of 1,799,000 hectares (April 2001 figures). The species of trees grown in NZ plantation forests include Radiata Pine (*Pinus radiata D. Don*), fir, and various other types of softwoods and hardwoods. Radiata pine accounts for 89% (1,608,000 hectares, April 2001 figures) of the plantation forest area in NZ (New Zealand Forestry Industry Facts and Figures, 2003). Compared to the extensive research and use of natural fibres like sisal, jute, hemp, kenaf, and flax, only limited documentation has been found on the use of radiata pine fibre as reinforcement for thermoplastic polymers.

Radiata pine is a short length fibre, medium density softwood. Its fibre length varies from 4mm to 8mm. Although native to California, it actually grows faster in NZ because of the ideal climatic and soil conditions, and advanced forest management techniques (Forest Enterprises Ltd., 2003). The fibre cells have uniform density and strength, although the cells near the centre of the trunk are definitely shorter and weaker.

2.2 Structure of wood fibre

An enhanced use of wood fibre for the manufacture of industrial commodities or niche products with minimal adverse environmental impact requires the knowledge of its basic structure, composition, and properties. The chemical composition and organization of wood fibre is first discussed in general, followed by the properties of wood fibre. The structure and properties of Radiata pine, and its use in this study is then elaborated upon.

2.2.1 Chemical composition

Wood fibre is composed of organic chemical substances, produced in the living cells of a tree near its cambium, and is classified as either (a) *cell wall components* or (b) extraneous substances called '*extractives*'.

The cell wall components form the structural member of the wood cell and determine the physical properties of wood. Cell wall components can be classified as *carbohydrates* or *phenolics*. Carbohydrates are linear polymers and account for 75% of the woody substance. Most of the phenolic material is *lignin*. Extractives can be important modifiers of the physical properties of wood. They can, for instance, affect the moisture content of wood. When extractive free wood is delignified under conditions that retain the carbohydrate fraction, the product formed is called *holocellulose*. Holocellulose can be separated into *cellulose* and *hemicellulose*.

a. Cellulose:

Cellulose is the primary component of the cell wall, and is composed of linear chain of glucose molecules. It consists of β-D-glucopyranose, with each glucose residue containing three hydroxyl units, and hence has a marked affinity for water. The swelling due to absorption of water is limited to the amorphous region of the fibre. It is a remarkably strong polymer and imparts tensile strength to wood, due to its highly crystalline nature. It undergoes gradual thermal degradation on heating at temperatures of around 250°C, and rapid pyrolysis above 250°C.

b. Lignin:

Lignin is a three dimensional complex polymeric substance. It is a completely amorphous substance, which softens at 165 to 175°C. It is responsible for the compressive strength of wood. Although it contains hydroxyl groups, it is hydrophobic in nature, and thus provides a certain degree of dimensional stability to the fibre

(Balasingam, 1997) by preventing undue swelling of the cell walls. It is responsible for providing structural strength to the fibre (Stamboulis *et al.*, 2001).

c. Extractives:

These are present in very small quantities, and are responsible for increasing the specific gravity and lowering the equilibrium moisture content. They govern the durability, colour, odour, and taste characteristics of wood, and also provide resistance against decay and insect attack.

2.2.2 Organisation of the cell wall

This section describes the importance of microfibrils and their orientation, on the mechanical properties of the composite material.

Cellulose molecules occur as discrete bundles called *elementary fibrils*, with an elliptical or rectangular cross-section. Each elementary fibril is composed of 50 to 80 cellulose molecules, aligned with the fibril axis. An aggregate of these elementary fibrils, held together by hydrogen bonds, form *microfibrils*.

Figure 2.1 shows the longitudinal section of an elementary fibril. It can be observed that the crystalline regions (represented by 'C' in the figure) are more densely packed than the amorphous regions ('A'). Water is present in all the regions except the crystalline region. The shrinking or swelling of wood is primarily a result of the addition of water to the amorphous regions of the cellulose microfibrils. Gaps between microfibrils also aid in the absorption of moisture. The microfibrils are organized into *lamina,* which are further organized into thicker units called *cell wall layers.* The organization of the cell wall of various types of fibres is similar to that described below, with the only variation occurring in the thickness of the different layers.

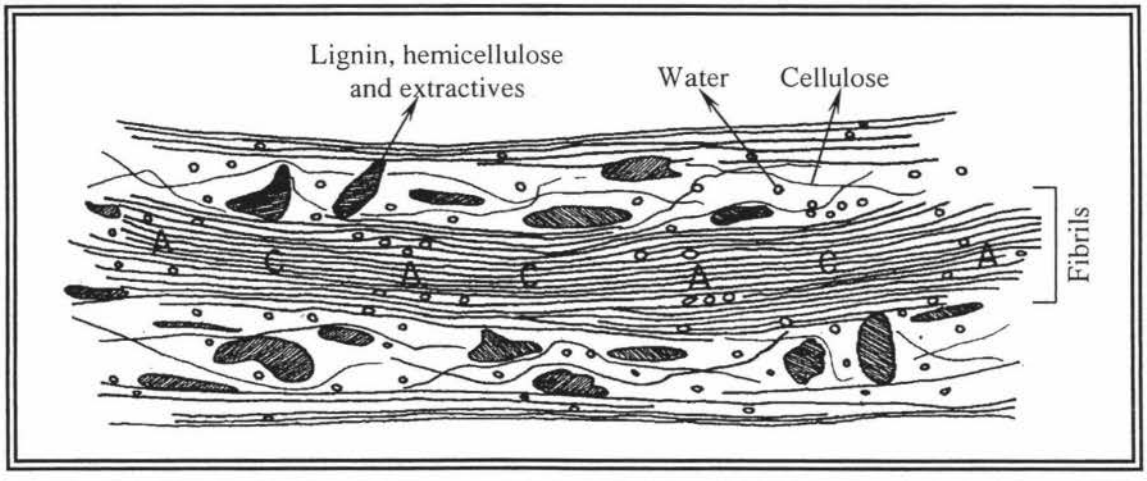


Figure 2.1 Longitudinal section of an elementary fibril (Bodig and Jayne, 1982)

Figure 2.2 shows the model of the cell wall layer. The *compound middle lamella* consists of the *middle lamella* (M), which acts as a bonding medium for interconnecting the cells, and the *primary wall* (P). The secondary wall is composed of three distinct layers, S_1, S_2, and S_3. The layer S_2 is the thickest of the three layers. The angle between the fibre axis and the microfibrils is called the *microfibril angle*. An important feature of these layers is the orientation of the microfibrils; especially layer S_2, where it is oriented at 10° to 30° from the cell axis, because of which, this layer tends to influence the behaviour of the fibre as a whole (Donaldson and Burdon, 1995; Jayaraman, 2003). The smaller the angle of the microfibril, higher is the tensile strength, while larger microfibril angles result in higher elasticity (Donaldson and Burdon, 1995).

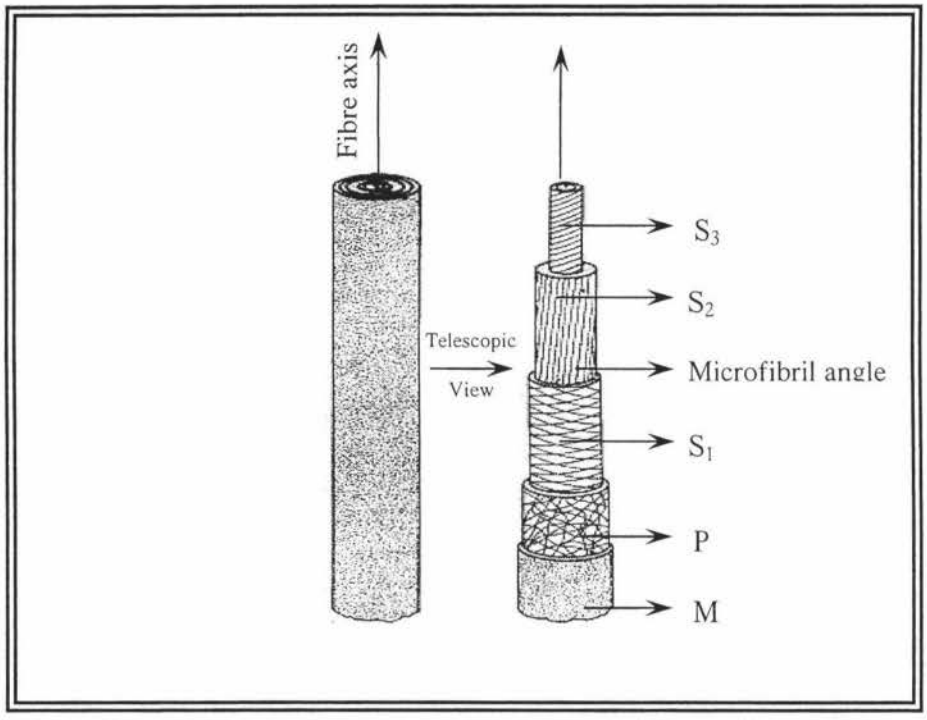


Figure 2.2 Cell wall model of a softwood tracheid. (Bodig and Jayne, 1982)

Thus, microfibrils and their orientation within the wood fibre play a significant role in determining the mechanical properties of the resulting composite material. But having said that properties like density, specific modulus, lignin content, and so on, should also be considered before the final decision is made on the choice of fibre used for developing the composite material.

2.3 Properties of wood fibre

Traditionally, various types of bast fibres (jute, hemp, and flax), leaf fibres (sisal) and seed fibres (cotton, kapok, coir) have been used for reinforcing polymers to

manufacture composites. Wood fibres are intrinsically anisotropic in nature, with widely varying properties (An anisotropic material possesses different properties in longitudinal and transverse directions). Its properties vary at various parts of the tree, between trees, and between various sites of plantation (Donaldson and Burdon, 1995). Comparative properties of some of the lignocellulosic fibres with glass fibres are given in Table 2.1, from which it is apparent that although natural fibres impart lower strength, their low density result in their specific strength and stiffness being comparable to that of glass (Brouwer, 2000; Biswas *et al.*, 2001).

Properties	Glass[a]	Flax[a]	Hemp[a]	Sisal[a]	Radiata Pine[b]
Density (gm/cc)	2.55	1.4	1.48	1.33	0.46
Lignin (%)	-	3 – 5	3 – 5	4 – 5	27
Cellulose (%)	-	65 – 85	65 – 85	85 – 88	40
Tensile strength (MPa)	2400	800 - 1500	550 - 900	600- 700	107 – 125
Tensile modulus (E) (GPa)	73	60 - 80	70	38	22
Specific Modulus (E/density)	29	26 - 46	47	29	47.8
Elongation at failure (%)	3	1.2 - 1.6	1.6	2 – 3	8 - 10
Microfibril angle (Deg.)	-	NA	NA	10 – 22	28
Average fibre length (mm)	-	NA	NA	NA	2 - 8
Moisture absorption (oven-dry) (%)	-	7	8	11	4.5
Price/Kg (US$), raw	1.3	1.5	0.6 - 1.8	0.6 – 0.7	0.6 – 0.75

Table 2.1 Properties of some selected natural fibres and glass fibre. (NA: Data not available) ([a]Mwaikambo and Ansell, 1999; Brouwer, 2000; [b]Kininmonth & Whitehouse, 1991; Eichhorn *et al.*, 2001; Abdalla *et al.*, 2002)

It has been acknowledged that the mechanical properties of WFRP composites depend on the cellulose & lignin content, degree of polymerisation, microfibril angle, strength of the fibre & resin, fibre length, fibre diameter, fibre fraction volume, orientation of the fibre in the composite, the interfacial bonding between the fibre and polymer, the location from where the fibres have been extracted, and whether the fibres are in filament or bundle form (Joseph *et al.*, 1995; Mwaikambo, 1999). Fibres with higher cellulose content, higher degree of polymerisation, and lower microfibril angle

exhibit higher tensile strength and modulus. The length of the fibre also plays a role in the strength on the fibre composite. The fibre must be above a critical length, which is dependent on the method adopted to process the composite mixture, and the fibre – polymer interfacial bonding. As the bonding increases, the critical length decreases. The strength of the composite increases with increase in fibre length, but beyond the critical length, the strength decreases (Joseph *et al.,* 1996). On the other hand, Karmaker and Youngquist (1996) noted that for the composite to be able to withstand the maximum stress, the fibre length had to be considerably more than the critical length, since at the critical length, the average stress transferred was only half of what was achieved by longer fibres. They also reported that processing methods like injection moulding caused significant attrition (wear and tear of the fibre), which could reduce the length of the fibre.

Apart from these material-specific variables, processing conditions like temperature and curing time (or consolidation time) also affect the mechanical properties of the composite (Peterson *et al.,* 2002; Fung *et al.*, 2003). These will be discussed later in this chapter.

2.4 Use of Radiata Pine fibre for this study

As can be observed from Table 2.1, the primary advantage of Radiata Pine is its low density, and high lignin content. The high lignin content of Radiata Pine fibre indicates that it is predominately hydrophobic in nature (Lee and McDonald, 2001; Abdalla *et al.*, 2002). If the absolute tensile strength or modulus of the various composite materials is compared, it is seen that the properties of Radiata Pine fibre are lower, which can be attributed to its high microfibril angle and low cellulose content. The specific modulus is a better measure of a composite material's structural strength than the absolute tensile strength (The Japan Carbon Fiber Manufacturer's Association: Glossary). Radiata pine fibre composites can therefore be recognized as a light structural material with high mechanical strength. It should be noted that the mechanical properties of other WFRP composites are the result of chemical modification of their structure, use of processing methods like compression moulding and thermoforming where the fibres are not subjected to high temperatures, and use of thermosetting polymers.

There is little information in the literature regarding the critical fibre length of the radiata pine. In the current research, an attempt has been made to determine the

effect of fibre length on the tensile strength of the composite material. The comparison has been limited to 10% fibre content.

The following sections detail the advancements made in various areas of the subject: processing of wood fibre composites, the chemical treatment to improve the interfacial bonding between the fibre and the polymer.

2.5 Feeding of fibre-polymer mixture

One of the issues to be considered while working with WFRP composites is the consistency of the mixture. When dealing with huge volumes and different ratios of fibre and polymer, it is necessary that the ratios are consistently accurate. This is necessary, if the properties of all the products moulded are to be uniform.

It has been an industry standard to compound and pelletize the mixture in a twin - screw extruder, because it served two purposes:

1. It is easier to feed pellets into an injection moulding machine than to directly feed the mixture.
2. The natural fibre and polymer (in granule form) are homogeneously blended such that the fibre is uniformly distributed in the polymer melt. This would improve the mechanical properties of the composite.

The disadvantages of pre-processing the fibre-polymer mixture in this form are:

1. The properties of the fibre would deteriorate considerably if the fibre – polymer mixture are initially compounded at 180°C (Coutinho *et al.*, 1997) and then subsequently injection moulded at a comparable temperature.
2. It would increase the cost of the manufacturing process, and hence of the final product.

For these reasons, the use of an extruder to homogeneously mix the fibre and polymer prior to injection moulding has been avoided in this project.

2.6 Influence of the polymer matrix

The matrix in a fibre-reinforced polymer composite material binds the fibres together, transfers applied load to these fibres, and protects them from harmful environmental effects. The requirements for the use of natural fibres to reinforce thermoplastic polymers are:

1. Melting temperature should be lower than the degradation temperature of natural fibres (that is, less than 200°C)
2. Adequate fibre wettability

3. Fibre – matrix bonding aided by mutual compatibility. The fibre must have as low moisture as possible in order to bond effectively with the polymer matrix.

A wide range of polyolefins has been employed as matrix for wood fibre reinforced polymers. Lee and McDonald (2001) assessed the mechanical properties of blends of radiata pine with three commodity plastics Low Density Polyethylene (LDPE), Polypropylene (PP), and Polystyrene (PS). They observed the greatest improvement in properties in wood fibre - LDPE composites than fibre - PS or fibre - PP composites. Since the fracture mechanism of fibre - LDPE and fibre - PS composites were due to fibre breakage, they concluded that LDPE and PS bonded well with the wood fibre, while the bonding was weak in the case of PP - wood fibre.

McHenry and Stachurski (2002) experimented with eucalyptus fibre reinforced nylon composites. Nylon has polar groups in its structure and hence is hydrophilic in nature. The tensile strength of the composites was found to be significantly higher when compared to the tensile strength of virgin Nylon bonds, which indicated that it was compatible with wood fibre. It has a melting point of 226°C. At this temperature, although the samples were subjected to degradation, it was kept as low as possible by minimising the consolidation time.

Peterson *et al.* (2002) investigated the performance of reinforcing polyhydroxybutyrate - polyhydroxyvalerate copolymer (*Trade name*: Biopol™) with wood fibre, and also the influence of fibre volume fraction on the biodegradability of the composite. The level of moisture content in the biodegradable composite is not clear from the paper. In their research, Biopol™ was subjected to bacterial attack, which decomposed the composite into its constituents of hydrogen, oxygen and harmless compounds. They concluded that the wood fibre act as conduits for the bacteria and the presence of about 15% of wood fibre accelerated the degradation of the biocomposite.

In this research, rotational moulding grade of medium density polyethylene (MDPE) (Trade name: COTENE™ 9048), supplied by KBL Rotational Moulders Ltd., Palmerston North was used as the polymer matrix. Some of its properties are given in Table 2.2.

Property	
Density (gm/cc.)	0.946
Melt Flow Index (gm/10 min)	5.5 to 6
Melting temperature (°C)	115

Table 2.2 Properties of COTENE™ 9048

COTENE™ 9048 is a medium density grade of polyethylene, and has a higher melt flow index than injection moulding grade of PE. Its density is even lower than injection moulding grade MDPE. Rotational moulding grade of PE was employed in this study for three reasons:

1. It is readily available in the powder form. If the injection moulding grade of PE were to be used, it would require the granules to be ground in order to mix homogeneously with the wood fibre, or would require the use of a twin screw extruder for the purpose. Both these measures result in increasing the cost of the final product.
2. It has a higher melt flow index, which is a measure of its viscosity. The viscosity of the molten polymer increases on addition of wood fibre to the polymer, thereby making it difficult to process the material. In order to circumvent this problem, a polymer with a higher melt flow index needs to be used.
3. The use of this polymer matrix would enable the author to study the critical length of the fibre. Berlin *et al.* (cited by Joseph *et al.*, 1996) reported that as the flow rate of the matrix increased, the critical length of the fibre decreased. Two sets of fibre lengths have been experimented with in the present project - one set less than 4mm and the other greater than 4mm up to 8mm. In light of the observation cited by Joseph *et a*l. (1996), it is expected that the critical length of the fibre would be less than 4mm.
4. Until now, there is no documentation on the use of *rotational moulding* grade of PE for processing WFRP composites by *injection moulding*. The low melt temperature of this polymer is expected to aid in the manufacture of the composites by injection moulding, by minimising the degradation of the fibre. Its low viscosity (or high melt flow rate) is expected to aid the molten polymer in its flow between the individual fibres, thereby wetting the fibres better, which is partially responsible for improved interfacial bonding (Balasuriya *et al.*, 2001; Jayaraman, 2003).

2.7 Processing WFRP composites

WFRP composites are processed by various techniques, depending on the application of the product being manufactured. These methods include extrusion, hot pressing (McHenry and Stachurski, 2002; Jayaraman 2003), forming (Peterson *et al.* 2002), thermoforming (Balasingam, 1997), compression moulding (Balasuriya *et al.*

2001, Abdalla *et al.* 2002) and injection moulding (Kramer and Youngquist, 1996; Lee and McDonald, 2001; Marek and Widdecke, 2001, Fung *et al.*, 2003).

Although injection moulding is *"a flexible process offering far more opportunities than extrusion, especially for small parts, making it feasible to manufacture high-value products"* (Beldzki and Sperber, 1999), it has not been investigated extensively primarily because researchers are of the opinion that *"the process requires expensive machinery and the high processing temperatures associated with the process would degrade the fibres"* (Jayaraman, 2003).

Injection moulding caused a significant reduction of fibre length, due to constant stress and shearing action of the screw in the machine barrel, as reported by Karmaker and Youngquist (1996). This caused long fibres to break and reduced the average fibre length to less than the critical length.

Balasuriya *et al.* (2001) studied the effects of processing methods (compounding vs. manual blending) and matrix melt flow rate (medium vs. low melt flow rate) on the mechanical properties (including overall flake wetting and flake distribution) of wood flake – polyethylene composites. The length of the wood flake ranged from 1mm to 4mm. The mixture was compression moulded after compounding or blending the mixture manually. They reported that flake wetting was dependent on the melt flow index of the polymer, than on the blending method. The tensile strength of the samples moulded after compounding was found to be higher than the manually blending the mixture. During compression moulding, the mixture is compressed under heat and pressure in the mould, and there is no relative movement between the fibre and polymer melt to orient the fibres, as in the case of compounding or injection moulding.

Lee and McDonald (2001) studied a practical method for blending and injection moulding radiata pine fibre with various polyolefins. The blends were in the form of pellets compounded using a single and a twin screw extruder. The barrel temperatures of the extruder in the two cases were 140°, 170°, 200°C and 150°, 170°, 200°C for LDPE, PP and PS respectively. The barrel temperatures while injection moulding LDPE, PP, and PS were maintained at 170°, 185° and 210°C respectively. The wood fibre was not treated prior to compounding or injection moulding. They reported that there was a decrease in tensile strength with increasing fibre content for LDPE and PP composites. They observed fibre fracture in the fibre-LDPE composites, which suggested that there was good adhesion between the fibre and the polymer.

Marek and Widdecke (2001) investigated the feasibility of injection moulding sisal fibres impregnated with cellulose acetate polymer. They reported that the strength of the composites increased when compared to the strength of virgin plastic. Increase in fibre content (from 11% to 30% by weight) increased the tensile, flexural and impact modulus of the composite. This was primarily because of the polar nature of the matrix, which aids in bonding with the sisal fibre.

Abdalla *et al.* (2002) processed silane-treated radiata pine reinforced polyethylene composite sheets by compounding and extruding. The extruder temperature was 165°C, and the wood fibre was compounded twice for maximum homogeneity. They reported that the tensile strength of the composite sheets decreased as the fibre content increased beyond 5%. They attributed this decrease to the effects of increased fibre agglomeration at higher fibre content. As in the case of Lee and McDonald (2001), the fibre-polymer mixture was subjected to high temperature and pressure during compounding and extruding, which could have degraded the fibre. This resulted in reduction of the tensile strength of the composite with increase in fibre content.

Peterson *et al.* (2002) experimented with processing a biodegradable composite sheet manufactured with wood fibre – Biopol™, by hot-pressing / thermoforming. Among the many aspects studied, they observed the interaction between platen temperature and consolidation time. They noted that when the fibre volume fraction was kept constant at 18%, tensile properties of the composite material decreased at higher temperatures (from 210°C to 240°C) with longer consolidation times. This is a key observation, as a similar study (effect of melt temperature) is being attempted in this project.

Melt temperature is an important processing parameter in injection moulding which has an effect on the product's quality and mechanical properties. The cylinder temperature and the nozzle temperature of the injection moulding machine is normally taken as the temperature of the melt. Some of the problems associated with low melt temperature are improper filling of the mould, flow lines appearing on the product; while high melt temperatures lead to flashing in the part, discolouration and burn marks, and sink marks appearing on the part (Rubin, 1973). There is no documentation in the literature regarding the effects of change in melt temperature on the mechanical properties of WFRP composite materials.

Jayaraman (2003) experimented with reinforcing PP with sisal fibres. Fibre mats were formed using a drop feed technique for the fibre, which eliminated any possible degradation of the fibre. Composite sandwiches were produced using vacuum forming and hot pressing techniques, and it was reported that the tensile strength initially decrease and then increased with fibre content up to 25%. It was suggested that at low fibre contents (9%) the fibre behaved like fillers and did not reinforce the composite, resulting in the reduction of its tensile strength.

2.8 Chemical treatment

Results published in the literature indicate that chemical treatment or the use of coupling agents for natural fibres like sisal, jute, flax, and hemp improved their ability to reinforce polymers, when compared to fibres that have not been subjected to such treatments (Karmaker and Youngquist, 1996; Coutinho *et al.,* 1997; Abdalla *et al.,* 2002). As explained earlier, natural fibres are prone to moisture absorption, poor wettability, and thermal & dimensional instability due to their structure and composition. Cellulose is hydrophilic by nature, and any increase in its content in wood, would prove detrimental to the properties of the composite (Kininmonth and Whitehouse, 1991). These fibres are polar in nature do not adhere well with polymer matrices, some of which are non-polar. Fibre - fibre interaction results from intermolecular hydrogen bonding, which limits the dispersion of the fibre in the matrix. The fibres are hence chemically treated by various methods to improve their structure, properties, and to aid dispersion of the fibre in the matrix. The following paragraphs explain the popular chemical techniques employed to achieve this.

Many researchers (Karmaker and Youngquist, 1996; Coutinho *et al.,* 1997; Mwaikambo and Ansell, 1999; Zafeiropoulos *et al.,* 2002a) have investigated and documented the effect of various chemical treatments on fibres. Reactive chemical treatment methods depend on reagents, which can chemically modify the structure of wood by reacting with the hydroxyl groups present. Primary changes in wood properties after the chemical treatment include, increased resistance to bio-degradation, and an improvement in dimensional stability towards variations in humidity. The disadvantages of such chemical treatments are increase in the weight of the fibre and cost of the pre-treatment process. Amongst the modifying agents used, the most successful are acetic anhydride, stearic anhydride, and methyl isocyanate.

Acetylation (reaction using acetic anhydride) has been found (Zafeiropoulos *et al.,* 2000) to improve thermal stability of flax fibres. The process imparts heat resistance to the fibres, which allows their use at elevated temperatures, for instance, to reinforce nylon. They have also found evidence that the process helps in reducing the swelling of wood in water, and improves the surface roughness and structure of fibres like flax, hemp, sisal, jute, and kapok (Mwaikambo and Ansell, 1999), which aids in improved interfacial bonding with polymers.

Alkalisation, treatment with varying amounts of sodium hydroxide, is found to bring about crystalline modification involving fibril swelling, which is essential for fibre-matrix adhesion (Mwaikambo and Ansell, 1999). But this method has not been found to be always successful, since it is dependent on the concentration of sodium hydroxide used for the treatment (Abdalla and Pickering, 2002; Jayaraman, 2003).

It is also possible to chemically treat the polymer matrix. Fung *et al.* (2003) investigated the effect of maleation of polypropylene on the interfacial bonding between the matrix and sisal fibre. They concluded that maleation of PP helped in reducing its glass transition temperature (T_g), which improved interfacial bonding between the fibre and the matrix. This allowed effective load transfer to the reinforcing fibres in the composite.

A perusal of the literature indicates that silane coupling agents are well suited to be used for treating radiata pine fibres (Balasuriya *et al.,* 2001; Abdalla and Pickering, 2002; Abdalla *et al.,* 2002). The prerequisite for using this coupling agent is that the fibre needs to have a specific amount of moisture (10% by weight) within itself to aid the hydrolysis of silane to silanol, which then reacts with hydroxyl groups of the fibre surface. This reaction is aided by the presence of cellulose in the fibre. It has been reported that silane treatment process enhances the bonding of the fibre with the polymer at low fibre concentration (about 5%). At higher fibre concentrations, fibre agglomeration takes place, and pre-treatment with sodium hydroxide to reduce this effect have been unsuccessful (Abdalla *et al.,* 2002).

From the aforementioned discussion, it is apparent that radiata pine fibres possess the properties for reinforcing polymers and enhance the mechanical properties of the composite material. Considerable inroads have been made in treating the fibres for improved bonding with the polymer matrix. Further, the technology to reduce the processing temperature of polymers that have a high melting point also exists (Jana and Prieto, 2002). This would aid in processing the composite by injection moulding.

Research in great depth has been conducted in the area of enhancing the properties of WFRP composites, but little documentation regarding the application of composites manufactured *without* such enhancement. The present project aims to identify an application for a composite material developed by manually mixing wood fibre and MDPE powder, and processed by injection moulding.

Section A of the next chapter "Testing of Composite Material: Methods" explains the methods adopted to mould and test the composite material, and Section B details the results of the tests. This is followed by the methods adopted to identify an opportunity, and develop a product idea that would utilise the composite material, and at the same time the results obtained are discussed.

CHAPTER 3 - SECTION A

TESTING OF THE COMPOSITE MATERIAL: METHODS

3.1 Introduction

Over the past few decades, the advent of new materials has paved the way for developing new stronger and lighter products. Some of these new materials are carbon fibre, glass fibre, Aramid fibre, Kevlar fibre, and more recently, wood fibre reinforced polymers. The advantages and limitations of WFRP composites have been detailed in the previous chapters. This chapter will begin with the process adopted for developing the composite material. The methods used to measure its properties are explained, and the results of the tests are reported.

3.2 Composite material development process

Figure 3.1 shows the flowchart of the material development process adopted for this project. The radiata pine fibre was initially stored in a chiller at 4°C to prevent its possible degradation due to the absorption of atmospheric moisture.

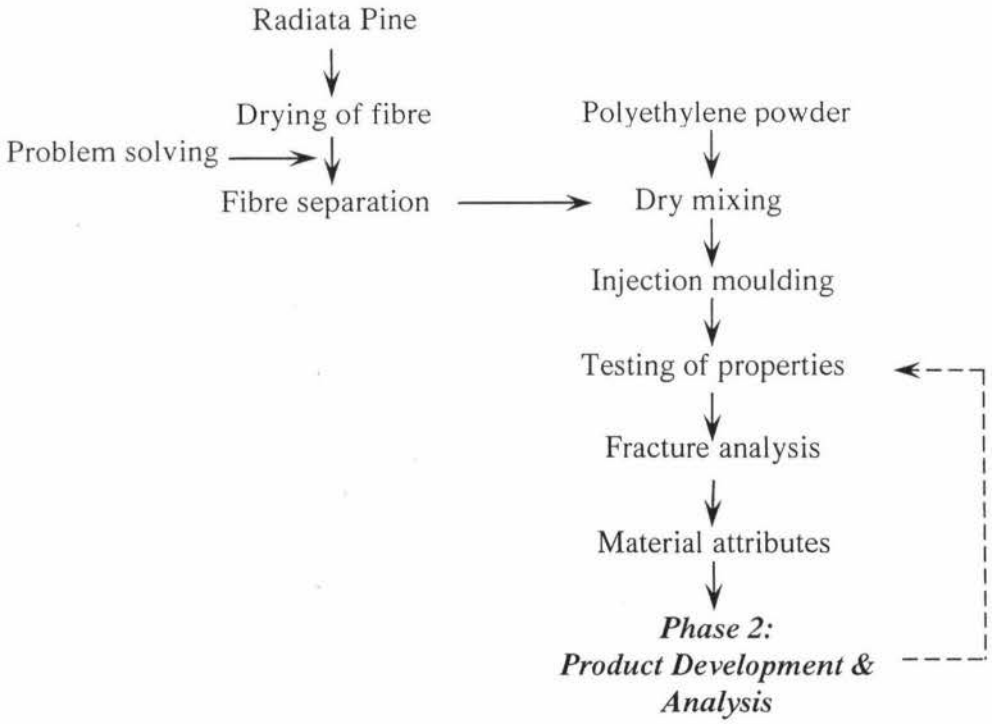


Figure 3.1 Flowchart of the WFRP composite material development process employed

3.3 Measurement of moisture content in the fibre

The most common method of determining the moisture content is by *"lost weight method"* (Bodig and Jayne, 1982). The moisture content was initially found to be 11%, and after oven drying, was found to be approximately 4.5%. The dried fibres were kept sealed in airtight plastic bags and refrigerated to prevent them from reabsorbing moisture. It was found that by this method, the fibre was affected due to the dampness in the refrigerator. The subsequent sets of dried fibre were kept in sealed plastic covers in a warm room at 34°C.

3.4 Mixing of wood fibre and polyethylene powder

This project aimed to eliminate the need to compound and granulate the fibre – polymer mixture. The wood fibre was dried in an oven at 105°C to 4.5% moisture content by weight. The fibres were then sieved manually with a 4mm and 8mm mesh sieve, in order to separate the longer length fibres from the shorter fibres. A kitchen mixer was used for mixing the fibre and polyethylene powder. Efforts were first made to separate the clumped pine fibres, using the mixer at a high speed. Although most of the fibres were separated, agglomeration of the fibres could not be eliminated altogether. This was clearly evident, when the fibres (20% by weight, and above) were mixed with Polyethylene powder. While most of the separated fibres mixed homogeneously with the PE powder, small clumps of fibre surfaced to the top of the container holding the mixture, which were removed manually. A small proportion of clumped fibres still remained in the mixture. The extent of homogeneity was not determined. For the current project, chemical treatments or the use of coupling agents have not been employed to improve the structure and properties of the fibre.

3.5 Injection moulding of test specimens

All samples were moulded on a COSMO TTI-330/110 (manufactured by Welltec Industrial Equipment Ltd.). Dumb-bell shaped tensile test samples were moulded with the virgin polyethylene powder (rotational moulding grade), polyethylene granules (injection moulding grade), and wood fibre – polyethylene powder (rotational moulding grade). Due to time and financial constraints, standard test samples with dimensions conforming to ISO 527 could not be moulded. The dimensions of the test sample are given in Appendix A.

Two types of nozzles were employed for moulding samples at various fibre percentages. For the samples with 10% and 20% fibre content, the standard machine nozzle was employed. This nozzle had an opening diameter of 3.175mm. For moulding samples at higher percentages (30% and 40%), a custom nozzle was made of mild steel, so that its nozzle diameter could be varied as required. These samples were moulded with the custom made nozzle, with an orifice diameter of 4mm.

The injection mould used for moulding the samples was a standard two-plate, single daylight, single cavity mould. The cavity was gated with an edge gate at one end (at the portion used for gripping the sample in the tensile testing machine). No cooling system was incorporated in the tool. All the samples were cooled for 10 seconds in the tool and then air-cooled. Only enough material for moulding twenty samples was introduced in the machine (at each temperature), in order to eliminate the effects due to degradation of the fibre-polymer mixture due to long residence time in the machine barrel. After changing the temperature, the machine barren was purged to remove any material residing in it from the previous run.

Three sets of specimens, as described below, were moulded.

1. High Density Polyethylene (HDPE) granules of injection moulding (IM) grade.
2. Medium Density Polyethylene (MDPE) powder of rotational moulding (RM) grade.
3. Mixture of wood fibre and MDPE.

For Sets 1 and 2, it has been documented that as the melt temperature increases (keeping the rate of cooling constant), the tensile strength of the material increases, as the crystallinity increases (Rubin, 1972). These samples were moulded at 175°C. As indicated in Chapter 2 (page 20-21), there is no documentation of the effects of melt temperature on the tensile strength of the WFRP composite. In light of this, for set 3, specimens were moulded at various temperatures in order to study the effect of melt temperature on the mechanical properties of the composite. The barrel temperatures (or melt temperature) were 155°, 175°, 195°, and 215°C. Twenty samples were moulded at each temperature. Since the mixture was in powder form, the material could not easily enter the barrel of the injection moulding machine, and required constant manual prodding.

For each temperature, the fibre content was varied progressively from 10% to 40%. Table 3.1 (page 27) gives the details of the temperatures, fibre content, and fibre length used for the experiments.

Trial	Fibre : PE	Inj. Temp. (°C)	Av. Fibre length (mm)
A	10:90	155	< 4
	10:90	175	< 4
	10:90	195	< 4
	10:90	215	< 4
B	10:90	155	4 – 8
	10:90	175	4 – 8
	10:90	195	4 – 8
	10:90	215	4 – 8
C	20:80	155	< 4
	20:80	175	< 4
	20:80	195	< 4
	20:80	215	< 4
D	30:70	155	< 4
	30:70	175	< 4
	30:70	195	< 4
	30:70	215	< 4
E	40:60	155	< 4
	40:60	175	< 4
	40:60	195	< 4
	40:60	215	< 4

Table 3.1 Details of variables for testing of WFRP samples

3.6 Tensile testing

A JJ Tensile Testing machine (manufactured by JJ Instruments Pty. Ltd., Australia) was used for the tensile testing of the samples. A load cell of 5KN was used. The gauge length was 50mm. The crosshead speed was set at 50mm/min for testing the

samples moulded with virgin polyethylene, while for testing the wood fibre reinforced polymer samples, the speed was set at approximately 5mm/min, in accordance with ISO 527 (Plastics - Determination of tensile properties). All samples were tested at room temperature (≈22°C ± 1°).

During the pilot test of the samples, it was observed that the gauge length of the test sample had a 0.3mm taper in it. This discrepancy of the sample resulted in its fracture at the location of its lowest cross-section. The injection mould was rectified, and new sets of samples were moulded and tested.

3.7 Microscopy

An Olympus BX51 confocal microscope was used to study the fracture area of the tensile test samples to analyse the mode of failure. Images of the area of the fracture were captured at 20x, with MagnaFIRE camera and image capturing software.

3.8 Statistical analysis

'Analysis Of Variance' (ANOVA) was used to determine the significance of the experimental variables namely, melt temperature, fibre content, and fibre length, on the mechanical properties of the composite material. The statistical package SAS Ver.8 was used to analyse the data. The interaction between the melt temperature & fibre content, and melt temperature & fibre length were also analysed. The effect of an experimental variable was termed significant, if the probability of its occurrence was less than 5% ($p < 0.05$). Appendix B gives the detailed input data, and results of the analysis.

3.9 Water absorption

For each fibre percentage (from 10% to 40%), five tensile test specimens were kept immersed in water at room temperature for 24 hours. The specimens were weighed before and after immersing in water. The percentage of water absorption of the material was calculated.

3.10 Colourability

While moulding the tensile test samples, 2% black master-batch was added to the fibre-polymer mixture. This was done to determine if the master-batch was able to imbue the wood fibre. Other colours were not experimented with since it hampered the microscopy analysis of the sample.

SECTION B

TESTING OF THE COMPOSITE MATERIAL: RESULTS

3.11 Effect of addition of wood fibre to virgin plastic

The injection pressure for moulding the tensile test specimens at various fibre content and melt temperatures is given in Table 3.2. As expected, it was observed that for a given fibre content, the injection pressure decreased with increase in melt temperature. On the other hand, for a given melt temperature, the injection pressure increased with increase in the fibre content. This indicated that addition of wood fibre increased the viscosity of the melt.

		Fibre content (%)			
	Melt Temperature (°C)	10	20	30	40
Injection Pressure (MPa)	155	72	88	100	110
	175	65	82	88	110
	195	60	80	86	100
	215	57	77	81	95

Table 3.2 Processing parameters for injection moulding the tensile test samples

Table 3.3 below gives the densities of the samples at various fibre contents. At a given melt temperature, with the increase in fibre content, the density increased. For a given fibre content, it was found that the density increased with increase in melt temperature, except for samples with 10% fibre content where the density decreased with increase in melt temperature.

Thus, the addition of wood fibre to the polymer melt, results in the increase of the composite material's viscosity and density. The increase in density of the composite material can be attributed to the increase in crystallinity of the polymer (Rubin, 1972).

		Fibre content (%)			
	Melt Temperature (°C)	10	20	30	40
Density (Kg/m^3)	155	974	973	992	1024
	175	947	988	995	1055
	195	936	988	1002	1058
	215	935	988	1014	1065

Table 3.3 Densities of the WFRP test samples at various fibre contents and melt temperatures.

3.12 Tensile properties of virgin HDPE, MDPE, and WFRP composites

Table 3.4 gives the comparative tensile strength, tensile modulus, and percentage elongation at break for virgin HDPE and rotational moulding grade MDPE, moulded at 175°C. The tensile strength of HDPE was found to be in close agreement with the data published in the literature (Balasuriya *et al.* 2001). MDPE was found to have lower tensile strength. This is because it has a lower molecular weight than HDPE, and the results are in close agreement with polymer theory and published data (Rubin, 1972; Balasuriya *et al.*, 2001; http://www.matweb.com/search/specificmaterialprint.asp?bassnum=PDW473).

	HDPE	MDPE
Tensile Strength (MPa)	20.5	18.33
Tensile Modulus (GPa)	1.2[a]	0.2
% Elongation at break	900	600

Table 3.4 Tensile properties of HDPE and MDPE ([a] Michell, 1986; Balasuriya *et al.*, 2001)

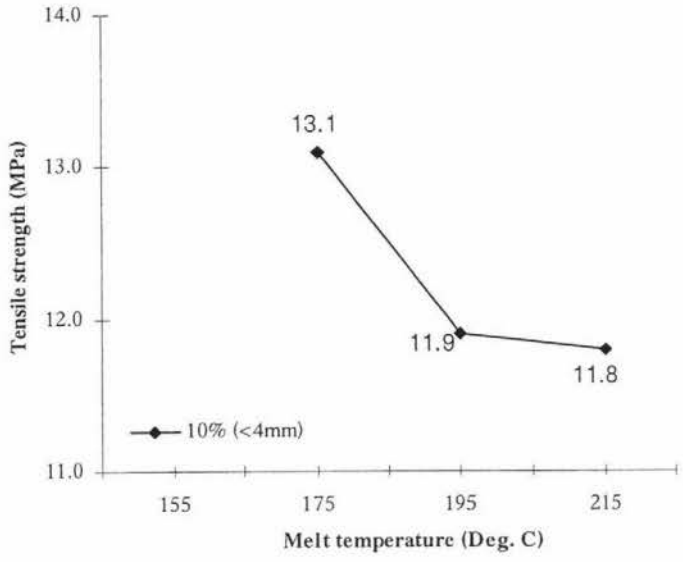
Tables 3.5a and 3.5b summarise the tensile test results of the WFRP composites moulded at 155°, 175°, 195°, and 215°C. The tensile strength of the composite was found to increase with increase in fibre content. At a fibre content of 10% (less than 4mm in length) and 20%, the tensile strength of the composite was found to be lower than that of virgin MDPE at all melt temperatures (Table 3.5a). In fact, at a fibre content of 10%, the tensile strength actually reduced with increase in melt temperature, as shown in Graph 3.1 (page 31).

Fibre content (%)	**10 (< 4mm)**				**20**			
Melt Temp. (°C)	**155**	**175**	**195**	**215**	**155**	**175**	**195**	**215**
Tensile strength (MPa)	-	13.1	11.9	11.8	16	15	15.5	17

Table 3.5a Tensile properties of the WFRP composite at 10% and 20% fibre content

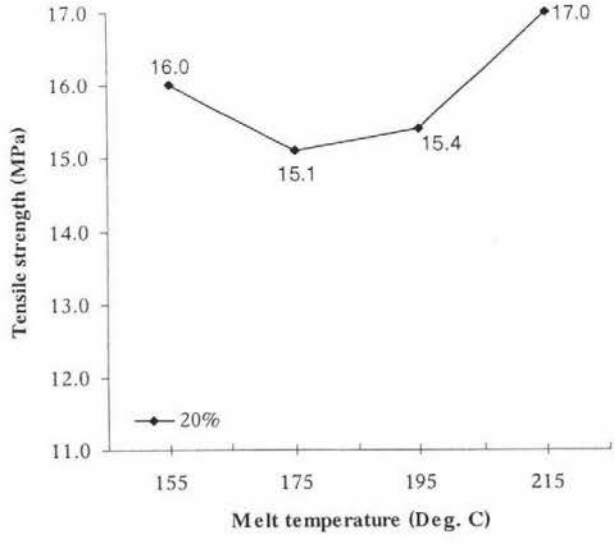
Fibre content (%)	**30**				**40**			
Melt Temp. (°C)	**155**	**175**	**195**	**215**	**155**	**175**	**195**	**215**
Tensile strength (Mpa)	19.0	20.3	17.4	17.6	17.3	18.2	19.1	-

Table 3.5b Tensile properties of the WFRP composite at 30% and 40% fibre content



Graph 3.1 Tensile strength of the WFRP composite with 10% fibre content

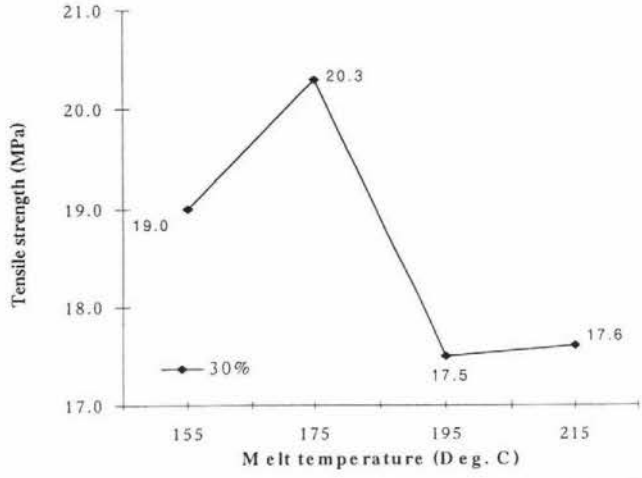
For samples with 20% fibre content, it was found that the tensile strength first decreased, and then increased, with increase in melt temperature, as shown in Graph 3.2. At temperatures like 195°C and 215°C, the polymer flows better between the fibres, thereby improving the interfacial bonding, which increases the tensile strength of the composite.



Graph 3.2 Tensile strength of the WFRP composite with 20% fibre content

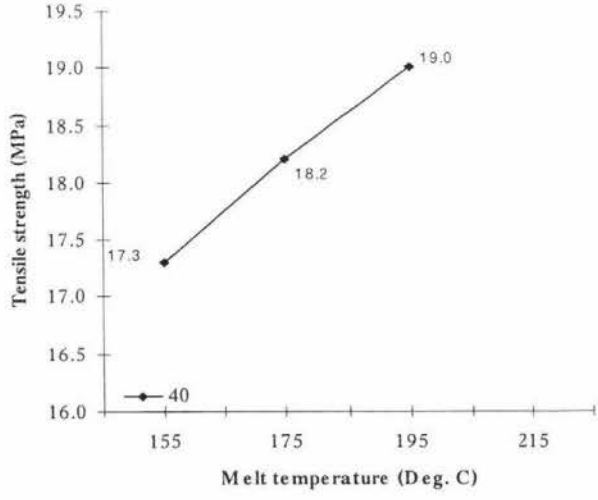
Given the fact that the tensile strength of the composite material with 10% and 20% fibre content was lesser than that of virgin MDPE, it can be concluded that at these low fibre contents, the wood fibre functioned like a filler and did not reinforce the polymer. This could be due to the low interfacial bonding between the wood fibre and the polymer, since sufficient fibre was not available to reinforce the polymer.

For higher fibre content, the tensile strength of the composite was found to be almost equal to or greater than of virgin MDPE sample. The composite material containing 30% wood fibre content, moulded at 175°C, was found to have the maximum tensile strength of 20.3MPa (Graph 3.3).



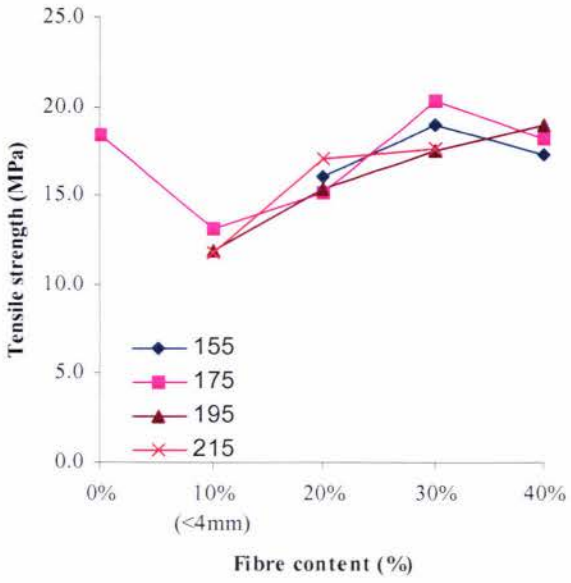
Graph 3.3 Tensile strength of the WFRP composite with 30% fibre content

As the fibre content was increased to 40%, the tensile strength began to increase with increase in melt temperature (Graph 3.4, page 33), but it dropped below the level of 30%. This could be because of the higher amount of fibre agglomeration at 40% fibre content.



Graph 3.4 Tensile strength of the WFRP composite with 40% fibre content

Graph 3.5 depicts the tensile strengths of all samples moulded at various fibre contents, for different melt temperatures. The tensile strength was first found to decrease (at 175°C) and then increased with increase in fibre content (up to 30%). It was then found to drop again.



Graph 3.5 Tensile strength at different fibre contents and melt temperatures.

At 10% fibre content, the maximum tensile strength was 13.1MPa. This increased to 17MPa for 20% fibre content. Although the tensile strength of the composite was still less than the tensile strength of virgin MDPE, it was higher than the tensile strength of the composite with 10% fibre content. This indicated that at 20% fibre content, reinforcement of the polymer is better. The ultimate tensile strength (UTS) of the composite with 30% fibre content increased to 20.3MPa, which was higher than the UTS of virgin MDPE, indicating that the fibre positively reinforces the polymer. The increase in the UTS of the composite material with the increase in fibre content is an indication of an improvement in the reinforcing property of the wood fibre. At 40% fibre content the UTS dropped to 19MPa, which could be attributed to the low fibre wetting due to increased agglomeration of the fibre in the composite.

The increase in tensile strength can be attributed to increase in the crystallinity of the polymer. Anything that affects the mobility of the polymer melt must affect its crystallinity (Rubin, 1972). The presence of wood fibre is thus thought to aid the crystallization of the polymer. The increase in density of the composite, and increase in the stiffness of the composite are further indications of the increase in crystallinity.

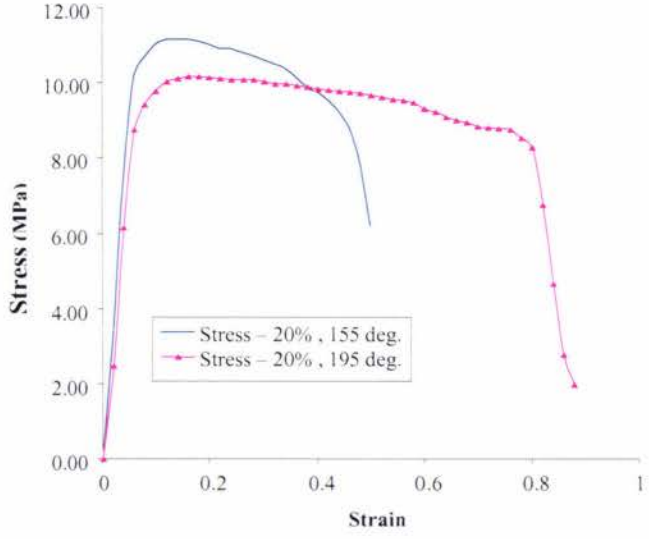
The conclusion that can be drawn from these observations is that a certain minimum amount of fibre content is required to reinforce the polymer. This is similar to the observation made by Jayaraman (2003) for sisal fibre reinforced polypropylene, but is contrary to the observations of Lee and McDonald (2001) and Abdalla *et al.* (2003), who observed a reduction in tensile strength with increase in fibre content beyond . The

possible explanation for the present composite material's behaviour is reduced fibre degradation and increased interfacial bonding between the pine fibre and the polymer.

3.13 Stress strain curves of the WFRP composite

The stress strain curves of the composite material at different fibre content were plotted from the load-displacement curves. At low fibre content (for instance, for 20% fibre content, shown in Graph 3.6) as the melt temperature increased, the material became more ductile, which is depicted by the increased strain to failure, and the decrease in its ultimate tensile strength.

At higher fibre contents, the material became more brittle, with low strain to failure. It was found on visual inspection that the stiffness of the composite material increased with fibre content.



Graph 3.6 Stress – strain curve for 20% fibre content composite at 155° and 195°C

3.14 Composite morphology

After the samples were subjected to a tensile test, their interfacial and fractured regions were analysed using a confocal microscope to understand the fibre orientation, effect of moulding the composites at various temperatures, and fracture mechanics. This would help determine the optimum temperature at which the samples could be moulded, so that the mechanical properties of the composite could be maximised. It would also help in understanding the cause of failure; whether the fracture was because of fibre fracture or fibre pullout. This would aid in deciding whether any form of chemical

treatment of the fibre or polymer was required to improve interfacial adhesion, thereby improving the properties of the composite.

3.14.1 Fibre orientation and fracture mechanics

3.14.1.1 *Fibre orientation:*

The general orientation of fibres in all samples moulded at various temperatures was found to be in the direction of melt flow (Figure 3.2). It was observed that most of the fibres were oriented uniformly, with a small proportion of the fibres (which were smaller in length) oriented randomly. Similar to the observation made by Balasuriya (2001), the fibres at various depths in the sample were difficult to differentiate, with no visible agglomeration, which indicate good dispersion in the polymer.

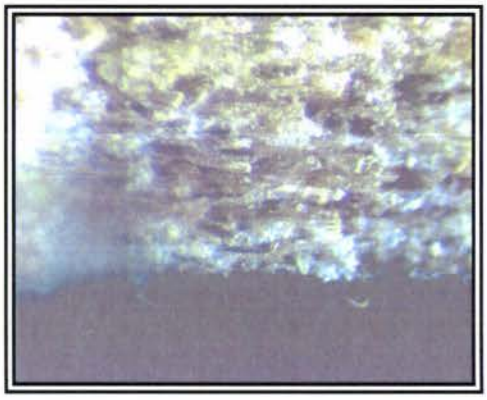


Figure 3.2 Fibre orientation of the sample (20% fibre content, moulded at 175°C)

The dispersion of the fibre in the sample (Figure 3.2 above) was lower when compared to the density of fibre dispersion in the samples with higher fibre content as seen in Figure 3.3.

Figure 3.3 Fibre orientation of the sample (30% fibre content, moulded at 175°C)

A possible explanation for this could be that at lower melt temperatures, the polyethylene powder was too cold to flow around the fibres and wet them. With the increase in melt temperature, the flow of the melt between the fibres improved. This

was further justified by the fact that it was more difficult to differentiate between the fibre and the polymer matrix in samples moulded at higher temperatures, when compared to those moulded at lower temperatures, and with low fibre content.

3.14.1.2*Fracture mechanics*

Close examination of the fractured region of the sample with a fibre content of 20% moulded at 155°C, showed the fibres to be randomly oriented. Fibre pullout was observed (Figure 3.4). This indicated that the interfacial bonding between the fibre and the polymer was not very strong, which explained why the tensile strength of the composite was less than that of virgin MDPE.

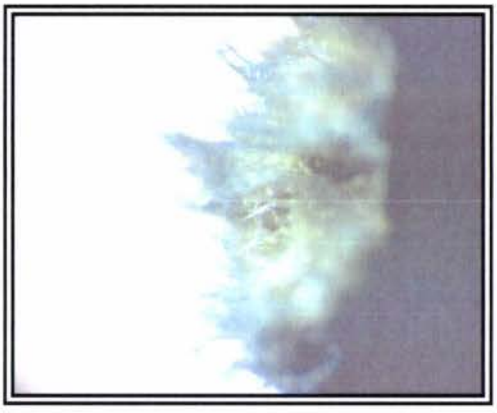


Figure 3.4 Fracture of the sample at 155°C (20% fibre content)

In samples with 10% and 20% fibre content, the fibres were loosely enveloped by the polymer, and when stretched, were easily displaced from their orientation. This explanation reinforced the previously made observation that at lower temperatures, the molten polymer was too cold to properly impregnate the fibre. The higher load bearing capability of the samples, accompanied by low elongation before fracture, also suggest that the interfacial bonding between the fibre and the polymer was weak.

Figure 3.5 (page 37) shows the fracture of the sample moulded at 195°C with a fibre fracton of 20%. Tearing of the polyethylene polymer was observed, which indicated better interfacial adhesion between the fibre and the polymer. The material was found to yield prior to fracture, which was a further indication of improved fibre – polymer adhesion.

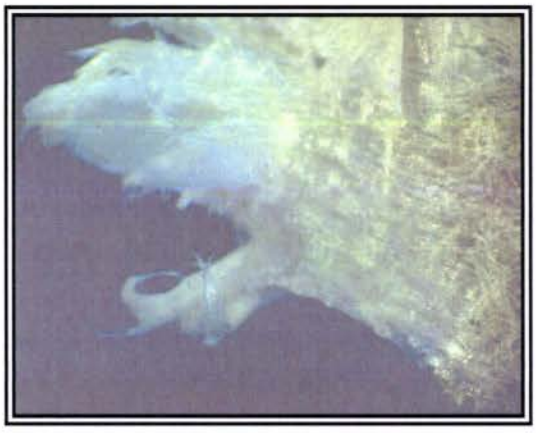


Figure 3.5 Fracture of the sample at 195°C (20% fibre content)

3.14.1.3 Effect of Clumping:

At higher fibre content, due to inter-fibre hydrogen bonding, fibre – fibre attraction could not be avoided. A sample with such an irregularity is shown in Figure 3.6 and the fractured region is shown in Figure 3.7

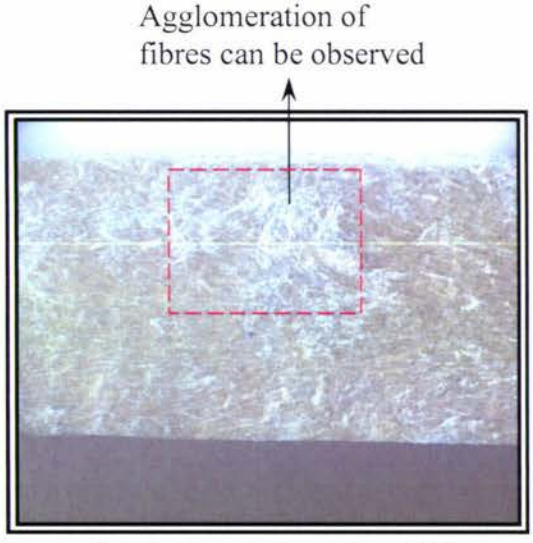


Figure 3.6 Effect of clumping of fibres

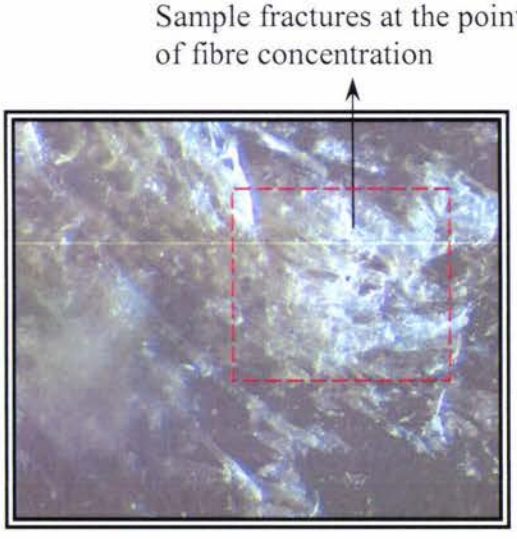


Figure 3.7 Fractured region

Such fibre clumping can prove to be detrimental to the strength of the composite material, because it results in non-uniform distribution of load, leading to simultaneous fracture at multiple locations in the sample, at loads well below its optimum load-bearing capacity.

3.14.1.4 Effects of melt temperature and fibre content:

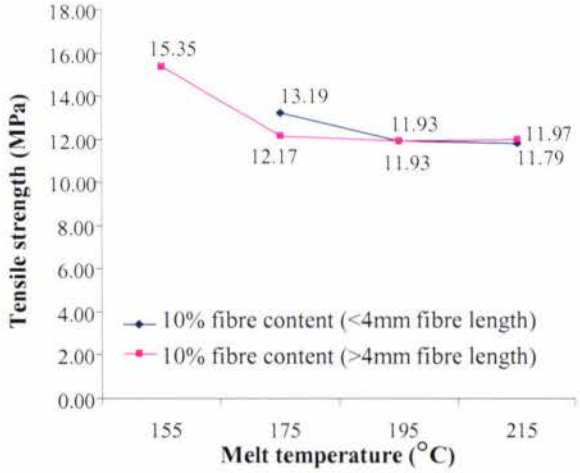
The statistical analysis performed using SAS (Appendix B) revealed that the effect of melt temperature by itself on the tensile strength of the composite was not highly significant ($p = 0.03$). On the other hand, the effect of fibre content by itself was

found to be highly significant ($p < 0.001$). Similarly, the interaction between melt temperature and fibre content was also found to be highly significant ($p < 0.001$). This indicates that the tensile properties of the material can be modified to a large extent by varying its fibre content alone, and to a lesser extent by changing the temperature at which the material is injected into the mould. The tensile strength is maximum when the fibre content – melt temperature combination is 30% & 175°C.

3.14.1.5 Effect of fibre length

Results of the statistical analysis revealed that at 10% fibre content, fibre length did not have a significant effect on the tensile strength of the composite material with 10% fibre content ($p = 0.2395$). Its interaction with melt temperature is also not significant ($p = 0.1116$). This shows that samples moulded at various melt temperatures will have nearly the same properties, irrespective of the fibre length.

The effect of change in fibre length on the tensile strength of the composite was not significant, as depicted in Graph 3.7. With the increase in fibre length, the tensile strength decreased with the increase in melt temperature. The result is in agreement with the fact that the critical length of the fibre is lower when a polymer matrix has a high melt flow rate. Based on the work by Joseph *et al.* (1996), it can be concluded that the critical length of radiata pine fibre is around 4mm.



Graph 3.7 Effect of fibre length on tensile strength of the 10% WFRP composites

With increase in fibre length, it was observed that the fibre distribution was not uniform (Figure 3.8, page 39). Areas where fibres were concentrated more than other regions can be seen. The flow of polyethylene around the fibres is also clearly visible.

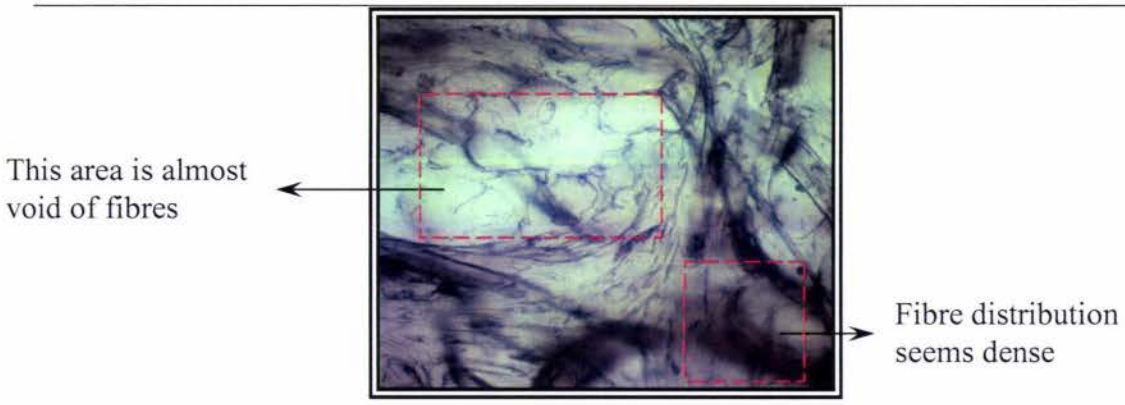


Figure 3.8 Orientation of fibres (fibre length: > 4mm, 10% fibre content)

It was observed that the longer fibres were subjected to pullout during the tensile test (Figure 3.9). The figure shows whole strands of fibres being pulled out.

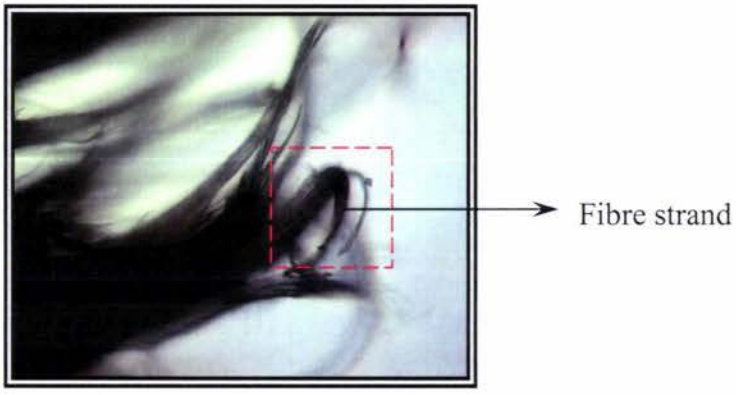


Figure 3.9 Fractured region of the sample (fibre length > 4mm, 10% fibre content)

As reported by Pickering *et al.* (2003), the decrease in tensile strength for composites with longer length fibres could have been because of non-uniform fibre dispersion in the composite.

3.15 Miscellaneous properties

3.15.1 Colourability

The black master-batch used was uniformly distributed throughout the length and thickness of the sample. Other colours were not attempted due to time constraint.

3.15.2 Flammability

The material was found to be flammable, but did not ignite instantaneously. It was observed that the flame was sooty. The composite did not melt or drip on ignition, which was observed with the virgin HDPE and MDPE samples.

3.15.3 Water absorption

When immersed in water the composite material absorbs moisture and gains weight as given in Table 3.6. An increase of 0.15% in weight was observed on immersion of the samples in water. The water uptake in the composite should be as low as possible in order to prevent degradation by bacterial and microbial attack.

Sample	Wt. of sample before immersing(g)	Wt. of sample 36hrs after immersing (g)	Difference of water uptake
A	6.6707	6.6808	0.0101
B	6.9239	6.9335	0.0096
C	6.7613	6.7761	0.0148
D	6.8467	6.8600	0.0133
E	6.9432	6.9480	0.0048
Average	6.8291	6.8396	0.0105

Table 3.6 Change in the weight of the composite due to water absorption

CHAPTER 4

PRODUCT DEVELOPMENT - METHODS & RESULTS

4.1 Introduction

This is *Phase 2* of the project. The results of "*Phase 1: Material Development and Testing*" are fed into the opportunity identification step of Phase 2.

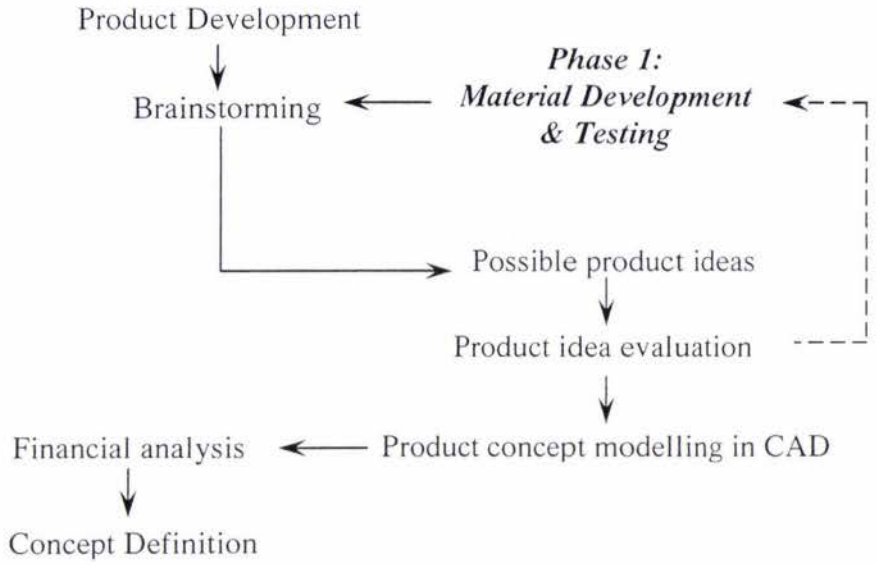


Figure 4.1 Flowchart of the WFRP product development process employed

4.2 Product Development Strategies

There are two strategies for introducing new products into the market: *market-driven* and *technology-driven*. Product Development and Management Association (PDMA®) generically defines market-driven strategy as '*allowing the marketplace to direct a firm's innovation process*'. This could imply that the company solicits customer's needs or conducts consumer and market research to guide their new product development. PDMA defined technology-driven products as '*a new product or new product strategy (that is) based on the strength of a technical capability*'. Innovative companies that develop true technology-driven products begin with a new technology that has often been discovered serendipitously. They then hunt for products that can make use of the technology. Instances of such products include 3M's Post-It™ Notepads and Scotchguard™ Fabric Protector family of products. There is consensus in the research community that any product that is driven solely by the market or technology is often doomed to fail, because they cannot be mutually exclusive (Volker, 1988; Cooper, 1994; Himmelfarb, (n.d)).

In this context, Himmelfarb (n.d) noted that while market-driven companies ran the risk of losing their market share to competitors who were more technology savvy, products developed purely on new technology had a greater risk of failure since the company lacked a market to which the product could be sold. The company had the burden of creating a market for the technology where none apparently existed at that time. The company then had to solicit customer needs and adapt the technology to suit the needs of the customer for the product to succeed in the market, since the new technology by itself was not sufficient to generate a market. The author argued that unless a company had surplus cash reserves and lots of time, it was better to avoid the development of technology-driven products.

The present project was based on the development of a technology-driven product. It involved the development of a wood fibre reinforced composite material, attempted to identify applications for the material, and tested a product concept.

The entire product development process can be divided into two stages: *Fuzzy Front End* (or Front End of Innovation) and *New Product Development process* (or Stage-Gate™ process). Miller (2002) notes, 'fuzzy front end begins at the point when a need exists that can be identified and technology exists that can meet the need'. Rosenau (1996) and Koen *et al.* (2002) are of the opinion that this distinction was made in order to stress the highly experimental, chaotic, and unpredictable nature of the initial phase of developing a new product, a scenario that was prevalent while developing new products based on technology-driven strategy. Those involved in developing the new technology had to first familiarize themselves of the real benefit and value of the new technology, before they could embark on actually developing a product based on the new technology (Himmelfarb, (n.d)).

In the current project, a composite material was developed, which involved reinforcing virgin MDPE powder with pine wood fibre. Some of its properties were studied as detailed earlier. This phase was purely experimental and involved working with various ratios of wood fibre and polymer. At that point of time, the application of the material was not clear, which indicated the fuzzy or uncertain nature involved in the development of a true technology-driven product.

4.3 Process adopted for the Fuzzy Front End (FFE) of New Product Development

The process adopted for the development of market-driven products has been well documented. Most of the processes for such products reported in the literature begin with listening to the voice of the customer, and have a dedicated stage at the start of the product development process to 'identify and understand the market and the customer's needs' (Cooper, 1994; Ulrich and Eppinger, 2000; Carson and Steller, (n.d)). Similar studies for technology-driven products are scarce. Some researchers have tried investigating the FFE of New Product Development in the hope of resolving some of its uncertainty, and establish some sort of structure to the stage (Rosenau, 1996; Koen *et al.*, 2002).

Rosenau (1996), in his research on the type of development process that a company could adopt for developing new products, limited the FFE to the idea generation and sorting stage. According to his theory, the plausible idea that resulted from the FFE process and entered the NPD process had to be analysed for unknowns relating to the market, technology used to develop the product, and production process. If these unknowns were substantial, the idea went through a *feasibility study* stage, which might result in some refinement to the idea.

Koen *et al.* (2002) developed a five-stage theoretical *New Concept Development* (NCD) model to explain the FFE stage prior to NPD (Figure 4.2, page 44). According to their model, FFE begins with *identifying an opportunity* that a company may want to pursue, followed by *analysis of the opportunity*. The opportunity could be a new manufacturing process or the development of a new material, aimed at capturing a competitive advantage, solving a problem, or reducing the cost, and should be driven by the company's goal. The next stage is to *identify an idea* that would make use of the new technology developed, which is analysed in the fourth stage of the NCD model. The two stages are iterative, wherein ideas are proposed, analysed, modified, in conjunction with the other stages of the model. Further, this stage may feed back into the opportunity identification stage, which demonstrates that the various stages proceed in a non-linear fashion. The final element, *concept definition,* justifies the investment that needs to be made by the company to take the idea from the concept level through to commercialization.

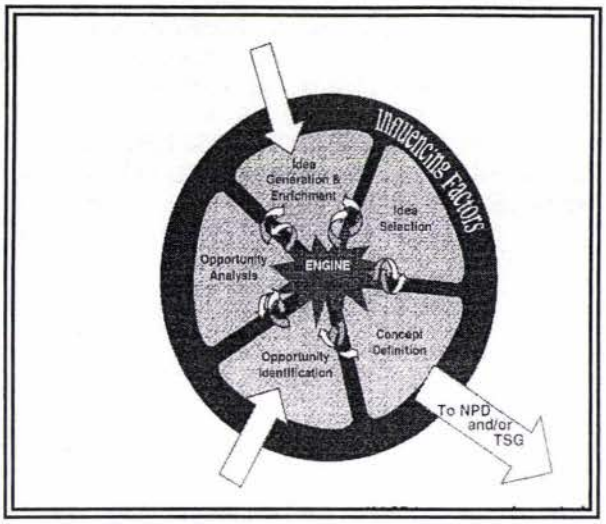


Figure 4.2 NCD model proposed by Koen *et al.* (2002) for the FFE stage

Kelley (2000) suggested a "*Concept-Centered Process*" model that began with identifying customer's needs and understanding the market (indicating a market-driven approach), but resulted in breakthrough, 'new-to-the-world' products at a faster speed, than those processes that required management control. This was because the process gave little importance to management support, and emphasised on quick, focused benchmarking to identify the relevant technology. From the model, it is not clear how advanced the technology would be. The process was thought to be suitable for consumer products, since the process laid importance on direct interaction with the customer.

In the present project, a development process similar to the NCD model (page 43) has been adopted. The availability of enormous amount of Radiata Pine fibre presented the issue of determining a use for it. This was transformed into an opportunity when a composite material was developed that possessed better tensile strength than virgin MDPE powder, and this phase was marked by significant amount of experimental activity and testing. This led to the idea generation stage, in which a structured method was adopted to generate product ideas. Since the idea involved substantial unknowns relating to the market, technical, and financial viability, a feasibility study was undertaken, the methods of which are discussed in the sections below.

4.4 Idea generation (Iteration 1)

Techniques used for idea generation

In recent years, many tools and techniques have been developed to generate ideas. These include techniques like *brainstorming* and *focus groups* with customers and lead users. Software tools that aid in idea generation like Idea Fisher® and

MindMapper® have also been developed. Feig (n.d) and Robson (2001) were of the opinion that business opportunities and new product ideas had to be customer-oriented from the FFE stage itself. Failure to listen to the voice of the customer at this stage would lead to loss of many good opportunities.

For the present research project, brainstorming technique was adopted to generate product ideas that would use the WFRP composite material. Customers and lead users were not approached during this stage, since the technical feasibility of the composite material had to be ascertained before their needs could be gathered. The Masterate student, along with three staff members, one each from the Product Development department, Manufacturing and Industrial Technology department, and Packaging Technology department, had a brainstorming session to come up with possible ideas for the new material. The basic criterion for generating ideas was that the product had to be injection mouldable, while the selection criterion was that the product had to be *new* to the market. More than 50 ideas were put forth, and have been categorised in Table 4.1.

Idea / Category	Sector	Type: Substitution/New
Fire logs, restaurant candles, fire starters	Consumer	Substitution
Benches, tables, chairs	Furniture	Substitution
Toys, bullets (air guns), props	Entertainment	Substitution
Picture frames, handles, can holders	Consumer	Substitution
Immobilization casts, helmets, safety gear	Medical / Safety	Substitution
Building foundation: permanent boxing	Building	*New*
Recycling bins	Environment	Substitution
Reflective cones	Transportation	Substitution
Toilet seats	Consumer	Substitution

Table 4.1 Results of the brain storming session

As can be seen from Table 4.1, all product ideas that the group came up with, except for one, were 'substitution' products. The building foundation permanent boxing product was selected because of its newness. The following paragraphs further elaborate on this product.

4.5 Building foundation insulation and boxing product

NZS 4218 '*Energy Efficiency – housing and small building envelope*' of the New Zealand Building Code (NZBC) specifies the minimum legal requirement for efficient energy use in New Zealand buildings. Insulation improves the comfort of the house, saving the house owner money on heating bills, and home maintenance (Anon., 1997). The standard lists different combinations of minimum R-values (thermal resistance value) of insulation that can be incorporated in a floor, roof, and wall of a building. New Zealand is divided into three zones – Zone 3 covers all of South Island and central plateau of North Island. The insulation requirements for areas in this zone are different from those of zones 1 and 2, which covers the remaining part of the country.

Data collected from the local Palmerston North City Council indicate that 99% of all residential buildings built in New Zealand have concrete flooring. For the purpose of building regulations, the thermal insulation value of concrete on-slab flooring is considered to be equal to that of foil insulated timber floors, both of which have an R-value of 1.3. This is actually the average relative thermal performance over the entire concrete floor area, although in reality, the R-value is the maximum at the centre of the floor and reduces towards the floor edges, where the heat loss is much greater. This indicates the need to insulate the foundation of the building, since it acts like a heat sink (Harper, 2003).

Attempts have been made to insulate the walls and foundation of residential buildings. The methods are based on research into heat flow paths from concrete slabs, which indicate that the heat loss can be interrupted by inserting insulation barriers at any point under or outside the building (Harper, 2003). Harper (2003) reported the methods of insulating the concrete foundation to prevent heat loss. The method employed a one-metre wide, 25mm thick Expanded Polystyrene (EPS) foam or sheet placed all around the perimeter of the foundation, as shown in Figure 4.3 (page 47). An obvious disadvantage of this system is that additional covering over the EPS foam insulation is required to protect it from dampness, mildew, mould, and wear and tear.

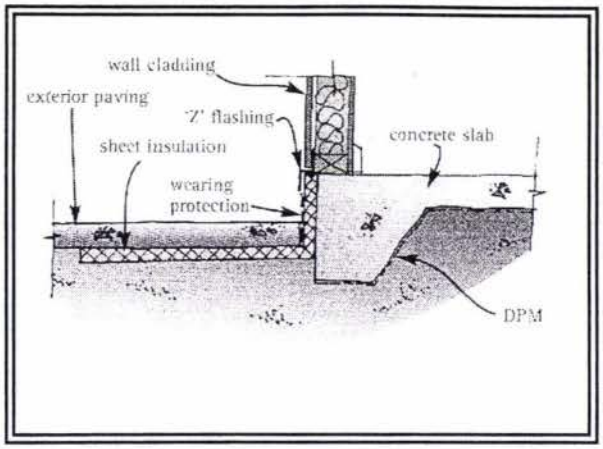


Figure 4.3 A method to insulate the building foundation (Harper, 2003)

Apart from the issue of insulating the house, building contractors and house owners face the following problems:

1. The formwork boxing, in its existing form, needs to be assembled before pouring the concrete, dismantled and cleaned after the concrete has set, so that the timber can be reused in the construction of the house. This is a tedious and time-consuming process.
2. Once the concrete has set and the formwork removed, the surface finish on the foundation exterior is quite rough and not aesthetic in appearance. Presently, this requires an additional step of plastering with cement, which is expensive and time consuming.

The proposed new product could be designed, which would provide the following benefits:

1. The product could improve the house insulation, depending on its R-value.
2. The product could be designed so that the concrete could be poured inside a block, which would then become a part of the foundation. This would reduce the labour involved in constructing the foundation by eliminating the use of timber. There would be no need to dismantle and clean the timber once the concrete had set.
3. It would be easier and less time consuming to assemble these blocks together than constructing the formwork boxing. The product could also incorporate clips within it that could support the reinforcement steel bars.
4. The product forms a part of the foundation and covers the foundation wall. By eliminating the use of timber, there would be no marks on the foundation

exterior, and when covered with the product would give the foundation a more finished look.

Having identified a need for a product that could be manufactured using the WFRP composite material, it was necessary to determine whether the material possessed the properties that met the demands of the product. Specifically, the material's R-value had to be measured. Based on the measured properties of the material, product concepts would be modelled using SolidWorks and their performance analysed using COSMOS software, to determine the technical viability of the material. A broad financial model would also be developed to assess the financial benefits of such a product. The following paragraphs explain the methods adopted to measure the new set properties, the design of the product concepts. The results of the tests and analysis of the performance of the concepts are also reported.

4.6 Opportunity Analysis (Iteration 2)

4.6.1 Measurement of WFRP composite material's thermal resistivity

The experimental apparatus was built as detailed by Brown (1988), with some modifications and assumptions. The apparatus is as shown in Figure 4.4 (page 49). It consists of the composite sample sandwiched between two mild-steel plates. Plate 'A' is maintained at a constant temperature of 90°C by circulating hot water through it. Plate 'B' is maintained at a lower temperature by circulating cold water through it. In order to ensure that the heat is uniformly applied on the sample, a thin aluminium plate (plate 'C') was placed between plate 'A' and the sample. Heat loss from plate 'A' was minimised by insulating the exposed surfaces by polyurethane (PU) foam.

A K-type thermocouple with a temperature range of –200°C to +1370°C was used to measure the temperature difference between the two surfaces. Two holes of diameter 0.8mm were drilled on the gauge length area of the test specimen, as close to the surfaces as possible, as shown in Figure 4.5. The probes of the thermocouple were inserted into the holes for a period of one hour, during which time the temperature of the hot plate stabilised. The difference in temperatures was noted directly from the thermocouple display.

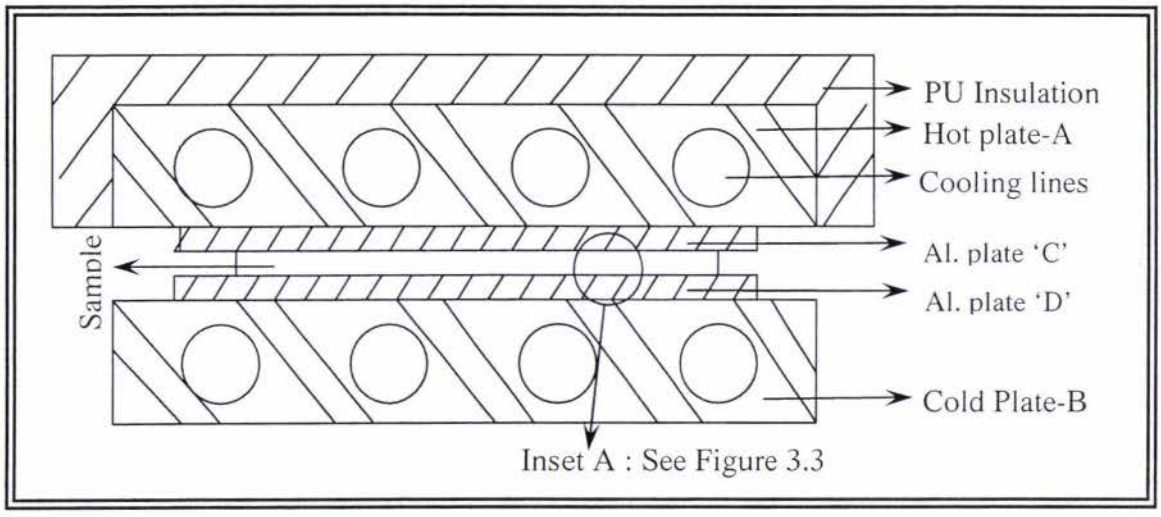


Figure 4.4 Apparatus to measure the R-value of the WFRP composite material.

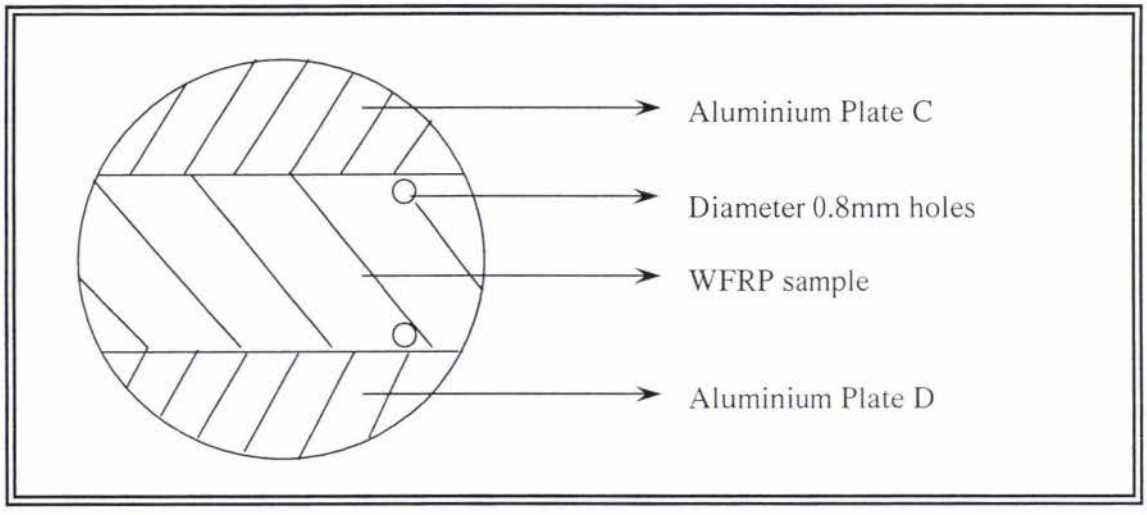


Figure 4.5 Enlarged view of Inset A in Figure 4.4

A number of assumptions were made while calculating the thermal resistivity of the material. They are:

1. Plates A, B, C, and D are perfect conductors, or that the major surfaces are isotherms.
2. The tensile test sample was used as the sample for determining its thermal resistivity. The surface area was determined by accurately modelling the sample using the CAD package, SolidWorks 2001 Plus.

The thermal conductivity of the material is given by using Fourier's Law of Heat Conduction,

$$K = \frac{Qx}{A(\partial T)} \qquad \text{... Eq. 4.1}$$

where,

K = Thermal conductivity of the material (W/mK)

Q = Amount of heat flow (W) in the direction of the thickness of the specimen

x = Thickness of the specimen (m)

A = Surface area of the sample (m^2)

∂T = Difference in temperature between the hot and the cold surfaces (K)

The thermal conductivity (K) of the WFRP composite material was determined using the 'k' value of MDPE. From Eq. 4.1a for a given sample,

$$K \alpha \frac{1}{\partial T} \quad \text{... Eq. 4.2}$$

$$k \alpha \frac{1}{\partial t} \quad \text{... Eq. 4.3}$$

For a given quantity of heat flow (Q) through the samples, Eq. 4.2 and 4.3 will be proportional. Thus,

$$K \alpha \frac{k(\partial t)}{\partial T} \quad \text{... Eq. 4.4}$$

The thermal resistance 'R' (mK/W) of the WFRP sample is then given by,

$$R = \frac{1}{K} \quad \text{...Eq. 4.5}$$

Known limitations of the apparatus are:

1. Certain unknown amount of heat loss occurs from the uninsulated surface of the hot plate 'A' and also from the Aluminium plate 'C'. This could result in the incomplete heat transfer from the hot plate to the specimen, through the aluminium plate.
2. The sample used was not a standard test specimen, and since the thermal conductivity is dependent on the area of the sample, the use of a non-standard specimen results in approximate values for 'R'. The results of this test are thus not completely accurate.

4.6.2 Results of the test to determine the R-value of the composite material

First, the amount of heat flow through a MDPE sample (k = 0.33) was calculated. The temperatures on the hot and the cold surface were measured to be 60.1°C and 57.2°C respectively after a period of one hour.

From Eq. 4.3, we know that,

$$k\alpha \frac{1}{(\partial t)}$$

where, k = 0.33 W/mK (of MDPE)

$\partial t = T_1 - T_2 = 60.1 - 57.2 = 2.9°C$ (or 2.9 K) (of MDPE)

The thermal conductivity of the WFRP composite (10%, 20% and 30% fibre content) was calculated for the same amount of heat flow. The temperatures were measured to be as given in Table 4.2.

Fibre content / Temp.	T_1 (°C)	T_2 (°C)	∂T (°C) = $T_1 - T_2$
10%	68.6	41.6	27
20%	65.3	42.6	23.3
30%	70.2	41.6	28.6

Table 4.2 Temperature gradient measured for WFRP composites at various fibre concentrations.

The values of 'R' of the WFRP composite at 10%, 20%, and 30% were determined to be as shown in Table 4.3 below. Detailed derivations of the values are given in Appendix C

Fibre content	Thermal Resistivity (R – Value) (mK/W)
10%	2.45
20%	2.77
30%	2.86

Table 4.3 Calculated R-values of WFRP composites at various fibre concentrations.

Walls that are externally insulated require an insulation with the R-value of 0.7 (Broeke, 2001; page 60). As shown above, the R-value of this product is more than 1.33 (R – value of EPS), which indicates the suitability of this material for use in a product developed for insulating building exteriors.

4.7 Idea Analysis (Iteration 1)

4.7.1 Product concept design: Methods

Insulation block concept designs were modelled using SolidWorks 2001 Plus. The next section details the various iterations. A static stress analysis was performed using COSMOS software, to analyse the behaviour of each concept. The material

properties specified for the model is as given in Table 4.3, which was then modelled with a solid mesh of size 10mm.

Boundary conditions: The two end faces of the insulation block are assumed to be immovable (depicted by the green arrows in Figure 4.6), that is, they do not undergo translation under the application of load. The two parallel inside faces, perpendicular to the fixed surfaces are subjected to a uniform and variable pressure of 23544 Pa (Appendix D), which is the pressure exerted by the concrete on the foundation formwork. The red arrows in Figure 4.6 depict this condition.

It needs to be mentioned here that the aspects of design to manufacture (DFM) have not been considered in great depth, as the purpose of this analysis was to test the feasibility of the product idea.

Property	Value
Elastic Modulus	0.2 GPa
Poisson's ratio	0.28
Tensile strength*	20.3MPa

Table 4.3 Properties assigned to the material of the CAD model to assess its behaviour (*UTS of WFRP composite containing 30% fibre, moulded at 175°C)

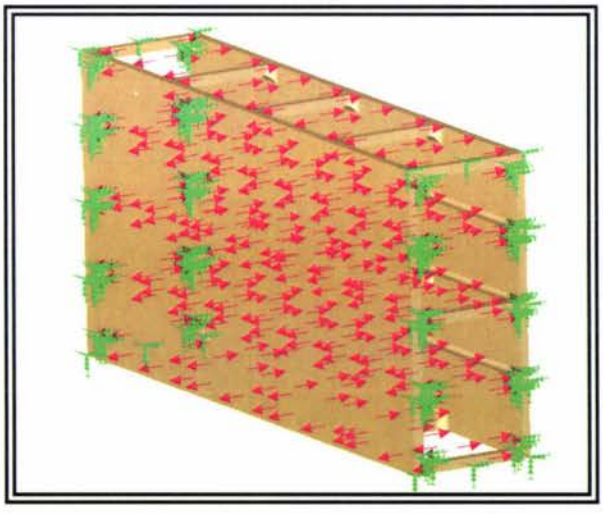


Figure 4.6 Boundary conditions for analysing the behaviour of the WFRP product.

4.7.2 Product concept design: Results

Figures 4.7 to 4.22 detail the iterations and results of the static analysis of the product concept to be used as a permanent formwork boxing and foundation insulator.

4.7.2.1 Iteration 1

The basic design is a hollow web structure, 10mm thick. It is 600mm in length, 300mm in width and the overall thickness is 150mm (Figure 4.7).

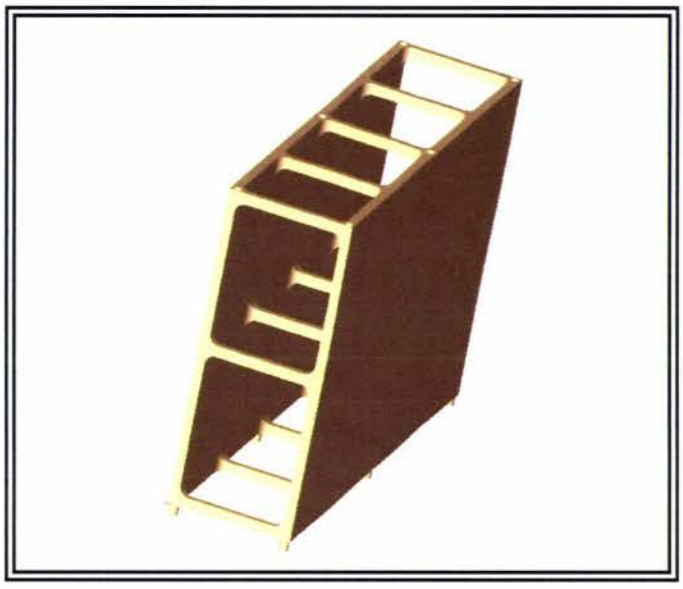


Figure 4.7 Concept 1 for foundation insulation product.

The pressure exerted by wet concrete on the foundation formwork would vary throughout the height of the foundation and depends on the composition of the concrete. The variable pressure exerted by wet concrete is given by Equation 4.6 (SolidWorks User's Manual, 2001).

$$p * (A + Bx + Cy + Dxy + Ex^2 + F y^2) = P(x,y) \quad \ldots \text{Eq. 4.6}$$

where,

p = a value by which the equation would be scaled to give the pressure at any point x,y on the part = 23544 N/m^2

P(x, y) = co-ordinates at which the pressure P is exerted = varies from 0 to 23544N/m^2, at co-ordinates (0m, 1m) and (0m, 0m) respectively.

A,.. .F = coefficients which will be scaled by 'p' to determine the pressure at that point.

It was determined that the pressure varied from 0N/m^2 at the top to 23544 N/m^2 at the bottom. One of the solutions to Eq. 4.6 which has been used for this analysis was derived to be,

$$P(x, y) = p(y^2 - 2y + 1) \quad \text{...Eq. 4.7}$$

The criteria for applying the variable load, the derivation of the equation and the coefficients A to F for the present product is given in Appendix D.

The displacement plot for concept 1 is shown in Figure 4.8. It indicates a maximum displacement of 5.4mm (orange areas in the plot).

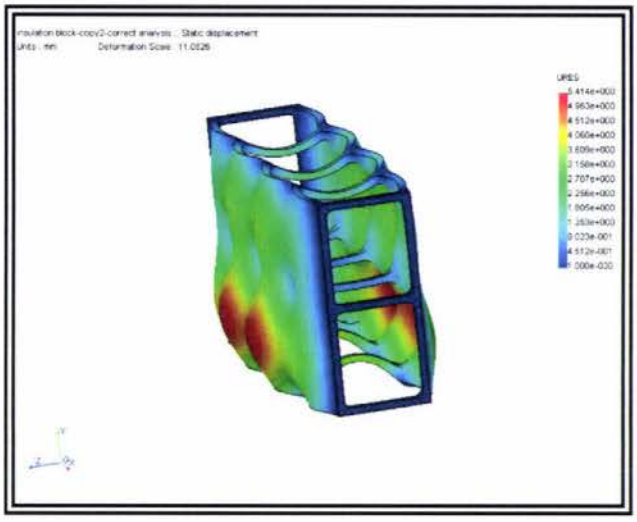


Figure 4.8 Displacement plot for Iteration 1

The maximum stress is in the centre rib, and has a magnitude of 5.69 x 10^6 Pa (5.69MPa) (Figure 4.9). The maximum stress induced in the product is well below the ultimate tensile strength of the material of 20.3MPa.

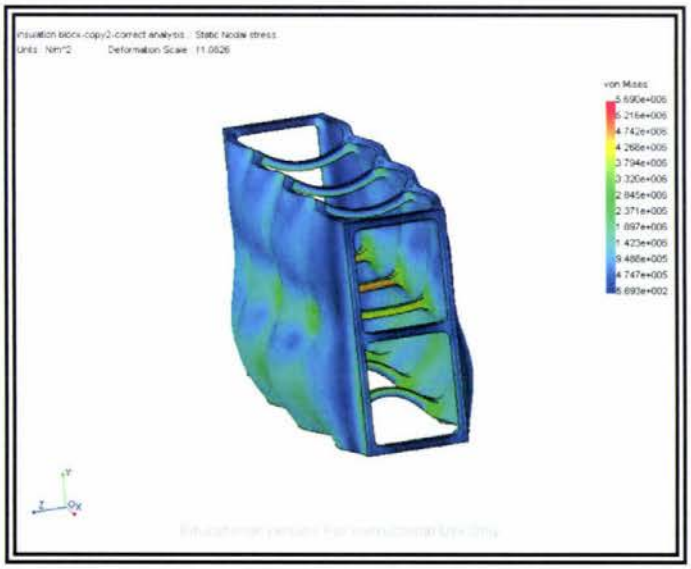


Figure 4.9 Stress plot for Iteration 1

From the stress strain curves developed earlier in Chapter 3, it was observed that the composite material suffered from a low strain to failure. For this concept, the central

rib, which is predicted to be the weakest section of the product, is subjected to a strain of 0.02 (Figure 4.10).

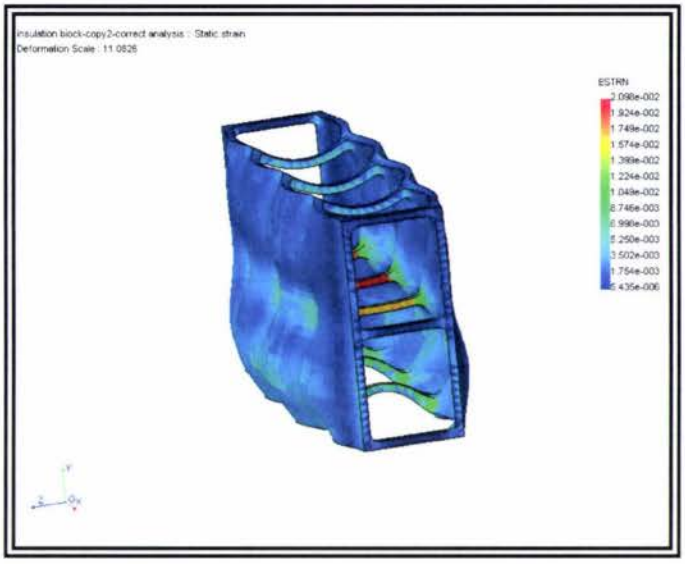


Figure 4.10 Strain plot for Iteration 1

4.7.2.2 Iteration 2

The design change for this iteration is the addition of a rib at three locations as shown in Figure 4.11 (page 56). From the first iteration, the area of maximum displacement and stress was observed. The addition of a rib of the same thickness as the part should help reduce the displacement on the product as well as the stress on the central connecting ribs.

Figure 4.11 Changes in product for Iteration 2

As anticipated, it can be observed from Figure 4.12 that the maximum displacement has dropped to 3.99mm from 5.4mm in the earlier iteration, due to the changes effected in the design of the part.

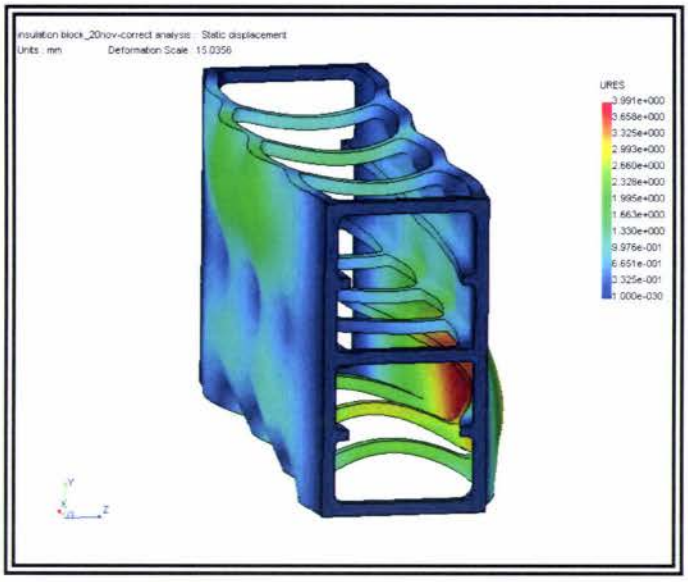


Figure 4.12 Displacement plot for Iteration 2

The maximum stress in the connecting also dropped to 4.73MPa from 5.69MPa as can be observed from Figure 4.13.

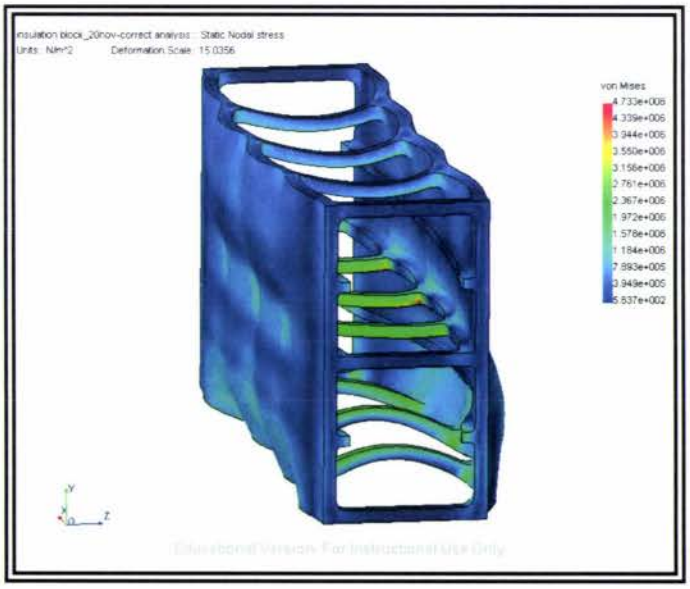


Figure 4.13 Stress plot for Iteration 2

The strain in the connecting ribs is also reduced from 0.02 to 0.01, as can be seen from the strain plot in Figure 4.14.

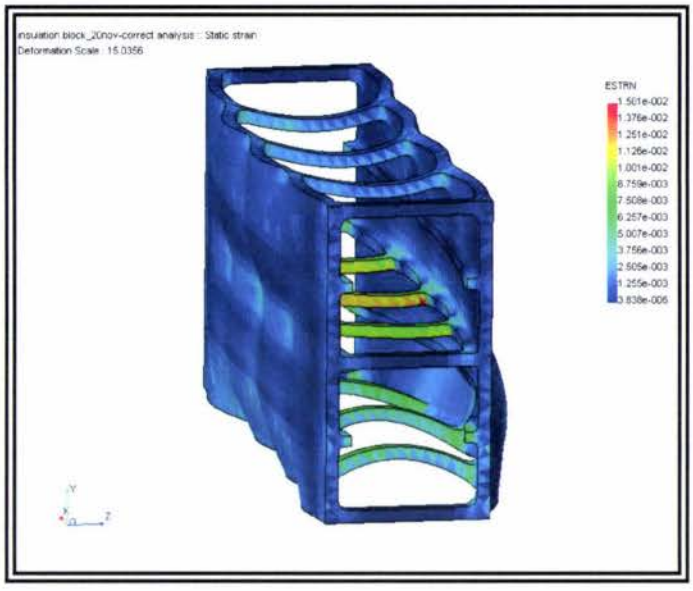


Figure 4.14 Strain plot for Iteration 2

4.7.2.3 Iteration 3

The basic design in this iteration is the same as that of Iteration 2, the only difference being in its length, which is now 300mm instead of 600mm. An additional vertical rib in the centre of the block has also been incorporated, as shown in Figure 4.15 (page 58). This was to minimise the buckling of the part.

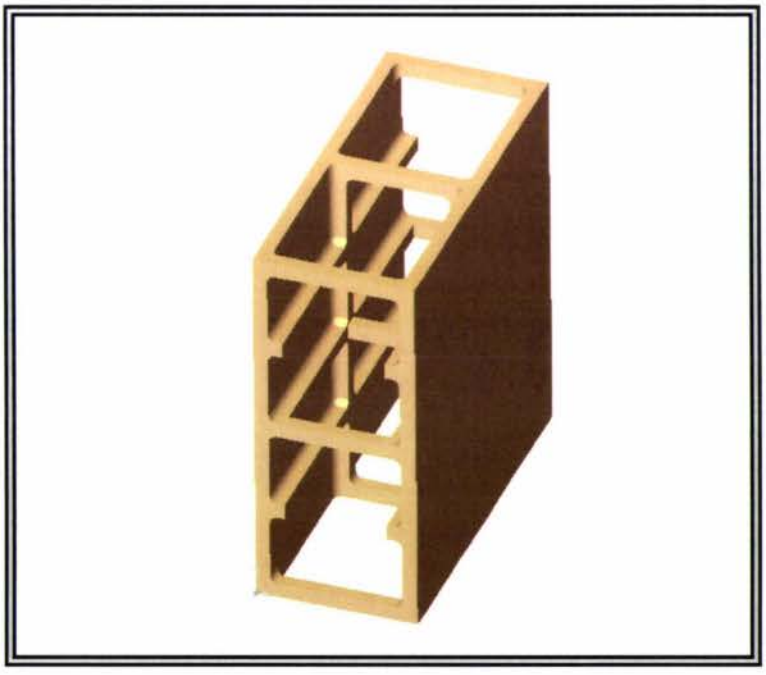


Figure 4.15 Iteration 3 for the proposed product

Under the variable pressure exerted by the wet concrete, it was found that the maximum displacement in the product was now 1.05mm at the base of the product (Figure 4.16).

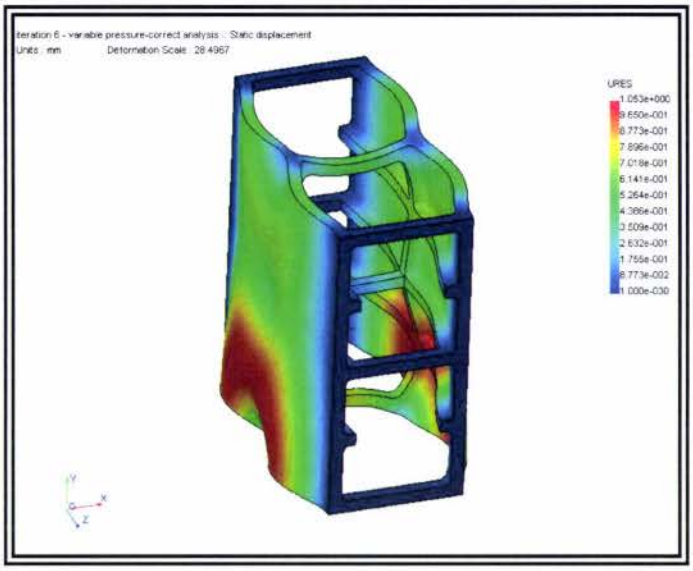


Figure 4.16 Displacement plot for Iteration 3

The maximum stress induced in the connecting ribs was 2.29MPa (figure 4.17), with a strain of 0.008 (Figure 4.18, page 59).

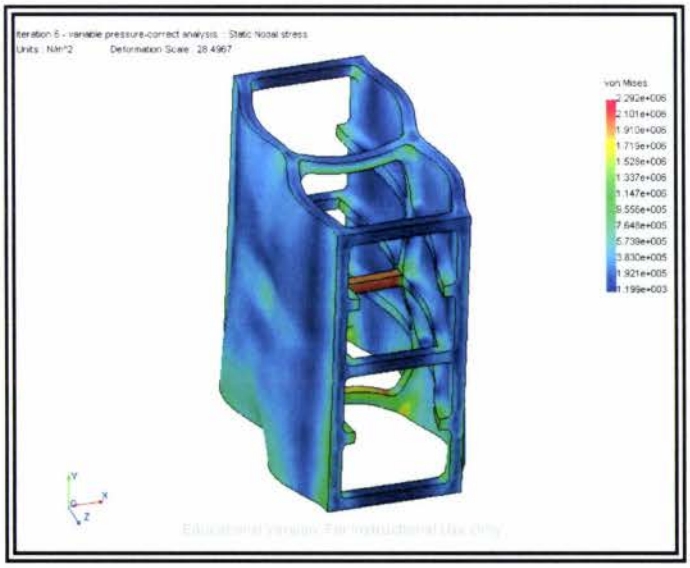


Figure 4.17 Stress plot for Iteration 3

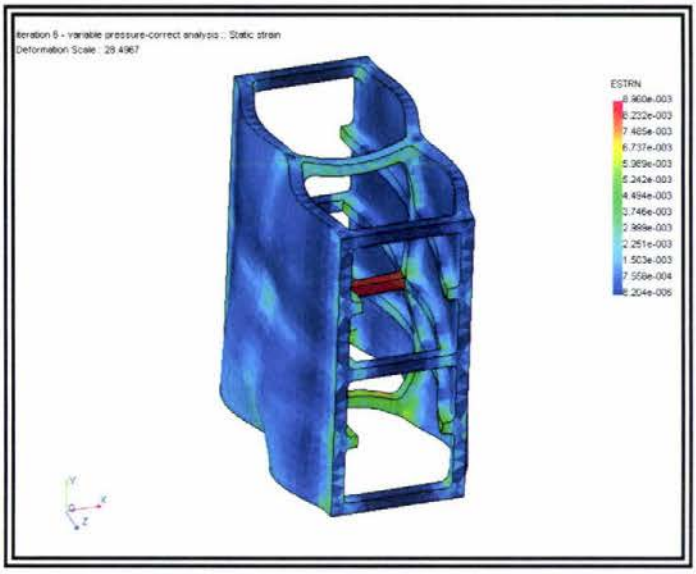


Figure 4.18 Strain plot for Iteration 3

4.7.2.4 Performance analysis as an assembly

Figure 4.19 shows the assembly of the product, as it would be used to construct the foundation. It has been included only to study the performance of the concept in its assembled form.

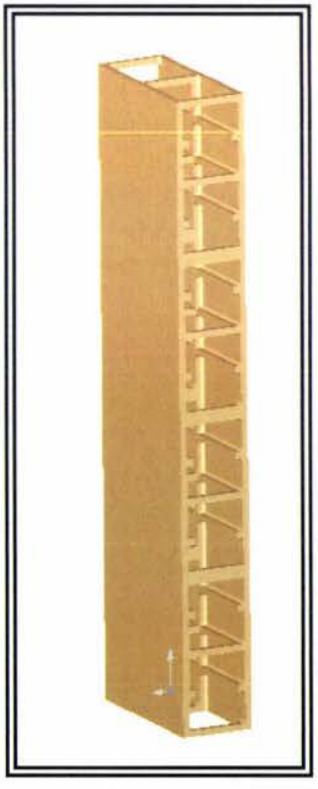


Figure 4.19 Complete assembly of the product

The maximum displacement in the assembly is found to be 1.28mm (Figure 4.20).

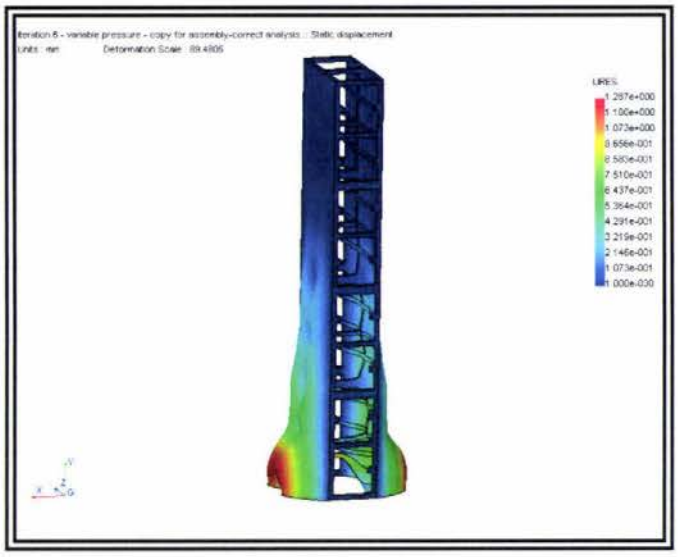


Figure 4.20 Displacement plot of the assembly

The maximum stress induced increases slightly to 2.65MPa (Figure 4.21).

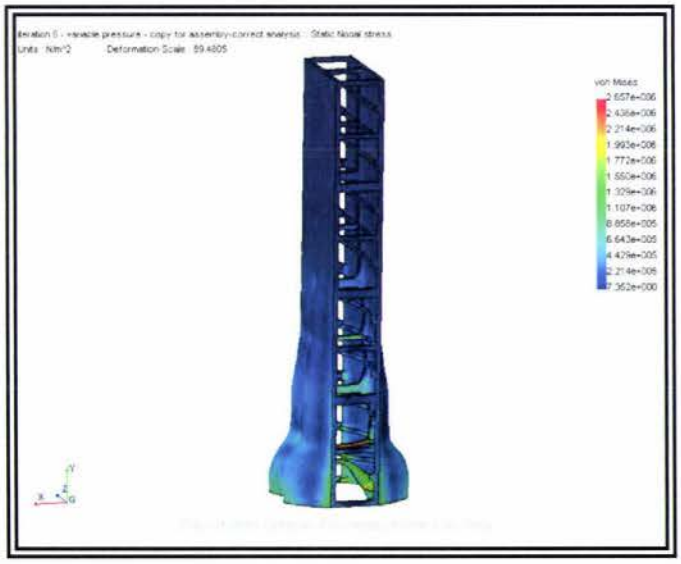


Figure 4.21 Stress plot of the assembly

The maximum strain is found to be 0.01 in the lowest connecting rib, as can be seen from Figure 4.22 (page 61).

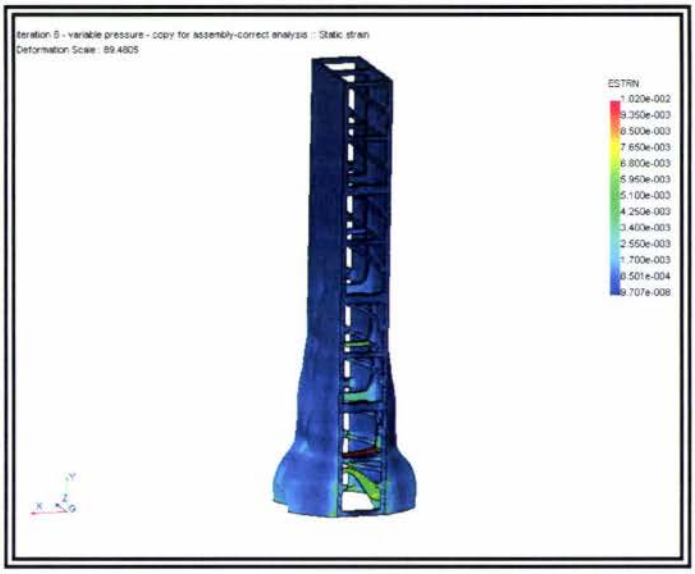


Figure 4.22 Strain plot of the assembly

In all the iterations, the maximum stress induced in the product is still well below the ultimate tensile strength of 20.3MPa for the material. At this stage, the analysis shows that it is feasible to use this material to manufacture the product.

4.8 Idea Analysis (Iteration 2) - Financial analysis

A financial model was developed using Microsoft® Excel to determine the cost of manufacturing the WFRP insulation product to build the foundation formwork boxing for one residential unit. It was then compared with the cost of building the formwork by traditional methods, to determine the financial viability of manufacturing the product.

Based on the assumptions made, a comparison of the prices reveals that it is cheaper to purchase the WFRP foundation blocks for constructing the concrete foundation, than building the formwork boxing. Appendix E (Table E-2) gives the detailed calculations for the cost of building the formwork boxing for *one residential unit* by the traditional method, which is about NZ$1837.46 (excluding material costs, because the timber would be recycled). Table E-3 (Appendix E) gives the detailed figures for manufacturing foundation blocks with the WFRP composite material for one residential unit, which is about NZ$906.16 (excluding the labour costs. See note in Table E-3).

The financial analysis is based on the number of building permits issued by the authorities in New Zealand, which was 28,546 in 2003. The growth in the number of permits to be issued from 2004 to 2007 has been projected to be a modest 15%, based

on similar growth from 1999 to 2003. For 2004, the number of permits to be issued has been projected to be 32,828. For the analysis, only single storied residential buildings have been considered, which account for 75% of the total dwelling units. For the year 2004, this figure is projected to be 24,621 units. A modest market share of 10% has been considered for the product when introduced into the market, which is assumed to fall (to say, 6%) in 2007, anticipating competition from similar products. This figure (10%) corresponds to 2,462 units for the year 2004, with a total perimeter length of 132,953 m., for which 221,588 blocks are required. The total number of blocks required for building the foundation, including the foundation height of one metre then translates to 738,628.

The perimeter length of one residential unit for building the foundation with the proposed product is 54m (See 'Note on Foundation plan' and notes in Table E-3, Appendix E). The number of blocks required for constructing a foundation 1m. high for one residential unit is estimated to be 300, the cost of which is estimated to be NZ$906.16 (excluding labour costs). Various scenarios have been projected in Appendix E, Table E-4. The cost of manufacturing the WFRP composite blocks is about one-half the cost of building the foundation with the formwork boxing, with most of the cost being attributed to the labour and overheads involved.

4.9 Discussion on the viability of the product

The proposed new product caters to the needs of two groups of customers. One group consists of builders and civil engineers who would find the product appealing because it eliminates the formwork boxing altogether. It makes the construction of the foundation less labourious. It includes a system to hold the reinforcement rods in place, thereby eliminating the need for manually tying them. Further it is relatively cheaper to assemble the foundation blocks rather than assemble the formwork boxing.

The other group of customers include the building owners, who would find the product's insulating property attractive. Further, since it forms an integral part of the foundation, it would cover the exterior wall of the foundation, and give the building a more pleasant appearance. This need has not been expressed by any house owner as yet, and has only been anticipated at this stage. It would be clearer when the formal consumer research is conducted in future.

The development process involved during this early stage is clearly iterative, as observed by Koen *et al.*, (2002). As progress is made in the development of the product,

more information is required to make good decisions, which force the product development team to loop back to a previous stage. In the present case, the mechanical properties were measured in the first phase of opportunity analysis. After a product idea was identified in the idea generation phase, more information relating the material (R-value) was required that was specific to the product under consideration. This new information was gathered by looping back to opportunity analysis stage for the second time. The analysis of the product concept design was itself an iterative process.

The design of the product is not yet complete. The product needs to be designed for manufacture and assembly. The present design has been to only evaluate the product's capability and technical feasibility. The results of the COSMOS analysis of the product performance under the pressure of wet concrete are within the limits of the ultimate tensile strength of the material.

By building the formwork boxing at a cost of NZ$36.16 a sq. m., there is no real advantage to the house owner. On the other hand, by incorporating the proposed product in the foundation, the overall insulation of the building will increase. It has been reported that as the level of insulation increases, although the individual cost of additional insulation will increase, the combined cost of insulation and heating energy declines (Page, 2001). Page (1998) reported that for a house in the South Island (say, Invercargill or Christchurch), the payback period for the cost incurred in installing additional insulation was about six years, while the payback period for locations in the North Island were much longer.

A comparison can be made for the WFRP composite blocks with 'Concrete Blocks'. The cost per concrete block is NZ$1.81 (excl. GST). If a block of size 400mm x 200mm x 150mm were to be used in place of a formwork boxing, 675 such blocks would be required to build a foundation for one residential building. This corresponds to NZ$1221.75, which is about the same as the cost of the WFRP composite product being proposed, since it includes the labour cost in manufacturing the concrete blocks.

From the aforementioned discussion, it can be concluded that the wood fibre reinforced composite product concept possesses the tensile properties required to substitute the standard formwork boxing presently used while constructing concrete foundations, provides a higher R-value, and thus has the potential to succeed.

4.10 Synopsis of the product concept – Concept Description

4.10.1 Advantages of the product concept:

i. Based on product function:

1. Provides thermal insulation – The material has R-value of more than 2.4, when compared to the R-value of 1.33 for 25mm thick EPS foam. By incorporating the WFRP block as an insulator, the overall building R-Value can be increased.
2. Improved appearance of the foundation – Can cover the marks and the rough surface finish left behind by the formwork boxing, if it were to be used.
3. Easy to assemble – The proposed interlocking mechanism of the blocks (still to be developed) can help do away with nails, pegs, and supporting timber studs. It also eliminates the need to dismantle and clean the timber blocks once the concrete is set.
4. Can serve as a permanent boxing – A maximum tensile strength of 20.3 MPa is achieved with 30% wood-fibre in the composite, when moulded at 175°C. It is capable of withstanding the variable pressure of upto 5.69MPa (for a height of 300mm) exerted by wet concrete.
5. Low moisture absorption – The composite material absorbs 0.15% of moisture in 36 hours. This characteristic of the material poses a distinct advantage when compared to the insulation method proposed by Harper (2003), since it eliminates the need for a protective cover.

ii. Based on financial viability:

Approximately six blocks measuring 600mm by 300mm by 154mm would be required to cover an area of one square meter of the foundation wall. For a product with these dimensions, it has been shown that it would be cheaper to manufacture the WFRP composite blocks than to build the formwork boxing by traditional methods.

4.10.2 Areas where more work are required in the development of the product:

1. Interlocking mechanism for assembling the blocks is yet to be designed – This might increase the manufacturing cost marginally.
2. Flammable material is used to manufacture of the product – a safety hazard. Fire retardants could be used while manufacturing, which might increase the part cost marginally. But the flammability characteristic of the product is not considered to be very crucial, given the fact that most of the building is made with materials having similar flammability characteristics.
3. More consumer research needs to be done, including field trials of prototypes, in order to determine the exact R-value of the building, and consumer needs.

4.10.3 Marketability of the product concept (projected for 2004):

1.	Market size	:	32,828 dwelling units
2.	Market growth rate	:	15%
3.	Market share for the product	:	10%
4.	Competition	:	Presently none
5.	Perceived product cost	:	NZ$3.00 per block
6.	Manufacturability	:	Yet to be studied.

CHAPTER 5

DISCUSSION

5.1 Critical analysis of the project

The current project was for a technology-driven product. The author was reviewing the literature on the latest research that was underway worldwide, when it was observed that there was a growing use of wood fibre to reinforce various types of polymers to yield composite materials. These materials were successfully being applied to manufacture automotive interior components. A visit to a leading wood panel manufacturing company in New Zealand, Fletcher Wood Panels, revealed the enormous pine wood fibre resource that this country had at its disposal. Further review of the literature revealed that although research into using radiata pine fibre to reinforce a range of thermoplastics and process it by injection moulding was underway, there was little evidence of commercial products being manufactured by this method. Further, although this material was being processed by other manufacturing techniques like thermoforming to manufacture products like interior components for automobiles, there was no documentation of the development process employed for such technology-driven products. In fact, significant debate has been devoted to the FFE phase of NPD in Product Development literature, with various models being suggested to improve the success rate of technology-driven products.

5.1.1 FFE Model for market-driven and technology-driven products

Miller (2002) quoted Reinertsen and Smith's observation that "*the Fuzzy Front End of New Product Development begins at a point when a need exists that can be identified and a technology exists that could meet that need*". This statement can be represented as in Figure 5.1.

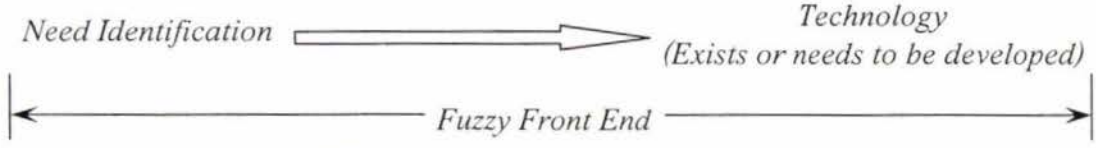


Figure 5.1 FFE model for market-driven product development

The development strategy for market driven products begins with the need or a problem identified by the user or customer. As the statement indicates, the technology that is required to cater to the identified need is assumed to exist or is developed at a later stage. Even if new technology is developed at a later stage to meet the need

identified, this strategy is market-driven product development, since it is the user's or customer's needs which drive the development of the new technology.

The aim of the current project was to identify and investigate the feasibility of manufacturing an injection moulded "new-to-the-world" product, which made use of radiata pine fibre. The market – driven product development model would not work very well for this project, the primary reason being, there was very little information in the literature about injection-moulding radiata pine fibre reinforced MDPE composites. Lee and McDonald (2001) had developed a method to formulate the composite material. Although this was relevant to the current project, there were a number of constraints for the author of this thesis, which made it impractical to work with the technology that they proposed. One of the main constraints was the non-availability of an extruder to compound the fibre – polymer mixture. This made it necessary for the author to first develop a method to formulate the composite material, which resulted in the development of a composite material using a process of manual blending followed by injection moulding.

True technology-driven products, akin to the project under consideration, do not start with identification of a need, but with the development and understanding of the new technology. The development of such products often involves significant risk and uncertainty. In order to manage such high risk new technology projects, Technology Stage-Gate™ (TSG) process has been proposed (Ajamian and Koen, 2002). The inherent drawback of the TSG process is that it isolates the development of the new technology from the product development process.

As was reported by Himmelfarb (n.d), the new technology developed would have to be adapted to suit the requirements of the user (Chapter 4, page 42). Hence, it is necessary to integrate the technology development process with the product development process. It is imperative that the scientists developing the new technology are aware of consumer needs and the product developers understand the benefits and limitations of the technology. At this early stage of technology development, there is normally no real understanding of its end use or application.

A new model is proposed for managing technology-driven products, which will be simply called "Technology Driven – Fuzzy Front End" (TD-FFE) (Figure 5.2, page 69). The initial experimentation to understand the new technology forms Stage-1 of the TD-FFE model. The development of the new technology will not be complete in this stage itself. To quote Ajamian and Koen (2002), "*One cannot schedule technology*

discovery, since the range of possible experiments and their outcomes is limitless, and it is often difficult to determine when the technology is ready to transition to product development". Hence, after some understanding has been gained regarding the new technology, ideas can be generated for its use, which forms Stage-2 of the TD-FFE model. A wide range of tools, methods and techniques including interaction with customers can be used to identify potential product ideas for incorporating the new technology. During this phase, the technology is further developed to determine if it meets the requirements posed by the opportunity. Further tests may have to be conducted to understand properties specific to the product idea identified.

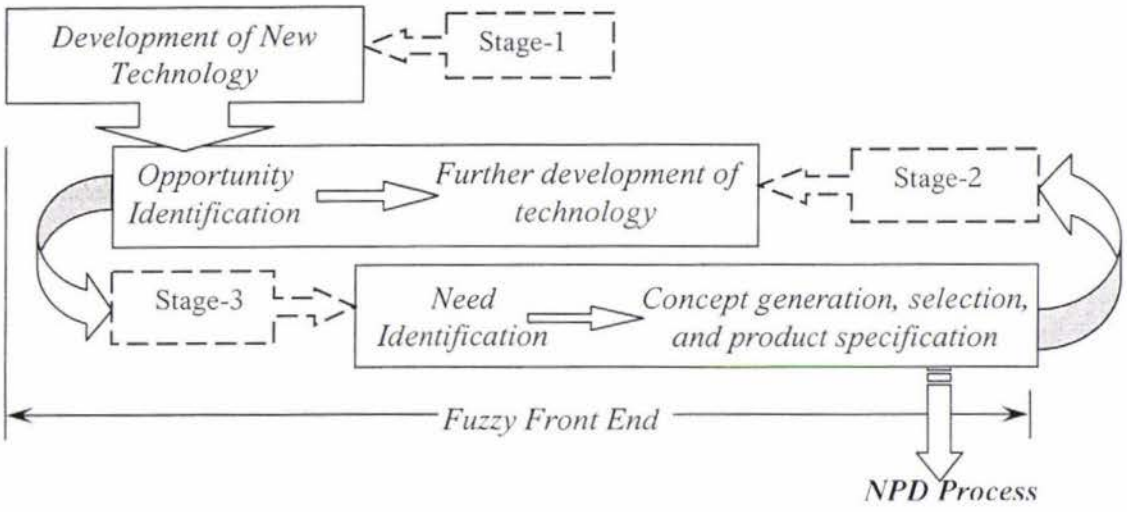


Figure 5.2 Proposed TD-FFE model for technology-driven products

Stage-3 can start while Stage-2 is underway, by conducting formal consumer research. Identification of customer needs aids in concept generation, analysis and selection. Stages-2 and -3 are iterative, akin to the NCD model proposed by Koen *et al.* (2002) (cited in Chapter 4, page 43). As consumer needs are identified and documented, new opportunities may be identified, which could be fed into Stage-2 of the TD-FFE model. The identification of consumer needs, leads to generation, analysis and enrichment of concepts for the product idea. Concepts can be selected based on the criteria published in the literature (Ulrich and Eppinger, 2000). The TD-FFE phase concludes with the *product specification* (Ulrich and Eppinger, 2000), the results of which are fed to a formal product development process to take the concept through to commercialization.

In this project, formal consumer research has not been undertaken yet. The various concepts generated and analysed are to be viewed as tests to determine the

feasibility of applying the material for the purpose intended and analyse its behaviour under specific conditions. This may be viewed as the second iteration of technology development (Stage 2).

5.1.2 Development of a new material leading to opportunity identification

The project began by investigating with the wood fibre and rotational moulding grade MDPE powder. The wood fibre was first stored in a chiller at 4°C to prevent it from degradation due to the absorption of moisture and growth of mould. The only resource that was available at the Industrial Engineering Laboratory at the University was a COSMO T330 injection moulding machine. This set limits on the method that could be adopted to mix the wood fibre and polymer, prior to injection moulding. To follow the process detailed in the literature meant that the author had to approach commercial companies possessing an extruder for assistance. But due to the sparse funds available for the project, this option was not followed upon. Further, one of the undocumented objectives of the project was to eliminate the use of all techniques that would increase the cost of the manufacturing process, unless absolutely necessary. These included granulating the wood fibre – polymer mixture using an extruder, chemically treating the wood fibre to improve its ability to bond with the polymer, and the use of coupling agents.

Discussions with staff members at the University revealed that a number of mixers of relatively small capacity were readily available. These included a planetary motion type of mixer and a couple of kitchen mixers. Trials were started with these mixers. Initially the planetary motion kind of mixer was employed on the assumption that the rotary as well as revolutionary motion of the blade would aid in homogeneously mixing the fibre and the polymer. At low fibre ratios (10% and 20%) the mixture was homogeneous. But at higher fibre ratios (30% and 40%) it became exceedingly difficult to avoid clumping of the fibres, which was found to be aided by the fibre - fibre attraction and the low speed of the mixer blade. For mixing the polymer with high fibre content, the kitchen mixer was used. Although this method was slow, it proved to be successful in homogeneously mixing the fibre – polymer mixture with little fibre clumping, because the high speed of rotation of the blades helped in separating the fibres, thereby breaking the hydrogen – hydrogen attraction between them. It was anticipated that because manual mixing was employed, the dispersion of wood fibre in the polymer would be compromised. This was not found to be the case at low fibre

content. At higher fibre contents, it was not possible to differentiate the polymer and wood fibre, given the resolution of the confocal microscope used. This could be analysed better using a Scanning Electron Microscope (SEM).

The wood fibre that was stored in a refrigerator was found to degrade with time due to the moist environment. Fresh fibre was procured, which was then stored in a warm room at 34°C. The results of all the samples that were moulded and tested for their tensile strength with the old material, had to be discarded as the test results were not repeatable. New samples were moulded and tested again. Although, some time was lost in the process and resulted in considerable rework, it was a learning experience by itself. Such issues are very common during the initial stages of developing a new technology because the behaviour of the material in certain environments are not always known at the beginning, which is why they form a part of the FFE stage of NPD.

During the second iteration of mixing the fibre with the polymer, the fibres were manually sieved prior to mixing, to separate the fibres as much as possible. This resulted in the fibres being separated into two groups based on their lengths: fibres that were less than approximately 4mm in length and fibres with length of 4mm to 8mm. This enabled the author to study the effect of the fibre length on the tensile properties of the composite material. Further work is required in this direction at other fibre percentages to determine its effect on the tensile properties of the composite material.

Injection moulding of samples with 10% and 20% fibre content was not difficult. The custom-made soft nozzle proved useful for moulding samples with fibre content of 30% and 40%. It was not possible to mould samples with 40% fibre content at 215°C, because the high barrel temperature resulted in the degradation and combustion of the cellulose in the wood fibre. There were issues with regards to the accuracy of the injection mould used to mould the sample. Although all efforts were made to mould them as accurately as possible, samples conforming to the dimensions specified in ISO 527 (Plastics - Determination of tensile properties) could not be moulded. But this does not imply that the results of the present test are erroneous.

For the current project only the tensile strength of the material was measured, which is not sufficient to map the properties of the material. Other mechanical properties like its flexural strength, impact strength, compressive strength, to name a few, also need to be measured and documented. These could not be measured at this stage as tooling to mould the samples were not available, and it was not feasible to build the same in a short span of time.

The ability to injection mould the wood fibre reinforced polymer samples presented a new material that was made of a renewable resource. As the inclusion of wood fibre reduced the amount of virgin plastic used, products manufactured with this material could be cheaper compared to those manufactured with virgin polymer.

5.1.3 Evaluation of brainstorming technique to generate *new* product ideas

As part of the 'idea generation stage' of Stage-3 of the TD-FFE model, a brain storming session was conducted to generate product ideas for the new material, because *"a good, fluid brainstorming session could generate as many as one hundred ideas per hour"* (Kelley, 2001). It was decided that only those ideas that led to the development of "new-to-the-world" products would be selected, and the product had to be injection mouldable. The intention was not to manufacture an existing product that could be substituted with the new material, but to develop a product that did not exist presently in the market. About fifty ideas were put forth during the session, of which only one was truly "new-to-the-world". This product idea, "*Insulator block and permanent formwork boxing for a building foundation*", was then taken up for further investigation.

Brainstorming technique is dependent on free uninhibited thinking to generate a large number of ideas. But the technique was not found to be highly successful in the present project due to the constraints that were set. This stifles the flow of ideas as suggested by Kelley (2001) and does not aid in generating a large number of 'wild' ideas, which are embryos for new products. Of course, there could be many other products that could be manufactured with this composite material by injection moulding, but their identification could be slow if limited only to this method. Given the time constraint for the project, it was decided to investigate the building foundation product further, and other techniques to generate product ideas were not explored.

5.1.4 Idea analysis using software simulation

The use of computer-aided-design (CAD) tools to reduce development time, development cost, and risk is not new (Eastman and Smith, 1996). They have become an indispensable tool to a product developer. They are not limited to just modelling of products for prototyping, but find application at every stage of the NPD process. The growing popularity of this tool in product development is an obvious indication that the results of computer-aided analysis have found acceptance with the management, engineers, and manufacturers to make good decisions about the product. For the current

project, the results of the static stress analysis indicate that it is possible to utilise this composite material for manufacturing the foundation product. Once the product design is modified to suit the needs of the customer (house owner and builder), the analysis can be rerun to verify the results.

5.1.5 Financial analysis

The financial analysis that has been conducted is quite approximate and many assumptions have been made, some of which are dependent on the organization manufacturing and selling the product. The high cost of the product is attributed to the high cost of MDPE powder. When purchasing large volumes of raw polymer discounted rates apply. This has not been considered in this analysis because it is subjective, and would affect the retail price of the product considerably. So the true retail price of the product would be lower than the price quoted in this analysis.

This project proves the New Concept Development model's basis that in the FFE stage of NPD, the phases are iterative and there is considerable looping back and forth in the effort to understand different aspects of the product during its development, which would enable the development team to make informed decisions. This is apparent in the new "*Technology Driven – Fuzzy Front End*" model that has been proposed for developing technology-driven products.

CHAPTER 6

CONCLUSION

6.1 Fuzzy Front End of New Product Development process for technology-driven products

The 'primary risk factor' that companies face today is *competition* (Volker, 1988). With technology changing rapidly, competition intensifying day-by-day, and the changing nature of customer needs, the long term survival of a company has been linked to its ability to develop and introduce a steady stream of new products into the market (Cooper, 1994; Spetsidis and Schamel, 2002). Embarking on New Product Development in such an environment can be both challenging and risky. It is no wonder then that from the total pool of raw ideas, only one-third of them are commercially successful (Spetsidis and Schamel, 2002).

Given the high failure rate of 'new' products, companies prefer to allow customer needs to dictate and guide the development of technology. Most of the products introduced in the market are line-extensions, brand-extensions and modifications to specific attributes of a product and do not conform to the term 'new product', which are based on truly new, original concepts.

No single Product Development Process works for all companies or all products within the same company, since each company and the product that it develops is unique. Even the types of strategy that a company may adopt to develop and market new products differ. This is generally clear from the organization's goal or mission statement. For instance, 3M is a company known for 'creating innovative products and services that respond to customer needs'. The company develops innovative technologies and solutions for adhesives, materials, chemicals, polymers, electronics, optics, life sciences and manufacturing processes (3M Corporate Website, http://www.3m.com/about3M/technologies/tech_landing.jhtml). The mission statement of the company reads, *'Innovative and Practical solutions from a diversified technological company'*

The present project, which was based on the development of a new composite material, illustrated the difference between a market-driven and technology-driven product development processes. Market-driven processes began with the identification of user needs and then identified existing or new technologies to develop products that suited the user's needs. The TSG process proposed by Ajamian and Koen (2002) for

dealing with the FFE stage of technology-driven products isolated the development of new technology from the product development process. The TD-FFE model proposed in this thesis began with the development of a new technology (in this project, a new material), and integrated this process with the product development process by taking the consumer needs into account at an early stage. This would aid in adapting the new technology to develop a product that would suit the needs of the consumer.

When the composite development process (Figure 1.1, page 7) is compared with the proposed TD-FFE model (Figure 5.2, page 69), it can be observed that Stage 1 (development of new technology) of the model corresponds to Phase 1 of the product development process. In order to develop useful products based on the new technology, it was necessary to first understand the material and its properties, and examine how the constituents of the material affected its overall behaviour. If the technologists developing a product had no understanding of the material properties, it would not be possible to cater to the needs of the users. Similarly, if the scientists developing the new technology had little understanding of the user's needs, they would not be able to adapt the technology to suit the user's needs. During Phase 2 of the development process, opportunities were identified and further testing of the properties of the material specific to the product under consideration was undertaken, which formed Stage 2 in the TD-FFE model.

6.2 WFRP composite material properties:

Although the quality of wood fibre is prone to seasonal variations, "*with today's know-how, the industrial demand for defined and reproducible raw materials can be satisfied. Using controlled agricultural plant growth and intelligent processing technology, it is possible to iron out the natural inhomogeneties and produce standardized high-quality fibres.*" (Kohler and Kessler, 1999).

The experiments conducted with the rotational moulding grade MDPE powder found the polymer to be suitable as a matrix material, which could be reinforced with radiata pine and processed by injection moulding. Manual blending of the fibre – polymer mixture followed by injection moulding prevented the degradation of the fibre. This indicated that multiple compounding of the fibre – polymer mixture (studies undertaken by Lee and McDonald (2001) and Abdalla *et al.* (2002)) degraded the wood fibre and had to be avoided if wood fibres were required to reinforce the polymer. It was also ascertained that a minimum amount of fibre content was required for the fibre to

act as a reinforcing agent. Below this threshold value, the fibre behaved like a filler (Jayaraman, 2003)

Following are the key results of the study into radiata pine fibre reinforced polymer composite material properties:

1. Addition of wood fibre to the polymer increased the density of the composite material from 947 kg/m^3 at 10% fibre content to 1055 kg/m^3 at 40% fibre content (moulded at 175°C). The viscosity of the material also increased.
2. Fibre content by itself had a significant effect on the tensile strength of the composite material, while the melt temperature by itself did not have a very significant effect on the tensile strength of the composite. The interaction of fibre content with melt temperature was also significant. The maximum tensile strength of about 20MPa was achieved when the composite was moulded at 175°C with a fibre content of 30%.
3. In contrast to the research conducted by Lee and McDonald (2001) (Chapter 2, page 19) and Abdalla *et al.* (2002) (Chapter 2, page 20), the tensile strength of the WFRP composite (the current project), increased with increase in fibre content (up to 30%). It is this author's inference that the decrease in the tensile properties observed by the other researchers was due to thermal degradation of the wood fibre because the wood fibre was processed at high temperatures more than once. This was avoided in the present project by adopting manual blending method to mix the wood fibre and MDPE powder, and by reducing the residence time of the material in the barrel of the injection-moulding machine. A similar observation was made by McHenry and Stachurski (2002) (Chapter 2, page 17) and Peterson *et al.* (2002) (Chapter 2, page 20)
4. Variation in the fibre length did not have a significant effect on the tensile properties of the composite material. Critical length of pine fibre is suggested to be around 4mm (Chapter 3, page 38).
5. The thermal resistivity of the composite (2.65mm thick) ranged from R2.45 for 10% fibre content to R2.86 for 30% fibre content.
6. The moisture absorption was found to be 0.15%. The presence of moisture is very essential for bacteria to attack the WFRP composite. Lower the moisture level in the composite, lower will be the chance of bacteria attacking it. The possibility of incorporating a bactericide in the composite material during its

manufacture needs to be investigated. This would enhance the value of the product proposed in this thesis.

6.3 Benefits of the foundation product proposed to be manufactured with the material

Given limiting factors like a new material and a specific processing method, *brainstorming* may not be the ideal technique to generate a *large number* of *new* product ideas, as the method calls for 'wild' and free thinking, and such boundaries stifle this. The method nevertheless was successful in identifying the foundation insulation and permanent formwork boxing product for buildings.

The success of technology-driven products is dependent on the new technology providing immediate benefits to users. Based on the research into the material properties and financial implications, the product offers *key benefits* for home owners and builders, to whom this product is aimed to cater to. Some of the benefits are:

1. Insulates the building, given its higher R-value, which means lower energy bills for the building owner
2. Provides an aesthetically pleasing appearance of the concrete foundation exterior
3. Helps the builder to construct the foundation faster, because assembly of the blocks is easier compared to building the formwork.

6.4 Scope for further development

The development of the product is by no means complete. More consumer research needs to be done, and field trials of prototypes conducted to confirm the practical feasibility of this product. This would also improve the accuracy of the financial estimates for the product. Further work is required to study the design for manufacturability issues of the product. Since the cost of the polymer material is high which increases the cost of the product, the use of cheaper a polymer matrix material could also be investigated.

At the stage where the project stands, chemical treatment of the fibre to improve its bonding with the polymer or reduce the amount of moisture absorption does not seem necessary. Further development of the product prototypes to test the practical viability of the product concept would enable the product development team to make an informed decision on this question. Based on these results, the management would be able to decide whether or not to take the concept through to production and commercially launch the product.

BIBLIOGRAPHY

Abdalla, A. and Pickering, K. (2002) The use of silane as a coupling agent for wood fibre composites. *The 3rd Asian-Australasian Conference on Composite Materials*, Auckland, New Zealand, January 2002

Abdalla, A., Pickering, K. L. and McDonald, A. G. (2002) Mechanical proeprties of thermoplastic matrix composites with silane-treated wood fibre, *The 6th International Conference on Flow processes in Composite Materials,* Auckland, New Zealand, February 2002, p. 111-117

Ajamian, G. M. and Koen, P. A. (2002) Technology Stage-Gate™: A structured process for managing high-risk new technology projects In: Belliveau, P.; Griffin, A.; Somermeyer, S., *The PDMA Toolbook for New Product Development*, 2nd edn., John Wiley & Sons, Inc., New York, USA

Anon. (1997) Insulation, *BUILD,* **February,** New Zealand: BRANZ, p. 49

Anon. (2003) One bullet, five empty chambers: Are new products really that dangerous? Killian & Company Advertising, Retrieved: 31st December 2003, from http://www.killianadvertising.com/wp4.html

Balasingam, G. (1997) Thermoforming of wood-fibre thermoplastic composites, Unpublished Master of Technology Thesis, University of Auckland, New Zealand

Balasuriya, P. W., Ye, L. and Mai, Y. W. (2001) Mechanical properties of wood flake - polyethylene composites. Part 1: Effects of processing methods and matrix melt flow behaviour, *Composites Part A: Applied Science and manufacturing.* **32:** 619-629

Berthelot, J. M. (1999) Composite Materials: Mechanical behaviour and structural analysis, New York: Springer-Verlag New York, Inc.

Biswas, S., Srikanth, G. and Nangia, S. (2001) Development of Natural Fibre Composites in India, *Proceedings of annual convention and trade show, COMPOSITES 2001,* (Composites Fabricators' Association at Tampa, Florida, USA, October 03-06,

2001)

Bledzki, A. K. and Sperber, V. E. (1999) Recent developments in wood-filled plastic: United States, Japan, and Europe, *The 5th International Conference on Woodfibre - Plastic Composites,* Forest Products Society, May 26-28, Madison, Wisconsin, USA, p. 187-192

Bodig, J. and Jayne, B. A. (1982) Mechanics of wood and wood composites, 2nd ed., Van Nostrand Reinhold Company Inc.

Bolton, Dr. J. (1997) Plant fibres in composite materials: A review of technical challenges and opportunities, *The Burgess-Lane Memorial Lectureship in Forestry,* Retrieved: 31st August, 2003, from http://www.forestry.ubc.ca/burgess/bolton.html

Broeke, J. (2001) ABC of house insulation, *BUILD,* **July / August 2001,** New Zealand: BRANZ, pp. 58-60

Brouwer, W. D. R. (2000) Natural fibre composites in structural components: Alternative applications for sisal? *Proceedings of a Seminar held by the Food and Agriculture Organization of the UN (FAO) and the Common Fund for Commodities (CFC) -* Technical Paper No. 14, 13th December 2000, Rome, Retrieved from http://www.fao.org/DOCREP/004/Y1873E/y1873e0a.htm on 15th July, 2003

Brown, R. P. (ed.) (1988) Handbook of plastic test methods, 3rd edn., John Wiley & Sons, Inc., New York, USA, p. 284-292

Carson, J and Steller, M. (2003) Maritime product development process: An approach from other industries, Steller Carson Associates, LLC., Retrieved: 31st December 2003, from http://www.stellercarson.com/articles/process.PDF

Chisholm, D. (2003) Durability of concrete edge foundations, *BUILD,* **August / September,** New Zealand: BRANZ

Clemons, C. M. (2000) Wood fibre plastic composites in the United States – History, current and future markets, *3rd International Wood and Natural Fibre Composites Symposium*, 19 – 20 September, Kassel, Germany

Bibliography

Cooper, R. G. (1993) Winning at new products: Accelerating the process from idea to launch, 2nd ed., Addison Webley Publishing Company

Cooper, R. G. (1994) New products: The factors that drive success, *International Marketing Review,* **11:** 60-76

COSMO - Operation Manual. Hong Kong: Welltec Industrial Equipment Ltd.

Coutinho, F. M. B., Costa, T. H. S. and Carvalho, D. L. (1997) Prolypropylene - wood fibre composites : Effect of treatment and mixing conditions on mechanical properties, *Journal of Applied Polymer Science,* **65:** 1227-1235

Donaldson, L. A. and Burdon, R. D. (1995) Clonal variation and repeatability of microfibril angle in Pinus Radiata, *New Zealand Journal of Forestry Science,* **25:** 164-174

Eastman, D. A. and Smith, P. G. (1996) Low-tech tools speed plastic parts, *Machine Design, (8th* August), Retrieved: 31st December 2003, from http://www.newproductdynamics.com/MD8-96/MD8-96.pdf, p. 40-46

Eichhorn, J. S., Baillie, A. C., Zafeiropolous, N., Mwaikambo, Y. L., Ansell, P. M., Dufresne, A., Entwistle, M. K., Herrera-Franco, J. P., Escamilla, C. G., Groom, L., Huges, M., Hill, C., Rials, G. T. and Wild, M. P. (2001) Current international research into cellulosic fibres and composites. *Journal of Materials Science,* **36:** 2107-2131

Elvy, S. B., Dennis, G. R. and Ng, L. T. (1995) Effects of coupling agent on the physical properties of wood - polymer composites, *Journal of Materials Processing Technology,* **48:** 365-371

Feig, B. (2003) The 5-minute guide to successful new products, Retrieved: 31st December, 2003 from http://www.businessknowhow.com/articles/nb1/marketing/5_minute_guide.htm

Forest Enterprises Ltd. (n.d) *Radiata Pine* Retrieved: 12th September 2003, from http://www.forestenterprises.co.nz/fgen/radiata_pine.htm

Fung, K. L., Li, R. K. Y. and Tjong, S. C. (2002) Interface modification on the properties

of sisal fibre reinforced polypropylene composites. *Journal of Applied Polymer Science,* **85:** 169-176

George, J., Sreekala, M. S. and Thomas, S. (2001) A review on interface modification and characterization of natural fiber reinforced plastic composites. *Polymer Engineering and Science,* **41:** 1471-1485 (Abstract)

Harper, J. (2003) Insulating concrete slabs. *BUILD,* New Zealand: BRANZ, **August / September,** p. 56-58

Hepworth, D.G., Vincent, J.F.V., Jeronimidis, G. and Bruce, D.M. (2000) The penetration of epoxy resin into plant fibre cell walls increases the stiffness of plant fibre composites, *Composites Part A: Applied Science and Manufacturing,* **31:** 599-601

Himmelfarb, Dr. P. A. (2003) Market pull vs. technology push, Retrieved: 31st December 2003, from http://www.bizbasics.com/html/market_pull_vs._tech_push.html

Jana, S. C. and Prieto, A. (2002) On the development of natural fibre composites of high temperature thermoplastic polymers. *Journal of Applied Polymer Science* **86:** 2159-2167

Japan Carbon Fiber Manufacturers Association: Glossary (n. d) Retrieved: 31st December 2003, from http://www.carbonfiber.gr.jp/english/jiten/yogo.html

Jayaraman, K. (2003) Manufacturing sisal - polypropylene composites with minimum fibre degradation, *Composites Science and Technology,* **63:** 367-374

Jones, M. S. (2002) Effects of UV radiation on building materials, *Paper presented at a UV workshop conference, New Zealand:* BRANZ

Joseph, K., Varghese, S., Kalaprasad, G., Thomas, S., Prasannakumari, L., Koshy, P. and Pavithran, C. (1996) Influence of interfacial adhesion on the mechanical properties and fracture behaviour of short sisal fibre reinforced polymer composites, *European Polymer Journal,* **32:** 1243-1250

Karmaker, A. C. and Youngquist, J. A. (1996) Injection moulding of polypropylene reinforced with short jute fibres, *Journal of Applied Science,* **62:** 1147-1151

Kelley, T. (2000) The art of innovation: Lessons in creativity from IDEO, America's leading design firm, Random House Inc., New York, USA

Kenny, J. M. (2001) Natural fibre composites in the European automotive industry, *The Sixth International Conference on Wood Fibre - Plastic Composites,* Forest Products Society, 15 – 16 May 2001 Madison, Wisconsin, p. 9-12

Kininmonth, J. A. and Whitehouse, L. J. (eds.) (1991) *Properties of New Zealand Radiata Pine: Volume 1 - Wood Properties*, New Zealand Ministry of Forestry, Rotorua, New Zealand

Koen, P. A., Ajamian, G. M., Boyce, S., Clamen, A., Fisher, E., Fountoulakis, S., Johnson, A., Puri, P. and Seibert, R. (2002) Fuzzy front end: Effective methods, tools, and techniques. In: Belliveau, P.; Griffin, A.; Somermeyer, S., *The PDMA Toolbook for New Product Development*, 2nd edn., John Wiley & Sons, Inc., New York, USA

Kohler, R. and Kessler, R. W. (1999) Designing natural fibers for advanced materials, *The Fifth International Conference on Wood Fibre - Plastic Composites,* Forest Products Society, 26 – 28 May 1999, Madison, Wisconsin, USA, p. 29-42

Lee, B. J. and McDonald, A. G. (2000) Wood fibre-plastic composite materials for injection moulding, *5th Pacific Rim Biobased Composites Symposium*, 10 – 14 December, Canberra, Australia

Lee, B. J., Mcdonald, A. G. and James, B. (2001) Influence of Fiber Length on the Mechanical Properties of Wood- Fiber/Polypropylene Prepreg Sheets. *Materials Research Innovations,* **4:** 97-103 (Abstract)

Marek, A. and Widdecke, H. (2001) Injection Moulding of Natural Fibre Reinforced Thermoplastics - Processing Technology With a Future? *Kunststoffe-Plast Europe* **91**, 60-+

McHenry, E. and Stachurski, Z. H. (2003) Composite materials based on wood and nylon fibre, *Composites Part A: Applied Science and Manufacturing,* **34:** 171-181

Michaud, V. and Mortensen, A. (2001) Infiltration processing of fibre reinforced

composites: governing phenomena, *Composites Part A: Applied science and Manufacturing,* **32:** 981-996

Michell, A. J. (1986) Composites containing wood pulp fibers, *Australian and New Zealand Pulp and Paper Industrial Technical Association,* **39:** 223-229

Miller, N. A., Stirling, C. D. and Vantilburg, V. S. M. (1995) Effects of fiber treatment on fibre - matrix interfacial bonding in Pinus Radiata fibre - thermoplastic composites, *Polymers & Polymer Composites,* **3:** 117-127

Miller, C. W. (2002) Hunting for hunting grounds: Forecasting the fuzzy front end, In: Belliveau, P.; Griffin, A.; Somermeyer, S. (eds.), John Wiley & Sons, Inc., New York, p. 37-62

Mwaikambo, L.Y. and Ansell, M.P. (1999) The effect of chemical treatment on the properties of hemp, sisal, jute and kapok for composite reinforcement, *Die Angewandte Makromolekulare Chemie,* **272:** 108-116

Natural fibre composites from upholstry to structural components, Centre of Lightweight Structures TUD-TNO, The Netherlands, Retrieved: 10th May 2003, from http://www.clc.tno.nl/projects/recent/flax.html

New Zealand Forest Industry - Facts and Figures 2002 - 03 (2003), New Zealand Ministry of Agriculture and Forestry, Retrieved: 30th July 2003, from http://www.nzfoa.nzforestry.co.nz/0602385nzfoafandf.pdf

Olesen, P.O. and Plackett, D.V. (1999) Perspectives on the performance of natural fibres, *Natural Fibres Performance Forum,* 27 – 28 May, Copenhagen, The Netherlands

Page, I. (1998) Cost savings through extra insulation *BUILD,* **May/June,** New Zealand: BRANZ, p. 8

Page, I. (2001) Is more insulation cost effective? *BUILD,* **March/April,** New Zealand: BRANZ, p. 8

Page, I. (2003) Use more insulation to save money. *BUILD,* **April / May**, New Zealand: BRANZ, p. 14 - 15

Peijs, T. (2002) Composites turn green, *E-Polymers,* Retrieved: 20th June 2003, from http://www.e-polymers.org/papers/peijs_110202.pdf

Peterson, S., Jayaraman, K. and Bhattacharyya, D. (2002) Forming performance and degradation of wood fibre - Biopol(TM) composites, *Composites, Part A: Applied Science and Manufacturing,* **33:** 1123-1134

Pickering, K.L., Abdalla, A., Ji, C., McDonald, A.G. and Franich, R.A. (2003) The effect of silane coupling agents on radiata pine fibre for use in thermoplastic matrix composites, *Composites Part A: Applied Science and Manufacturing,* **34**(10): 915-926

Platts, M.J. (1989) Wood - epoxy composites for large wind turbines. *Proceedings of the Institution of Mechanical Engineers: Design in composite materials,* **2**

Principia Partners (2003) Big Market for Injection Molded Wood-Plastic Composites, Retrieved: 9th September 2003, from http://www.principiaconsulting.com/releases_wpcreach300mil.cfm

Robson, W.A. (2001) Growth forum: Fear of the customer... A survival guide for the fuzzy front end, *Visions Magazine,* Product Development and Management Association, April, Retrieved: 10th December 2003, from http://www.pdma.org/visions/apr01/growth_forum.html

Rosenau Jr., M. D. (1996) Choosing a development process that's right for your company. In: Rosenau Jr., M. D.; Griffin, A.; Castellion, G. A. and Anschuetz, N. F. (eds.), *The PDMA Handbook for New Product Development*, 2nd edn., John Wiley & Sons, Inc., New York, USA

Rowell, M.R., Sanadi, R.A., Caulfield, F.D. and Jacobson, E.R. (1997) Utilisation of natural fibres in plastic composites: Problems and opportunities. *Lignocellulosic - Plastics Composites,* p. 23-51

Rubin, I.I. (1972) *Injection moulding : Theory and practice*, New York: John Wiley & Sons

Schartel, B., Braun, U., Schwarz, U. and Reinemann, S. (2003) Fire retardancy of

polypropylene / flax blends. *Polymer,* **44:** 6241-6250

Smith, G. (1998) Idea generation techniques: A formulary of active ingredients, *Journal of Creative Behaviour,* **32:** 107-133

Smith, P.G. and Reinertsen, D.G. (1991) *Developing products in half the time,* 2nd edn., Van Nostrand Reinhold, USA

Spetsidis, N. M. and Schamel, G. (2002) A consumer - based approach towards new product development through biotechnology in the agro-food sector, *Market Development for Genetically Modified Foods,* p. 63-79

Stamboulis, A., Baillie, C. A., and Peijs, T. (2001) Effects of environmental conditions on mechanical and physical properties of flax fibres, *Composites Part A: Applied Science and Manufacturing,* **32:** 1105 – 1115

Stevens, G. and Burley, J. (1997) 3000 raw product ideas = 1 commercial success, *Research Technology Management,* **40**

The Japan Carbon Fiber Manufacturer's Association: Glossary (n.d), Retrieved: 22nd July 2003, from http://www.carbonfiber.gr.jp/english/jiten/yogo.html

Ulrich, K. T. and Eppinger, S. D. (2000) *Product Design and Development*, 2nd edn., McGraw-Hill

Volker, M. (1988) Technology push vs. market pull, *9th Annual Canadian MBA Conference: Management of Technology,* McMaster University, Canada, Retrieved: 31st December 2003, from http://www.sfu.ca/~mvolker/biz/pushpull.htm

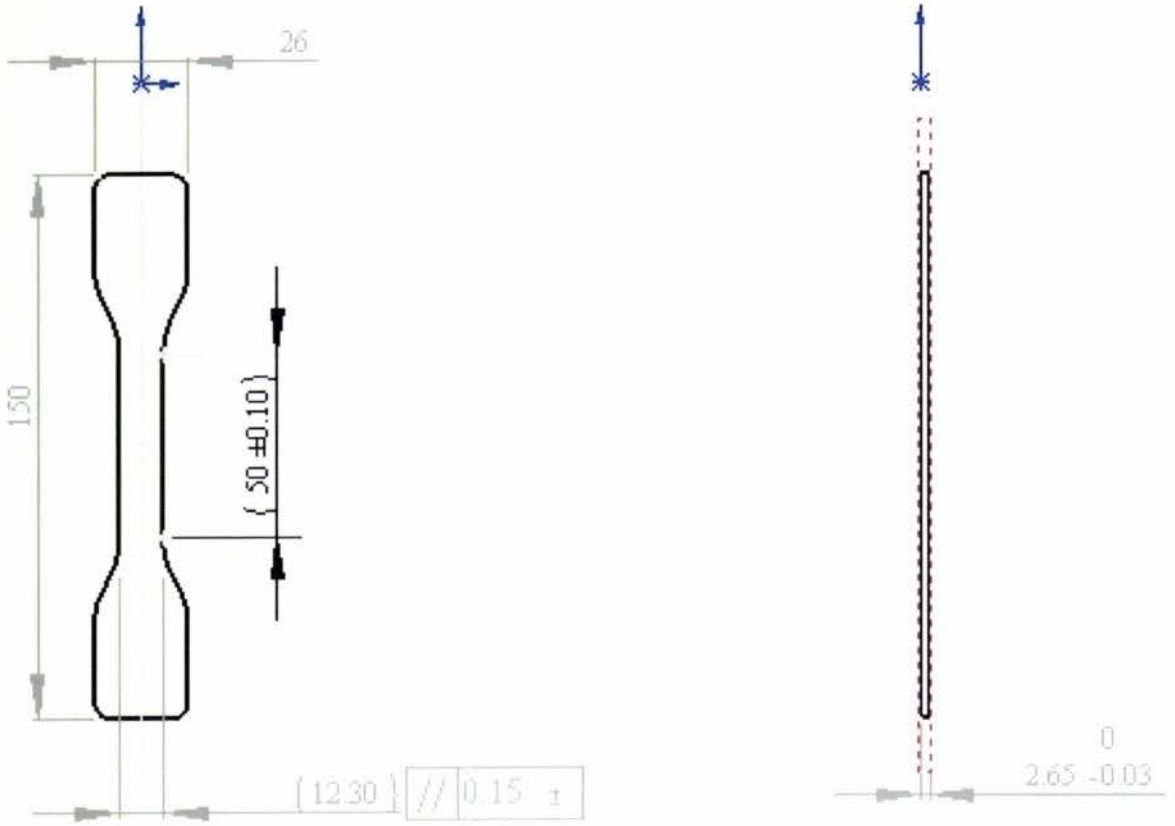
Warnes, J. (2002) Wood Plastic Composites - Flexible Materials of the Future. *BUILD,* **October / November 2002,** New Zealand: BRANZ, p. 54 - 55

Zafeiropoulos, N. E., Baillie, C. A. and Matthews, F. L. (2000) A study of the effect of surface treatment on the thermal stability of flax fibres. *Advanced Composite Letters,* **9:** 291 – 294 (Abstract)

Zafeiropoulos, N. E., Baillie, C.A. and Hodgkinson, J. M. (2002a) Engineering and

characterisation of the interface in flax fibre / polypropylene composite materials, Part I: Development and investigation of surface treatments, *Composites Part A: Applied Science and Manufacturing*, 33: 1083 - 1093

Zafeiropoulos, N. E., Baillie, C. A. and Hodgkinson, J. M. (2002b) Engineering and characterisation of the interface in flax fibre / polypropelene composite materials. Part II: The effect of surface treatments on the interface. *Composites Part A: Applied science and Manufacturing*, 33: 1185 - 1190



Notes: Remove all flashes from the gauge length area.

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

BREAK AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN	Vish		02/12
CHKD	Vish		02/12
APPVD	Vish		02/12
MFG			
Q.A			

Massey University

FIRST

Wood Fibre Reinforced
Composite - Tensile test Specimen

MATERIAL:
Wood Fibre - MDPE Composite

DWG NO

A4

WEIGHT: 7.6g

SCALE:1:2

SHEET 1 OF 1

Appendix B – Results of statistical analysis

The SAS System
INPUT DATA

Obs	Fibre_ length(mm)	Fibre_ content(%)	Melt_ temp(°C)	Tensile_ strength(Mpa)
1	4	10	155	14.26
2	4	10	155	16.55
3	4	10	155	15.95
4	4	10	155	15.33
5	4	10	155	14.98
6	4	10	175	12.75
7	4	10	175	13.33
8	4	10	175	13.50
9	4	10	175	13.58
10	4	10	175	12.79
11	4	10	195	12.09
12	4	10	195	11.88
13	4	10	195	12.02
14	4	10	195	11.71
15	4	10	195	11.93
16	4	10	215	11.52
17	4	10	215	11.74
18	4	10	215	11.51
19	4	10	215	11.96
20	4	10	215	12.23
21	4	20	155	15.83
22	4	20	155	16.37
23	4	20	155	16.14
24	4	20	155	15.09
25	4	20	155	16.45
26	4	20	175	15.36
27	4	20	175	14.87
28	4	20	175	14.85
29	4	20	175	15.74
30	4	20	175	14.84
31	4	20	195	14.81
32	4	20	195	15.79
33	4	20	195	15.58
34	4	20	195	15.00
35	4	20	195	16.02
36	4	20	215	18.57
37	4	20	215	17.33
38	4	20	215	17.25
39	4	20	215	15.42
40	4	20	215	16.89
41	4	30	155	18.84
42	4	30	155	18.01
43	4	30	155	18.33
44	4	30	155	18.90

Obs	Fibre_ length	Fibre_ content	Melt_ temp	Tensile_ strength
45	4	30	155	19.46
46	4	30	175	17.14
47	4	30	175	19.00
48	4	30	175	20.64
49	4	30	175	22.07
50	4	30	175	20.90
51	4	30	195	16.58
52	4	30	195	15.49
53	4	30	195	18.50
54	4	30	195	18.75
55	4	30	195	18.04
56	4	30	215	18.19
57	4	30	215	17.91
58	4	30	215	17.04
59	4	30	215	17.42
60	4	30	215	17.64
61	4	40	155	13.01
62	4	40	155	18.90
63	4	40	155	18.60
64	4	40	155	19.34
65	4	40	155	17.82
66	4	40	175	19.46
67	4	40	175	19.34
68	4	40	175	17.66
69	4	40	175	16.33
70	4	40	175	16.33
71	4	40	195	19.90
72	4	40	195	18.66
73	4	40	195	19.10
74	4	40	195	18.20
75	4	40	195	18.51

Two-factor Analysis of Variance (ANOVA)

The GLM Procedure

Class Level Information

Class	Levels	Values
Fibre_content	4	10 20 30 40
Melt_temp	4	155 175 195 215

Number of observations 75

Two-factor Analysis of Variance (ANOVA)

The GLM Procedure

Dependent Variable: Tensile_strength Tensile_strength

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	14	427.4445147	30.5317510	24.53	<.0001
Error	60	74.6831200	1.2447187		
Corrected Total	74	502.1276347			

R-Square	Coeff Var	Root MSE	Tensile_strength Mean
0.851267	6.859637	1.115670	16.26427

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Fibre_content	3	340.5519900	113.5173300	91.20	**<.0001**
Melt_temp	3	11.5899933	3.8633311	3.10	**0.0332**
Fibre_cont*Melt_temp	8	66.4148500	8.3018563	6.67	**<.0001**

Two-factor Analysis of Variance (ANOVA)

The GLM Procedure

Level of Fibre_content	N	-------Tensile_strength------ Mean	Std Dev
10	20	13.0805000	1.56337514
20	20	15.9100000	1.00467329
30	20	18.4425000	1.52326821
40	15	18.0773333	1.75223721

Level of Melt_temp	N	-------Tensile_strength------ Mean	Std Dev
155	20	16.9080000	1.86438815
175	20	16.5240000	2.88204313
195	20	15.9280000	2.78351841
215	15	15.5080000	2.81041736

Level of Fibre_content	Level of Melt_temp	N	-------Tensile_strength------ Mean	Std Dev
10	155	5	15.4140000	0.88103916
10	175	5	13.1900000	0.39414464
10	195	5	11.9260000	0.14536162
10	215	5	11.7920000	0.30670833
20	155	5	15.9760000	0.55070863
20	175	5	15.1320000	0.40468506
20	195	5	15.4400000	0.51696228
20	215	5	17.0920000	1.12943349
30	155	5	18.7080000	0.55899016
30	175	5	19.9500000	1.91517623
30	195	5	17.4720000	1.39074440
30	215	5	17.6400000	0.44266240
40	155	5	17.5340000	2.58903071
40	175	5	17.8240000	1.53832051
40	195	5	18.8740000	0.65884748

Appendix C

Derivation of R-values for WFRP composites at various fibre contents:

Thermal conductivity and resistivity for WFRP at 10% fibre content

Using Eq. 4.5,

$$K_{10} = \frac{K(MDPE)x(\partial t)}{(\partial T)}$$

Where, K(MDPE) = 0.33 W/mK

∂t = 33.1K (temperature difference for LDPE sample)

∂T = 26.8K (temperature difference for 10% WFRP sample)

$$= \frac{0.33x33.1}{26.8} = 0.407 \text{ W/mK}$$

Hence,

$$\mathbf{R_{10}} = \frac{1}{0.407} = \mathbf{2.45 \text{ mK/W}}$$

Thermal conductivity and resistivity for WFRP at 20% fibre content

$$K_{20} = \frac{K(MDPE)x(\partial t)}{(\partial T)} = \frac{0.33x33.1}{30.1} = 0.36 \text{ W/mK}$$

Hence,

$$\mathbf{R_{20}} = \frac{1}{0.36} = \mathbf{2.77 \text{ mK/W}}$$

Thermal conductivity and resistivity for WFRP at 30% fibre content

$$K_{30} = \frac{K(MDPE)x(\partial t)}{(\partial T)} = \frac{0.33x33.1}{31.3} = 0.34 \text{ W/mK}$$

Hence,

$$\mathbf{R_{30}} = \frac{1}{0.34} = \mathbf{2.86 \text{ mK/W}}$$

APPENDIX D

Derivation of the equation for determining the variable pressure exerted by wet concrete on the foundation formwork boxing:

From the theory of fluid mechanics, the pressure 'P' (in N/m^2) exerted by fresh concrete on the foundation formwork boxing could be determined by,

$$P = \rho g h$$

where,

ρ = Density of the fluid (Kg/m^3) = $2400 kg/m^3$ for fresh concrete

g = Acceleration due to gravity (m/s^2) = $9.81 m/s^2$

h = Height (or depth) of the fluid in the container = 1m

$\Rightarrow$ P = 2400 x 9.81 x 1

= 23544 N/m^2

The pressure exerted would vary from $0 N/m^2$ at the top of the formwork to $23544 N/m^2$ at the base of the formwork as shown in Figure B.1

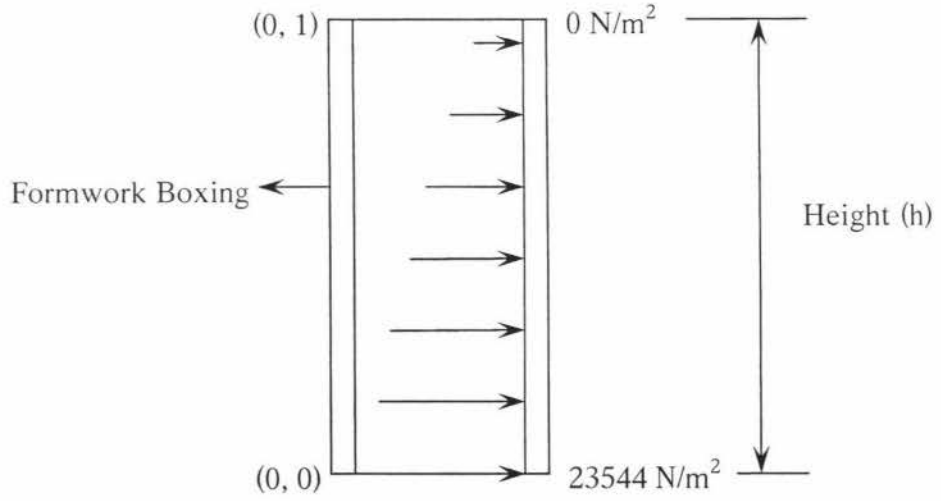


Figure B.1 Pressure triangle of concrete on the foundation formwork boxing

It should satisfy the Equation B.1 below (SolidWorks User's Manual, 2001).

$$p * (A + Bx + Cy + Dxy + Ex^2 + F y^2) = P(x,y)$$

where,

p = a value by which the equation would be scaled to give the pressure at any point *x,y* on the part = $23544 N/m^2$

Appendix D – Equation for variable pressure

P(x, y) = co-ordinates at which the pressure P is exerted = varies from 0 to 23544N/m^2, at co-ordinates (0m, 1m) and (0m, 0m) respectively.

A,.. .F = coefficients which will be scaled by '*p*' to determine the pressure at that point.

To find the coefficients A to F:

At P (0, 0), from Equation B.1 we have,

$$P(0, 0) = p * (A) = 23544 \quad \text{... Eq. B.2}$$

Let **A = 1**

$$\Rightarrow p = 23544$$

At P (0, 1),

$$\Rightarrow p * (A + C + F) = 0$$

$$\Rightarrow pA + p (C + F) = 0$$

$$\Rightarrow 23544 + 23544 (C + F) = 0$$

$$\Rightarrow 23544 (C + F) = -23544$$

$$\Rightarrow C + F = -1$$

$$\Rightarrow \mathbf{C = -(F + 1)}$$

One of the values of C and F that would satisfy the Equation B.1 could be,

$$F = 1$$

$$\Rightarrow C = -2$$

One of the possible coefficients are:

A = 1, B = 0, C = -2, D = 0, E = 0, F = 1

And one of the equations that would satisfy the Equation B.1 is,

$$\boldsymbol{P(x, y) = p (y^2 - 2y + 1)}$$

Appendix E – Financial Analysis

Table E-1 Building Consents Issued – May							
	Value $(million)	Total Dwelling Units No.(3)	Area (m^2) (000)	Total Value $(million)	Dwelling Alterations & Additions	Domestic Outbuildings	Total Residential Buildings
					Value $(million)		
Year Ended May:							
1999	229.5	22061	3513	2931	511.3	182.6	3624.9
2000	306.6	24736	4121	3414.9	542.8	182.6	4140.3
2001	195.9	19303	3388	2841.8	555.3	163	3560.1
2002	298.6	22309	4088	3578.6	635.6	159.4	4373.6
2003	507.7	28546	5046	4661.3	686.8	187.3	5535.4
Monthly							
2001	24.7	1856	324	270.6	50.2	17.3	338
	19.8	1640	280	238.6	39.8	12.2	290.6
	13.6	1690	297	264.5	49.8	14	328.3
	34.8	2020	366	301.4	58.9	13.5	373.9
	17.8	1678	317	267.6	51.6	11.6	330.8
	21.8	1931	340	299.8	53.3	14.5	367.6
	31.2	2148	360	298.4	55.9	15	369.3
	25.8	1497	318	306.2	45.6	10.5	362.3
2002	7.5	1486	286	248.9	49.3	10.5	308.8
	32.6	1745	336	293.3	49.3	12.2	354.8
	30.8	1986	381	333.7	53.4	12.1	399.1
	30.5	2206	380	338.8	56.7	13.6	409.2
	32.2	2282	427	387.4	72	19.6	479
	16.5	1864	358	316	51.1	13.8	380.9
	63.6	2738	475	417.3	58.6	15.8	491.7
	17.2	2105	398	351.8	54	14	419.9
	42.1	2420	417	386.2	57.4	15.4	459

	119.7	3412	488	457.7	63.2	17	537.8
	55.4	2432	423	405.6	58.1	17.6	481.2
	34.2	2532	429	381.5	52.3	13.7	447.6
2003	22.5	1995	365	340.3	50.5	12	402.8
	5	1797	359	330.4	53.4	14.3	398.2
	35.7	2537	464	435.7	63.5	18	517.2
	61.5	2232	398	400.3	57.6	16.7	474.6
	34.3	2482	472	438.4	67	19.1	524.4

(Table E-2) Costing to build the formwork by the traditional method

Standard data

Total area (floor) of data (2) (sq. m.)*	5046000	5802900
Misc. overheads	0.1	
Cost of timber (100mm x 40mm, One metre long) (NZ$) (≈)	6.46	
Timber required to construct a foundation of height one metre (approx.) ##	1120	
Wastage involved	0.1	
Cost per peg (NZ$) *** (incl. of 12% GST)	3.09	
# of pegs used / metre	2	
Floor area (sq. m.) per unit	177	
Width of the the floor of the residential building (m.) ##	9.4	
Length of floor of the residential building (m.) ##	18.8	

Market details

		2003	2004	2005	2006	2007
1	Market growth (%) #		0.15	0.15	0.15	0.15
2	Residential building permits issued in 2003 *	28546	32827.9	37752.09	43414.9	49927.13
3	Market (dwelling units per year) **	21409.5	24620.93	28314.06	32561.17	37445.35
4	Market share (%)	0.1	0.1	0.1	0.08	0.06
5	Market share (units)	2140.95	2462.093	2831.406	2604.894	2246.721
6	Total floor area of data (3) (sq. m.) *	3784500	4352175	5005001	5755751	6619114
7	Floor area of data in (5) (sq.m.)**(a)	378450	416295	457924.5	494558.5	524232
8	Perimeter length of foundation per unit residential blding (m.) ##	111.76	111.76	111.76	111.76	111.76
9	Total perimeter length of foundation of data in (5) (m.)	239272.6	275163.5	316438	291122.9	251093.5

Costs

10	Total cost of timber to build 1metre tall foundation wall (NZ$) (≒)	7235.2
11	Cost of Pegs (inclusive of recycling)	172.6692
12	Number of hours worked per person per day	8
13	Wage rate per hour (NZ$)	30
14	Number of days worked on building the formwork by one person	3.5

	Cost per residential unit	*NZ$*
15	Direct materials (timber + pegs, excl. wastage)	7407.869
16	Direct labour ****	840
17	Variable overhead (misc. expenditure like nails, etc)	824.7869
18	Cost of building the formwork boxing per residential unit (NZ$)	9072.656
19	**Actual cost of building the formwork boxing per residential unit (NZ$) (δ)**	**1837.456**

Notes and assumptions:

* Data from Statistics New Zealand, www.stats.co.nz

** Considering only single storeyed residential buildings (75%) of total dwelling units, data from Statistics New Zealand and PNCC

*** Pegs considered here - 2 pegs / metre, size of each peg 750mm, (assummed to be recycled about 4 times)

(Peg cost data from Placemakers, Palmerston North)

**** 3.5 days (@ 8 hrs per day) for constructing a 177sq.m house, by one person, @ $30 per hour

Includes time for building, taking off and cleaning the timber boxing

See note on Floor plan on page 98A.

(≈) Radiata Pine, H3 treated timber decking board, price from www.carters.co.nz. Quoted price is retail, inclusive of GST.

(⊨) The timber will completely be recycled after the formwork is disassembled and cleaned

(δ) This is data in (18) – Data in (10) (which includes an approximate 10% wastage in timber used.)

The following additional costs have not been considered, which could increase the cost of building one sq. m. of formwork boxing

i. Cost of finishing the foundation by plastering.

ii. Time required to assemble the steel reinforcement

Appendix E – Financial Analysis

Note on foundation plan:

Consider the floor plan given in Figure E-1. The floor is rectangular in shape with the length of the floor assumed to be twice the floor width. The foundation thickness is 130mm (as specified by New Zealand Building Code).

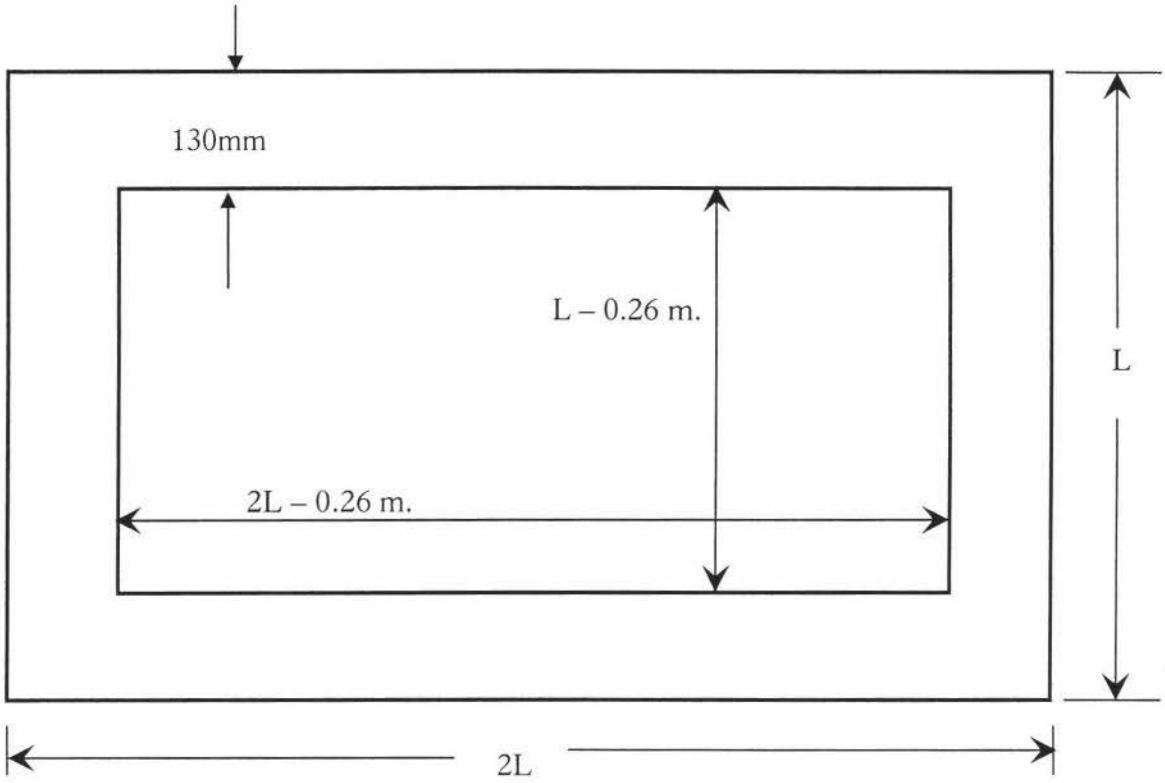


Figure E-1 Foundation plan of a residential unit

The total *floor* area of a residential building is about 177sq. m. Thus,

$$2L^2 = 177 \Rightarrow L = \sqrt{\frac{177}{2}} \Rightarrow L = 9.4\text{m}$$

Timber is required on either side to construct the foundation wall. Hence the total perimeter of one residential unit

$$= 6L + 6L - 1.04$$

$$= 12\ (9.4) - 1.04$$

$$= 111.76\text{ m.} \approx \mathbf{112\ m.}$$

(Note that this is only while constructing the foundation using the traditional method, and is not the case while using the proposed product.)

Number of timber required for building the formwork boxing:

Length of timber = 1m. Width of timber = 100mm (10 timbers to build 1m high foundation). Thus for a perimeter length of 112 m., and a height of 1m, total number of timber required is approximately **1120**.

(Table E-3) Financial details for manufacturing the foundation block made of the WFRP composite material

Standard details

Total foundation area of data in '2' (sq. m.) (for 2003 and 2004 respectively)*	5046000	5800690
Weight per block (kg)	1.2	
Number of blocks required to cover a foundation height of one metre	3.3	
Length of block (m.)	0.60	
Block Height (m.)	0.30	
Block width (m.)	0.15	
Manuf. Margin (%)	15	
Retailer's Margin (%)	20	
Wood fibre cost per kg. (NZ$)	0.4	
Manufacturer's cost of MDPE per kg. (NZ$) [‡]	2	
GST (%)	12	
Foundation area / unit (sq. m.)	176.7	
Wood fibre content (%)	30	
MDPE Content (%)	70	

Market Details

		2003	2004	2005	2006	2007
1	Market growth (%) [#]		15%	15%	15%	15%
2	Residential building permits issued *	28546	32828	37752	43415	49927
3	Market (dwelling units per year)**	21410	24621	28314	32561	37445
4	Product market share (%) [§]	10%	10%	10%	8%	6%
5	Product market share (units)	2141	2462	2831	2605	2247
6	Total foundation area of data (3) (sq. m.) *	3783059	4350517	5003095	5753559	6616593
7	Floor area of data in (5) (sq.m.) **	378306	435052	500310	460285	396996
7a	Perimeter length of foundation per residential unit (m.) ***	54	54	54	54	54
7b	Number of blocks reqd. to cover the the foundation of one residential unit (including foundation height)	300	300	300	300	300
8	Total perimeter length of data in (5) (m.) (excluding foundation height)	115611	132953	152896	140664	121323

9	Number of blocks reqd. to cover the perimeter length of the foundation (excluding height of foundation)	192686	221588	254827	234440	202205
10	Total number of blocks reqd. to cover the foundation for data in (5) (including foundation height)	642285	738628	849422	781468	674016

Material costs per block

11	Cost of Radiata pine per block (NZ$) €	0.14
12	Cost of MDPE per block (NZ$) €	1.68
13	Total cost of materials (NZ$) per block	1.82
14	Total cost of material per residential unit (NZ$)	547.20

Variable cost per block

15 Direct labour : Not considered. See note below.

Selling Price per block

16	Manuf. selling price (NZ$)	1.82
17	Mfg selling price (inclusive of manuf.'s margin) (NZ$) §§§	2.09
18	Retailer gross margin (NZ$)	0.41
19	Retail price, GST-excl (NZ$)	2.51
20	**Retail price, GST-incl (NZ$) per block**	**3.02**
21	**Cost of building formwork boxing with WFRP blocks for one residential unit (NZ$)**	**906.16**

Notes and assumptions:

* Data for 2003 from Statistics New Zealand, www.stats.co.nz, foundation area projected for 2004 and beyond

** Considering only single storeyed residential buildings (75%) of total dwelling units, data from Statistics New Zealand and PNCC

*** The moulded blocks take the 2 sides of the foundation into consideration. Thus, the perimeter length of the foundation considered will only be 6L in this case. See 'Floor Plan' (Appendix E, page 98) for details.

\# Based on the growth from 1999 to 2003

€ Cost of PR per kg = NZ$0.5, cost of RM grade MDPE per kg = NZ$2.00,
Please note that the cost of MDPE powder for such high volumes will include discounts, which has not been considered in this analysis.

§ Assumed to drop, because of anticipated competition

§§§ Assuming that the manufacturer's margin is 20%
Fixed costs (for eg., cost of the injection mould) have not been considered.
⅃ Resin pricing data from http://www.plasticsnews.com/subscriber/resin/price1.html

A Note on Labour cost:
Labour cost has not been considered for this analysis. This is because in a real world situation, the chief labour cost involved (operating the injection moulding machine) is based on a fixed daily wage of the operator and overheads. Without knowing the actual daily production volumes of the blocks, including this cost would lead to erroneous costing. Further the labour cost must also include the cost for assembling the blocks prior to constructing the foundation, which is not known at the present time.

Appendix E – Financial Analysis

Scenario I

Scenario I : Housing market share remains constant, product market share increases

Pdt. market share		Housing market share		Retail price per block	Price per sq. m.
%	units	%	units	(NZ$)	(NZ$)
10	2,462	15	24,612	7.92	50.78
20	4,924	15	24,612	6.63	43.04
30	7,386	15	24,612	6.06	39.62
40	9,848	15	24,612	5.72	37.58
50	12,310	15	24,612	5.49	36.20
60	14,772	15	24,612	5.32	35.18
70	17,234	15	24,612	5.18	34.34
80	19,696	15	24,612	5.08	33.74
90	22,158	15	24,612	4.99	33.20
100	24,620	15	24,612	4.91	32.72

Scenario II

Scenario II : Housing market share increases, product market share remains constant

Pdt. market share		Housing market share		Retail price per block	Price per sq. m.
%	units	%	units	NZ$	NZ$
10	2,462	15	24,612	7.92	50.78
10	2,783	30	27,832	7.66	49.22
10	3,104	45	31,044	7.44	47.90
10	3,425	60	34,255	7.25	46.76
10	3,747	75	37,467	7.09	45.80
10	4,068	90	40,678	6.94	44.90
10	4,282	100	42,819	6.86	44.42

Scenario III

Scenario III : Housing market increases, product market share increases

Pdt. market share		Housing market share		Retail price per block	Price per sq. m.
%	units	%	units	NZ$	NZ$
10	2,462	15	24,612	7.92	50.78
30	8,350	30	27,832	5.91	38.72
45	13,970	45	31,044	5.37	35.48
60	20,553	60	34,255	5.04	33.50
75	28,100	75	37,467	4.82	32.18
90	36,610	90	40,678	4.66	31.22
100	42,819	100	42,819	4.58	30.74
100	64,229	200	64,229	4.38	29.54